

RESEARCH REPORT



Influence of Application Factors on the Performance of Elastomeric Waterproofing Membranes



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**INFLUENCE OF APPLICATION
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MEMBRANES**



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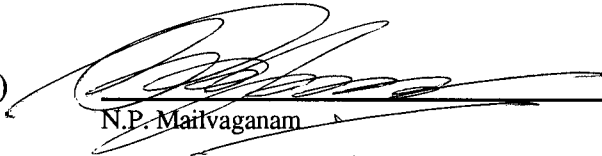
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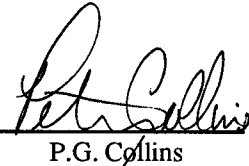
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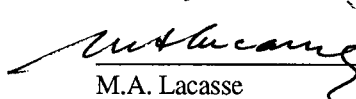
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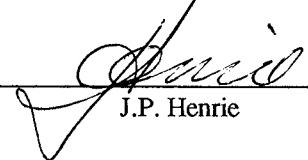
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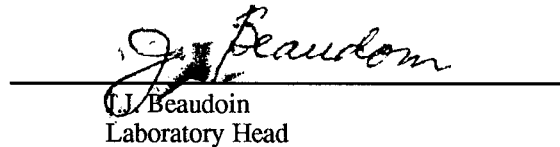

N.P. Maitvaganam


P.G. Collins


M.A. Lacasse


J.P. Henrie

Approved


J.J. Beaudoin
Laboratory Head

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Much of the material presented in this study draws from interviews and discussions held with individuals from consulting companies, contractors, applicators and membrane manufacturers. They are deserving of our thanks.

EXECUTIVE SUMMARY

The deck slab of a parking garage in addition to serving as a structural diaphragm and wearing surface, must provide protection for the space below. These functions require a deck that is impervious to liquids; stopping water from seeping through cracks. Current practice includes the sealing of the top surface of the deck by penetrating sealers and elastomeric membranes. This study is limited to a discussion on the use of membranes.

The protection that elastomeric parking garage membranes afford is contingent upon how well and for how long they function in service. This is dependent not only on the material characteristics of the membrane system but also on how well it is installed. Most are cold liquid applied self adhering elastomers which vary in chemical composition and method of application. Individual properties of the membranes are governed by the many factors peculiar to each material. For example, ambient temperatures and relative humidity conditions can affect application properties such as viscosity, flow characteristics, pot life, curing rate and extent of cure, film continuity and coverage (film thickness) achieved. Therefore most materials on the market require a minimum surface temperature of 10°C (50°F)¹. Many of the parking garage waterproofing systems are installed by licensed applicators who are trained by the manufacturers of such products. However, poor on-site practice and an indifference to quality control during installation often produces a final product with dubious performance.

Premature material deterioration is one of the most frequent and serious problems. The degradation processes of these materials are quite complex and dependent on a variety of factors including composition and structural defects produced during the compounding of the finished product². Damage to the product may result in the formation of defects which will act as weak sites during its subsequent service life^{3,4}. Therefore, membrane manufacturers specifications pertaining to substrate surfaces, suitable application temperatures, mixing ratios and mixing times should be adhered to so that the incidence of defects is kept to a minimum.

The work presented here was commissioned by Canada Mortgage and Housing Corporation to provide a guide that will be useful to engineers and others involved either in the execution of parking garage repairs or the installation of a membrane in new construction. It constitutes Phase II of the broad study on membranes. In Phase I the evaluation of the performance of various membranes to chemical, physical and mechanical factors causing degradation was investigated⁵. The significance of findings in Phase I was that criteria for selection identified in the various standards were inadequate to ensure the proper selection of materials for the job at hand. In the absence of appropriate performance limits, these

criteria were found to serve best as a screening mechanism. They provide limited assurance that an applied membrane will perform as claimed by the manufacturer.

This study sets out to bring together not only previous research done in house, but also research done throughout North America⁶⁻¹⁹. It identifies the range of application problems and defects that result from poor field practice during the installation of currently available membrane systems in Canada. Issues relating to the variation in ambient temperature and humidity conditions, workmanship factors and surface preparation are discussed. This study focuses on the problems that arise when manufacturers specifications relating to application parameters are ignored for the sake of expediency. Along with the causes for the resultant problems, critical changes in the viscosity and cure rate which influence the method of application (viz. spraying, squeegee) and the development of important properties are identified.

OBJECTIVES

The objectives of this study were to identify key parameters affecting the proper installation and optimum curing of elastomeric parking garage membranes. In this regard, the effects produced by the variation in ambient conditions during application of the membrane system, the influence of poor field practice and the different types of surface preparation techniques were investigated. More specifically, the study focused on the following factors:

1. The effects produced on the curing of the elastomeric membrane and hence its properties by variation in relative humidity while temperature remained constant.
2. The effects produced on the curing of the elastomeric membrane by variation of the curing temperature at constant relative humidity.
3. Effects due to workmanship factors such as (a) poor mixing, (b) incorrect proportioning of the components and (c) mixing and placing at temperatures below that stipulated by the manufacturer.
4. Variation in membrane properties due to different surface preparation.

METHODOLOGY

Information relating to field practices used in the installation of elastomeric parking garage membranes was ascertained by a review of the literature, interviews with applicators, membrane manufacturers, owners of garages and by visits to sites by Technical Officers involved in this study. Following a collation of the key installation parameters that influence membrane performance, an experimental program was designed to provide verification of the effects cited in the literature as well as those observed by technical personnel in the field. The experiments were also intended to elucidate possible mechanisms responsible for the incorporation of defects during the application stage.

The effects produced by varying ambient application temperatures and humidities were determined from changes to critical mechanical properties in comparison to those obtained under normal conditions. Poor field practice was simulated by applying the membranes under conditions contrary to those stipulated by the manufacturer. For example, poor mixing was obtained by mixing the two components for one third of the manufacturers recommended mixing time while a 15% variation in the resin and hardener components constituted incorrect proportioning.

Critical measurements of reaction kinetics and viscosity under varying ambient temperatures provided an insight into the possible mechanisms responsible for both altered values of key properties as well as the incorporation of defects during the installation stage.

FINDINGS

Under the test conditions that simulated variations in ambient climatic conditions and poor workmanship practices, the following changes to material properties were observed.

- In general, the variation of humidity at constant temperature affected the curing of the membrane. Curing under high humidities resulted in greater changes to the tensile properties (tensile strength, elongation, energy to rupture and modulus of elasticity) than under low humidities. Long term elongation, however, was found to be less affected by relative humidity variation.
- Variation of ambient temperature at constant humidity affected the rate and extent of curing of the membrane, especially at early ages (up to 7 days). Thereafter, in most cases, little change in tensile properties was observed.
- Changes in temperature can have a dramatic effect on the viscosity of the liquid elastomer used in waterproofing membranes. Viscosity values, dependent on the application technique, can affect the properties of the finished product due to altered (from the normal state) response in shear, sagging and self levelling properties. This can affect membrane thickness which is vital in ensuring that projected advantages are provided in the field^{2,13}. Low temperature effects, which increase the viscosity, appeared to have a greater impact on the application properties than high temperature effects.
- The permeance, and hence waterproofing characteristics, of certain membranes can be seriously affected by changes in ambient temperature and humidity conditions. Whereas curing at high relative humidity (at standard temperature) and both low and high temperatures (at standard

humidity) caused an increase in permeance, only low relative humidities (at standard temperature) resulted in any decreases in permeance.

- It is important to adhere to manufacturers stipulated mix proportions of the components. Deviations can result in considerable changes in tensile properties, especially at early ages.
- The effects on the adhesion of the membrane to concrete due to incorrect mix proportions was evaluated with different surface preparation techniques. No trends were seen in the adhesion of the membrane to concrete when excess resin was used. When excess hardener was used, however, shotblasted surfaces gave lower values than either sandblasted or water jet blasted surfaces.
- The shot blasting technique resulted in the largest surface profile. Since some of the recommended membrane thicknesses fall below this profile, its use with very thin membranes should be reviewed. Furthermore, certain membranes, when placed in thicker than recommended layers have a tendency to foam.
- The effects due to poor mixing of membrane components were similar to those observed for incorrect proportioning of the components.
- The interval between mixing and application of the membrane affects the degree of adhesion to the concrete substrate. The optimal time interval after mixing is less than 30 minutes. After 30 minutes large decreases in adhesion were noted.
- The time of application of the subsequent coats can significantly influence intercoat adhesion. Intercoat adhesion problems can arise if the interval between application of the successive coats is delayed too long.

RECOMMENDATIONS

Code requirements dictate that the standing multi-deck parking garage must be at least 50% open to the elements^{1,8}. Therefore, they are subject to wind chill factors that in northern climates can drop floor level temperatures to many degrees below zero and diurnally raise slab temperatures to above freezing. Since installed elastomeric parking garage membranes will be subject to such drastic thermal variations, it is important that the properties of the installed product be ensured by proper vigilance throughout the installation. The following recommendations are suggested.

- Waterproofing membranes must adhere well to concrete. Consequently, many specifications stipulate proper surface preparation according to membrane manufacturers instructions. The actual surface preparation procedures used will depend on the trowelled surface or the presence of contaminants or curing compounds. A minimum surface profile of 0.2 to 0.4 mm (8 to 10 mils) would be required to remove oil and stubborn surface contaminants¹³. Due to the large amounts of dust generated during sandblasting, it is not permitted in many closed areas and a shotblasting machine is used instead. However, previous work²⁰ has shown that shotblasting leaves a fractured near surface which is susceptible to delamination. Also, this investigation has shown that this technique produces the largest profile. Since some of the recommended thicknesses fall below this profile, its' use with very thin membranes, as well as those that foam when placed in thicker than recommended sections should be reviewed.
- Each liquid elastomeric system has special application requirements that are peculiar to that system. Different ingredients influence not only coating application techniques, but also determine substrate requirements. Weather conditions such as ambient temperature and humidity affect the quality of the application and subsequent performance of the membrane. Below a certain temperature many materials will be too viscous to form a continuous film of the correct thickness and the adhesive bond to concrete is reduced. Therefore the influence of ambient temperature and relative humidity conditions on important application properties such as viscosity, flow characteristics, pot life, curing continuity of film formed and coverage per coat should be ascertained prior to the installation of the membrane.
- Two component systems are sensitive to the proportioning of the base resin and curative. Since mixing ratios vary among the available systems manufacturers recommendations should be adhered to. Most systems call for thorough mixing of the components to uniform consistency.
- During application, samples of the film should be taken on an appropriate base and coupons for tensile property tests should be obtained from these specimens. The results of these tests may be compared with those stated in product data sheets. In this way, the quality of the installed product and the efficiency of the mixing and spreading can be monitored².
- The ability of a membrane to prevent the ingress of moisture and chloride ions is currently determined by the crack bridging test (ASTM C957). Previous work showed that membranes passing this test are still subject to reflective cracking in the field^{7,13}. Such failure is probably due to defects incorporated into the membrane by substrate movement during its early curing⁹. When elastomeric membranes are applied under temperatures below that specified by the

manufacturer they are likely to be subjected to movement in the early curing stages, prior to the development of full elastomeric properties. Thus proper application temperatures are imperative to future membrane performance.

- Since the time of application of subsequent coats influences intercoat adhesion, the material should be applied soon after mixing. The mixing of only enough material for use within a reasonable time is recommended.
- Some membranes are susceptible to foaming when placed in thicknesses exceeding that stipulated by the membrane manufacturer. The applicator of such membranes should incorporate proper on site quality control procedures to ensure correct membrane thickness is achieved.
- Specification should define the type of parking membrane required and the quality of the installed system. Such specifications should include^{2,8,12}:
 - thickness of the membrane to suit the in-service conditions.
 - limitations and requirements imposed by weather conditions during application.
 - stipulations on concrete quality and finishes to meet requirements of the membrane.
 - stipulation that the garage not be subjected to vehicular traffic prior to proper curing of the membrane system. In this regard the prevailing ambient conditions should receive due consideration.
 - requirement of a test area of sufficient size which allows for a valid appraisal.

RÉSUMÉ

La dalle de plate-forme d'un stationnement de garage, en plus de servir de diaphragme structural et de surface de résistance, doit offrir une protection aux espaces inférieurs. Ces qualités exigent que la dalle résiste aux liquides et qu'elle empêche l'eau de pénétrer dans les fentes. Les pratiques actuelles comprennent le scellage de la surface supérieure de la dalle au moyen de scellants et de membranes élastomères. La présente étude se borne à une discussion sur l'usage de ces membranes.

La protection qu'offrent les membranes pour un stationnement de garage dépend de la fréquence et de la durée de l'usage qu'on en fait. L'efficacité repose non seulement sur les caractéristiques de la composition du matériau, mais aussi sur la manière dont il est posé. La plupart des membranes consistent en un liquide froid auto-adhérent dont la composition chimique et le mode d'application varient. Plusieurs facteurs pertinents à chaque matériau régissent les propriétés particulières des membranes. Par exemple, les températures ambiantes et les conditions d'humidité relative peuvent agir sur les propriétés d'application telles que la viscosité, les caractéristiques propres à l'écoulement, les chances et l'importance de voir le produit gagner en efficacité avec le temps, la consistance de la pellicule et sa récupération, c'est-à-dire son épaisseur. En l'occurrence, la plupart des matériaux sur le marché requièrent une température de surface minimum de 10 °C, soit 50 °F, pour leur application¹. Nombre de membranes pour stationnement à l'épreuve de l'eau sont installées par des techniciens formés chez les fabricants des membranes. Pourtant, une pratique inadéquate sur place et une insouciance vis-à-vis du contrôle de la qualité lors de l'application donnent souvent lieu à une performance douteuse.

La détérioration prématurée du matériau représente l'un des problèmes les plus sérieux et les plus fréquents. Les processus de dégradation de ces matériaux sont assez compliqués et relèvent d'une variété de facteurs comprenant les imperfections dans la composition et la structure survenue lors de l'assemblage du produit final². Les dommages que subit le produit peuvent

provenir de la formation d'imperfections qui détériorent sa qualité^{3,4}. Par conséquent, les fabricants devraient accompagner leurs produits d'explications claires relativement aux surfaces substrates, aux températures idéales d'application, aux proportions et aux durées de mixage, de manière à diminuer le plus possible les risques d'imperfections.

La Société canadienne d'hypothèques et de logement a demandé la réalisation de cette étude afin de guider les ingénieurs et les autres travailleurs chargés d'effectuer des réparations dans un stationnement de garage ou d'installer une membrane dans une nouvelle construction. L'étude représente la phase II d'une plus vaste recherche sur les membranes. La phase I touchait à l'évaluation de la performance de diverses membranes soumises à des facteurs chimiques, physiques et mécaniques causant une détérioration⁵. L'essentiel des résultats de cette première étape montrait que les critères de sélection repérés dans les diverses normes ne suffisaient pas à assurer un bon choix des matériaux pour le travail à accomplir. En l'absence de limites de performance appropriées, on a trouvé que ces critères offraient le meilleur système de sélection. Ils fournissent une assurance relative de la performance indiquée par le fabricant, une fois la membrane appliquée.

L'étude vise à regrouper non seulement les recherches nationales précédentes, mais également celles qui ont été réalisées un peu partout ailleurs en Amérique du Nord⁶⁻¹⁹. Elle offre un éventail des problèmes d'application et des défaillances résultant de méthodes inappropriées lors de l'installation des types de membranes actuellement sur le marché au pays. Les questions relatives à la variation de la température ambiante et des conditions d'humidité, aux facteurs liés à la qualité du travail et la préparation de la surface sont commentées. L'étude met l'accent sur les problèmes qui surviennent quand les particularités des fabricants concernant les paramètres d'application sont ignorées pour accélérer le processus. Les sérieux changements dans la viscosité ou dans les chances de succès influençant le mode d'application (au moyen d'un vaporisateur ou d'un balai en caoutchouc), et la découverte de propriétés importantes ont également figuré dans l'étude, au même titre que les causes des problèmes.

OBJECTIFS

Cette étude avait pour objectifs de déterminer les principaux paramètres qui influent sur la pose appropriée et le durcissement optimal des membranes élastomères destinées aux garages de stationnement. C'est ainsi qu'on a examiné les effets produits par la variation des conditions ambiantes lors de l'application d'une membrane, l'influence d'une mauvaise technique de mise en oeuvre et les différentes techniques de préparation de la surface. Les chercheurs se sont particulièrement intéressés aux facteurs suivants :

1. les effets produits sur le durcissement de la membrane élastomère et, par le fait même, sur ses propriétés à la suite d'une variation de l'humidité relative alors que la température demeure constante;
2. les effets produits sur le durcissement de la membrane élastomère à la suite d'une variation de la température de durcissement en humidité relative constante;
3. les effets de facteurs liés à l'exécution comme (a) un mauvais mixage, (b) un mauvais dosage du béton et (c) le mixage et la mise en place du béton à des températures inférieures aux recommandations du fabricant;
4. la variation des propriétés de la membrane résultant d'une préparation différente de la surface.

MÉTHODE

L'information concernant les techniques d'exécution utilisées pour mettre en oeuvre une membrane élastomère pour garage de stationnement a été vérifiée au moyen de documents, d'entrevues menées auprès de poseurs, de fabricants de membranes et de propriétaires de garages, et au moyen de visites effectuées par des agents techniques participant à la présente étude. Après avoir réuni les paramètres de pose clés qui influent sur la performance de la membrane, on a conçu un programme expérimental destiné à confirmer les effets mentionnés dans la documentation de même que ceux observés sur le terrain par les agents techniques. Ces expériences visaient également à déterminer les mécanismes pouvant entraîner des défauts lors de l'application.

On a déterminé quelles répercussions pouvait avoir une variation de la température et de l'humidité ambiantes à l'application en observant les changements qui survenaient aux propriétés mécaniques essentielles comparativement à celles qui étaient obtenues dans des conditions normales. Les mauvaises techniques d'exécution ont été simulées en appliquant les membranes dans des conditions contraires à celles préconisées par les fabricants. Par exemple, on a réalisé un mauvais mixage en mélangeant les deux composants pendant le tiers du temps de mixage recommandé, tandis qu'on simulait un mauvais dosage en modifiant de 15 % les proportions de résine et de durcisseur.

Des mesures critiques de cinétique et de viscosité prises dans diverses conditions de température ambiante ont fourni des renseignements sur les mécanismes pouvant être à l'origine de l'altération des valeurs des propriétés clés ainsi que de la production de défauts au moment de la pose.

RÉSULTATS

Dans les conditions d'essai qui ont simulé les variations au chapitre des conditions climatiques ambiantes et des mauvaises techniques d'exécution, on a pu observer les changements suivants aux propriétés des matériaux.

- En général, la variation de l'humidité, à température constante, a influé sur le durcissement de la membrane. Le durcissement dans des conditions d'humidité élevées a entraîné des changements plus importants aux propriétés mécaniques à la traction (résistance à la traction, allongement, énergie à la rupture et module d'élasticité) que dans des conditions de faible humidité. L'allongement à long terme, toutefois, s'est avéré moins sensible à la variation de l'humidité relative.
- La variation de la température ambiante, en humidité constante, a influé sur la vitesse et l'efficacité du durcissement de la membrane, surtout aux stades initiaux (jusqu'à 7 jours). Ensuite, dans la plupart des cas, les propriétés mécaniques à la traction ont peu changé.
- Les changements de température peuvent avoir des effets considérables sur la viscosité de l'élastomère liquide employé pour les membranes d'imperméabilisation. Les valeurs de

viscosité, selon la technique d'application, peuvent influencer sur les propriétés du produit fini parce que les propriétés de cisaillement, d'abaissement et d'autolissage sont différentes (par rapport à l'état normal). C'est ainsi que l'épaisseur de la membrane peut varier, un élément crucial qui assure que les avantages prévus sont bel et bien présents sur le terrain^{2,13}. Les basses températures, qui augmentent la viscosité, semblent avoir plus d'effet sur les propriétés d'application que les températures élevées.

- Les caractéristiques de perméance et, par conséquent, d'imperméabilité de certaines membranes peuvent être sérieusement modifiées par des changements de température et d'humidité ambiantes. Tandis que le durcissement en humidité relative élevée (à température normale) ainsi qu'à température basse et élevée (à humidité normale) a entraîné une augmentation de la perméance, seule l'humidité relative élevée (à température normale) s'est traduite par une diminution de la perméance.
- Il importe de se conformer aux dosages stipulés par les fabricants des composants. Les écarts peuvent avoir d'importantes répercussions sur les propriétés à la traction, surtout durant les premiers stades du durcissement.
- Les effets sur l'adhérence de la membrane au béton qui découlent d'un mauvais dosage des proportions ont été évalués pour différentes techniques de préparation de la surface. On n'a pu observer aucune tendance pour ce qui est de l'adhérence de la membrane au béton lorsqu'on utilise un excès de résine. Une utilisation excessive de durcisseur a toutefois produit sur les surfaces grenillées des valeurs inférieures à celles obtenues pour les surfaces traitées au jet de sable ou d'eau.
- Le grenillage a permis d'obtenir le profil superficiel le plus important. Comme l'épaisseur recommandée pour certaines membranes est inférieure à ce profil, l'utilisation de cette technique devrait être revue dans le cas des membranes très minces. En outre, certaines membranes, lorsqu'elles sont appliquées en couches plus épaisses que ce qui est recommandé, ont tendance à mousser.
- Les effets résultant d'un mauvais mixage des composants de la membrane étaient similaires à ceux observés lorsque les proportions étaient mal dosées.

- L'intervalle qui sépare le mixage des composants et l'application de la membrane influe sur le degré d'adhérence au substrat de béton. La période optimale qu'il faut prévoir après le mixage est de moins de 30 minutes. Après cette période, on remarque une forte diminution de l'adhérence.
- Le moment où les couches subséquentes sont appliquées peut avoir une influence significative sur l'adhérence des différentes couches. Des problèmes peuvent survenir lorsque l'intervalle entre l'application des couches successives est trop long.

RECOMMANDATIONS

Le code exige que les garages de stationnement autoportants à plusieurs étages soient ouverts vers l'extérieur d'au moins 50 %^{1,8}. Ils sont donc exposés au facteur de refroidissement du vent qui, en climat nordique, peut abaisser de nombreux degrés sous zéro la température au sol et qui peut aussi, le jour, faire augmenter la température de la dalle au-dessus du point de congélation. Comme les membranes élastomères posées dans les garages de stationnement sont soumises à des écarts de température aussi prononcés, il importe que les propriétés du produit installé soient garanties par une pose soignée. Les recommandations suivantes vont en ce sens.

- Les membranes d'imperméabilisation doivent offrir une bonne adhérence au béton. C'est pourquoi de nombreuses spécifications stipulent que la surface doit être préparée conformément aux instructions du fabricant de la membrane. Les méthodes utilisées pour préparer la surface dépendent de la face arasée ou de la présence de contaminants ou de produits de cure. Un profil superficiel minimal de 0,2 à 0,4 mm (0,008 à 0,01 po) serait nécessaire pour enlever les huiles et les contaminants de surface persistants¹³. En raison de la grande quantité de poussière que cette méthode produit, le sablage au jet est interdit dans de nombreux endroits fermés et il faut alors recourir à une machine à grenailage. Toutefois, des travaux antérieurs²⁰ ont montré que le grenailage pouvait entraîner une fissuration de la surface, une caractéristique favorisant le délaminage. En outre, cette étude a fait ressortir que cette technique permet d'obtenir le plus important profil. Étant donné que certaines des épaisseurs recommandées sont inférieures à ce profil, on serait avisé d'évaluer son utilisation dans le cas de membranes très minces et pour celles qui

moussent lorsqu'elles sont placées dans des sections plus épaisses que ce qui est recommandé.

- Chaque élastomère liquide possède son mode d'application particulier. Les différents ingrédients influent non seulement sur les techniques de pose, mais déterminent aussi les exigences relatives au substrat. Les conditions climatiques comme la température et l'humidité ambiantes agissent sur la qualité de l'application et sur la performance ultérieure de la membrane. Au-dessous d'une certaine température, de nombreux matériaux sont trop visqueux pour former une pellicule continue d'épaisseur appropriée et leur adhérence au béton est réduite. Par conséquent, avant de poser la membrane, il faut déterminer l'effet de la température et de l'humidité relative ambiantes sur d'importantes propriétés d'application comme la viscosité, les caractéristiques d'écoulement, la durée d'emploi, la continuité du durcissement de la pellicule formée de même que la couverture par couche.
- Les mélanges binaires sont sensibles au dosage de la résine et de l'agent de vulcanisation. Étant donné que les proportions de dosage varient d'un produit à l'autre, on se conformera aux recommandations du fabricant. La plupart des produits requièrent un mixage soigné des composants jusqu'à obtention d'une consistance lisse.
- Au moment de l'application, il faut prélever des échantillons de pellicule sur une base appropriée ainsi que des éprouvettes qui serviront à mettre à l'essai les propriétés à la traction. Les résultats de ces essais peuvent être comparés avec ceux qui figurent sur les fiches techniques des produits. De cette façon, il est possible de contrôler la qualité du produit posé de même que l'efficacité du dosage et l'étalement².
- La capacité d'une membrane à prévenir l'infiltration d'humidité et d'ions chlorure est actuellement déterminée par essai d'extensibilité au niveau des fissures (ASTM C957). Des travaux antérieurs ont montré que les membranes qui subissent cet essai avec succès sont toujours susceptibles de subir des fissurations par réflexion en service^{7,13}. Une telle défaillance est probablement causée par les défauts qui sont imprimés à la membrane par le mouvement du substrat durant les premiers stades du durcissement⁹. Lorsque les membranes élastomères sont appliquées à des températures inférieures à ce que précise le fabricant, elles peuvent être soumises à un mouvement au début du durcissement, avant

que les propriétés élastomères ne soient complètement atteintes. Il est donc essentiel de respecter les températures d'application appropriées pour garantir la performance à long terme de la membrane.

- Comme le moment d'application des couches subséquentes influe sur leur adhérence, le produit devrait être appliqué peu après son mixage. On recommande de ne préparer que la quantité de produit suffisante pour une période raisonnable d'utilisation.
- Certaines membranes peuvent mousser lorsqu'elles sont placées en épaisseurs excédant les épaisseurs prescrites par le fabricant de la membrane. Le technicien chargé d'appliquer de telles membranes doit procéder à des contrôles de qualité appropriés sur place afin de s'assurer qu'il obtient la bonne épaisseur de membrane.
- Les spécifications doivent définir le type de membrane de stationnement requis ainsi que la qualité de l'ensemble une fois posé. Ces spécifications doivent inclure les suivantes^{2,8,12} :
 - la membrane doit être suffisamment épaisse pour convenir aux conditions de service;
 - limites et exigences imposées par les conditions climatiques au moment de l'application;
 - prescriptions de la qualité du béton et revêtements de finition convenant au type de membrane;
 - prescription que le garage ne soit pas soumis à la circulation des véhicules avant l'obtention d'un bon durcissement; à cet égard, les conditions ambiantes doivent être prises en considération;
 - prévision d'une zone d'essai appropriée de dimensions suffisantes permettant une évaluation valide.



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I. INTRODUCTION

Membrane selection should always be based not only on a careful study of material properties but also on an evaluation of its performance under field conditions similar to those expected for the intended application. However, the correct assessment of a membranes performance is at present difficult because of a lack of appreciation of the degree to which a variation in ambient temperature and humidity conditions, surface preparation and other workmanship factors affect critical membrane properties. A derth of information relating to the causes and mechanisms which cause defects to be incorporated in the product during installation further contributes to the problem. Performance of the product is therefore highly dependent on prevailing ambient conditions and the care exercised during installation. The work presented in this report endeavors to address the potential problems encountered in the application of the product in the field.

The project was initiated in March, 1992. The work done here constitutes Phase II and addresses the issues of:

1. The sensitivity of the available membrane systems performance to various application variables.
2. Identification of the causes and mechanisms responsible for the formation of defects.
3. Measures to be taken to avoid such problems.

The results obtained from the study were derived from laboratory experiments, field observations and testing of field samples. Information obtained from applicators, membrane manufacturers, owners of garages and consultants was used in the designing of suitable experiments.

Overall project coordination was done by N.P. Mailvaganam. Major tasks were charged to the following: Dr. M. Lacasse (experimental design and analysis of results), Mr. P.G. Collins (laboratory testing, collation and analysis of results) and Mr. J. Henrie (site visits and field testing).

II. LABORATORY INVESTIGATION

A. Experimental

Various factors that influence the performance of elastomeric parking garage membranes during installation were investigated. These were: (a) the ambient weather conditions, (b) workmanship, (c) substrate surface preparation and (d) the application technique itself.

1. The effects due to ambient weather conditions were investigated by observing differences that occurred by curing membrane samples in an environmental chamber at selected temperatures and

humidities. Free film membrane samples for determination of tensile properties were cast on silicon release paper and tensile peel adhesion samples were cast on lightly sandblasted mortar substrates. In both cases the prepared samples were immediately placed in the environmental chamber. Five climatic conditions were chosen, considered representative of the varying conditions under which membranes are installed. These conditions can be classified essentially into two categories: isothermal (22°C) with varying humidity (30%, 50% and 85% RH); and isohydral (50% RH) under varying temperature (5°C, 22°C and 38°C).

Tensile strength, elongation, energy to rupture and modulus of elasticity (ASTM D412) were determined after curing for 1, 7 and 28 days at each condition. After 28 days, samples were prepared for determination of water vapour transmission (ASTM E96) and adhesion to a mortar substrate. The latter was determined using the peel method (ASTM C794). These tests were performed at standard conditions (22°C; 50% RH).

2. Workmanship factors were investigated by determining the effects of poor mixing and incorrect proportioning of membrane components. These factors were not, of course, investigated for the single component neoprene membrane. Poorly mixed samples were prepared by blending the resin and hardener, or catalyst, for one third of the manufacturers recommended mixing time. Incorrect proportioning was used to simulate incomplete decanting or full use of one of the components. Samples were prepared with a 15% excess of resin, or hardener, over the manufacturers recommended mixing ratios. Free film samples for both poorly mixed and incorrectly proportioned specimens were cast on silicone release paper and cured at standard conditions [Appendix 1 provides of mixing ratios for each membrane].

Tensile strength, elongation, energy to rupture and modulus of elasticity were determined from tensile tests on free film specimens after curing for 1, 7 and 28 days. After 28 days specimens were prepared for determination of water vapour transmission. These tests were performed at standard conditions.

3. Effects due to differences in surface preparation focused on evaluating three techniques: water jet blasting, sandblasting and shot blasting. The surface of 1220mm x 1830mm (4' x 6') concrete slabs was prepared using each method and subsequently cut into 150mm x 300mm (6" x 12") specimens. Samples of each membrane and primer (if specified) were then applied to the specimens. After 28 days, adhesion to the substrate was determined using a tensile pull-off test.

The effects on membrane to substrate adhesion due to substrate surface moisture conditions were also investigated. Wet surface conditions were created by first saturating the slabs with water for 24 hours and then allowing the substrate to achieve a saturated surface dry condition, which was achieved in ambient laboratory conditions before application of the membrane or primer.

Workmanship factors (poor mixing, incorrect proportioning and mixing at sub ambient temperatures) were also investigated for each surface preparation technique to determine the effect they had on adhesion to concrete.

4. The effects of ambient temperature at which the membrane is mixed and placed on the viscosity of the system was investigated. This provides information concerning the ease of application of the system and the ability to achieve the proper membrane thickness. Membrane components were conditioned at 5°C, 22°C and 38°C for 24 hours prior to testing. Viscosity and shear stress profiles as a function of shear rate were determined on a Bohlin Visco 88 viscometer. Temperature based profiles of the viscosity were then compiled for each membrane.

5. The effects of ambient conditions on the rate of membrane cure were ascertained by the determining the reaction rates of each membrane using conductive calorimetry on a Technical Innovations Calorimetry System.

B. Test Methods

1. Tensile Properties (ASTM D412)

The tensile strength, percent elongation, energy required to rupture the system and modulus of elasticity between 35% and 60% (cord modulus method) of the maximum load for free film membrane specimens were determined after 1 day, 7 days and 28 days curing at the specified curing conditions (5°C, 22°C and 38°C) on an Instron Model 1122 Universal Testing Machine fitted with an extensometer. Samples were extended at a rate of 50mm/min.

2. Water Vapour Transmission (ASTM E96)

After curing for 28 days at the indicated conditions, water vapour transmission, permeability and permeance were determined using the wet cup method. In order to eliminate the variation of permeance values caused by the differences in sample thickness, comparison of the water vapour transmission properties of the membranes was based on an empirical value of permeance. This was calculated using the average values of permeability determined from the tests and the average thickness of the membrane samples. This relationship is given in the equation below:

calculated permeance = average permeability x average thickness

3. Adhesion to Concrete by Direct Pull-off (ASTM D4541)

A pneumatic adhesion tester (PATTI 2A from SEMicro Corp.) was used to determine the adhesive bond strength of the membrane specimens applied to the surface of concrete substrates. For each specimen, average bond pull-off strengths were obtained by testing four 50 mm (2") diameter aluminum dollies affixed to the cured membrane (28 days at standard conditions) with an epoxy adhesive. The mode of failure was also observed.

4. Adhesion to Concrete by Peel (ASTM C794)

The adhesive peel strength of the membrane specimens applied to the surface of mortar substrates was determined on an Instron Model 1122 Universal Testing Machine. The free end of the membrane was peeled from the surface of the substrate at an angle of 90° to the horizontal. The peel front was maintained closely beneath the line of tension through the use of a sliding table to which the specimen substrate was attached.

III. FIELD INVESTIGATION

A. Jobsite Inspections and Field Sampling

Field investigation consisted of job site inspection, monitoring of the installation process and field sampling.

1. At the job site locations, photographs were taken prior to installation, during the application of the membrane and after the job was finished. Membrane thickness was monitored and in-situ bond strength was determined using the direct pull-out method. Concrete cores, with intact membrane, were obtained for subsequent laboratory investigation. The following membranes were sampled during their installation at the stipulated locations:

Membrane	Location
PDM1	Place du Portage, Hull, Quebec
PDM2	PWC Building, Toronto, Ontario
PDM3	City Hall, Ottawa, Ontario
PDM4	Pontiac, Michigan
PDM5	Islington Tower, Toronto, Ontario
PDM6	McArthur Place, Ottawa, Ontario

2. Field applied samples, produced by approved applicators, were collected for PDM1, PDM2, PDM3, PDM4 and PDM5. These samples consisted of full systems (i.e. including wear course) applied to

a sandblasted concrete substrate. After curing 28 days at standard conditions in the laboratory the bond strength to the concrete was determined using the direct pull-off method.

Concrete cores were extracted from various sections of the garage with a 100 mm diameter diamond bit core drill. These cores were used to subsequently evaluate the membrane thicknesses of the applied systems from microscopic examination in the laboratory.

B. Test Methods

1. Film Thickness

Wet film thickness was monitored by using a wet film thickness gauge. Dry film thickness was determined from micrographs taken of cores using a scanning electron microscope. Minimum and maximum range values of thickness were reported.

2 Adhesion to Concrete by Direct Pull-off (ASTM D4541)

The adhesive bond strength of membrane samples applied to the surface of concrete substrates was determined as previously described in Section II.B.3.

IV. RESULTS AND DISCUSSION

A. Laboratory Investigations

1. Ambient Weather Conditions

(a) Constant Temperature Properties

i) Tensile Properties

Tensile Modulus Values for modulus of elasticity are given in Tables 1 to 3 and in Figures 1 to 5. The modulus of elasticity is a measure of the resistance of a material to deform under an applied stress and it is expected that high modulus systems are less likely to deform than low modulus systems. Based on the values observed and as an aid for reviewing results, an arbitrary rating scale has been applied to the membranes that describe the relative values of modulus of elasticity. Results above 3 MPa are considered a 'high' modulus system, values between 3 MPa and 1 MPa a 'moderate' modulus systems and results that are less than 1 MPa a 'low' modulus system. These values can also be used in conjunction with values of energy to rupture to evaluate the performance of the waterproofing membrane.

Curing at 85% RH resulted in a lower modulus of elasticity at an age of 28 days, except for PDMS, where the results were comparable to those seen at 50% RH. Curing in a high humidity condition can also cause increases in modulus at early ages of cure in comparison to 50% RH. Curing at 30% RH

did not adversely affect the 28 day modulus, which was comparable to that attained at 50% RH, except for PDM4, where curing at 30% RH increased modulus of elasticity.

Table 1
Development of Tensile Modulus (MPa) as a Function of Relative Humidity
Membrane Cured 1 Day

System	22°C 30% RH		22°C 50% RH		22°C 85% RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	3.07	0.30	1.13	0.08	3.29	0.60
PDM2	0.96	0.10	0.88	0.05	0.67	0.03
PDM3	0.72*	0.72	0.82	0.12	1.00	0.09
PDM4	1.69	0.23	0.69	0.05	1.29	0.45
PDM5	0.61	0.05	0.35	0.04	0.38	0.12

* data taken after 2 days

Table 2
Development of Tensile Modulus (MPa) as a Function of Relative Humidity
Membrane Cured 7 Days

System	22°C 30% RH		22°C 50% RH		22°C 85% RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	11.06	4.80	3.82	0.16	3.50	0.33
PDM2	2.39	0.14	1.90	0.14	1.52	0.08
PDM3	1.98	0.21	3.24	0.24	1.37	0.14
PDM4	2.46	0.23	1.79	0.05	1.60	0.35
PDM5	0.67	0.03	0.45	0.05	0.48	0.01

Table 3
Development of Tensile Modulus (MPa) as a Function of Relative Humidity
Membrane Cured 28 Days

System	22°C 30% RH		22°C 50% RH		22°C 85% RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	4.42	0.45	4.85	0.27	3.67	0.35
PDM2	2.32	0.12	2.09	0.10	1.69	0.16
PDM3	3.54	0.40	3.48	0.26	1.49	0.07
PDM4	2.75	0.07	2.29	0.18	1.66	0.21
PDM5	0.73	0.14	0.70	0.06	0.66	0.06

PDM1 was a high modulus system; at 28 days, the modulus of elasticity obtained when cured at 85% RH was lower than those seen at 30% or 50% RH. PDM2 can be considered a moderate modulus system. Curing at 30% RH yielded higher moduli and at 85% RH lower moduli when compared to 50% RH. PDM3 was a high modulus system, except when cured at 85%, where this curing condition drastically reduced the modulus of elasticity. PDM4 was a moderate modulus system, again, except when cured at 85% RH, in which a reduction in the modulus was observed. Curing at 30%RH increased the

modulus. In the case of PDM5, a low modulus system, curing at 85% RH resulted in a modulus of elasticity greater than that seen when cured at 50% RH.

For PDM5, little change was seen in modulus of elasticity after 1 day curing regardless of curing humidity. Systems PDM2 and PDM4 evidenced little change in modulus of elasticity after 7 days curing. Little change in modulus was seen when PDM3 was cured at 50% or 85% RH after 7 days. When cured at 30% RH, however, this system exhibited a steady increase in modulus of elasticity. For PDM1, little change was seen in modulus of elasticity after 1 day at 85% RH. Curing at either 30% or 50% RH yielded increases at each age.

Energy to Rupture The values of energy to rupture are presented in Tables 4 to 6 and in Figures 6 to 10. Energy to rupture is a measure of the amount of work required to rupture the membrane sample and it is calculated as the area under the load-deformation (i.e. stress-strain) curve. The highest energies result from systems that have both a high tensile strength and elongation capacity (this is the ideal case). High energies can also result from systems that have either a very high tensile strength (e.g. PDM1) or very high elongation (e.g. PDM5). Conversely low energies result from poor tensile strength and poor elongation. This value can be used to evaluate the potential performance of a system. In general, a high energy system is likely to perform better for a longer period than a low energy system.

Curing at 85% RH essentially had no effect on the energy to rupture observed at 28 days age in comparison to the results seen at 50% RH, whereas curing at 30% RH resulted in decreases in the energy to rupture in comparison to 50% RH at 28 days.

Again, an arbitrary scale based on the observed values has been applied to the membranes. Energies to rupture above 3 J (Joules) are considered high, between 3 J and 1.2 J are considered moderate and below 1.2 J are considered low.

Table 4
Energy to Rupture (J) as a Function of Relative Humidity
Membranes Cured 1 Day

System	22°C 30% RH		22°C 50% RH		22°C 85% RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	1.27	0.12	1.48	0.41	2.28	0.14
PDM2	1.05	0.17	1.17	0.28	1.25	0.37
PDM3	0.05*	0.01	0.15	0.01	0.34	0.04
PDM4	1.00	0.10	0.84	0.32	0.81	0.26
PDM5	1.84	0.27	1.92	0.25	1.69	0.27

* data taken after 2 days

Table 5
Energy to Rupture (J) as a Function of Relative Humidity
Membranes Cured 7 Days

System	22°C 30% RH		22°C 50% RH		22°C 85% RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	0.93	0.41	1.87	0.47	1.78	0.19
PDM2	1.42	0.26	1.35	0.31	1.57	0.57
PDM3	0.40	0.10	0.50	0.13	0.61	0.05
PDM4	0.98	0.15	0.96	0.14	0.87	0.14
PDM5	1.78	0.23	2.66	0.39	2.19	0.13

Table 6
Energy to Rupture (J) as a Function of Relative Humidity
Membranes Cured 28 Days

System	22°C 30% RH		22°C 50% RH		22°C 85% RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	1.22	0.30	2.15	0.58	2.07	0.60
PDM2	1.27	0.18	1.52	0.30	1.29	0.18
PDM3	0.57	0.07	0.60	0.13	0.61	0.06
PDM4	1.29	0.48	0.90	0.11	0.88	0.27
PDM5	2.20	0.48	3.36	0.11	3.40	0.51

Except when cured at 30% RH, PDM1 can be considered a system with moderate energies to rupture. Curing at 30% RH lowered the energy to rupture; the value is representative of a low energy system. The energies to rupture seen at 50% and 85% RH were equivalent. At each humidity, PDM2 can be considered a moderate energy system. In comparison to 50% RH, curing at either 30% RH or 85% RH resulted in similar decreases in the energy to rupture at 28 days. The lowest rupture energies for all membranes cured at each humidity was obtained for PDM3. These values are independent of the curing humidity. At 28 days age, the energy to rupture PDM4 is low. Curing at either 50% RH or 85% RH resulted in similar energies to rupture, whereas curing at 30% RH, yielded an increase. The energy to rupture PDM5 at 28 days can be considered high, except when cured at 30% RH; at that humidity, a decrease in the energy to rupture was observed.

With the exception of PDM5, there was essentially no change in energies to rupture observed after 7 days (for PDM2 and PDM4 this is after 1 day). For PDM5, curing at 50% or 85% RH exhibited increasing energies at all ages.

Elongation The effects of varying the relative humidity of cure at constant temperature on elongation capacity are shown in Tables 7 to 9 and in Figures 11 to 16. Essentially, the elongation observed at 28 days was insensitive to changes in relative humidity, except PDM4 cured at 85% RH, which showed an

increase in capacity compared to 50% RH and PDM5 cured at 30% RH, which exhibited a decrease. PDM5 had the highest elongation capacity, regardless of curing condition.

Table 7
Development of Elongation (%) as a Function of Relative Humidity
Membranes Cured 1 Day

System	22°C 30%RH		22°C 50%RH		22°C 85 %RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	271	20	448	41	367	18
PDM2	417	51	375	46	388	53
PDM3	244*	36	226	14	251	12
PDM4	308	9	316	14	320	24
PDM5	918	49	831	11	863	20

* data taken after 2 days

Table 8
Development of Elongation (%) as a Function of Relative Humidity
Membranes Cured 7 Days

System	22°C 30%RH		22°C 50%RH		22°C 85 %RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	178	48	319	37	263	19
PDM2	296	35	268	29	270	22
PDM3	249	14	205	21	203	9
PDM4	221	16	267	20	327	31
PDM5	686	78	844	45	833	16

Table 9
Development of Elongation (%) as a Function of Relative Humidity
Membranes Cured 28 Days

System	22°C 30%RH		22°C 50%RH		22°C 85 %RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	238	28	268	33	280	40
PDM2	274	17	284	26	253	11
PDM3	259	26	236	17	219	14
PDM4	245	22	266	18	331	32
PDM5	762	82	882	21	888	69

In all cases, there was little change seen in the elongation capacity after 7 days of cure. However, both PDM1 and PDM2 exhibited large decreases in elongation capacity between 1 and 7 days, as did PDM4 and PDM5 when both cured at 30% RH.

Tensile Strength The tensile strength development under curing conditions of varying relative humidity (30%, 50%, 85%) at constant temperature (22°C) are shown below in Tables 10 to 12 and Figures 16 to 20.

Table 10
Tensile Strength Development (MPa) as a Function of Relative Humidity
Membranes Cured 1 Day

System	22°C 30%RH		22°C 50%RH		22°C 85 %RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	8.01	0.24	5.71	0.85	14.56	3.10
PDM2	4.36	0.28	3.73	0.45	2.90	0.39
PDM3	0.49*	0.07	2.40	0.45	2.96	0.31
PDM4	5.45	0.83	2.51	0.19	4.63	2.01
PDM5	7.16	0.43	3.33	0.39	3.37	1.08

* data taken after 2 days

Table 11
Tensile Strength Development (MPa) as a Function of Relative Humidity
Membranes Cured 7 Days

System	22°C 30%RH		22°C 50%RH		22°C 85 %RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	10.72	1.62	15.22	1.28	12.38	1.92
PDM2	7.25	0.58	5.57	0.69	4.54	0.24
PDM3	5.70	0.66	8.39	0.88	3.48	0.41
PDM4	6.24	0.57	5.28	0.41	5.82	1.05
PDM5	8.15	0.29	4.94	0.35	4.36	0.17

Table 12
Tensile Strength Development (MPa) as a Function of Relative Humidity
Membranes Cured 28 Days

System	22°C 30%RH		22°C 50%RH		22°C 85 %RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	9.01	1.31	16.45	2.26	13.36	2.66
PDM2	6.50	0.20	6.28	0.42	4.75	0.38
PDM3	11.01	1.64	10.31	1.39	4.08	0.36
PDM4	7.28	0.77	6.71	0.29	6.37	0.92
PDM5	8.27	1.01	7.19	0.39	6.00	0.58

Generally, of all the products evaluated, PDM1 developed the strongest tensile strength at every curing age and condition, with the exception of samples cured for 28 days at 30% RH. Curing at high humidity produced a lower tensile strength at 28 days, except for PDM4, which was comparable to that seen at 50% RH. For the high humidity condition, PDM1 developed significantly higher strengths than

the other membranes. At 28 days, lower humidities did not affect tensile strength as much as high humidities, except for PDM1, which was severely retarded. With the exception of PDM3, early strength development was improved at low humidities.

ii) Water Vapour Transmission

The average permeabilities and calculated average permeances of each waterproofing membrane determined through water vapour transmission studies are presented in Table 13. Permeability is a material property, such that meaningful comparisons may only be made within a product group to see how the ambient curing conditions affect that particular membrane.

Curing PDM1 in a condition of high humidity appeared to increase the permeability of the membrane, whereas exposure to a low humidity during curing had no effect. For PDM2, curing at a low humidity was shown to decrease, and a high humidity increased the permeability. Curing at either a low or high humidity increased the permeability of PDM3, although the effect of a high humidity cure was much greater than that of a low one. A similar response was seen for PDM4, however, in this case, the effect of a low humidity resulted in a higher permeability in comparison to that of a high humidity cure.

Table 13
Effect of Curing Humidity on Permeability and Permeance of Waterproofing Membranes

Membrane	Permeability ($\times 10^{-10} \text{g/Pa}\cdot\text{s}\cdot\text{m}^2$)			Permeance ($\times 10^{-7} \text{g/Pa}\cdot\text{s}\cdot\text{m}$)		
	30% RH	50% RH	85% RH	30% RH	50% RH	85% RH
PDM1	1.10	1.11	1.53	2.16	2.17	3.00
PDM2	1.96	2.35	2.92	2.07	2.50	3.11
PDM3	0.75	0.44	1.40	1.70	1.00	3.18
PDM4	1.84	1.33	1.47	1.98	1.43	1.58
PDM5	1.13	2.21	4.24	1.55	3.03	5.81

Permeance is a performance characteristic and may be used to compare the membranes. The urethane membranes performed much better than the neoprene at both normal and high humidity curing conditions than at the low humidity cure. Overall, PDM4 performed the best. Although it didn't always have the lowest permeability, it was the least affected by changes in humidity.

It was observed that the permeance was highly dependant upon the membrane thickness and even small deviations in the thickness of a membrane had a large effect on the permeance of the system. It was also seen that the presence of cracks or pinholes seriously increased the observed permeance.

iii) Adhesion to Concrete

The effects of varying the humidity of cure (constant curing temperature 22°C) on the adhesion of waterproofing membranes to a mortar substrate are shown in Table 14. The values represent the work done, in Joules, to peel the specimen a distance of 10 mm.

Curing at both low and high relative humidities resulted in reduced adhesion of PDM1. The adhesion of PDM2 was mostly independent of humidity, although curing at 50% RH resulted in the lowest adhesive strength. Curing PDM3 at a low humidity dramatically improved adhesion to the mortar substrate, whereas curing it at a high humidity significantly lowered the adhesion. The adhesion of PDM4 was essentially equivalent when cured at either 50% or 85% relative humidity. The results in both cases were, however, low in comparison to values typically obtained for the other membranes cured at standard conditions. For PDM5, it was not possible to peel the sample and consequently the adhesion was greater than the cohesive strength of the membrane. Since it was possible to peel the samples at both low and high humidity curing it can be stated that curing at these reduced the adhesion of PDM5. In this instance, the effects of a high humidity cure appeared to be greater than those achieved for a low humidity condition.

Table 14
Effect of Curing Humidity on Adhesion to a Mortar Substrate

Membrane	Work of Adhesion (Joules)		
	30% RH	50% RH	85% RH
PDM1	0.10	0.21	0.07
PDM2	0.16	0.12	0.15
PDM3	0.33	0.17	0.07
PDM4		0.07	0.09
PDM5	0.25	*	0.16

* samples failed cohesively in the membrane; no peel achieved

(b) Constant Humidity Properties

i) Tensile Properties

Tensile Modulus The values observed for modulus of elasticity are presented in Tables 15 to 17 and in Figures 21 to 25. Generally, there are similar responses to those cured in constant temperature conditions.

Curing at 5°C led to decreases in the modulus of elasticity, both at early ages and at 28 days cure. For all membranes no increases in the modulus of elasticity were observed for samples cured 28 days at 5°C. In contrast, curing at 38°C led to an increase in modulus at early ages. At 28 days cure, however, curing conditions of 38°C only produced small changes in modulus of elasticity, except for PDM4, which exhibited a moderate decrease.

Table 15
Development of Tensile Modulus (MPa) as a Function of Temperature
Membrane Cured 1 Day

System	5°C 50% RH		22°C 50% RH		38°C 50% RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	1.27	0.27	1.13	0.08	3.03	0.29
PDM2	0.21*	0.01	0.88	0.05	1.50	0.23
PDM3	0.44*	0.05	0.82	0.12	2.14	0.15
PDM4	0.49	0.15	0.69	0.05	1.77	0.23
PDM5	0.51	0.11	0.35	0.04	0.75	0.05

* data taken after 2 days

Table 16
Development of Tensile Modulus (MPa) as a Function of Temperature
Membrane Cured 7 Day

System	5°C 50% RH		22°C 50% RH		38°C 50% RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	2.55	0.29	3.82	0.16	4.72	0.44
PDM2	1.70	0.10	1.90	0.14	1.81	0.16
PDM3	2.14	0.33	3.24	0.24	3.30	1.19
PDM4	1.67	0.12	1.79	0.05	2.01	0.06
PDM5	0.81	0.14	0.45	0.05	0.75	0.04

Table 17
Development of Tensile Modulus (MPa) as a Function of Temperature
Membrane Cured 28 Days

System	5°C 50% RH		22°C 50% RH		38°C 50% RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	2.40	0.28	4.85	0.27	4.43	0.41
PDM2	2.00	0.08	2.09	0.10	1.79	0.10
PDM3	2.17	0.07	3.48	0.26	3.27	0.34
PDM4	1.83	0.13	2.29	0.18	1.73	0.05
PDM5	0.62	0.04	0.70	0.06	0.80	0.03

Again, results were categorized according to the scheme developed in the previous section (high >3 MPa, moderate between 3 and 1 MPa and low <1 MPa). PDM1 was a high modulus system, except when cured at 5°C, where the modulus was moderate. Curing at 5°C resulted in a significant decrease in modulus of elasticity at 28 days in comparison to curing at 22°C, while curing at 38°C resulted in only a slight decrease. PDM2 had a moderate modulus and the values observed were comparable at 7 and 28 days cure at each curing temperature. At 28 days cure the modulus obtained when cured at 5°C and 22°C were similar. With the exception of curing at 5°C, which resulted in a moderate modulus of elasticity, PDM3 was a high modulus system; at 28 days cure, the modulus for samples cured at 5°C was

significantly lower than that seen at either 22°C or 38°C, which were comparable. PDM4 was a moderate modulus system; at 28 days cure similar decreases in the tensile modulus were observed at 5°C and 38°C in comparison to 22°C. PDM5 was a low modulus system; values observed were comparable for all three curing temperatures at all ages.

For PDM5, little change in moduli was seen after the first day of curing. For PDM2, PDM3 and PDM4 little change in modulus was seen after the seventh day of curing. For PDM1, little change in tensile modulus was seen after 7 days when cured at 5°C, whereas moduli exhibited steady increases with age when cured at 22°C or 38°C.

Energy to Rupture The values for energy to rupture are presented in Tables 18 to 20 and in Figures 26 to 30. There is a greater variability in response to variations in curing temperature than with humidity.

With the exception of PDM4, curing at 38°C resulted in a decrease in energy to rupture in comparison to 22°C. Curing at 5°C had no discernable trend: PDM1 and PDM4 exhibited increases at 28 days cure in comparison to 22°C; PDM3 and PDM5 showed decreases; and PDM2 was unchanged.

Table 18
Energy to Rupture (J) as a Function of Temperature
Cured 1 Day

System	5°C 50% RH		22°C 50% RH		38°C 50% RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	1.43	0.12	1.48	0.41	1.54	0.30
PDM2	0.64*	0.14	1.17	0.28	0.54	0.25
PDM3	0.11*	0.01	0.15	0.10	0.23	0.11
PDM4	0.55	0.20	0.84	0.32	0.76	0.29
PDM5	1.77	0.17	1.92	0.25	2.21	0.21

* data taken after 2 days

Table 19
Energy to Rupture (J) as a Function of Temperature
Membranes Cured 7 Days

System	5°C 50% RH		22°C 50% RH		38°C 50% RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	2.26	0.38	1.87	0.47		
PDM2	1.17	0.18	1.35	0.31	0.55	0.35
PDM3	0.39	0.11	0.50	0.13	0.35	0.02
PDM4	1.12	0.05	0.96	0.14	1.44	1.10
PDM5	2.30	0.35	2.66	0.39	2.55	0.47

Table 20
Energy to Rupture (J) as a Function of Temperature
Membranes Cured 28 Days

System	5°C 50% RH		22°C 50% RH		38°C 50% RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	2.49	0.26	2.15	0.58	0.99	0.35
PDM2	1.53	0.12	1.52	0.30	0.60	0.39
PDM3	0.44	0.09	0.60	0.13	0.35	0.06
PDM4	1.14	0.22	0.90	0.11	1.04	0.44
PDM5	2.30	0.56	3.36	0.11	2.77	0.11

Again, systems were characterized according to values established as being of high, moderate or low energies to rupture. At 28 days cure, the energies required to rupture PDM1 were moderate, except when cured at 38°C, which required a low energy to rupture the membrane. When cured at 5°C, there was a small increase in the observed energy to rupture in comparison to 22°C. The energies required to rupture PDM2 at 28 days cure were low, except when cured at 38°C, which was very low. The energies to rupture seen at 5°C and 22°C were comparable at 28 days. The energies required to rupture PDM3 were very low and equivalent to those seen in the constant temperature study. Curing at either 5°C or 38°C resulted in decreases in the energy to rupture in comparison to curing at 22°C. The energies required to rupture PDM4 were low; small and moderate increases in energy to rupture were seen at 38°C and 5°C respectively, in comparison to 22°C. The energy required to rupture PDM5 was high when cured 28 days at 22°C; decreases in the energy to rupture were seen at both 5°C and 38°C.

With the exception of PDM1 cured at 38°C and PDM5 cured at 22°C there was little change observed in energies to rupture after 7 days for each system (for PDM2 at 22°C and 38°C and for PDM3, this was after 1 day).

Elongation The effects of varying curing temperature at constant humidity on the elongation capacity of membranes are shown in Tables 21 to 23 and in Figures 31 to 35.

With the exception of PDM3 and PDM4, curing at 38°C yielded a lower overall elongation at 28 days cure. Curing at 5°C may provide an initial improvement in elongation capacity, but did result in increased capability for any of the membranes, with the exception of PDM1. Overall, PDM5 had the highest elongation capacity at each curing temperature.

For PDM1, curing at 38°C yielded a lower elongation at 28 days cure, whereas curing at 5°C provided a greater elongation than that seen when cured 22°C. For this membrane, regardless of the curing temperature, a decrease in elongation capacity was seen after the first day of cure; with the smaller

decrease observed at the lowest curing temperature and the larger decrease at the higher temperature. There was a very wide range of results observed for PDM2 at 1 day. At 28 days cure the elongation seen at 38°C was lower than that seen at either 5°C and 22°C, which were comparable. For PDM3, the early capacities were comparable at all three curing temperatures. At 28 days cure, curing at 38°C resulted in an increase in elongation in comparison to 22°C. Curing at 5°C, however, resulted in a decrease in capacity in comparison to 22°C. The elongation capacity seen at 28 days when PDM4 was cured at 38°C was higher than that seen at either 5°C or 22°C, which were comparable. At 28 days cure a decrease in elongation capacity was seen when PDM5 was cured at 38°C in comparison to 5°C or 22°C, which were similar.

Table 21
Development of Elongation (%) as a Function of Temperature
Membranes Cured 1 Day

System	5°C 50%RH		22°C 50%RH		38°C 50 %RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	403	18	448	41	286	29
PDM2	577*	67	375	46	241	22
PDM3	211*	10	226	14	209	16
PDM4	341	45	316	14	299	32
PDM5	957	46	831	11	886	59

* data taken after 2 days

Table 22
Development of Elongation (%) as a Function of Temperature
Membranes Cured 7 Days

System	5°C 50%RH		22°C 50%RH		38°C 50 %RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	320	34	319	37	162	26
PDM2	268	15	268	29	204	33
PDM3	174	11	205	21	237	31
PDM4	266	13	267	20	301	49
PDM5	790	101	844	45	723	37

With the exception of PDM1 cured at 22°C, only small fluctuations in elongation were observed between 7 and 28 days cure for all other membranes. For PDM1, curing at 22°C provided a moderate decrease in elongation capacity between 7 and 28 days cure.

Table 23
Development of Elongation (%) as a Function of Temperature
Membranes Cured 28 Days

System	5°C 50%RH		22°C 50%RH		38°C 50 %RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	366	24	268	33	184	25
PDM2	286	13	284	26	208	23
PDM3	179	8	236	17	278	37
PDM4	275	18	266	18	347	3
PDM5	813	39	882	21	664	12

Tensile Strength The effects of varying curing temperature (5°C, 22°C and 38°C) on the tensile strength under conditions of constant relative humidity (50% RH) are shown in Tables 24 to 26 and in Figures 36 to 40.

Overall, curing at 38°C increased the early strength development of most membranes, whereas with the exception of PDM1 and PDM5, curing at 5°C greatly retarded early strength development. The effects on 28 day tensile strength for membrane scured at 38°C were variable. The results also indicated that little change occurs after 7 days of cure.

Table 24
Tensile Strength Development (MPa) as a Function of Temperature
Membranes Cured 1 Day

System	5°C 50%RH		22°C 50%RH		38°C 50 %RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	6.06	1.24	5.71	0.85	10.70	0.78
PDM2	1.06*	0.12	3.73	0.45	4.41	0.92
PDM3	1.46*	0.17	2.40	0.45	6.00	0.56
PDM4	1.86	0.53	2.51	0.19	5.90	1.25
PDM5	4.91	0.89	3.33	0.39	6.88	0.64

* data taken after 2 days

Table 25
Tensile Strength Development (MPa) as a Function of Temperature
Membranes Cured 7 Days

System	5°C 50%RH		22°C 50%RH		38°C 50 %RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	11.58	0.96	15.22	1.28	9.55	1.03
PDM2	4.52	0.21	5.57	0.69	4.58	0.71
PDM3	4.77	0.66	8.39	0.88	9.90	4.25
PDM4	4.92	0.36	5.28	0.41	6.73	1.21
PDM5	6.78	1.20	4.94	0.35	8.91	0.45

Table 26
Tensile Strength Development (MPa) as a Function of Temperature
Membranes Cured 28 Days

System	5°C 50%RH		22°C 50%RH		38°C 50 %RH	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
PDM1	11.51	1.95	16.45	2.26	9.13	1.65
PDM2	5.66	0.24	6.28	0.42	4.24	0.34
PDM3	4.92	0.32	10.31	1.39	11.21	1.82
PDM4	5.48	0.55	6.71	0.29	6.59	0.26
PDM5	6.27	0.19	7.19	0.39	8.82	0.61

Decreases in the 28 day tensile strength were observed when PDM1 and PDM2 were cured at either 5°C or 38°C in comparison to values seen for curing at 22°C. Curing at 38°C had a more pronounced effect for both membranes. The tensile strengths of PDM3 and PDM4 at 28 days when cured at either 22°C or 38°C were similar. Curing either membrane at 5°C resulted in decreases in the observed tensile strength with a pronounced effect observed on PDM3. Curing PDM5 at 38°C yielded an increase in 28 day tensile strength whereas a decrease when cured at 5°C in comparison to curing at 22°C.

For all membranes, most of the tensile strength was achieved in the first seven days of cure, hence, little change was observed in the values of tensile strength between 7 and 28 days cure.

ii) Water Vapour Transmission

The average permeabilities and calculated average permeances of each waterproofing membrane determined through water vapour transmission studies are presented in Table 27.

Table 27
Effect of Curing Temperature on Permeability and Permeance
of Waterproofing Membranes

Membrane	Permeability ($\times 10^{-10} \text{g/Pa}\cdot\text{s}\cdot\text{m}^2$)			Permeance ($\times 10^{-7} \text{g/Pa}\cdot\text{s}\cdot\text{m}$)		
	5°C	22°C	38°C	5°C	22°C	38°C
PDM1	1.76	1.11	1.37	3.45	2.17	2.69
PDM2	2.66	2.35	5.78	2.83	2.50	6.15
PDM3	1.76	0.44	1.12	4.00	1.00	2.55
PDM4	1.52	1.33	1.92	1.63	1.43	2.06
PDM5	3.45	2.21	2.34	4.73	3.03	3.21

For PDM1, curing at either elevated or lowered ambient temperatures resulted in an increase in the system permeability compared to curing at room temperature. Curing at 5°C, however, yielded the larger increase. Curing PDM2 at 38°C significantly increased the permeability, whereas a cure at 5°C showed a smaller increase. Curing PDM3 at either 5°C or 38°C resulted in significant increases in the

permeability, with 5°C yielding the larger change. For PDM4, curing at either 5°C or 38°C also yielded significant increases in permeability, although in this instance curing at 38°C yielded the larger change. For PDM5, curing at 5°C resulted in significantly higher permeability and curing at 38°C yielded a small increase in permeability.

Generally the urethanes (PDM1 to PDM4 incl.) performed better than the neoprene (PDM5). Again, PDM4 was the least changed by variations in the curing temperature, although it is evident from these studies that temperature changes during cure can, however, cause significant changes in the permeability of the system and hence the permeance.

(iii) Adhesion to Concrete.

The effects of variable curing temperatures at a constant relative humidity of 50% on the adhesion of waterproofing membranes to a mortar substrate are given in Table 28. The values are presented as the work done, in Joules, to peel a sample a distance of 10 mm.

Table 28
Effect of Curing Temperature on Adhesion to a Mortar Substrate

Membrane	Work of Adhesion (Joules)		
	5°C	22°C	38°C
PDM1	0.12	0.21	0.02
PDM2	0.15	0.12	0.09
PDM3	0.10	0.17	0.20
PDM4	0.07	0.07	0.12
PDM5	*	*	0.26

* samples failed cohesively in the membrane; no peel achieved

Curing PDM1 at 5°C resulted in a significant reduction in adhesion compared to curing at 22°C, as did curing at 38°C. The adhesion of PDM2 was slightly improved when cured at 5°C and slightly reduced at 38°C. Conversely, the adhesion of PDM3 deteriorated when cured at 5°C and improved at 38°C. Curing PDM4 at either 5°C or 22°C yielded equivalent adhesion, both cases being low in comparison to the adhesion achieved by the other urethane membranes cured at standard conditions. Curing at 38°C resulted in a significantly higher adhesion. Again, for PDM5 it was not possible to achieve a successful peel for all samples as certain specimens failed in the membrane. However, for those samples cured at 38°C, peel was possible. Hence, it appears that curing at high temperatures reduced the adhesion. However, this condition resulted in the highest value of adhesion observed of all specimens tested.

2. Workmanship

(a) Incorrect Proportioning

i) Tensile Properties

Tensile Modulus The values determined for modulus of elasticity are presented in Tables 29 to 31 and in Figures 41 to 44. At 28 days cure, the use of excess resin resulted in increased modulus of elasticity, except for PDM4, which was unchanged. The use of excess hardener lowered the modulus of elasticity in PDM2 and PDM4 but had little effect on either PDM1 or PDM3. Incorrect proportioning had a greater effect on the early cure performance of systems than on the performance at 28 days.

Table 29
Development of Tensile Modulus (MPa) as a Function of Workmanship
Membranes Cured 1 Day

System	Poor Mixing		Excess Resin		Correct Proportions		Excess Hardener	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
PDM1	2.42*	0.52	1.26*	0.24	1.13	0.08	4.44	1.09
PDM2	0.90	0.04	1.07	0.05	0.88	0.05	0.28	0.05
PDM3	**		**		0.82	0.12	0.03*	0.02
PDM4	1.00	0.13	0.25	0.02	0.69	0.05	0.94	0.10
PDM5	na		na		na		na	

* data taken after 2 days

** samples too soft to handle

na: not applicable

Table 30
Development of Tensile Modulus (MPa) as a Function of Workmanship
Membranes Cured 7 Days

System	Poor Mixing		Excess Resin		Correct Proportions		Excess Hardener	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
PDM1	5.24	0.21	3.43	0.11	3.82	0.16	5.60	0.24
PDM2	2.08	0.17	2.23	0.27	1.90	0.14	1.04	0.04
PDM3	**		0.10	-	3.24	0.24	3.52	0.46
PDM4	1.95	0.19	1.97	0.18	1.79	0.05	1.40	0.05
PDM5	na		na		na		na	

** samples too soft to handle

na: not applicable

Systems have again been categorized according to their values as being high, moderate or low modulus membranes. PDM1 can be considered a high modulus system at all mixing proportions. At 28 days cure, excess hardener and correct proportioning had similar moduli, while excess resin was somewhat higher. Excess hardener resulted in a low modulus of elasticity at each age for PDM2. Excess resin and correct proportioning values were comparable at each age and can be considered moderate. At 28 days cure, PDM3 can be considered a high modulus system. The use of excess resin severely degraded moduli at early ages of cure. The use of excess hardener yielded a modulus of elasticity at 28 days cure

slightly greater than that seen at the correct proportions. PDM4 can be considered a moderate modulus system. Excess hardener yielded a modulus at 28 days cure that was lower than either excess resin or correct proportioning, which were equivalent.

Table 31
Development of Tensile Modulus (MPa) as a Function of Workmanship
Membranes Cured 28 Days

System	Poor Mixing		Excess Resin		Correct Proportions		Excess Hardener	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
PDM1	7.26	0.55	6.39	0.42	4.85	0.27	5.00	0.50
PDM2	2.47	0.13	2.38	0.04	2.09	0.10	1.31	0.10
PDM3	3.83	0.52	4.27	0.41	3.48	0.26	3.82	0.55
PDM4	2.07	0.11	2.25	0.14	2.29	0.18	1.76	0.13
PDM5	na		na		na		na	

na: not applicable

With the exception of PDM1 and PDM3 having both been prepared with excess resin, only small changes in modulus of elasticity were seen after 7 days cure.

Energy to Rupture The energy to rupture values for samples prepared at incorrect proportions are presented in Tables 32 to 34 and in Figures 45 to 48. The use of excess resin resulted in increases to the observed energies to rupture for all systems. With the exception of PDM4, the use of excess hardener resulted in energies to rupture at 28 days cure that were lower than those seen at the correct mixing proportions.

Table 32
Energy to Rupture (J) as a Function of Workmanship
Membranes Cured 1 Day

System	Poor Mixing		Excess Resin		Correct Proportions		Excess Hardener	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
PDM1	2.55*	0.81	1.76*	0.05	1.48	0.41	1.57	0.98
PDM2	1.79	0.18	2.06	0.43	1.17	0.28	0.95	0.15
PDM3	**		**		0.15	0.01	0.002*	0.001
PDM4	0.63	0.09	0.57	0.15	0.84	0.32	0.82	0.11
PDM5	na		na		na		na	

* data taken after 2 days

** samples too soft to handle

na: not applicable

Classification according to that described previously indicates that PDM1 is a moderate energy system. The use of excess amounts of resin resulted in specimens having a greater energy to rupture at 28 days cure than those prepared with correct proportioning. At 28 days age, however, the energy required to

rupture samples prepared with excess hardener was lower. At the correct proportions and with excess hardener, PDM2 was a low energy system, whereas with an excess of resin it was a high energy system. Significant decreases in energy to rupture were seen at 28 days cure with the use of excess hardener. Conversely, a dramatic increase in the energy to rupture was observed at 28 days cure with the use of excess resin. PDM3 was a very low energy system. At 28 days cure, the energy required to rupture PDM3 was independent of proportioning. At early ages (i.e. 1 and 7 days cure) there were marked differences, especially with excess resin. PDM4 was a low energy system. The use of excess resin or excess hardener resulted in increased values of energy to rupture in comparison to correct proportioning.

Table 33
Energy to Rupture (J) as a Function of Workmanship
Membranes Cured 7 Days

System	Poor Mixing		Excess Resin		Correct Proportions		Excess Hardener	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
PDM1	3.02	0.50	2.95	0.51	1.87	0.47	1.96	0.23
PDM2	2.35	0.78	3.17	0.82	1.35	0.31	1.45	0.19
PDM3	**		0.04	-	0.50	0.13	0.58	0.15
PDM4	0.55	0.09	0.98	0.21	0.96	0.14	1.15	0.15
PDM5	na		na		na		na	

** samples too soft to handle

na: not applicable

Table 34
Energy to Rupture (J) as a Function of Workmanship
Membranes Cured 28 Days

System	Poor Mixing		Excess Resin		Correct Proportions		Excess Hardener	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
PDM1	2.71	0.23	2.90	0.89	2.15	0.58	1.60	0.40
PDM2	2.41	0.54	4.44	0.51	1.52	0.30	0.93	0.15
PDM3	1.15	0.11	0.69	0.14	0.60	0.13	0.52	0.18
PDM4	0.49	0.09	1.21	0.19	0.90	0.11	1.29	0.27
PDM5	na		na		na		na	

na: not applicable

Only small changes in energies were observed for PDM1 after the seventh day of cure for any of the proportions. After 7 days, little change was seen in energy to break for PDM2 prepared with excess hardener or with correct proportioning. Excess resin samples on the other hand, exhibited a steady increase with age. Excess hardener and correct proportioning samples of PDM3 exhibited little change in energy to rupture after the seventh day of cure. Samples prepared with excess resin exhibited a small but steady increase. For PDM4 all three proportioning conditions exhibited little change after the seventh day of cure.

Elongation The elongation capacity for samples prepared with excess amounts of resin and hardener as well as those prepared at the correct proportions are shown in Tables 35 to 37 and in Figures 49 to 52. For each membrane type, at 28 days cure the resultant elongations were somewhat comparable at each mixing proportion. At early ages (up to 7 days) the variation based on mixing proportions were more pronounced. With the exception of PDM2, the use of excess resin resulted in higher initial elongation capacity.

Table 35
Development of Elongation (%) as a Function of Workmanship
Membranes Cured 1 Day

System	Poor Mixing		Excess Resin		Correct Proportions		Excess Hardener	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
PDM1	356*	53	457*	42	448	41	255	43
PDM2	449	35	378	41	375	46	587	63
PDM3	**		**		226	14	205*	46
PDM4	271	20	557	40	316	14	283	19
PDM5	na		na		na		na	

* data taken after 2 days

** samples too soft to handle

na: not applicable

Table 36
Development of Elongation (%) as a Function of Workmanship
Membranes Cured 7 Days

System	Poor Mixing		Excess Resin		Correct Proportions		Excess Hardener	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
PDM1	274	21	357	20	319	37	247	17
PDM2	327	38	300	44	268	29	383	8
PDM3	**		245	-	205	21	208	23
PDM4	177	14	280	38	267	20	345	11
PDM5	na		na		na		na	

** samples too soft to handle

na: not applicable

Table 37
Development of Elongation (%) as a Function of Workmanship
Membranes Cured 28 Days

System	Poor Mixing		Excess Resin		Correct Proportions		Excess Hardener	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
PDM1	227	22	231	19	268	33	242	15
PDM2	328	22	327	21	284	26	323	28
PDM3	170	10	187	14	236	17	168	24
PDM4	184	21	279	38	266	18	292	27
PDM5	na		na		na		na	

na: not applicable

The use of either excess resin or excess hardener in PDM1 resulted in similar slight decreases in elongation capacity at 28 days compared to correct proportioning. Small increases were seen in the 28 day elongation when PDM2 was prepared with either excess resin or excess hardener compared to correct proportioning. When PDM3 was prepared with either excess resin or hardener, similar moderate decreases in the elongation at 28 days were observed in comparison to correct proportioning. At 28 days cure the elongations observed for PDM4 were comparable at each mixing proportion.

After the seventh day of curing, little change was seen in the values of elongation for PDM2 and PDM4 at each mixing proportion. Significant decreases were observed between 7 and 28 days for PDM1 and PDM3, both prepared with excess resin. At the correct proportions, PDM1 exhibited a small decrease between 7 and 28 days, while with excess hardener the response was unchanged. For PDM3, a small increase was seen between 7 and 28 days at the correct proportions while with excess hardener a decrease was observed.

Tensile Strength The tensile strength development for samples with excess amounts of resin and hardener are shown in Tables 38 to 40 and in Figures 53 to 56. The use of excess amounts of hardener increased the early strength development of the membranes, whereas excess amounts of resin retarded it. At 28 days cure, however, excess hardener resulted in ultimate strengths that were lower than those achieved with the correct proportions. With the exception of PDM2, the use of excess amounts of resin did not result in a greater ultimate strengths.

Table 38
Tensile Strength Development (MPa) as a Function of Workmanship
Membranes Cured 1 Day

System	Poor Mixing		Excess Resin		Correct Proportions		Excess Hardener	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
PDM1	9.75*	1.29	5.96*	0.81	5.71	0.85	11.69	1.17
PDM2	4.57	0.58	4.40	0.37	3.73	0.45	1.80	0.08
PDM3	**		**		2.40	0.45	0.06*	0.02
PDM4	3.00	0.50	1.50	0.13	2.51	0.19	3.00	0.38
PDM5	na		na		na		na	

* data taken after 2 days

** samples too soft to handle

na: not applicable

For PDM1, excess amounts of hardener resulted in increased tensile strength at early ages. Excess amounts of resin lowered the tensile strength to the extent that after 1 day, samples were not sufficiently cured to handle. After 7 days curing, however, the results in all cases were equivalent. At all ages, the use of excess resin in PDM2 resulted in tensile strengths that were greater than those seen at the correct proportions. Conversely, the use of excess hardener resulted in tensile strengths at all ages that

were lower than those seen when prepared at the correct proportions. Both the use of excess resin and excess hardener severely retarded the early strength development of PDM3. At 7 days cure, samples with excess hardener and the correct proportions yielded similar strengths, while excess resin samples still exhibited retarded strength development. At 28 days cure, there was a dramatic increase in the strength of samples prepared with excess resin, such that the observed strength was comparable to that seen with the correct proportions. The values of tensile strength were greater than those seen with excess hardener. For PDM4, the use of excess resin resulted in lower 1 day strengths while excess hardener resulted in slightly greater strength compared to correct proportioning. The strengths seen at 28 days cure from excess resin and correct proportioning were equivalent.

Table 39
Tensile Strength Development (MPa) as a Function of Workmanship
Membranes Cured 7 Days

System	Poor Mixing		Excess Resin		Correct Proportions		Excess Hardener	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
PDM1	17.19	1.28	14.61	1.06	15.22	1.28	14.76	0.97
PDM2	7.32	0.56	7.08	0.55	5.57	0.69	4.23	0.12
PDM3	**		0.30	-	8.39	0.88	9.00	1.90
PDM4	3.95	0.21	6.12	1.35	5.28	0.41	5.14	0.19
PDM5	na		na		na		na	

** samples too soft to handle

Table 40
Tensile Strength Development (MPa) as a Function of Workmanship
Membranes Cured 28 Days

System	Poor Mixing		Excess Resin		Correct Proportions		Excess Hardener	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
PDM1	18.99	1.40	18.14	2.74	16.45	2.26	13.01	1.48
PDM2	8.76	0.36	8.85	0.68	6.28	0.42	4.27	0.15
PDM3	7.97	1.28	10.18	1.34	10.31	1.39	8.23	1.95
PDM4	4.07	0.38	6.74	0.61	6.71	0.29	5.55	0.19
PDM5	na		na		na		na	

na: not applicable

ii) Water Vapour Transmission

The average permeabilities and calculated average permeances of each waterproofing membrane determined through water vapour transmission studies are presented in Table 41.

Only very small changes were observed for PDM1 with excess amounts of the components. Excess resin resulted in an increase in permeability while excess hardener yielded a decrease. Significant

changes in the permeability of PDM2 were also observed. Excess resin yielded a very large increase in permeability. Excess hardener resulted in a significant decrease in permeability. For PDM3, both excess resin and excess hardener yielded increases in the permeability; excess resin providing the largest increase. Excess resin in PDM4 resulted in a significantly higher permeability. The use of excess hardener yielded essentially no change in permeability.

Table 41
Effect of Workmanship Factors on Permeability and Permeance
of Waterproofing Membranes

System	Permeability ($\times 10^{-10}$ g/Pa·s·m)				Permeance ($\times 10^{-7}$ g/Pa·s·m ²)			
	Excess Resin	Correct Prop.	Excess Hard.	Poor Mixing	Excess Resin	Correct Prop.	Excess Hard.	Poor Mixing
PDM1	1.28	1.11	1.05	1.21	2.51	2.17	2.06	2.37
PDM2	3.95	2.35	1.65	2.20	4.20	2.50	1.76	2.34
PDM3	0.97	0.44	0.70	1.64	2.20	1.00	1.52	3.73
PDM4	1.69	1.33	1.30	1.96	1.82	1.43	1.40	2.10

When mixed at the correct proportions, PDM3 performed the best, followed by PDM4, PDM1 and PDM2. Excess resin always caused an increase in the permeance. For PDM2 and PDM3, this increase was particularly significant. The changes caused by excess hardener were varied, but the magnitude of the change was not as great as the those caused by excess resin.

(b) Poor Mixing

i) Tensile Properties

Tensile Modulus The moduli of elasticity for poorly mixed samples are presented in Tables 29 to 31. For PDM1 higher values for the tensile modulus were obtained for samples cured at each age in comparison to those correctly proportioned. Using the rating system, at 28 days cure, PDM1 can be considered a high modulus system even when poorly mixed. The moduli were equivalent at early ages for PDM2; at 7 and 28 days cure, the tensile modulus of the poorly mixed samples were slightly greater than those correctly mixed. The modulus of elasticity for PDM3 at 28 days was equivalent for both poor and correct mixing. For PDM4, the modulus of elasticity was equivalent at each curing age.

Little change was seen after 7 days cure in the modulus of poorly mixed samples of PDM2 and PDM4, whereas large increases were observed for PDM1 and PDM3.

Energy to Rupture The energy of rupture for poorly mixed samples are presented in Tables 32 to 34. After 28 days cure, poor mixing resulted in an increase in the energy to rupture for all membranes, except for PDM4, which exhibited a decrease.

In comparison to properly mixed samples, the energy to rupture for poorly mixed samples of PDM1 was higher not only at early ages, but also at 28 days cure. Once again, systems were categorized according to the previously outlined scheme. PDM1 was a high energy system in both mixing cases. For PDM2 the energy required to rupture the system was consistently higher for the poorly mixed samples at all ages. This system can be considered of moderate energy. Poorly mixed samples of PDM3 required greater energies to rupture the system at 28 days. In both mixing cases this energy was low. The poorly mixed samples of PDM4 had a lower energy to rupture than the properly mixed samples at all ages. This can be considered a low energy system.

Only small changes were observed in the energy to rupture after 7 days for PDM1, PDM2 and PDM4. Since PDM3 was too soft to handle at 7 days, the increase seen in energy to rupture can be considered large.

Elongation The elongation capacity for poorly mixed samples are presented in Tables 35 to 37. Poor mixing of samples resulted in decreased elongation capacities at 28 days cure, except for PDM2, which saw a slight increase.

Poor mixing samples of PDM1 exhibited an elongation capacity that was uniformly lower than the properly mixed samples at each age. Poor mixing resulted in an elongation capacity for PDM2 that was uniformly higher at each age compared to the properly mixed samples. At 1 and 7 days age, PDM3 had failed to cure sufficiently to handle and test, hence, no values could accurately be determined. Nevertheless, at 28 days, the elongation capacity was lower for the poorly mixed samples. Poorly mixed samples of PDM4 exhibited a moderate decrease in elongation capacity in comparison to the correctly mixed samples.

All membranes, except PDM3, exhibited large decreases in elongation capacity between 1 and 7 days cure. After 7 days only small changes were seen. For PDM3, trends could not be determined since the system did not adequately cure in the first 7 days of testing.

Tensile Strength The results for the tensile strength development for improperly mixed samples are given in Tables 38 to 40. Poor mixing of membrane components resulted in tensile strengths for PDM1 and PDM2 that were greater than those seen when properly mixed. The tensile strengths of PDM3 and PDM4 were seen to decrease when poorly mixed.

For PDM1 the tensile strength was increased slightly at all ages when poorly mixed. For PDM2, the tensile strength at 28 days cure was considerably higher when poorly mixed. The early strength

development of PDM3 was severely retarded up to 7 days. At 28 days cure the tensile strength was lower when poorly mixed. The 1 day tensile strength observed for PDM4 was greater when poorly mixed. Poor mixing, however, yielded considerably lower strengths at 28 days cure.

After 7 days of cure, little change in tensile strength was observed for poorly mixed samples of PDM1, PDM2 and PDM4. Since the strength development of PDM3 was badly retarded, no trends could be determined.

ii) Water Vapour Transmission

The average permeabilities and calculated average permeances resulting from poor mixing are given in Table 41.

With the exception of PDM2, poor mixing of the membrane components led to an increase in both the permeability of the membrane (a material property) and its permeance (a measure of performance). For PDM4 and especially PDM3, these increases were large. Only small increases in these values were observed for PDM1. Both permeability and the related permeance of PDM2 were seen to decrease slightly. The changes seen in PDM1 and PDM2 may not be very significant.

3. Surface Preparation

The effects of surface preparation and surface condition on adhesion of waterproofing membranes are given in Table 42. Concrete slabs were prepared using three techniques resulting in widely different surface profiles. These were water jet blasting, resulting in the smoothest surface; sandblasting, resulting in a lightly textured surface; and shotblasting, resulting in a coarsely textured surface.

The adhesion of the membranes to the surface of the differently textured substrates was evaluated under both wet (saturated surface dry) and dry conditions. The results indicated that in the case of a shot blasted surface, the adhesion of each waterproofing membrane was reduced when applied to wet substrates. With the exception of PDM2, adhesion to a sandblasted surface also decreased when that substrate was not dry. The changes in adhesion caused by wet and dry surfaces on the water jet blasted surface varied according to the type of membrane evaluated. A decrease in adhesion to the wet substrate was observed for PDM1 and PDM5. Increases in adhesion were seen for PDM2, PDM3 and PDM4.

For substrates prepared to wet conditions, shotblasting resulted in the lowest adhesion and the water jet blasting yielded the strongest adhesion for each membrane. This suggests that more coarsely textured surfaces have a greater tendency to allow water to pool and would take longer to dry to optimum

conditions. The mode of failure observed for the specimens on the dry, shotblasted surface was an adhesive failure either at the interface or in the near surface layer of the substrate. For the dry, sandblasted surface the mode of failure was variable. In some instances it was cohesive in the substrate, in others it was partially cohesive and in some, it was adhesive in the near surface layer of the substrate. The mode of failure observed on the dry, water jet blasted surface was either fully or partially cohesive in the substrate. On the wet substrates, however, the mode of failure was predominantly adhesive, either at the interface or in the near surface layer. The exception to this was PDM2 on the water jet blasted substrate which was partially cohesive in the substrate.

Table 42
Effect of Surface Condition on Adhesion to Concrete (MPa)

Membrane	Dry Substrate			Wet Substrate		
	Shotblast	Sandblast	Water Jet	Shotblast	Sandblast	Water Jet
PDM1	2.84	3.91	3.50	0.73	0.83	1.54
PDM2	2.78	2.98	2.48	2.20	3.14	3.79
PDM3	2.34	3.83	2.74	1.25	1.99	3.28
PDM4	2.57	3.04	2.73	2.05	2.68	2.87
PDM5	1.94	2.92	3.48	1.58	1.69	3.04

The effects of incorrect proportioning on the adhesion of waterproofing membranes to the textured concrete surfaces are given in Table 43. As a point of comparison, the adhesion of membranes to different textured surfaces at the correct mix proportions is provided in Table 44, in which optimum conditions exist for systems placed 15 minutes after mixing. The effects seen were varied for each membrane and surface condition. No definite trend based on surface preparation or proportioning can be seen.

The use of both excess resin and excess hardener caused decreases in the adhesion of PDM1 on all three surfaces. These decreases were larger for samples prepared with excess hardener than for samples prepared with excess resin. For samples prepared with either excess resin or excess hardener, the weakest adhesion resulted when placed on a shotblasted surface and the strongest adhesion occurred when placed on a water jet blasted surface.

The use of excess resin in PDM2 yielded increases in the tensile adhesion on each of the different types of surface textured substrates. The use of excess hardener reduced the adhesion to the water jet blasted substrate but had no effect on the adhesion to either sandblasted or shotblasted concrete surfaces. For samples prepared with either excess resin and excess hardener the lowest adhesion was obtained when placed on the shot blasted surface and the highest adhesion was achieved when applied to the water jet blasted surface.

Table 43
Effect of Incorrect Proportioning on Adhesion to Concrete (MPa)

Membrane	Excess Resin			Excess Hardener		
	Shotblast	Sandblast	Water Jet	Shotblast	Sandblast	Water Jet
PDM1	3.57	3.81	4.29	2.62	3.73	4.04
PDM2	3.75	3.89	4.09	3.26	3.61	3.28
PDM3	4.28	3.79	4.61	2.89	4.43	4.42
PDM4	2.57	3.84	4.36	2.22	3.32	2.92

The adhesion of PDM3 when prepared with either excess resin or excess hardener can vary considerably. Excess resin increased the adhesion on shotblasted and water jet blasted substrates, but decreased it on sandblasted surfaces. Excess hardener decreased the adhesion to a shotblasted or sandblasted substrate but had no effect on the water jet blasted surface. There were no trends with surface roughness seen with the excess resin samples. Shotblasted surfaces had weaker adhesion than either sandblasting or water jet blasting for excess hardener samples.

Excess resin increased the adhesion of PDM4 on a sandblasted surface, but lowered it on a shotblasted or water jet blasted surface. Excess hardener decreased the adhesion on all three types of surface preparation. For samples made containing excess resin, a shotblasted surface yielded the weakest adhesion and water jet blasting yielded the strongest adhesion. For samples made with excess hardener, the weakest adhesion was found on the shot blasted surface. The sandblasted surface provided the strongest adhesion.

The effects of time of application of the waterproofing membrane after its mixing are given in Table 44. Generally, a shot blasted surface yielded the poorest adhesion regardless of the time of application. However, a number of other trends were also observed. For PDM1, both shot blasted and sand blasted surface produced a decrease in adhesion for application times ranging between 15 and 30 minutes, but little change between 30 and 45 minutes. On a water jet blasted surface, the loss in adhesion was only observed after 30 minutes. The adhesion of PDM2 was fairly independent of the application time, although slight decreases were seen. This system also had the least variability in adhesion due to surface preparation. The adhesion of PDM3 appeared to peak at 30 minutes and then began to decrease. Adhesion of PDM4 to each surface was fairly uniform up to 30 minutes after mixing; between 30 and 45 minutes small decreases were seen.

Table 44
Effect of Time of Application After Mixing on Adhesion to Concrete (MPa)

System	15 min			30 min			45 min		
	Shot	Sand	Water	Shot	Sand	Water	Shot	Sand	Water
PDM1	3.70	4.14	4.42	2.90	2.98	4.50	2.82	2.90	3.04
PDM2	3.65	3.51	3.62	3.32	3.32	3.31	3.36	4.14	3.28
PDM3	3.97	4.73	4.43	4.40	4.64	4.68	3.70	4.31	4.26
PDM4	3.59	3.34	4.48	3.54	3.11	4.40	3.04	3.04	4.06
PDM5	2.36	4.20	3.59	3.68	4.11	3.98	3.64	4.07	4.03

The effects of cold mixing of the membranes on adhesion to concrete are presented in Table 45. Membrane components were conditioned for 24 hours at lowered temperatures (5°C to 10°C) prior to mixing and application.

Table 45
The Effect of Cold Mixing on Adhesion to Concrete (MPa)

Membrane	Shotblasting	Sandblasting	Water Jet
PDM1	3.61	3.32	4.20
PDM2	3.04	3.72	3.37
PDM3	3.64	4.70	4.45
PDM4	2.36	3.29	3.14
PDM5	3.26	3.56	2.92

4. Viscosity

Changes in viscosity due to temperature fluctuations can have serious effects on the ease and degree of mixing, the ease of application and obtaining the correct membrane thickness. These effects vary according to the recommended method of application viz. spraying, squeegee and so on. Accordingly, the effects of temperature on the viscosity of the waterproofing membranes were investigated.

Membrane components were conditioned at the test temperature for at least 16 hours prior to mixing. It was not possible to condition and test PDM1, PDM2 and PDM4 at 5°C as gelation of at least one of the membrane components occurred. The lowest temperature at which these systems were tested was 10°C.

Viscosity profiles for the waterproofing membranes are presented in Figures 57 to 61. The profile for PDM5 indicated that it was insensitive to changes in temperature; observed values ranged between 1 Pa·s at low shear rates and 0.2 Pa·s at higher shear rates. The variation in response between 5°C and 38°C was quite narrow.

The remaining membranes all exhibited wide variations in viscosity with changes in test temperature. In general, the effects of higher temperatures (38°C) on viscosity were not as marked as those observed at lower temperatures (5°C and 10°C). A comparison of the profiles obtained for PDM2 and PDM3 indicated similar changes in viscosity at different test temperatures. Within the group of polyurethane based membranes, these two products had the lowest viscosities. At 38°C the viscosity observed for these two membranes was roughly 1 Pa·s; at 25°C it was approximately 2 Pa·s; and at 10°C it was roughly 7 Pa·s. When PDM3 was cooled to 5°C the viscosity jumped to about 20 Pa·s. The profile for PDM1 indicated that it falls in the middle of the observed responses. At 38°C the viscosity was roughly 4 Pa·s, at 25°C it was roughly 6 Pa·s and at 10°C it ranged from 20 to 25 Pa·s. PDM4 consistently had the highest viscosity. At 38°C the viscosity was 5 Pa·s, at 25°C it was roughly 9 Pa·s and at 15°C it jumped to 20 to 25 Pa·s. When cooled to 10°C the viscosity further increased to 40 Pa·s.

The variation of viscosity with shear rate was more pronounced at the lower temperatures than at the higher ones. The viscosity was seen to increase, sometimes significantly, with a decrease in shear rate.

The observed changes in product viscosities have significant impact on spraying, sagging and levelling. The shear rates at which these phenomena occur are different. Spraying is a high shear rate phenomenon, generally occurring between 10^3 and 10^4 sec^{-1} . Sagging and levelling are low shear rate phenomena, generally found between 0.01 and 1 sec^{-1} .

For typical coating systems, shear rates ranging between 10^3 and 10^4 sec^{-1} correspond to viscosities between 0.1 and $2 \text{ Pa}\cdot\text{s}$ ¹⁸. The increases seen in the viscosity of some membrane systems with a corresponding decrease in temperature remove them from this range. Increasing temperature, with its corresponding decrease in viscosity, should not have a serious effect on the spraying of most membrane systems.

Sagging of waterproofing membranes on vertical surfaces such as coves and slanted surfaces such as ramps can lead to improper membrane thicknesses at various portions of the parking deck. Many membrane properties are dependent on the thickness achieved in the installed product and ultimately their performance may suffer if thicknesses fall below stipulated values. In the simplest case of a Newtonian fluid on a vertical surface, the velocity, v , at which a fluid sags is governed by the expression:

$$v = \rho g T^2 / 2\eta$$

where ρ = density, g = gravitational constant, T = membrane thickness and η = viscosity. For a given membrane thickness, a decrease in viscosity resulting from increases in temperature will cause an increase

in the sagging velocity. If the sagging velocity increases, the final thickness of the membrane will decrease.

When membrane systems are placed by squeegee, they must be able to flow sufficiently to produce a uniform surface thickness. This levelling process depends on the size of the squeegee marks, X , the wet film thickness, T , the surface tension, σ and the viscosity, η . The relaxation time, t , for the levelling process is related to the aforementioned variables by the equation:

$$t = K\eta X^4 / \sigma T^3$$

where K is a proportionality constant. As the relaxation time is proportional to viscosity, an increase in viscosity with a corresponding decrease in temperature would relate to longer relaxation times and poor flow out. In such instances uniform membrane thickness may not be achieved and the protection offered by the membrane would vary across the surface of the concrete slab.

5. Reaction Kinetics

Reaction kinetics were monitored by measuring the heat evolved from small samples of the membrane for a period of 24 hours using conductive calorimetry. This was done for membranes PDM1, to PDM4 inclusively. As no reaction occurs for PDM5, it was not possible to perform conductive calorimetry on the system.

From plots of heat of evolution as a function of time, the total cumulative heat evolved could be calculated. Generally, it was observed that in the first few hours of cure a sharp increase in the heat evolved was followed by a significant decrease. Beyond approximately 10 hours, only slight changes in heat evolved were perceived. Since, typically, the changes seen after 1 day of cure were considered small in relation to the preceding 24 hours, this was taken to be the time at which 100% completion of cure was achieved. Using the value of cumulative heat evolved after 24 hours as representative of 100% cure, it was possible to calculate the degree of cure for each membrane as a function of time by evaluating cumulative heat evolved at a given time and relating it to that obtained for 100% cure. The degree of cure is simply the ratio of these two values and can be expressed as a percentage as indicated in Figure 62.

The degree of cure relates to both the rate of tensile property development and the degree of adhesion of the membrane. In the later case, adhesion may be the intercoat adhesion between successive layers in addition to adhesion to the substrate. Intercoat bonding is achieved only if a sufficient number of chemically reactive 'sites' are present on the initial layer of the membrane. This, in turn, can only be assured if the cure is not yet complete, otherwise, the degree of adhesion between successive layers will necessarily be reduced, thus increasing the chances of intercoat delamination. In the former instance, the

membrane must be sufficiently cured in the first 24 hours to resist foot traffic that invariably occurs during the application process.

The degree of cure for chemically cured membranes is shown as a function of the curing time in figure 62. The rate at which the cure advances can be characterized by the slope of the reaction curves, with large slopes being indicative of high rates of reaction and conversely, shallow slopes low rates. For each product it is observed that the rate advances within two distinct phases: the initial phase, characterized by a rapid cure (large slope), occurs within the first 3 hour period; lower rates of cure (shallow slope) are seen within the second phase. Within the second phase, a flat curve would indicate that the membrane had reached complete cure, with an increase in slope indicative of a membrane that requires further time to reach the fully cured state. In this respect, PDM2 has the largest slope within the second phase of cure of the four membranes evaluated, suggesting that this product is the least susceptible of the four to intercoat delamination. However, it appears from the results that most of the membranes have attained a degree of cure sufficiently high to bring attention to the possibility of intercoat adhesion problems if the time between successive layers is excessive. This can be exacerbated by secondary problems, such as the occurrence of dust from other jobsite activities settling on the membrane.

Reaction kinetics of these membrane systems are evidently affected by changes in temperature with higher temperatures causing faster reactions. Thus the completion of cure will occur sooner and this will reduce the time required between application of successive layers. Lower temperatures will have the opposite effect and the rates of reaction will necessarily decrease. The degree of cure achieved within the same time frame employed for cure at standard conditions may be insufficient to withstand the stresses imparted by the applicators and consequently the membrane may be damaged during this initial curing phase.

B. Field Investigations

1. Job Site Inspections

The installation of PDM1 was inspected at Place du Portage, Hull. The consistency in application was monitored with by measuring the wet film thickness. These values ranged from 0.82 - 0.87 mm (32 -34 mils). This corresponds to an expected 0.77 - 0.79 mm (30-31 mils) dry film thickness.

The installation of PDM3 was inspected at City Hall, Ottawa. Inspection of level P-1 showed the substrate to be in good condition. Level P-2, however, showed extensive shrinkage cracking. The surface was prepared by shotblasting. Larger scale repairs were performed with an epoxy patching material. Photograph #1 shows a patch repair of roughly 1 m² size. The cracks along edge of the patch have

resulted from the shrinkage of the patching material from the side of the concrete substrate. The striations visible across the deck, which are running tracks from the shot blasting machine may have contributed to the pulling away of the patch from the concrete substrate. Since surface preparation is often done within days of patching, the practice of patching after surface preparation should be stipulated. Shrinkage cracks were routed out and filled with a urethane joint sealant. Photographs #2, #3 and #4 show the repair process for cracks. In Photograph #2 a routed crack is being filled with the urethane sealant. The extensive degree of cracking on level P2 is shown in photograph #3. The final stage of repair is the application of a strip of membrane over primer along the crack. Photograph #4 shows that even with these preparations, some cracks can still reflect through the membrane. Here, the possible crack reflection during service could be prevented by the incorporation of a strip of glass fibre matt prior to the application of the membrane². After all repairs were completed the primer was applied, followed 24 hours later by application of the membrane. Both primer and membrane were spray applied. Photograph #5 shows the application of primer and Photograph #6 shows typical application of the membrane. Note that after spraying this system is back rolled to ensure the permeation of the membrane into pores and to drive out entrapped air. On level P-1, the membrane was applied at 0.33 -0.36 mm (13-14 mils) to achieve a 0.26 mm (10 mil) dry film thickness. On level P-2, the membrane was applied at 0.64 mm (25 mil) to obtain a 0.51 mm (20 mil) dry film thickness. It was found that at this thickness extensive air bubbling occurred. The surface coat was ground off and a subsequent 0.26 mm (10 mil) dry film thickness coating applied to fill in the voids. Grinding the surface of applied coats is bad practice. It is often done within 24 hours and tends to severely stress the membrane/concrete bond interface. The completed system is shown in Photograph #7 (newly finished) and Photograph #8 (after 24 hours).

The installation of PDM5 was inspected at the Islington Tower, Toronto. Inspection of the garage indicated that the substrate was in good condition. Surface preparation was done by shotblasting. Cracks on the deck were observed and repairs performed with either a cementitious or an epoxy grouting material. It is crucial that the epoxy grouts used in such repairs should be fast curing so that they are not susceptible to attack by solvents contained in the primer, which is usually applied 24 hours after patching. Typical repairs to the substrate are illustrated in Photograph #9. The primer was applied 24 hours after completion of the repairs. The membrane was spray applied when the primer reached a 'tacky' state. This is shown in Photograph #10. The membrane was applied at 0.69 mm (27 mil) wet to achieve a 0.51 mm (20 mil) dry film thickness.

The installation of PDM6 was inspected at McArthur Plaza, Ottawa and the inspection of the garage was performed during installation of the membrane. The deck was shotblasted and in good condition, although a small amount of shrinkage cracking was observed. After repairs were carried out (as typically shown in Photograph #11), the membrane was applied by squeegee (see photographs #12 and

#13) at a thickness of 0.82 - 0.87 mm (32-34 mils) wet to obtain 0.77 - 0.79 mm (30-31 mils) dry film thickness.

2. Field Sampling

The results from tests performed on field prepared samples are given in Table 46. Bond strength determinations were performed on samples prepared by the manufacturers approved applicators. These values represented the adhesion of the full system to a sandblasted concrete substrate. The dry film thicknesses listed are values for the full system (including wear course). Cross sections of these systems are presented in Photographs 14 to 22. In each photograph, unless otherwise stated, the concrete substrate is at the bottom.

Photograph 14 is a cross section of PDM1. It shows very good membrane to concrete adhesion, as no delaminations are visible along the bond line. It also shows poor aggregate embedding, as shown by the exploded portion of the wear course.

The cross sections in Photographs 15 and 16 are of PDM2. Both show good membrane to substrate adhesion. The variations in membrane thickness due to an irregular or varied surface profile is illustrated in Photograph 15. The membrane thickness at the left hand side is almost twice that in the center. Note, however, the discontinuity between the membrane and the wear course. This discontinuity could lead to adhesion problems. Both good and poor encapsulation of aggregate is shown in Photograph 16. The significance of poor aggregate encapsulation should be considered in terms of lowered abrasion and UV resistance. Dislodging of the aggregate will reduce the abrasion resistant component of the wear course and render the surface slippery. Also, previous work⁵ showed that the presence of aggregate reduced the UV degradation of the resin matrix.

Photographs 17 and 18 show cross sections of PDM3. Poor encapsulation of aggregate is shown in Photograph 17, as evidenced by the very thin layer of wear course surrounding the aggregate particles. Photograph 18 shows a close-up of the membrane portion on the right hand side of Photograph 17. Note the discontinuity and partial delamination between the two membrane layers and especially between the membrane and wear course. Both photographs do show good adhesion to concrete.

A cross section of PDM4 is shown in Photograph 19, with the concrete substrate along the right hand side of the photograph. Delamination from the substrate is evident here, as are some air bubbles in the membrane and poor encapsulation of the wear course.

Photographs 20 and 21 show cross sections of PDM5 with the wear course. The rough surface of the membrane and the tears along the interface were caused by the core drill. It is not possible to state the condition of the system without damage. This system does not appear to fill occlusions, as seen on the extreme left and extreme right of Photograph 20.

The layers of PDM6 are quite visible in Photograph 22. It illustrates both the adhesion to the substrate and encapsulation of aggregate in the wear course. There is, however, a sharply defined interface between membrane and wear course. This discontinuity may present adhesion problems.

Table 46.
Properties of Field Applied Samples

Membrane System	Adhesion to Concrete (MPa)		System Thickness (mm)
	Average	Std. Dev.	
PDM1	3.16	0.43	
PDM2	2.54	0.31	1.2 - 1.6
PDM3	2.84	0.13	0.6 - 2.0
PDM4	2.69	0.39	1.8 - 2.0
PDM5	1.78	0.25	0.7 - 1.1*
PDM6			1.1 - 1.4

* membrane only

V. CONCLUSIONS

The work presented in this report has shown that the properties of the final product not only depend on the characteristics of the materials but more importantly on the care taken throughout the installation of the membrane system. The adverse effects produced by variation in ambient temperature, relative humidity, poor surface preparation and poor workmanship ascertained in this investigation are summarized below. The readers attention is drawn to the use of the term "tensile properties" which as previously mentioned, encompasses the properties: tensile strength, elongation, energy to rupture and modulus of elasticity. In specific references, however, the individual property terms are used.

1. In general, the curing of the membranes was affected by variations in humidity at constant temperature. The following changes from those observed in materials cured under standard conditions were noted:

- Up to a period of seven days tensile strength, energy to rupture and modulus of elasticity increased.
- In most cases little change in tensile properties was observed after the initial increase up to seven days curing.

- Specimens cured under a high humidity condition produced the effects provided below:
 - lower long term (28 day) tensile strengths;
 - no adverse effects on elongation capacity and similar energies to rupture;
 - lower values for modulus of elasticity, with the exception of PDM5.
- Specimens cured under a low humidity condition showed the following effects:
 - no adverse effects on tensile strength, with the exception of PDM1;
 - showed no improvement of elongation capacity;
 - did not adversely effect long term (28 day) modulus of elasticity.

Overall, the curing of the membranes under a high humidity condition resulted in greater changes to the tensile properties than under a low humidity condition. Elongation after a long term of cure was found to be insensitive to changes in relative humidity.

2. The effects produced by the variation of temperature at constant humidity on the rate and extent of curing the membranes was ascertained from the results detailed below.
 - General trends observed under these conditions included an increase in tensile strength, energy to rupture and modulus of elasticity and a decrease in elongation capacity up to seven days cure. Thereafter, in most cases, little change in these tensile properties was noted.
 - In comparison to standard conditions, curing of the membranes at a low temperature gave the following results:
 - retardation of tensile strength and a decrease in elongation capacity;
 - depending on the system, a decrease in the modulus of elasticity and varying effects on the energy to rupture.
 - Curing at a high temperature produced the following:
 - variable effects on energy to rupture and tensile strength;
 - a decrease in elongation capacity;
 - little effect on modulus of elasticity.
 - Changes in temperature can have a significant effect on the viscosity of the uncured waterproofing membrane system. Low temperature effects, which tend to increase the viscosity of the systems, appeared to have a greater impact on application characteristics than high temperature effects. For example, viscosity values, depending on the application technique, can affect the properties of the finished product due to the response in shear, sagging and self levelling properties.
3. Variation in ambient conditions may seriously affect the permeance of certain membranes. While curing at a high relative humidity (at either high or low temperatures) caused an increase in permeance, a low relative humidity resulted in a decrease in permeance. In all cases, the permeance of

the neoprene membrane (PDM5) was affected to a greater extent by temperature and humidity changes than the urethane based membrane systems

4. Deviation from the manufacturers stipulated mix proportions of the components can result in considerable changes in tensile properties, especially at early ages of cure.
 - Tensile strength values decrease with the use of excess hardener, but no serious effects were observed (at 28 days) when excess resin is used.
 - Long term values for elongation capacity showed that this property was not seriously affected by incorrect mix proportions (either excess resin or hardener).
 - The effect of incorrect proportioning on energy to rupture and modulus of elasticity was variable in the different membranes.
 - The membranes waterproofing characteristics, as given by the permeance values, were affected by incorrect proportioning. Excess resin increased permeance values while excess hardener produced variable results in the different membranes.
 - The effects due to incorrect proportioning differed in the three surface preparation techniques investigated:
 - no trend was seen in the adhesion of the membrane samples when excess resin was used
 - for samples prepared with excess hardener, shotblasted surfaces gave lower values than either sandblasted or water jet blasted surfaces. Previous work ²⁰⁻²³ showed that the method weakens the resultant near surface layer of the concrete, due to impact damage from the shot. Also, because this technique resulted in the largest surface profile, its use with very thin coat membranes such as PDM3 should be reviewed. The magnitude of the shotblasted profile can often be as great as the thickness of the application lift itself. This would require approximately twice the lift thickness to achieve a uniform correct coverage. It has been seen that when PDM3 is placed in a thick layer, it has a tendency to foam.
5. Poor mixing of the membrane components gave results that were similar to those noted for incorrect proportioning.
 - Changes in the tensile properties were observed as follows:
 - PDM1 and PDM3 gave results similar to that obtained when excess resin was used
 - PDM3 gave results similar to that obtained when excess resin was used, except for energy to rupture, which did not follow this trend
 - the changes observed for PDM4 were quite varied and no direct correspondence could be drawn between poor mixing and incorrect proportioning

6. The interval between mixing and application of the membrane influenced the degree of adhesion achieved by the membrane to the concrete substrate as well as intercoat adhesion between successive membrane coats.
 - The optimal time for application of the membranes investigated was less than 30 minutes. After 30 minutes large decreases in membrane/concrete adhesion was noted.
 - Preliminary studies of the reaction kinetics of the various membranes indicated that intercoat adhesion problems can arise if the interval between application of the successive coats is delayed too long.

7. Poor embedment of the aggregate (as seen in the electron micrographs) will result in the ready dislodging of these particles at early ages. Consequently, critical properties, such as abrasion resistance and resistance to UV degradation, are significantly affected at the early stages of the service life of the membrane. Furthermore, dislodging of the aggregate can result in slippery surfaces, particularly in areas subject to constant shearing forces, such as ramps.

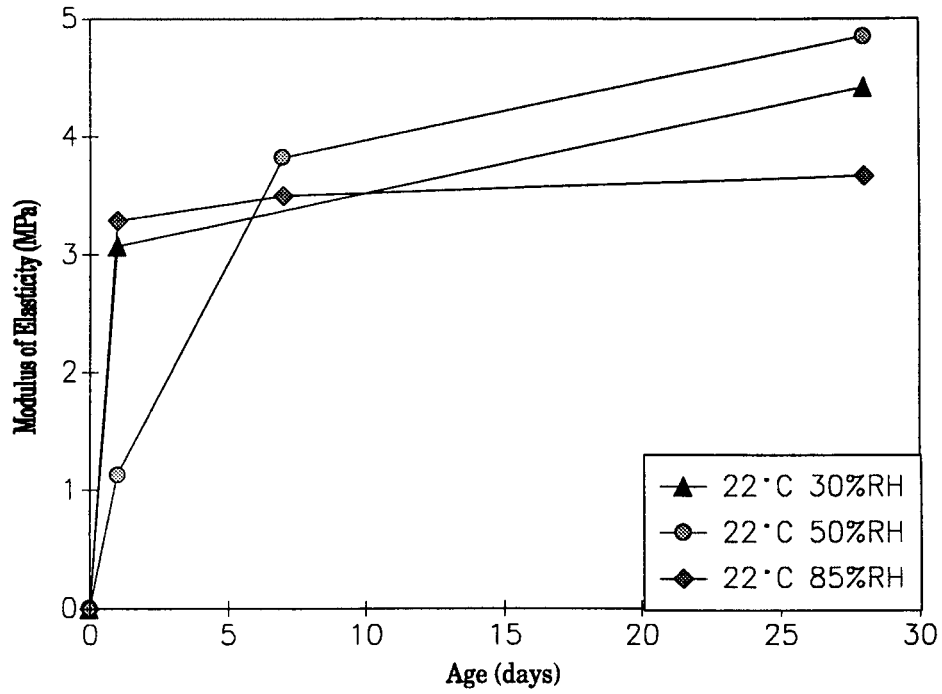


Figure 1. Modulus of Elasticity of PDM1 as a Function of Relative Humidity

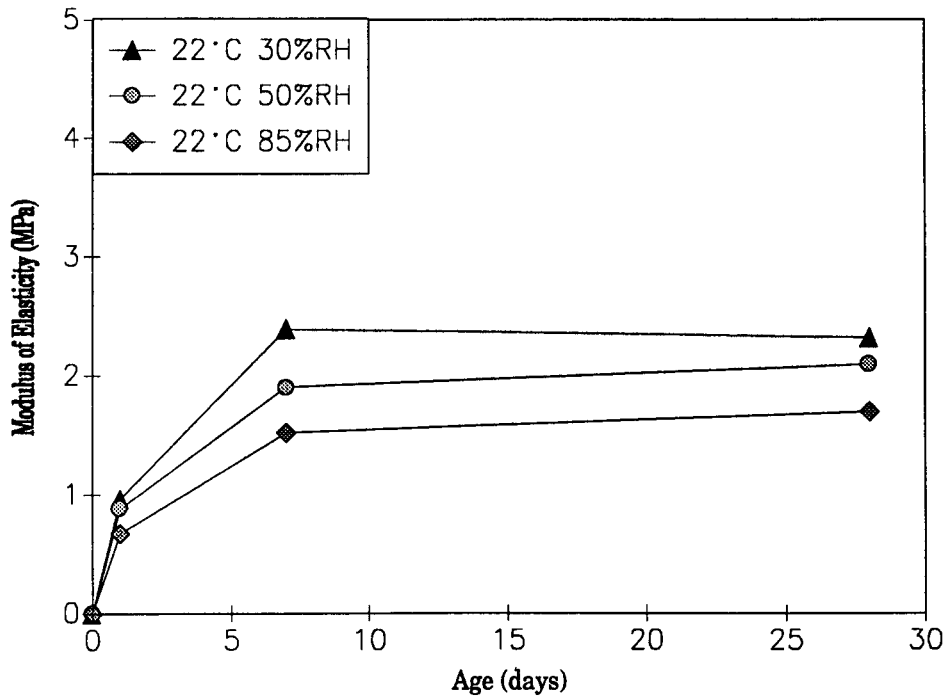


Figure 2. Modulus of Elasticity of PDM2 as a Function of Relative Humidity

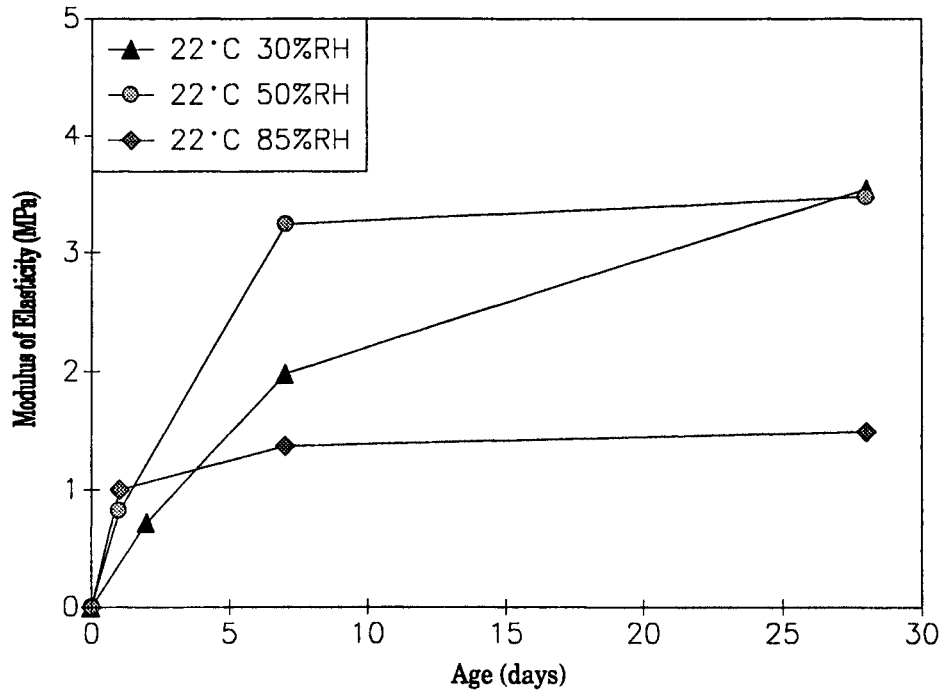


Figure 3. Modulus of Elasticity of PDM3 as a Function of Relative Humidity

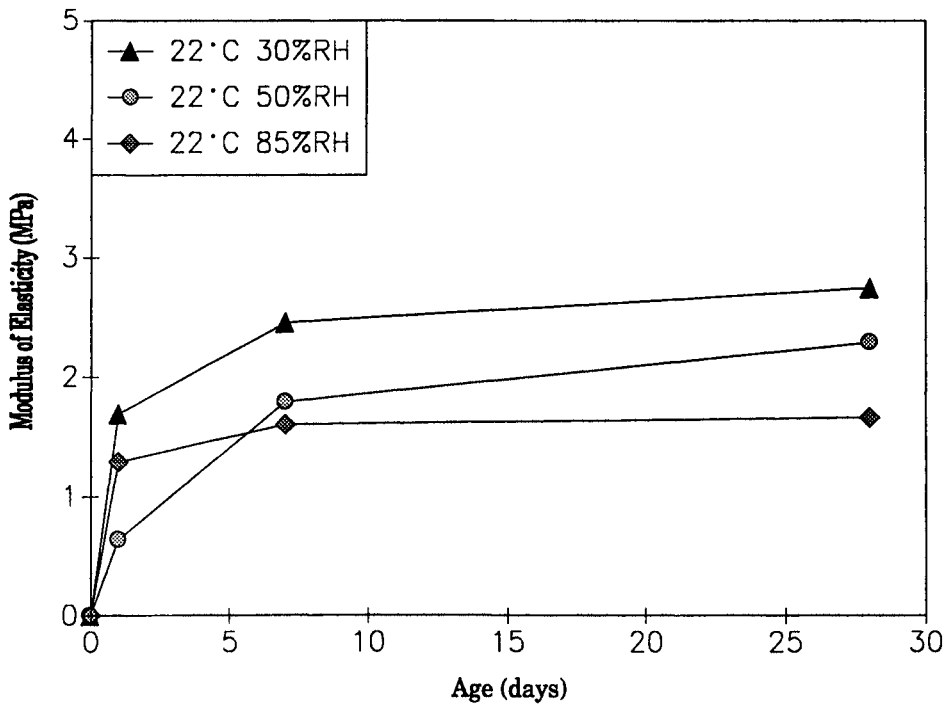


Figure 4. Modulus of Elasticity of PDM4 as a Function of Relative Humidity

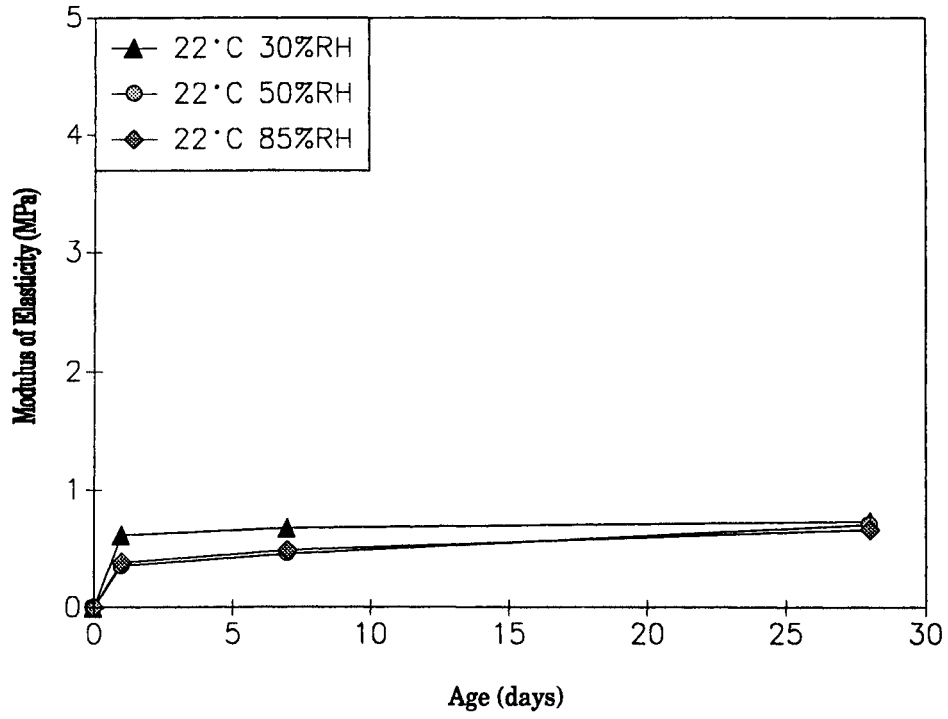


Figure 5. Modulus of Elasticity of PDM5 as a Function of Relative Humidity

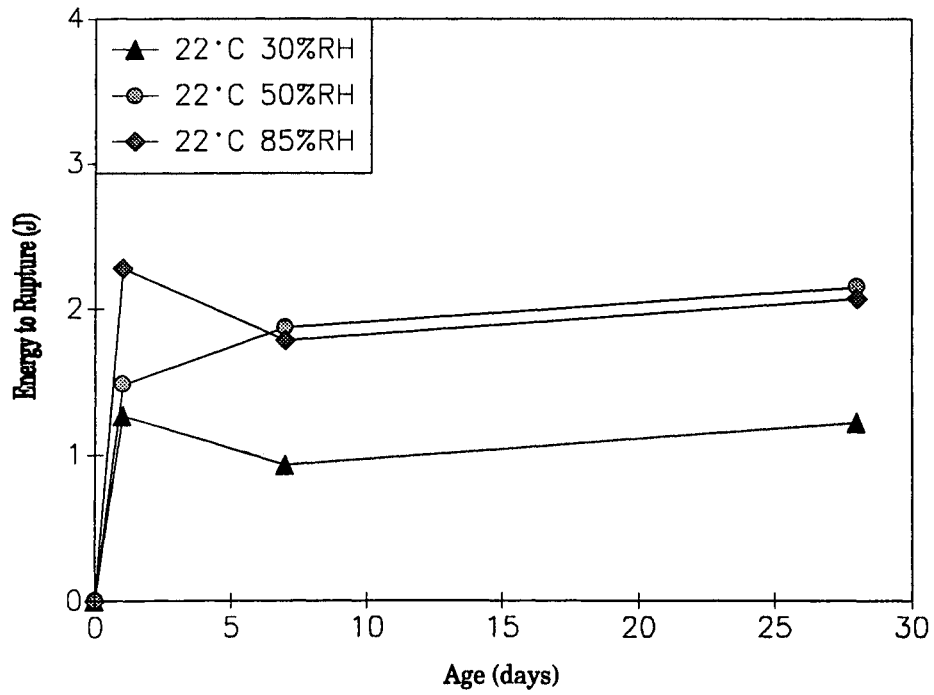


Figure 6. Energy to Rupture for PDM1 as a Function of Relative Humidity

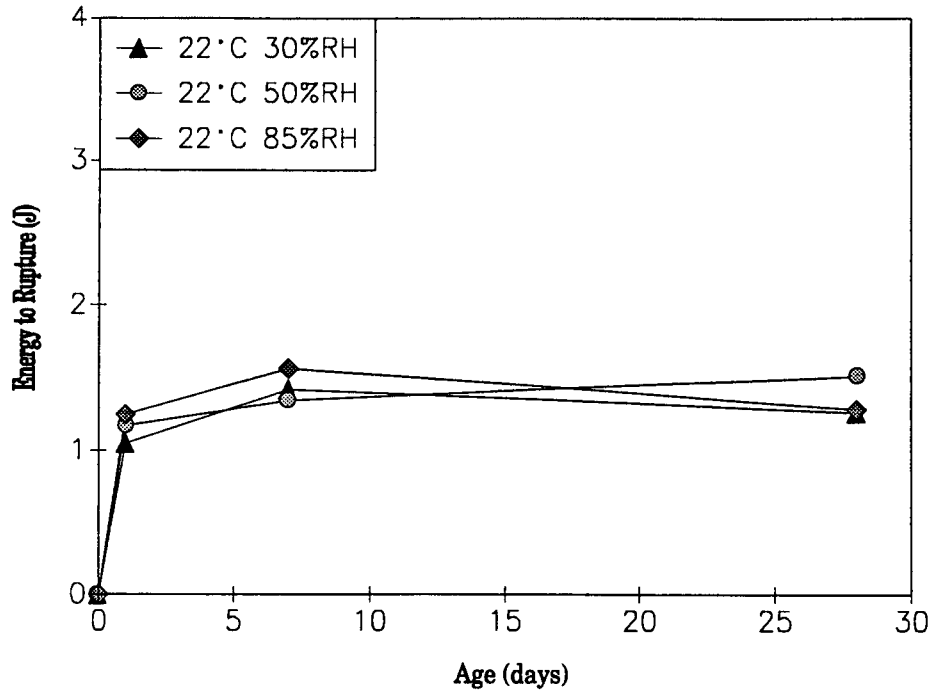


Figure 7. Energy to Rupture for PDM2 as a Function of Relative Humidity

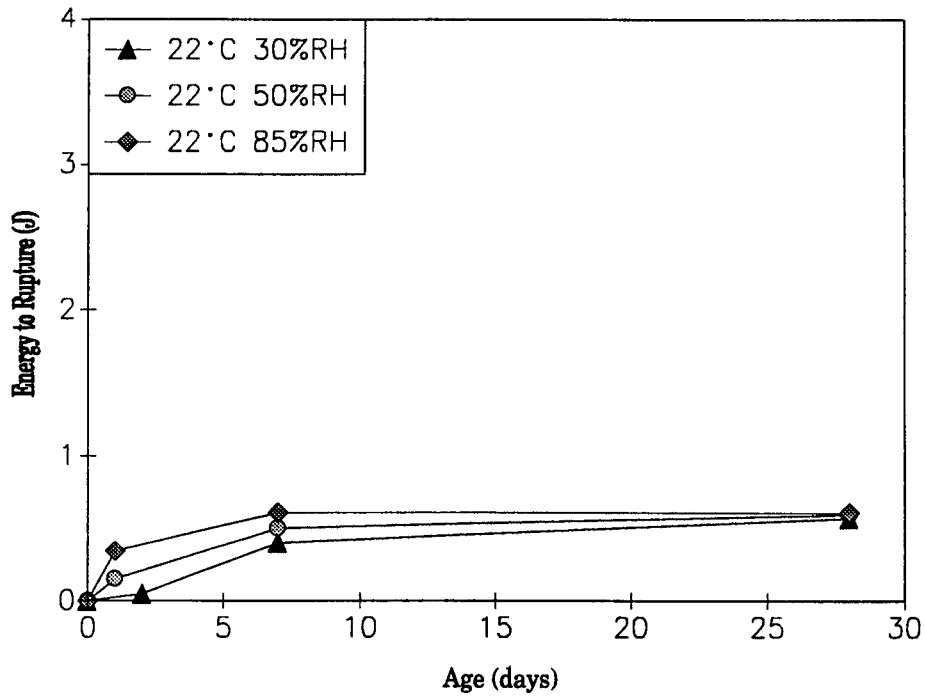


Figure 8. Energy to Rupture for PDM3 as a Function of Relative Humidity

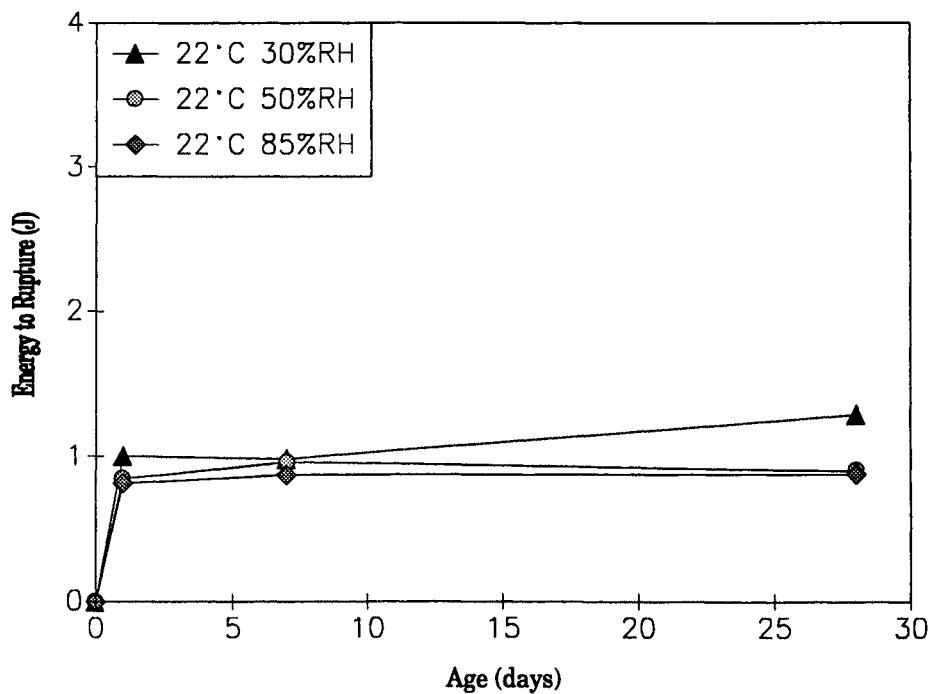


Figure 9. Energy to Rupture for PDM4 as a Function of Relative Humidity

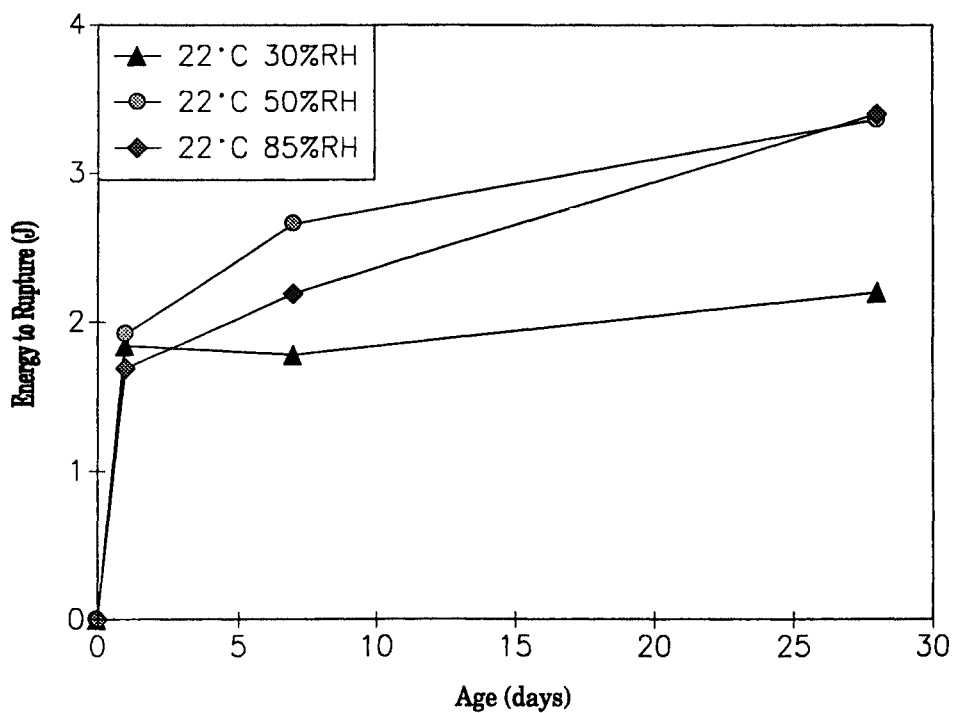


Figure 10. Energy to Rupture for PDM5 as a Function of Relative Humidity

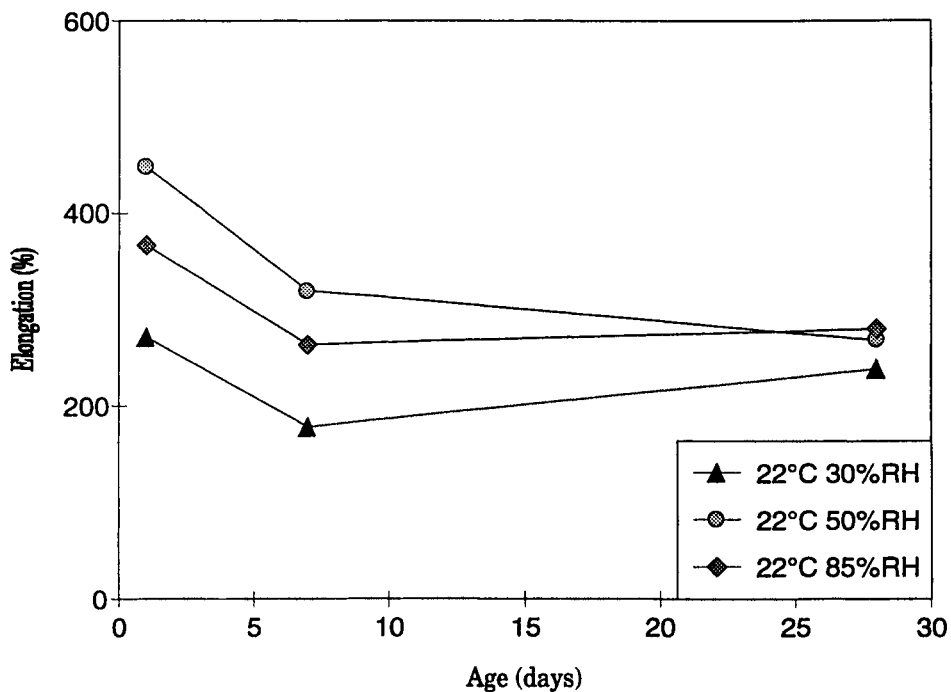


Figure 11. Elongation Development of PDM1 as a Function of Relative Humidity

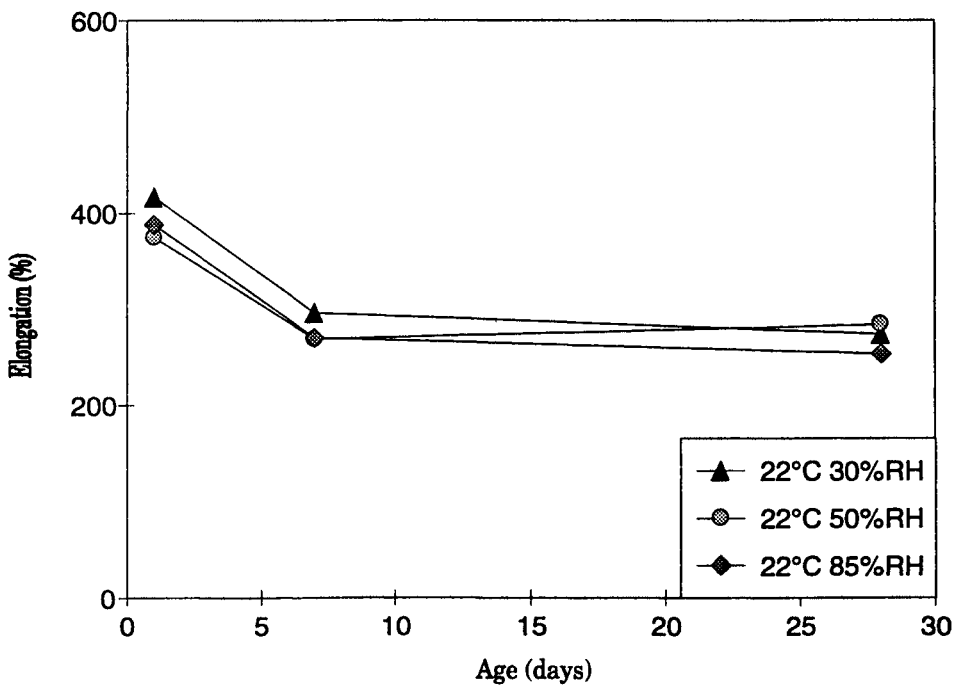


Figure 12. Elongation Development of PDM2 as a Function of Relative Humidity

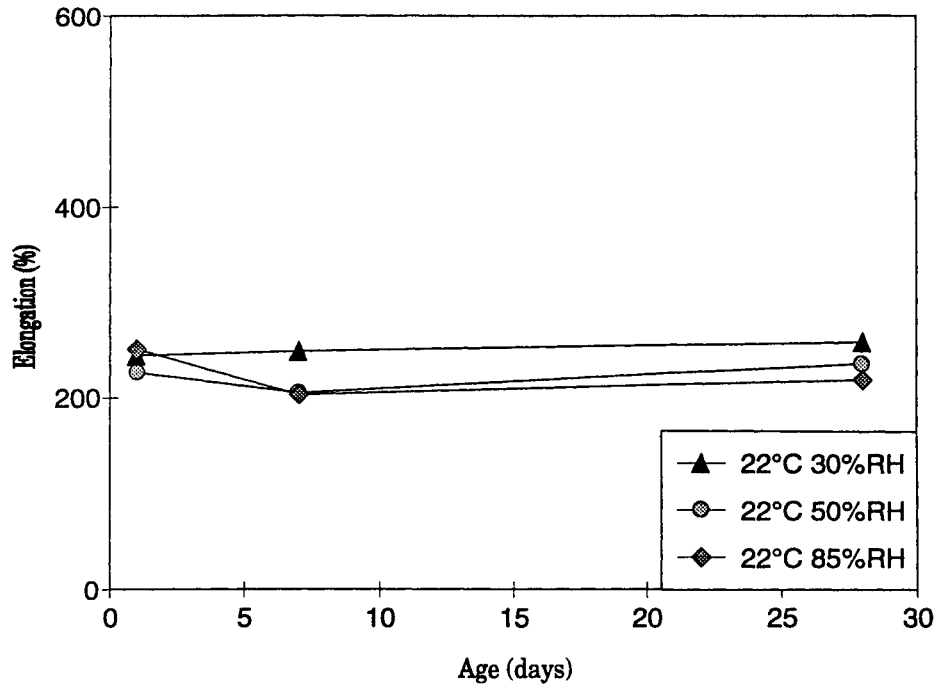


Figure 13. Elongation Development of PDM3 as a Function of Relative Humidity

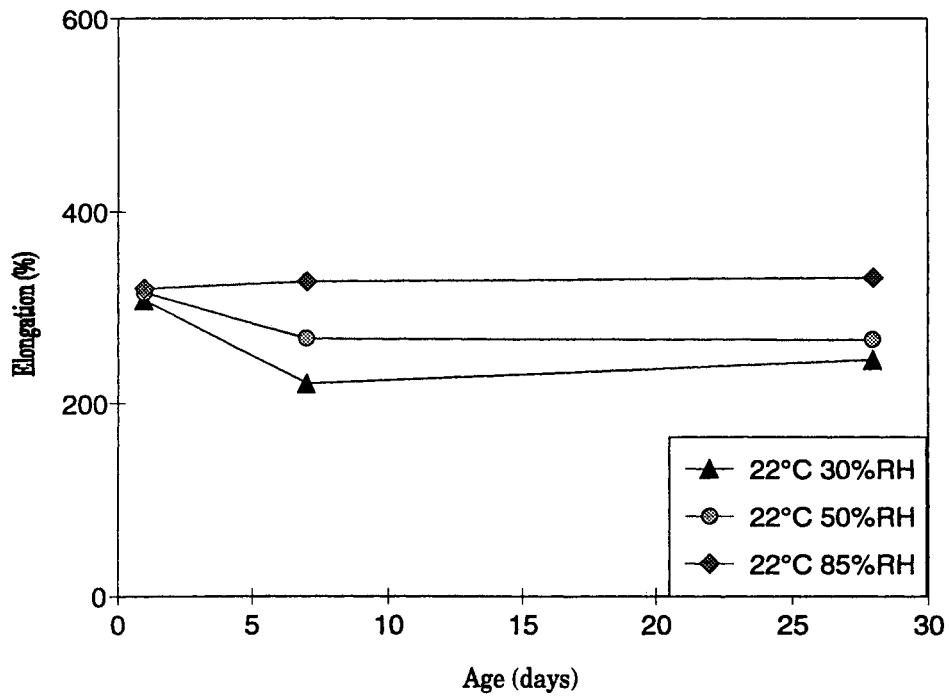


Figure 14. Elongation Development of PDM4 as a Function of Relative Humidity

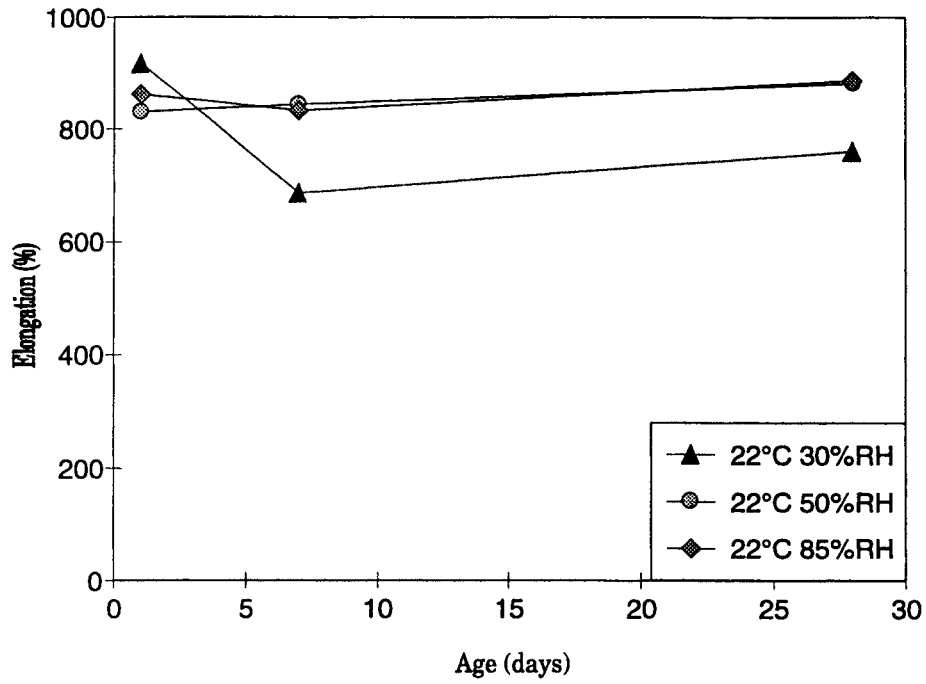


Figure 15. Elongation Development of PDM5 as a Function of Relative Humidity

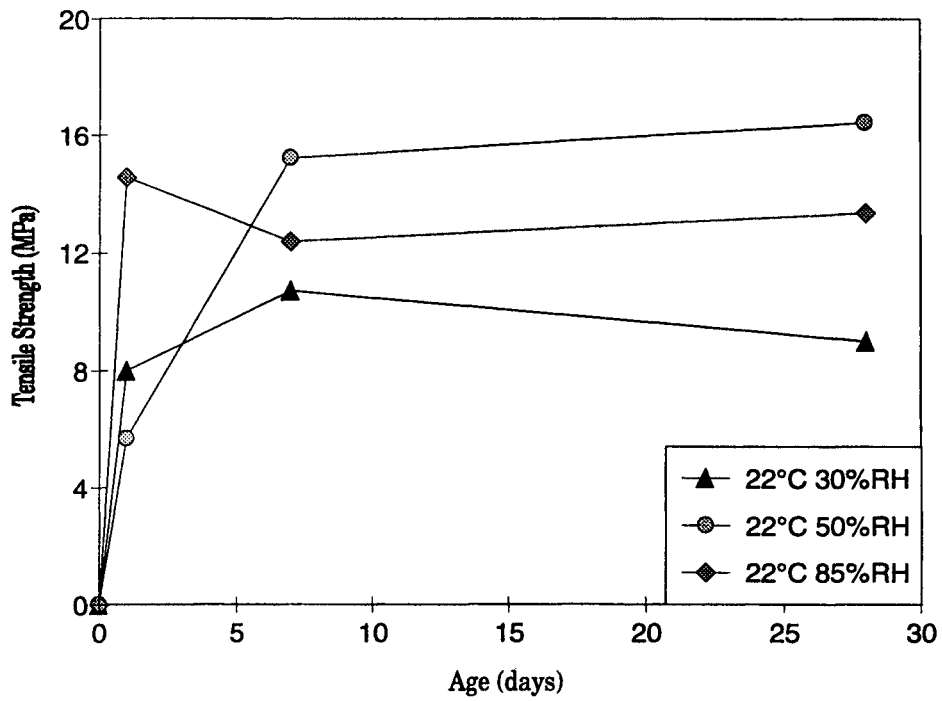


Figure 16. Tensile Strength Development of PDM1 as a Function of Relative Humidity

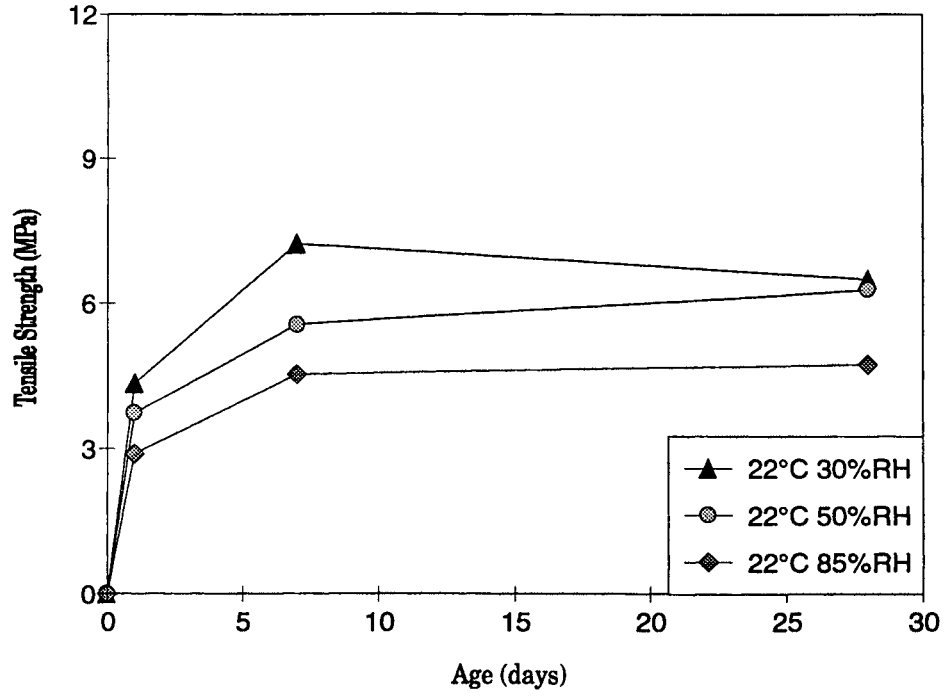


Figure 17. Tensile Strength Development of PDM2 as a Function of Relative Humidity

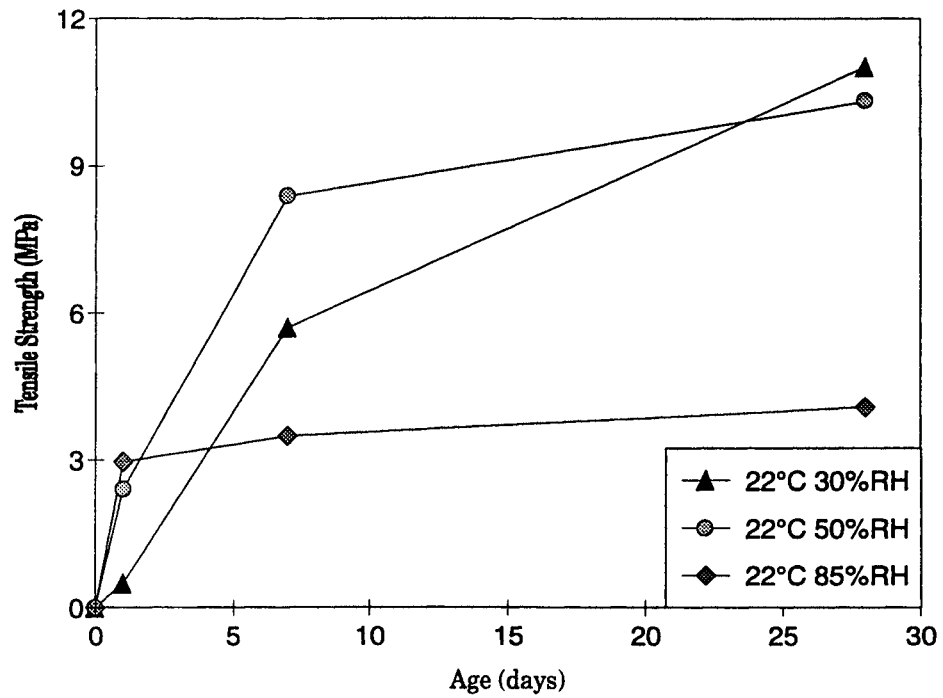


Figure 18. Tensile Strength Development of PDM3 as a Function of Relative Humidity

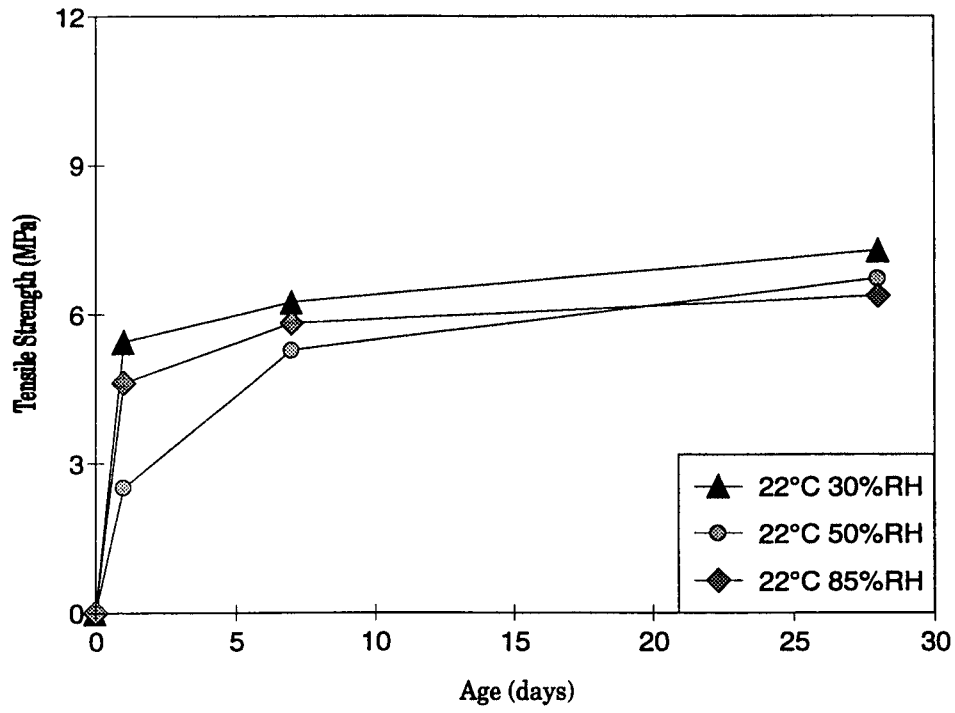


Figure 19. Tensile Strength Development of PDM4 as a Function of Relative Humidity

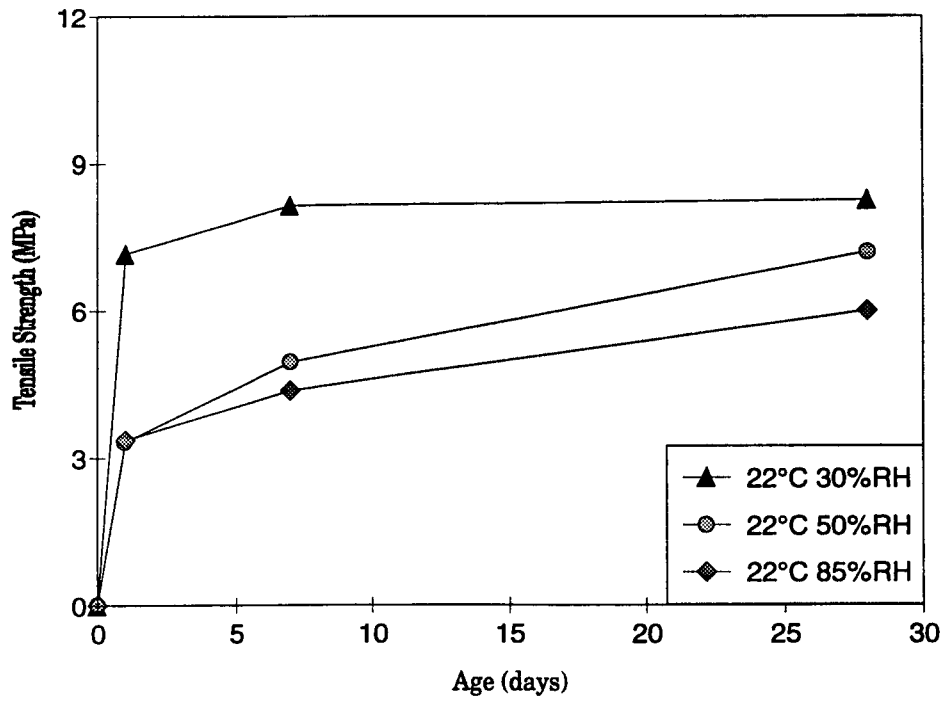


Figure 20. Tensile Strength Development of PDM5 as a Function of Relative Humidity

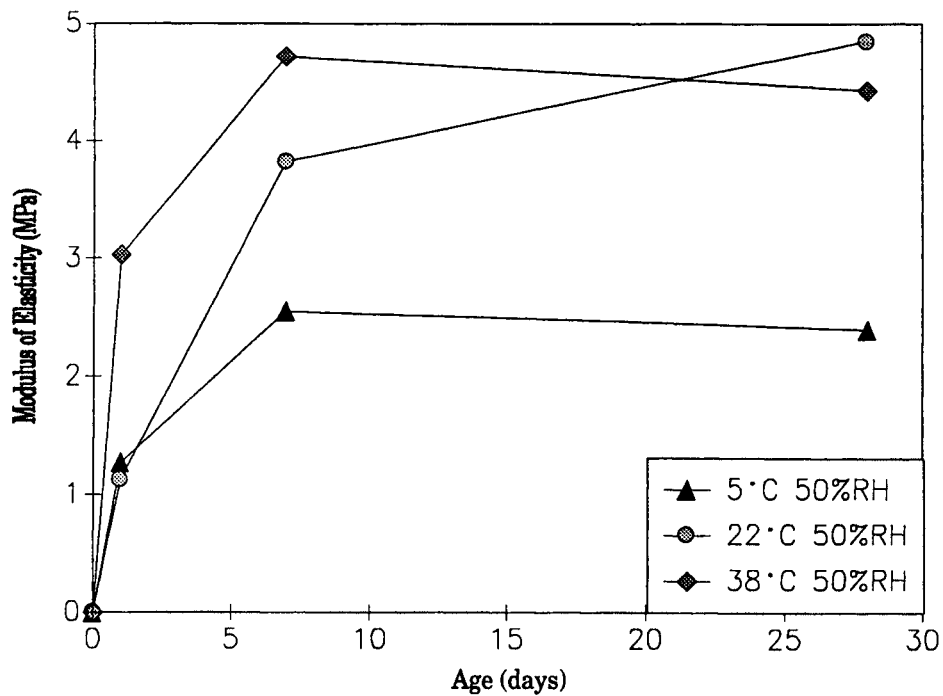


Figure 21. Modulus of Elasticity of PDM1 as a Function of Temperature

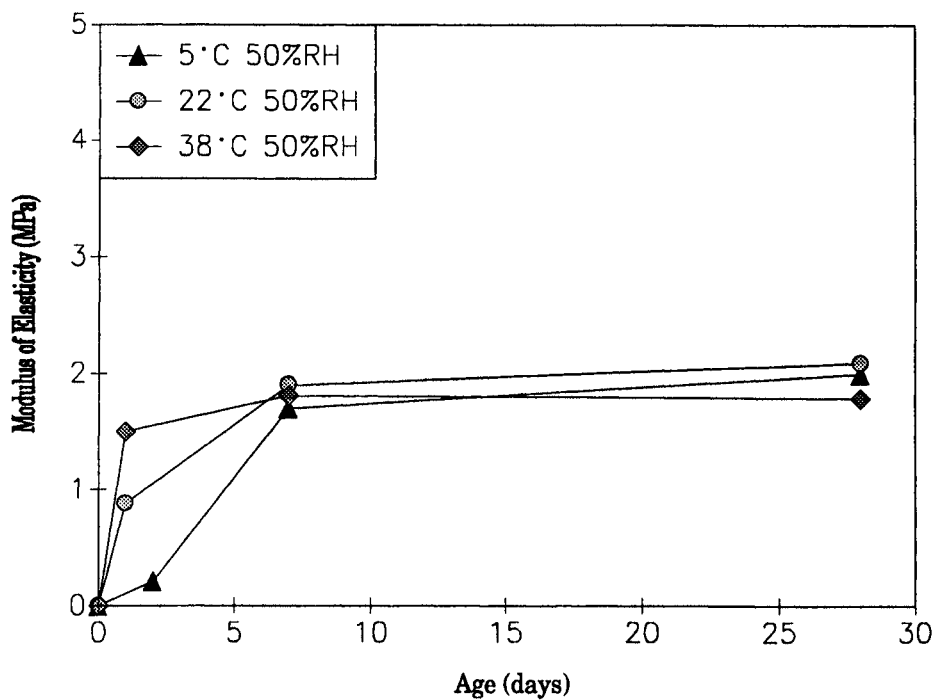


Figure 22. Modulus of Elasticity of PDM2 as a Function of Temperature

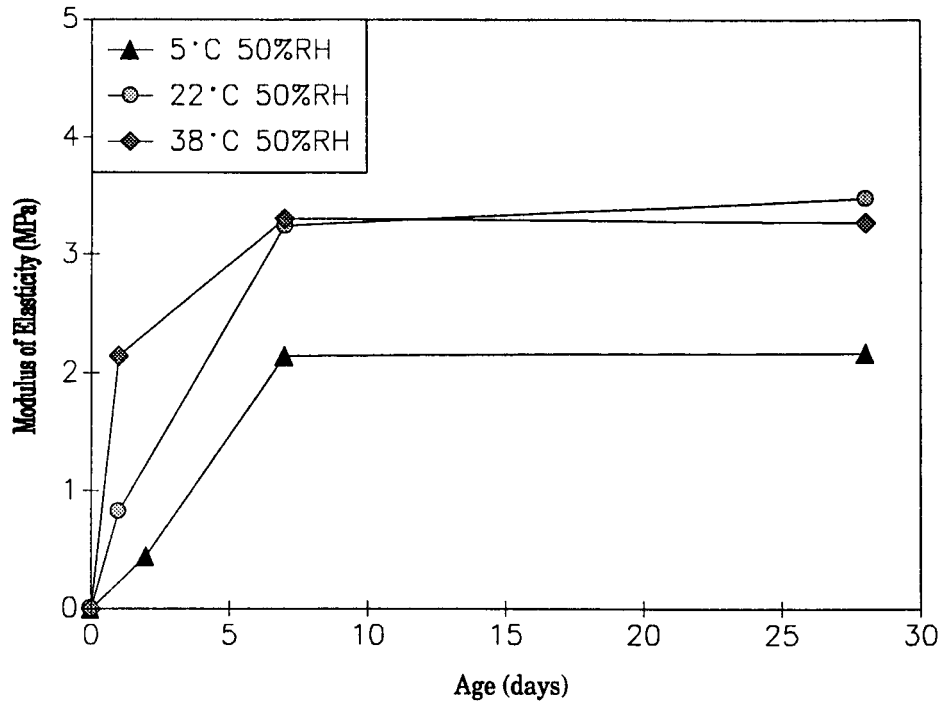


Figure 23. Modulus of Elasticity of PDM3 as a Function of Temperature

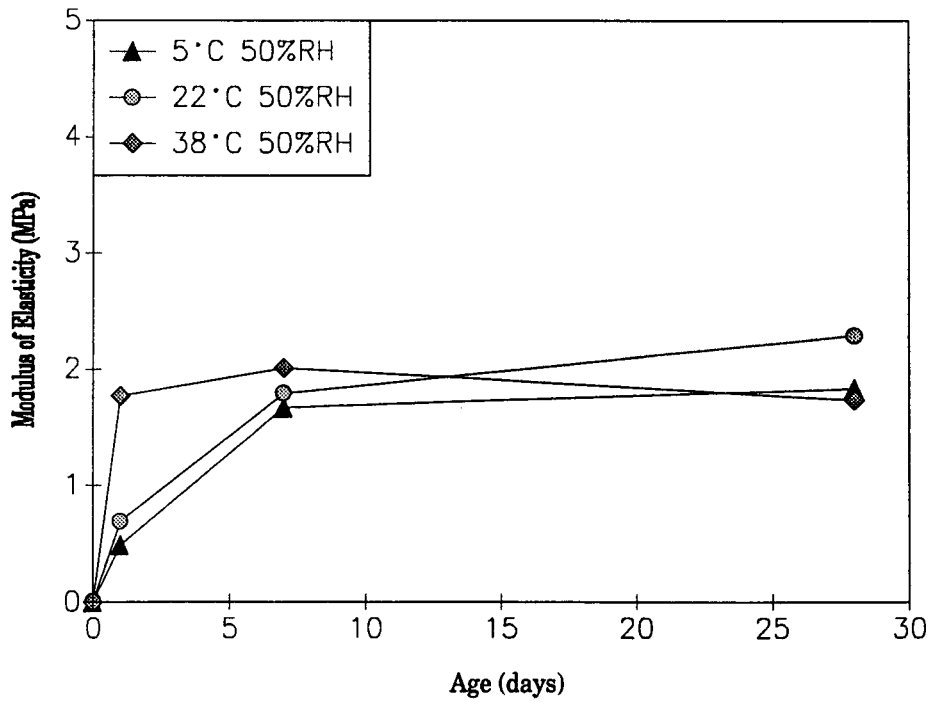


Figure 24. Modulus of Elasticity of PDM4 as a Function of Temperature

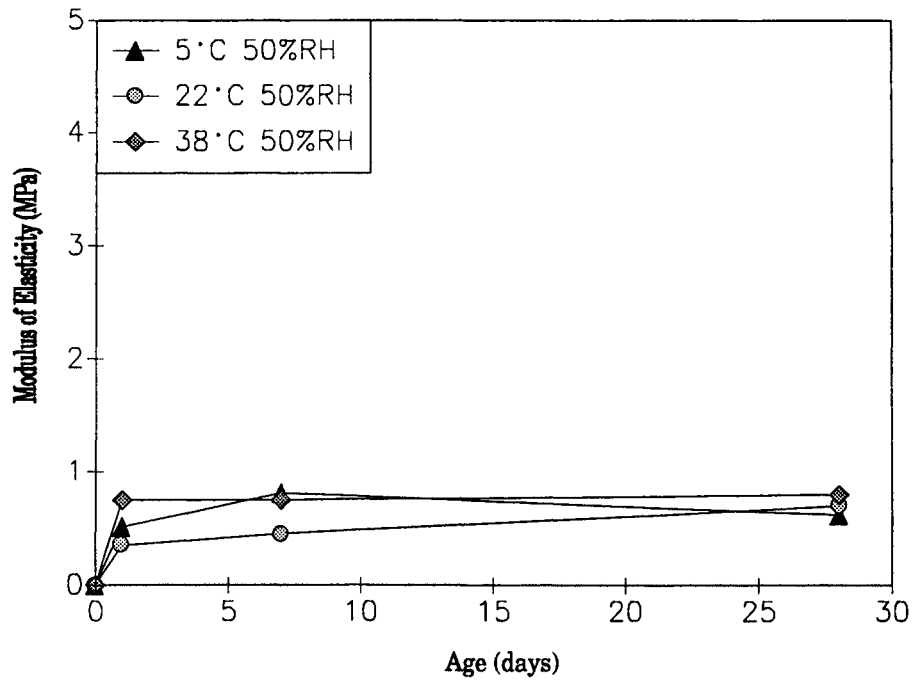


Figure 25. Modulus of Elasticity of PDM5 as a Function of Temperature

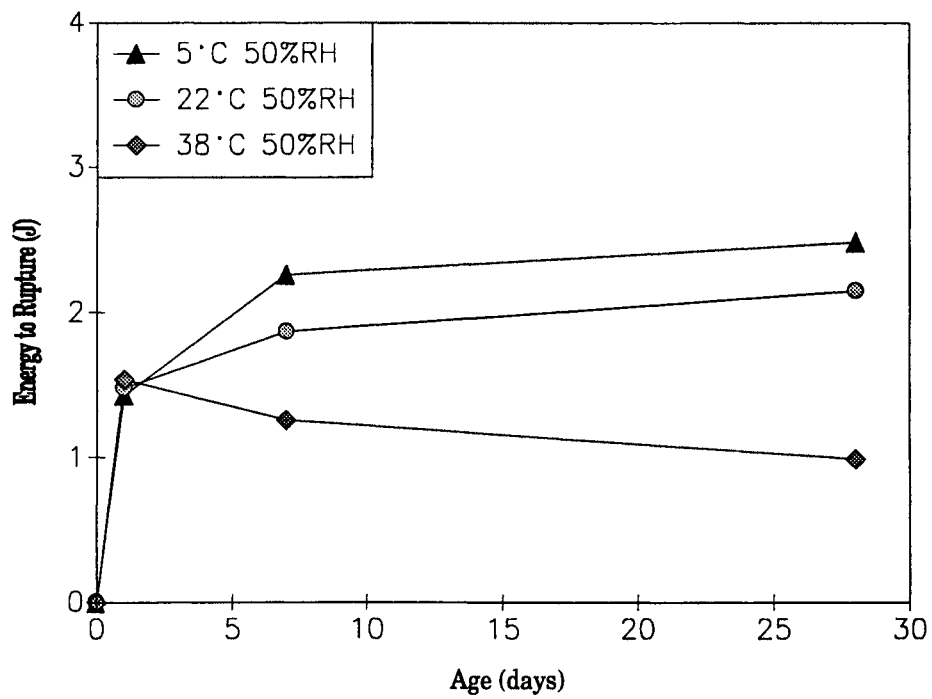


Figure 26. Energy to Rupture for PDM1 as a Function of Temperature

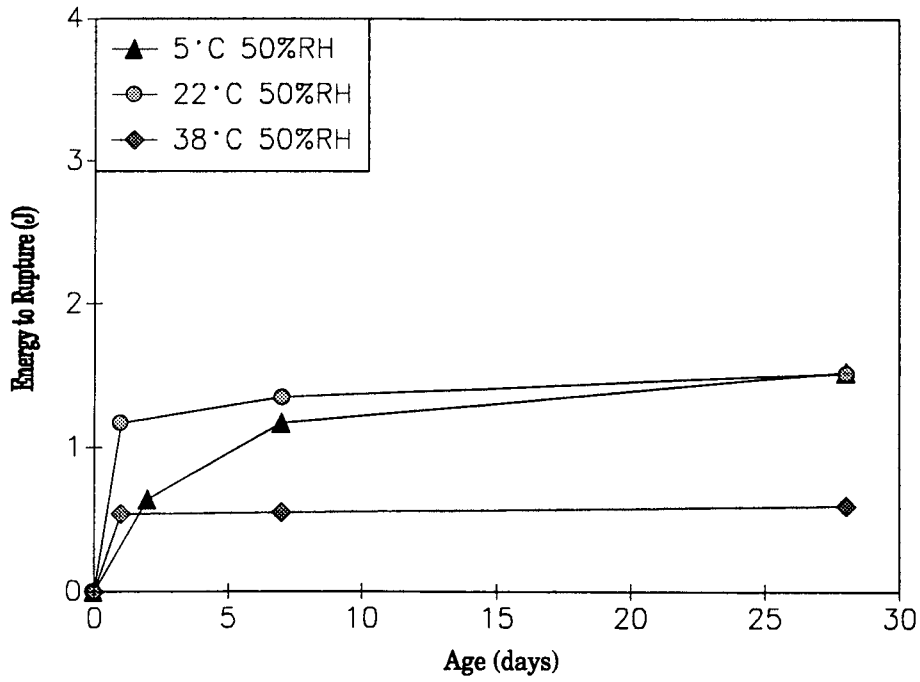


Figure 27. Energy to Rupture for PDM2 as a Function of Temperature

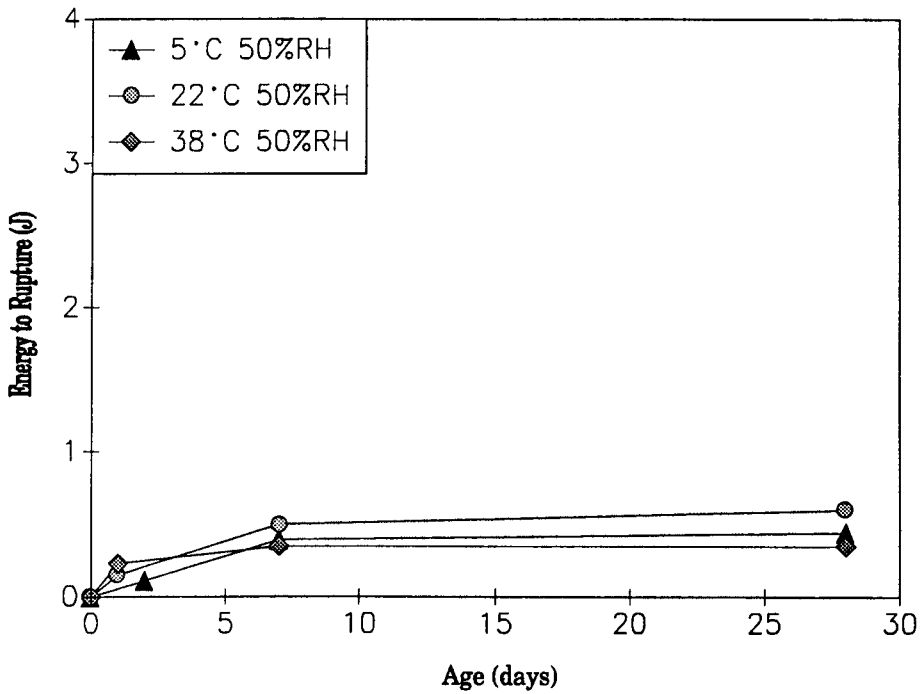


Figure 28. Energy to Rupture for PDM3 as a Function of Temperature

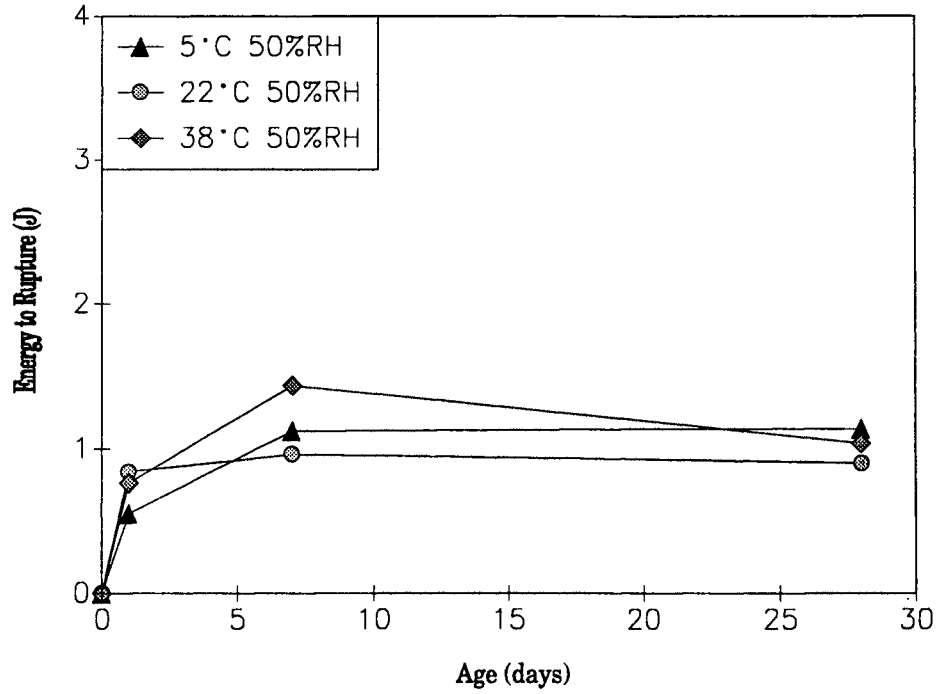


Figure 29. Energy to Rupture for PDM4 as a Function of Temperature

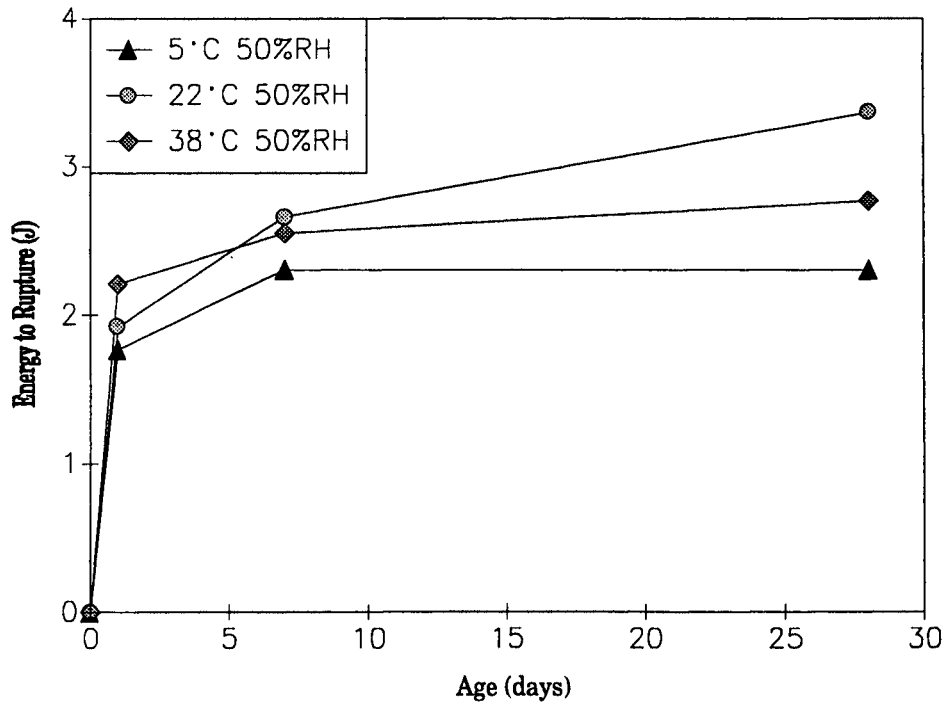


Figure 30. Energy to Rupture for PDM5 as a Function of Temperature

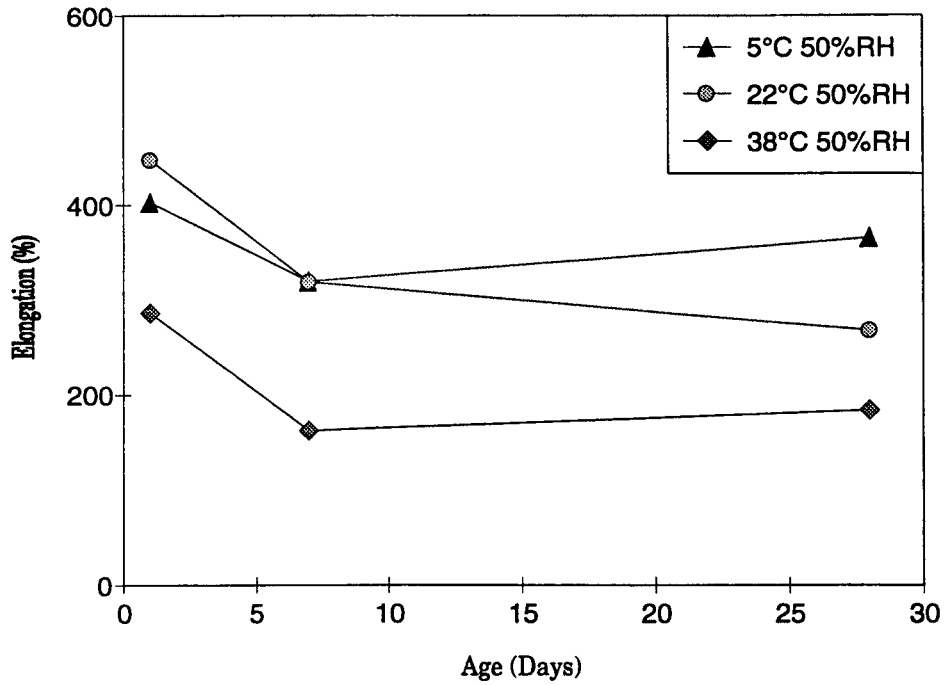


Figure 31. Elongation Development of PDM1 as a Function of Temperature

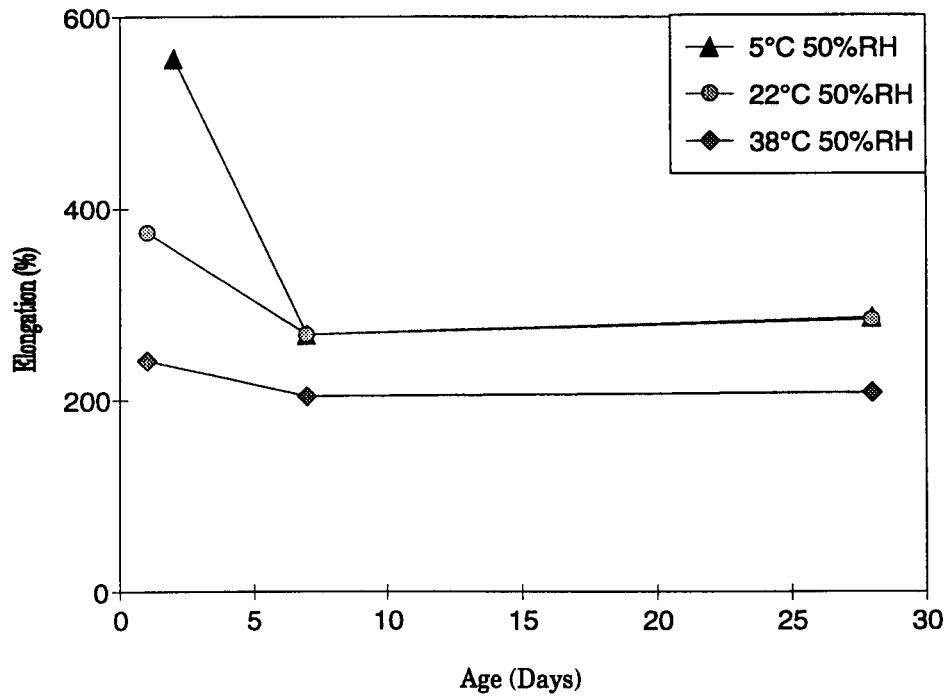


Figure 32. Elongation Development of PDM2 as a Function of Temperature

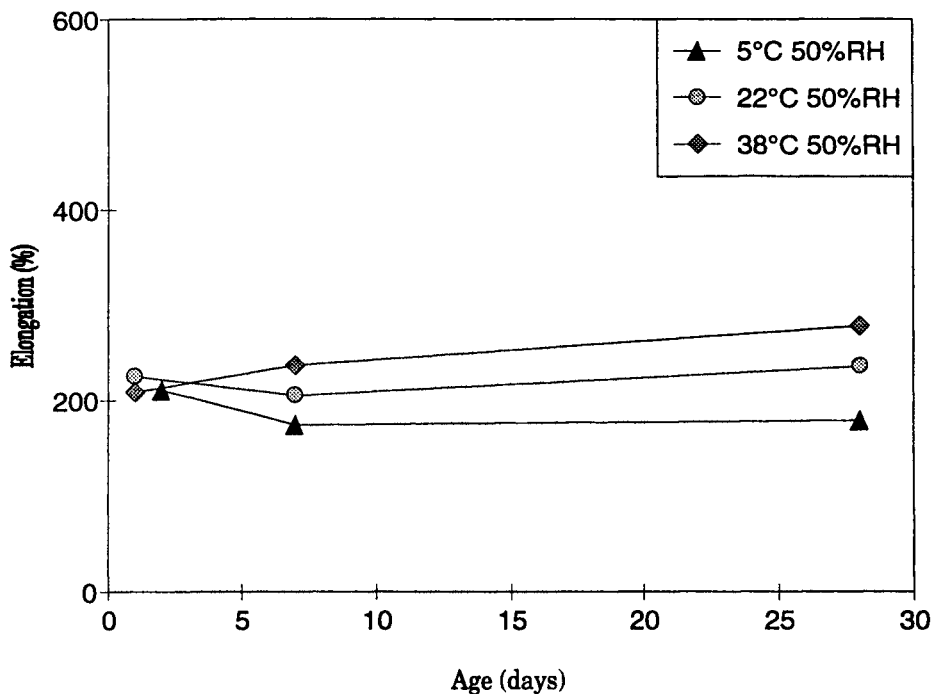


Figure 33. Elongation Development of PDM3 as a Function of Temperature

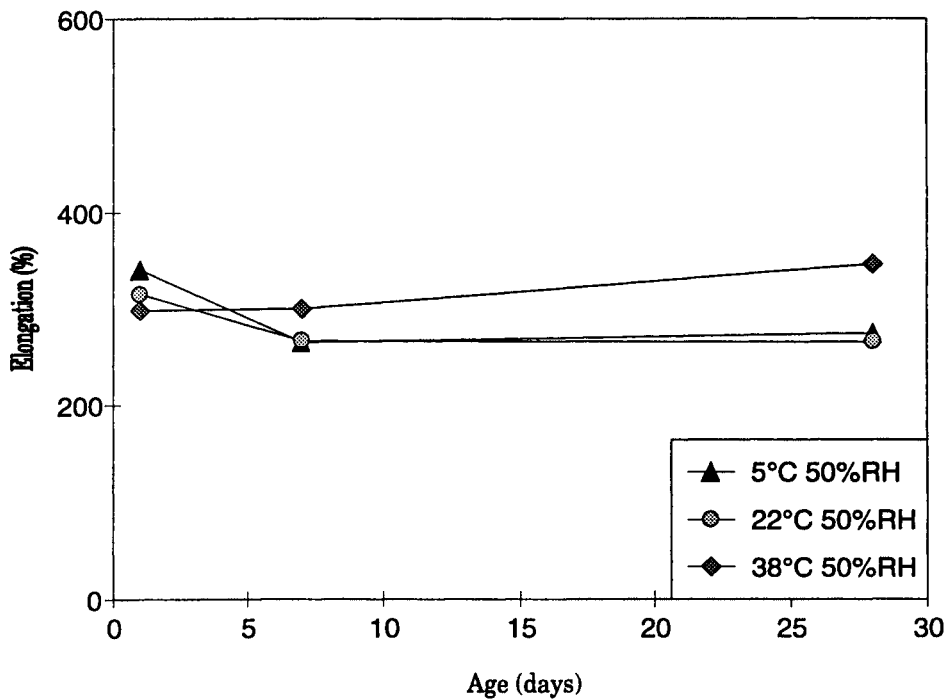


Figure 34. Elongation Development of PDM4 as a Function of Temperature

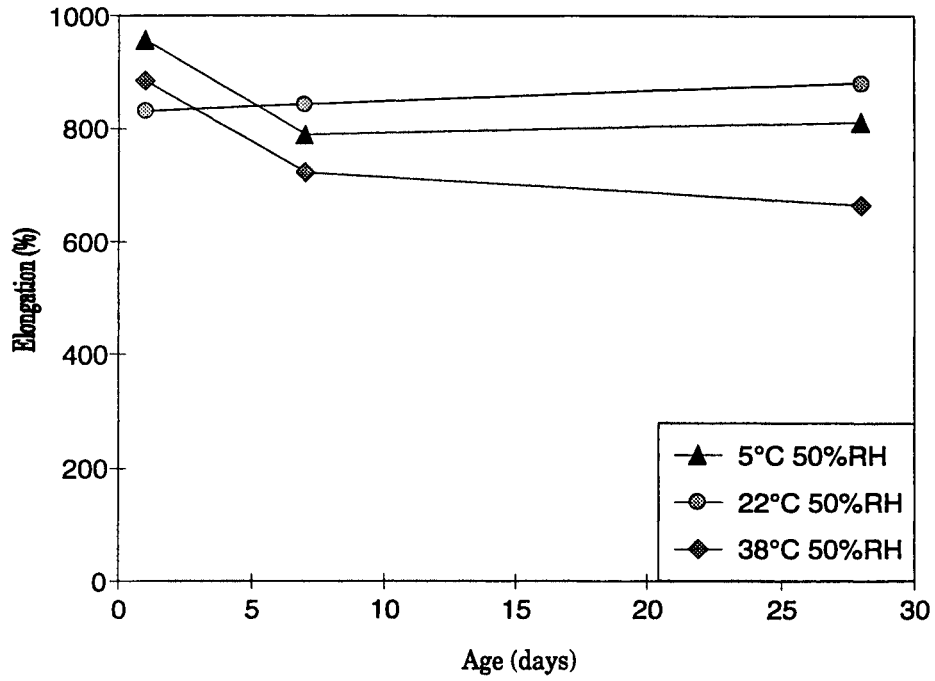


Figure 35. Elongation Development of PDM5 as a Function of Temperature

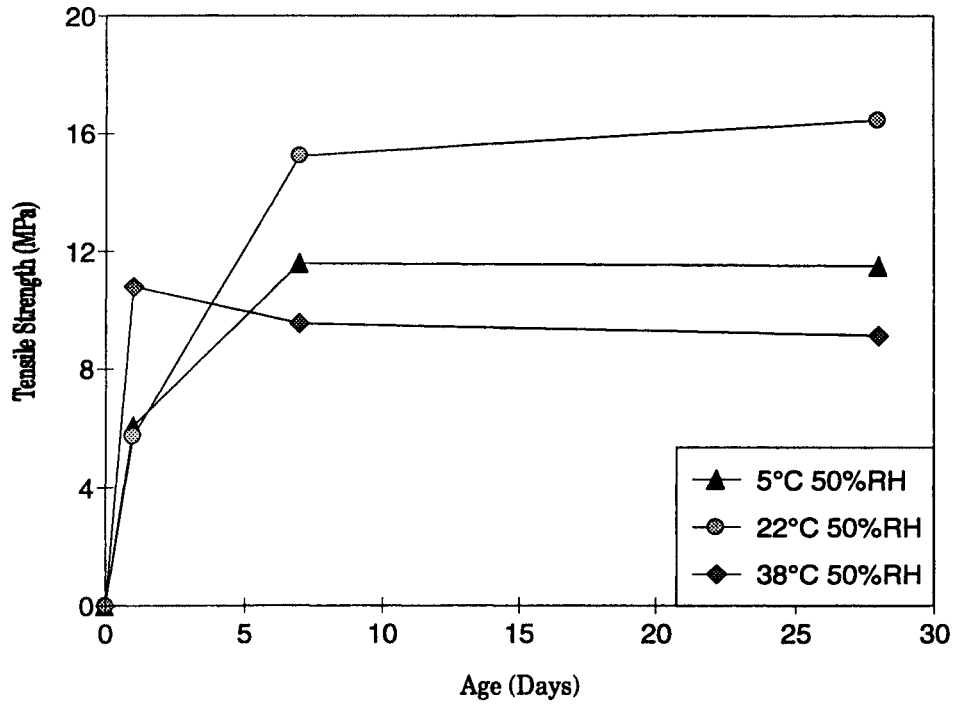


Figure 36. Tensile Strength Development of PDM1 as a Function of Temperature

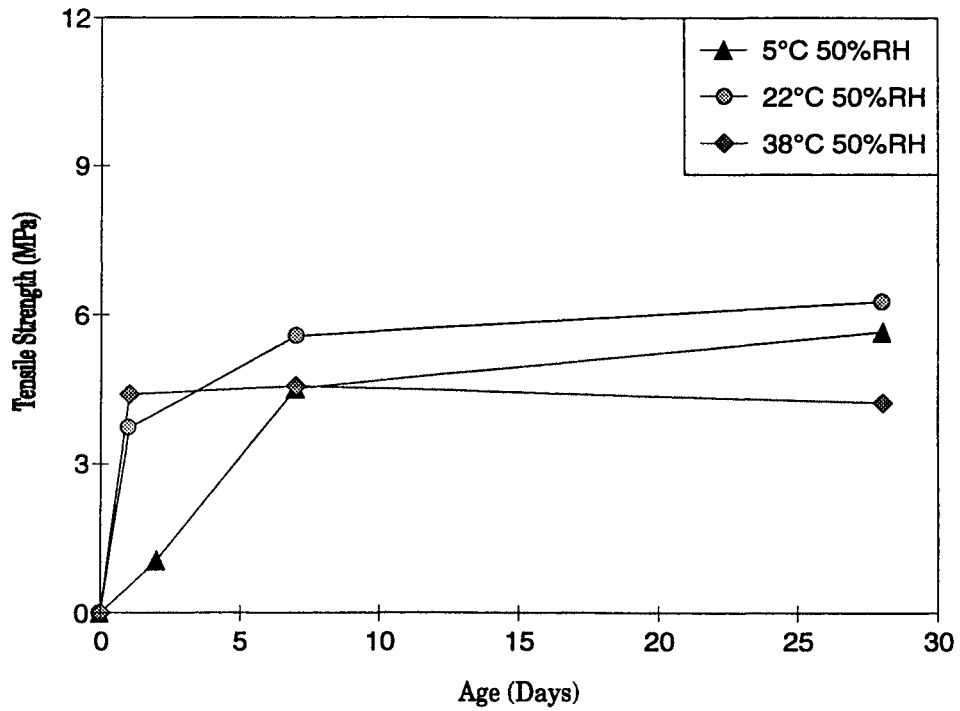


Figure 37. Tensile Strength Development of PDM2 as a Function of Temperature

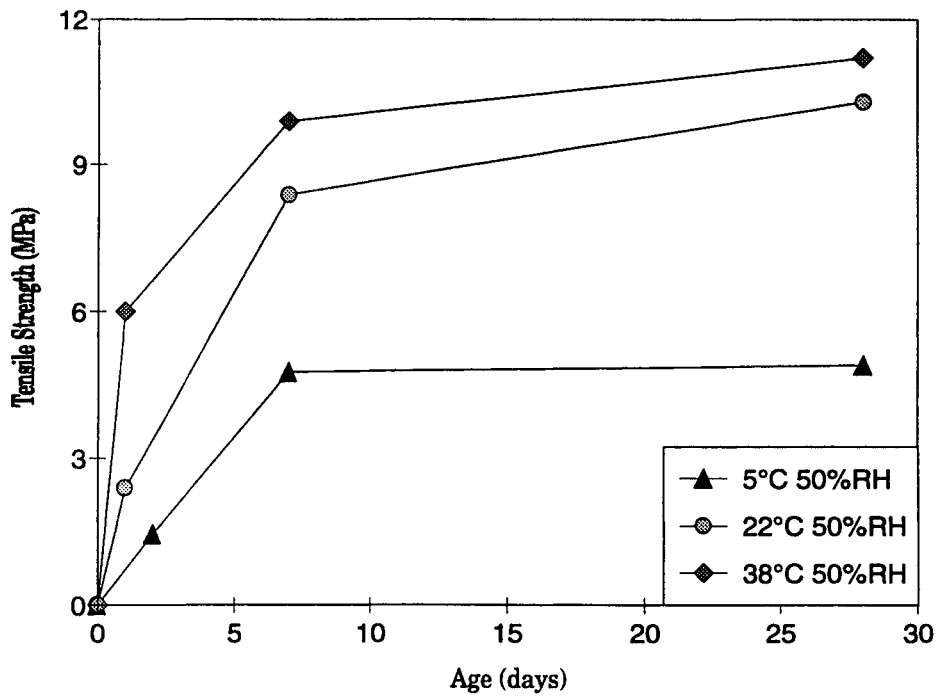


Figure 38. Tensile Strength Development of PDM3 as a Function of Temperature

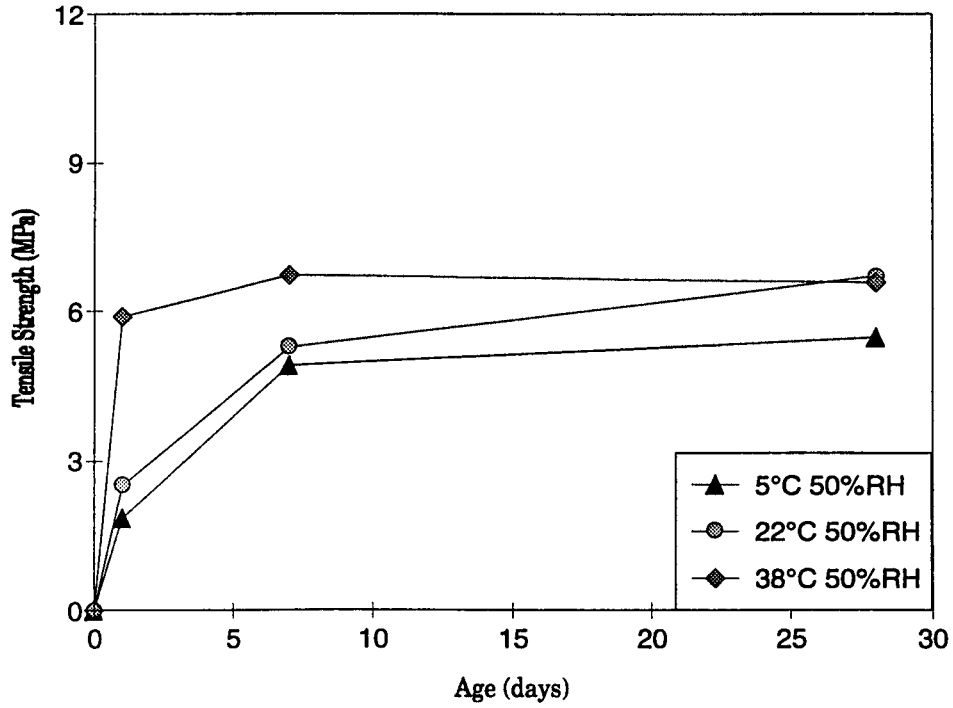


Figure 39. Tensile Strength Development of PDM4 as a Function of Temperature

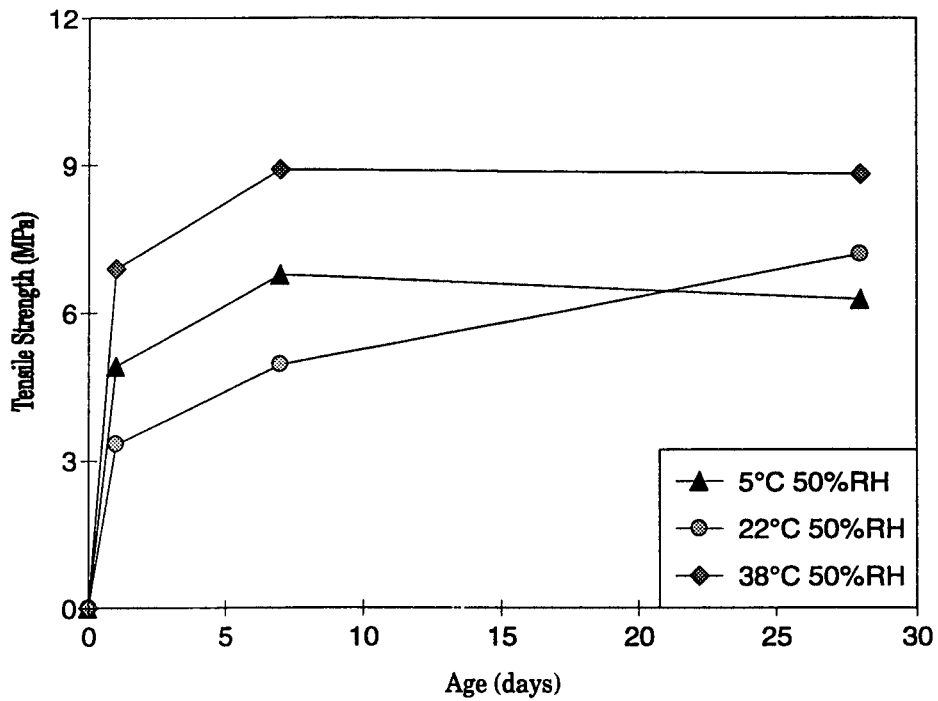


Figure 40. Tensile Strength Development of PDM5 as a Function of Temperature

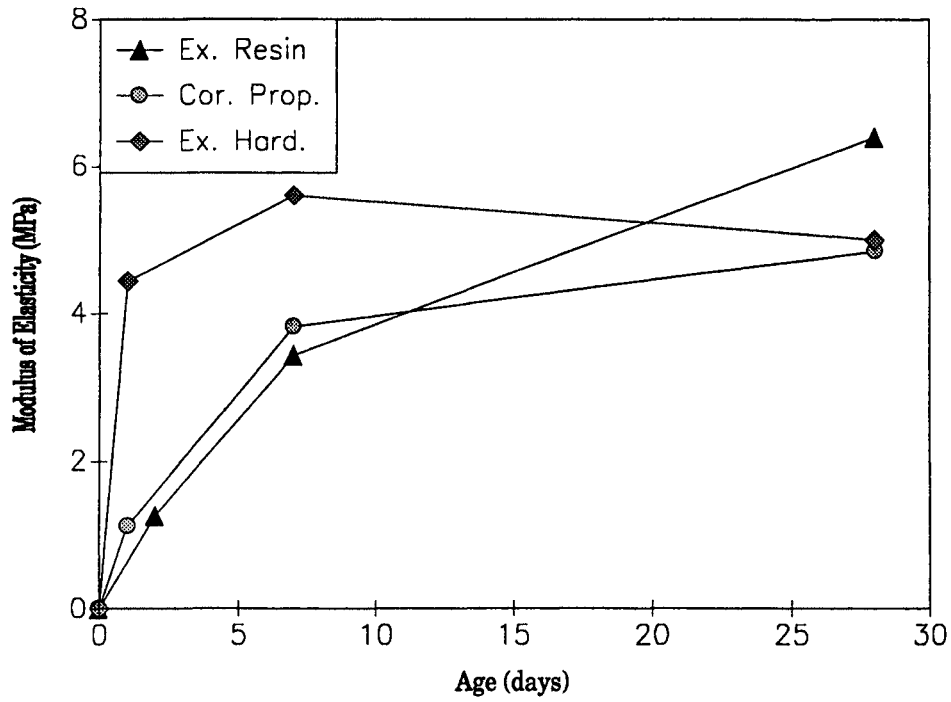


Figure 41. Effect of Incorrect Proportioning on Modulus of Elasticity of PDM1

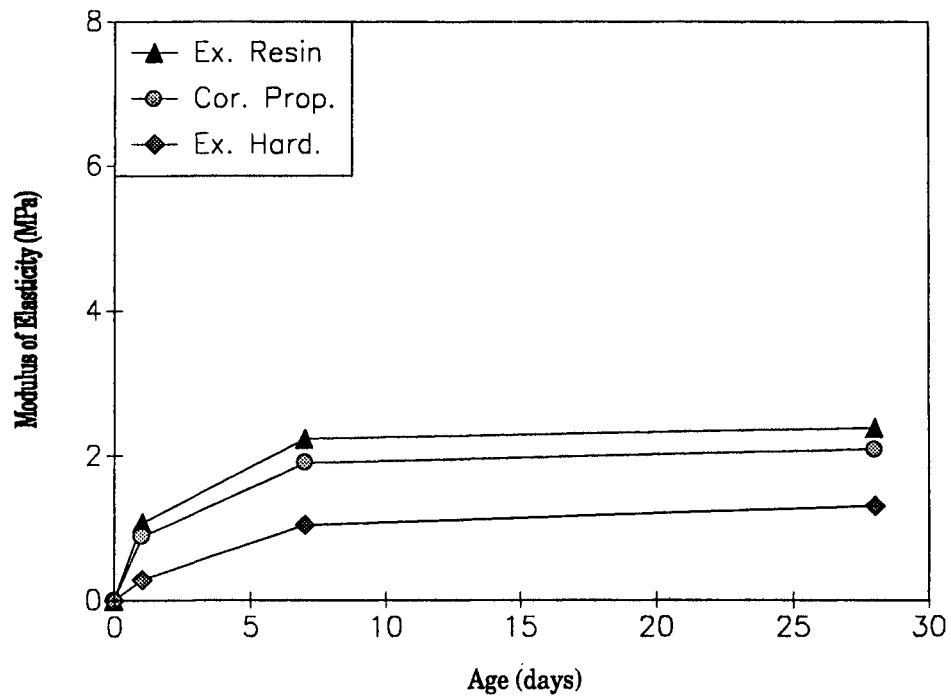


Figure 42. Effect of Incorrect Proportioning on Modulus of Elasticity of PDM2

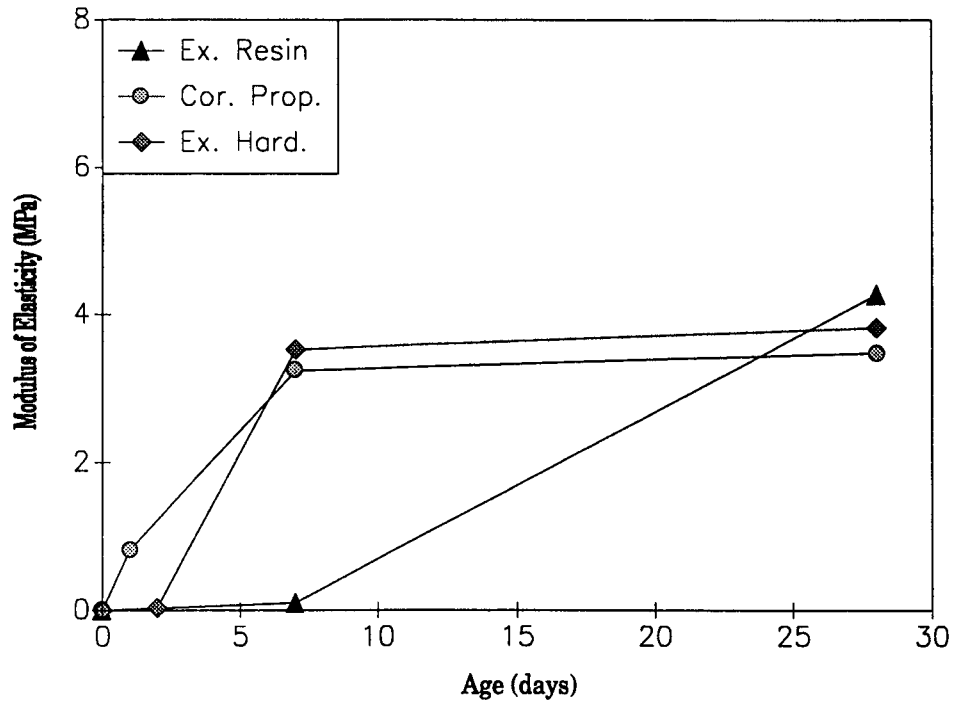


Figure 43. Effect of Incorrect Proportioning on Modulus of Elasticity of PDM3

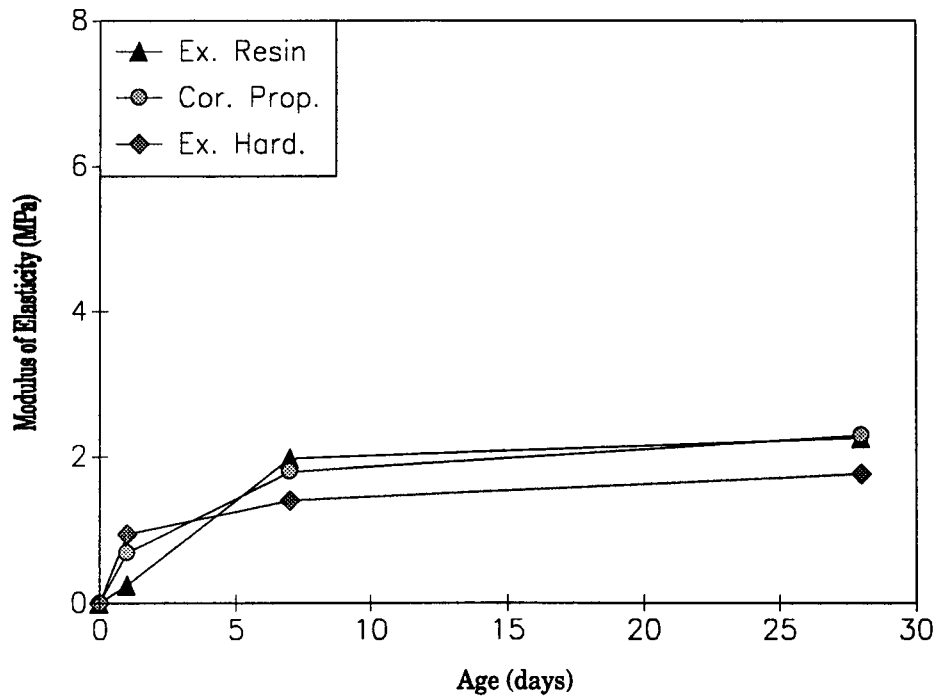


Figure 44. Effect of Incorrect Proportioning on Modulus of Elasticity of PDM4

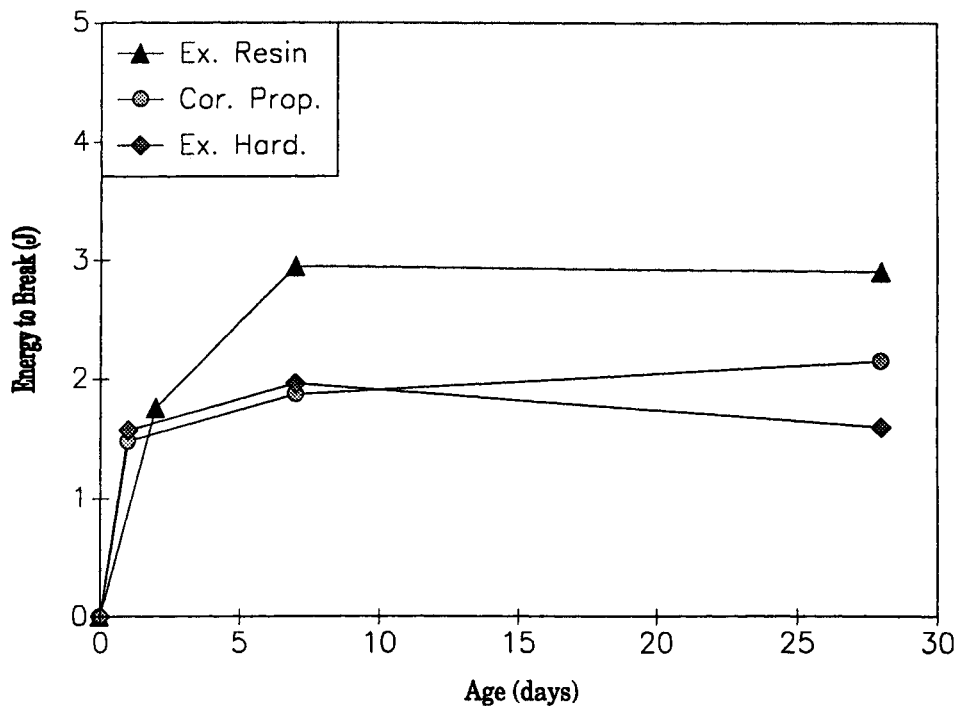


Figure 45. Effect of Incorrect Proportioning on Energy to Rupture PDM1

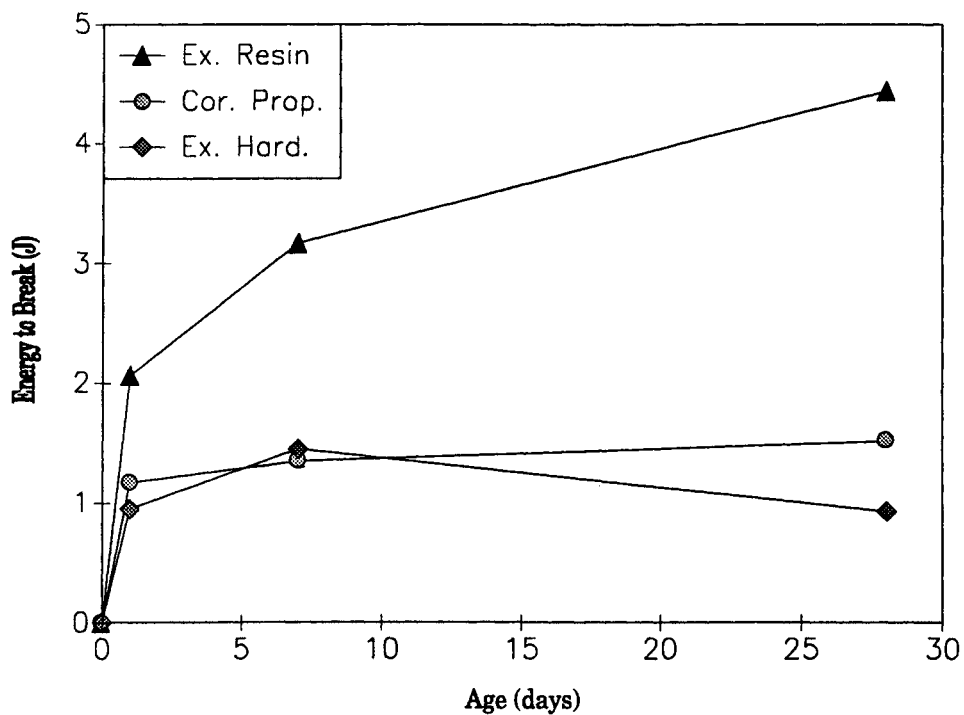


Figure 46. Effect of Incorrect Proportioning on Energy to Rupture PDM2

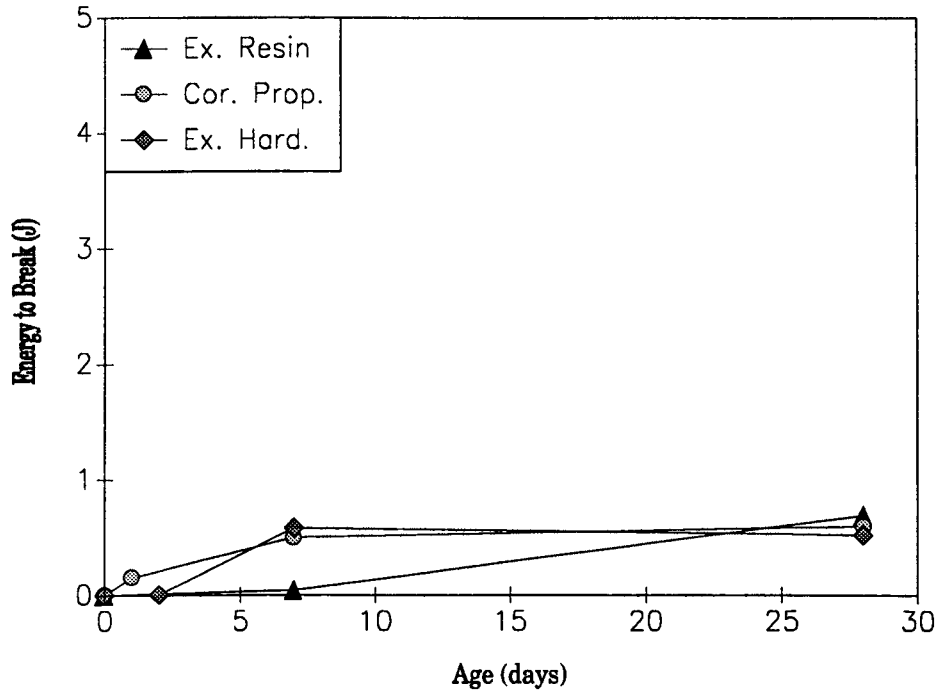


Figure 47. Effect of Incorrect Proportioning on Energy to Rupture PDM3

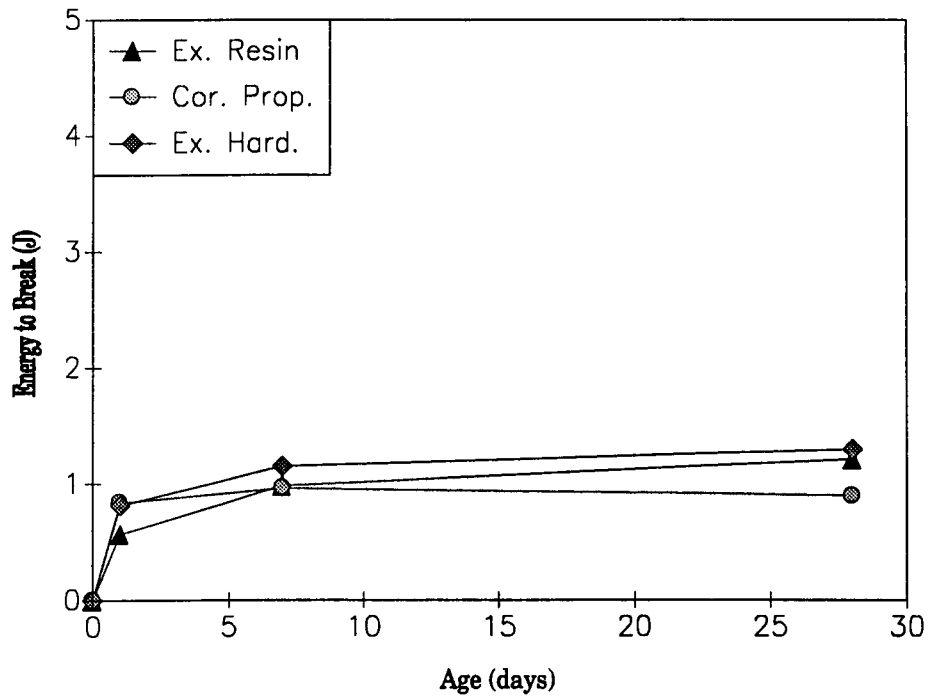


Figure 48. Effect of Incorrect Proportioning on Energy to Rupture PDM4

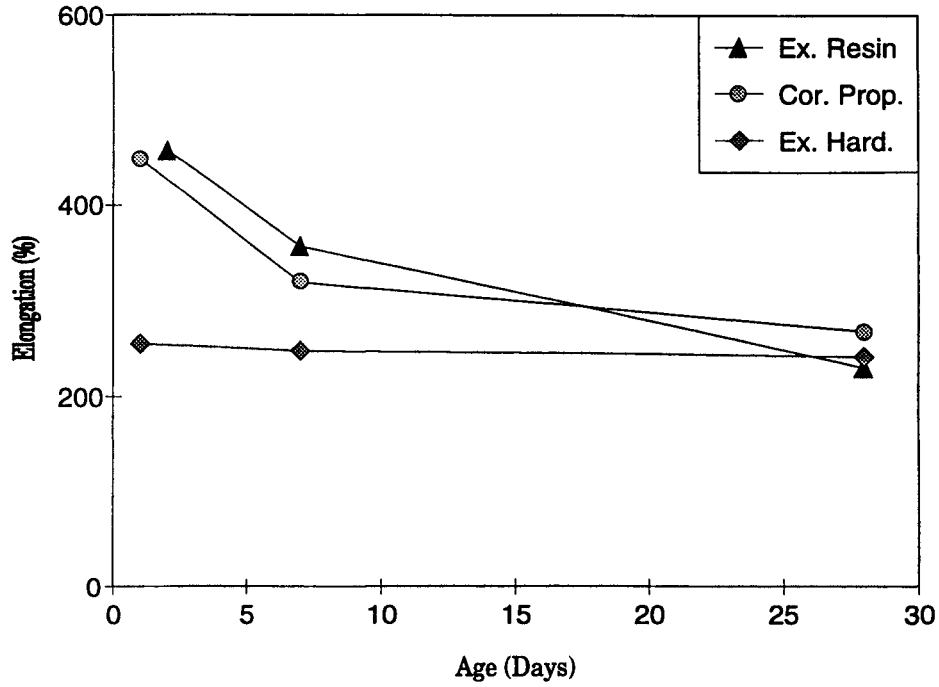


Figure 49. Effect of Incorrect Proportioning on Elongation of PDM1

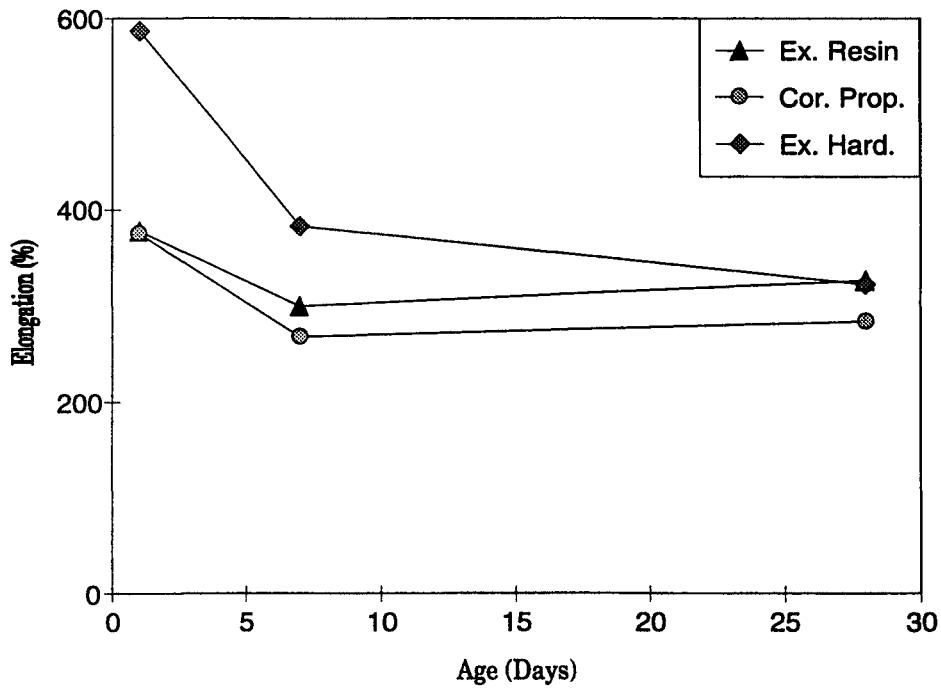


Figure 50. Effect of Incorrect Proportioning on Elongation of PDM2

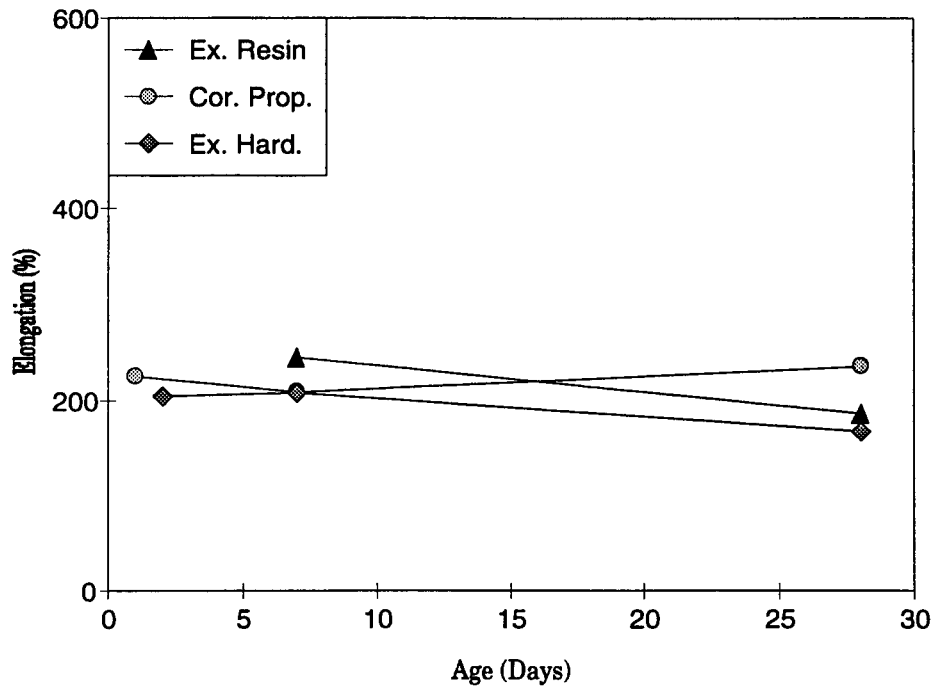


Figure 51. Effect of Incorrect Proportioning on Elongation of PDM3

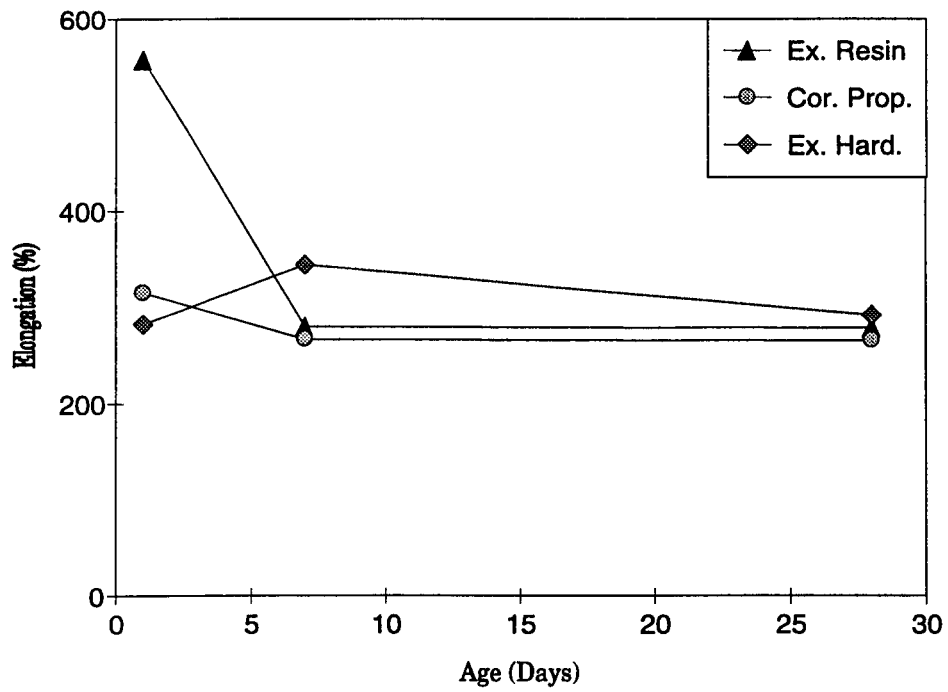


Figure 52. Effect of Incorrect Proportioning on Elongation of PDM4

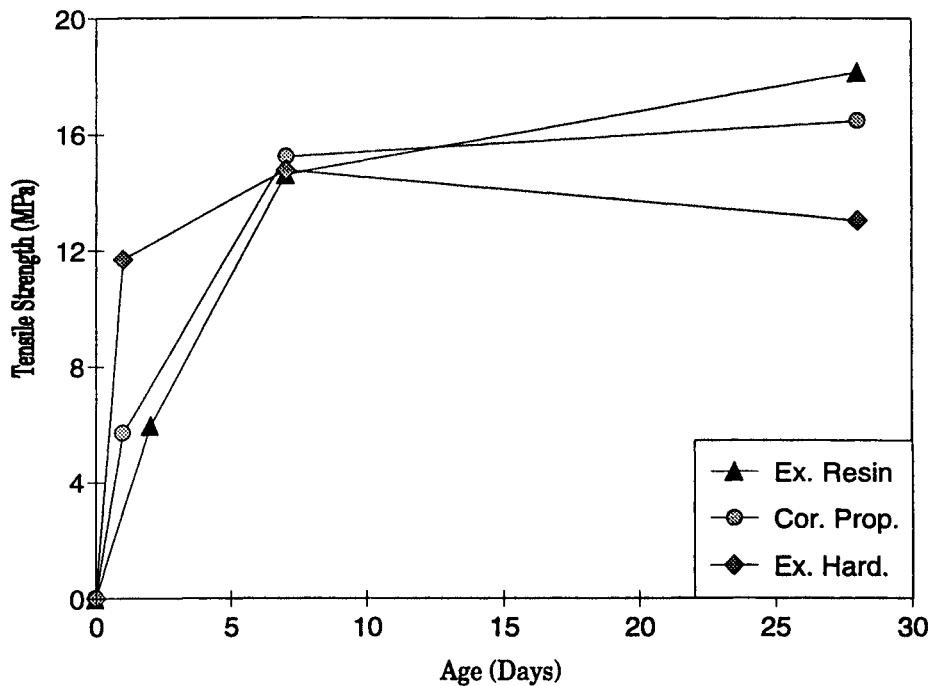


Figure 53. Effect of Incorrect Proportioning on Tensile Strength of PDM1

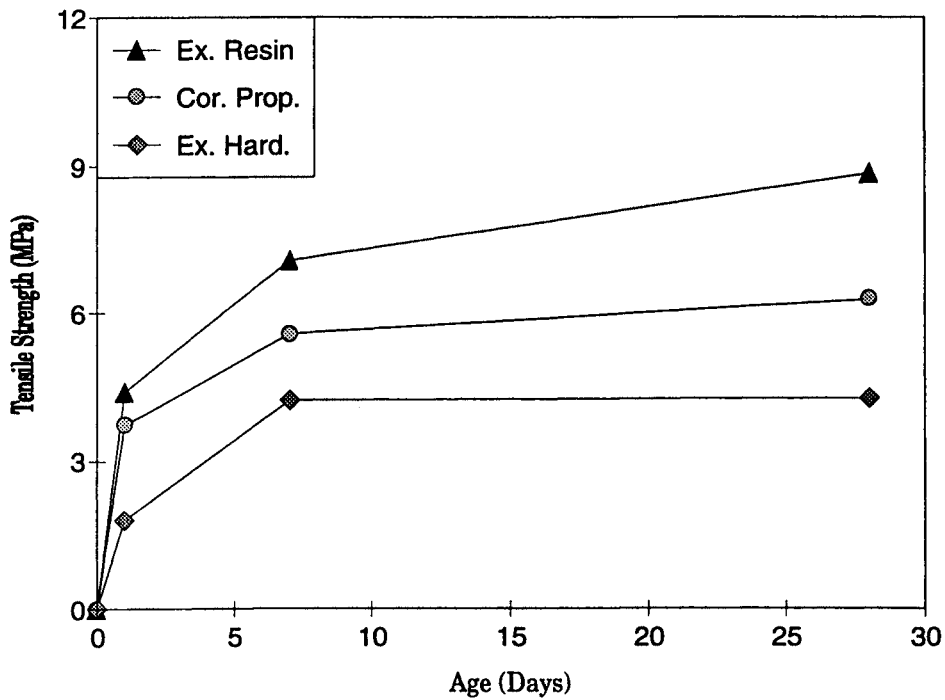


Figure 54. Effect of Incorrect Proportioning on Tensile Strength of PDM2

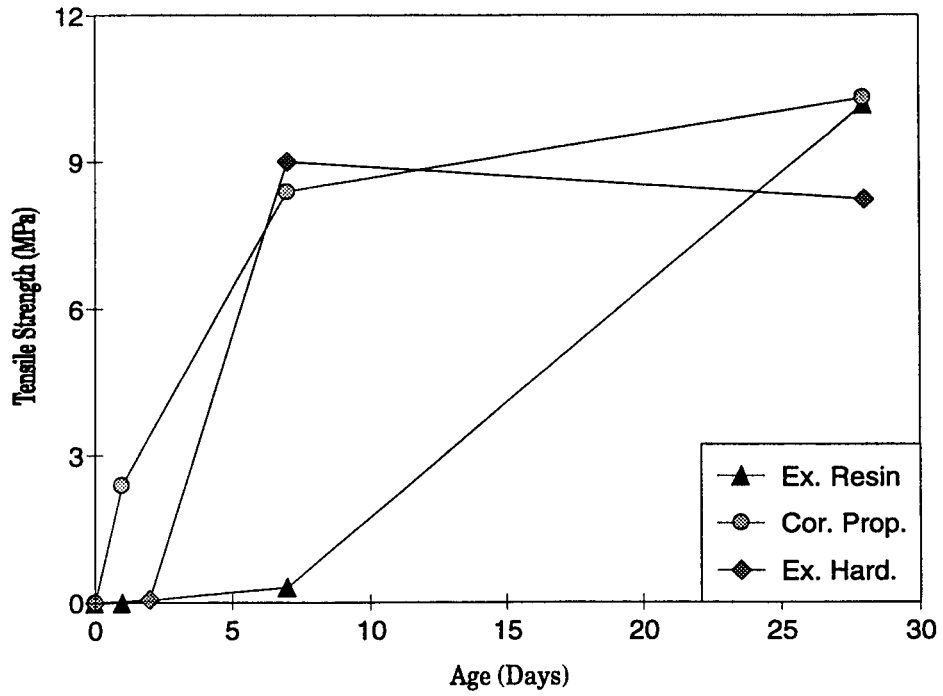


Figure 55. Effect of Incorrect Proportioning on Tensile Strength of PDM3

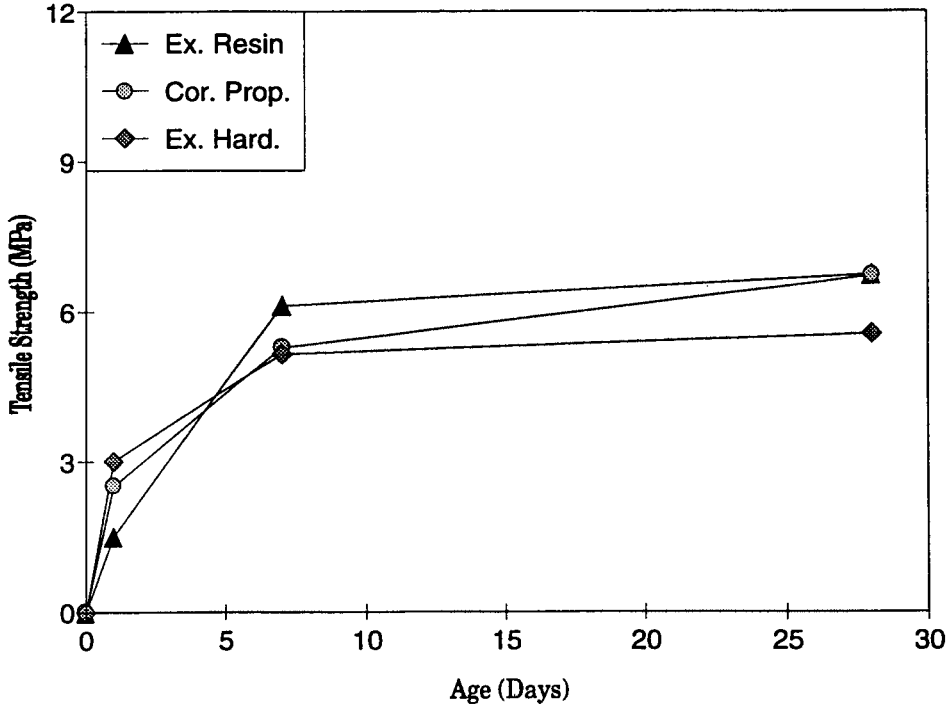


Figure 56. Effect of Incorrect Proportioning on Tensile Strength of PDM4

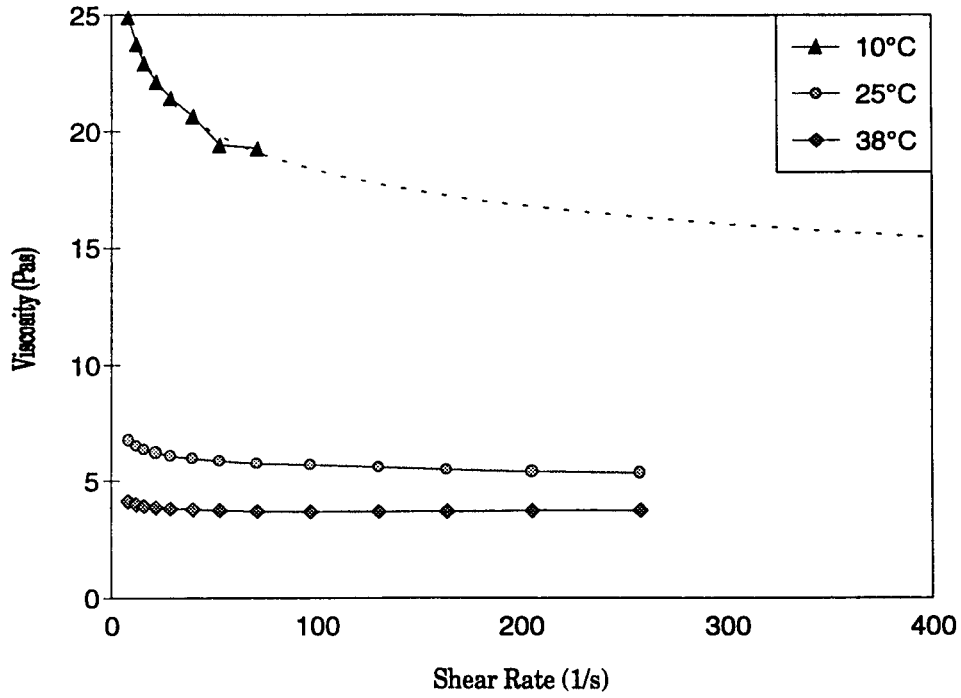


Figure 57. Effect of Temperature on Viscosity of PDM1

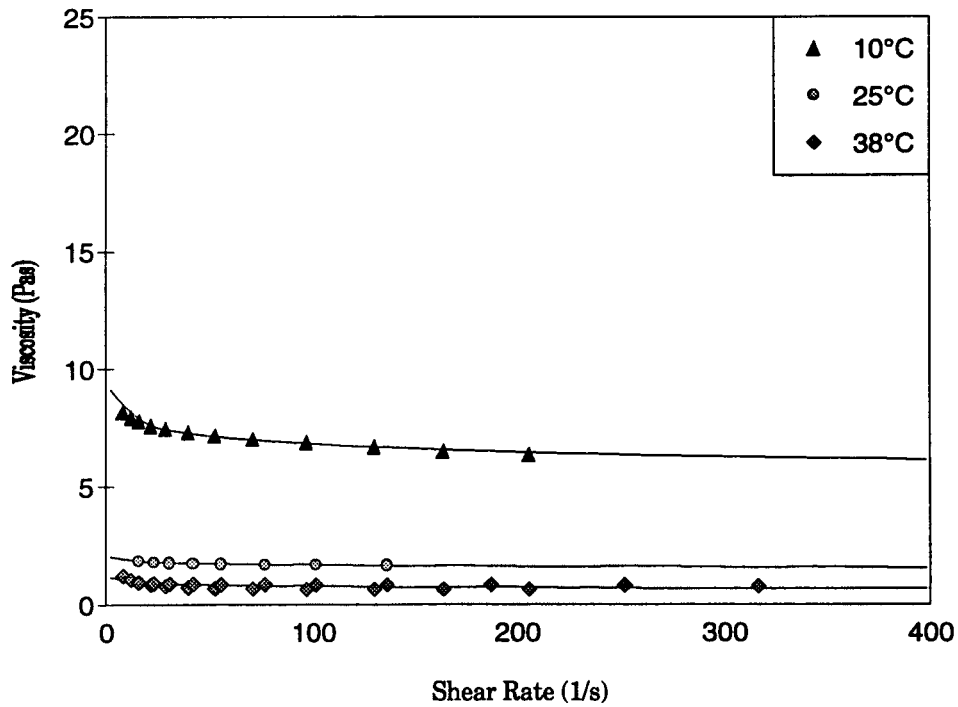


Figure 58. Effect of Temperature on Viscosity of PDM2

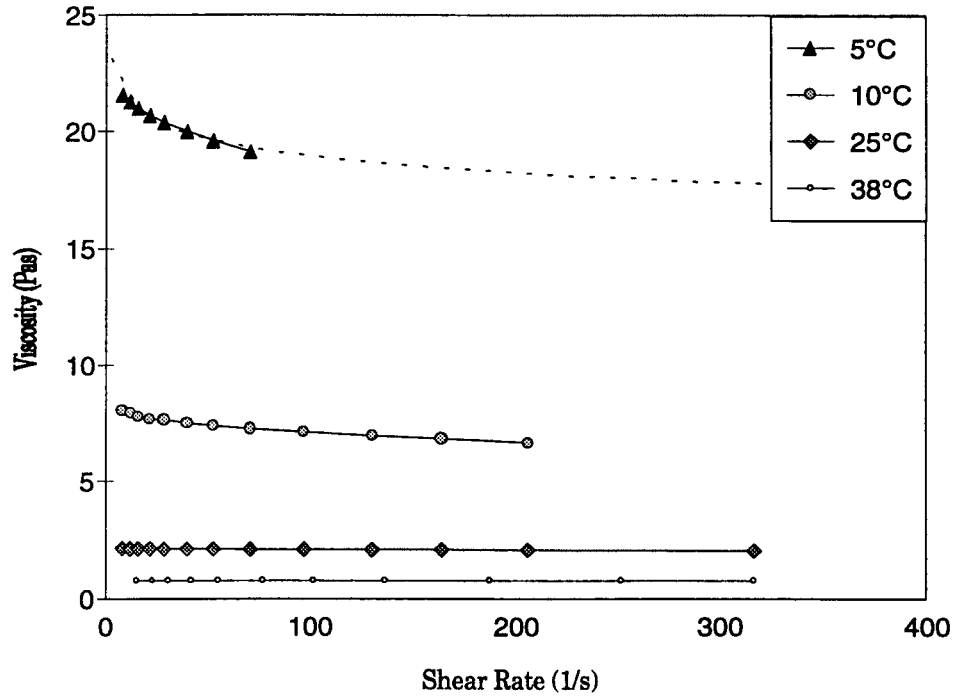


Figure 59. Effect of Temperature on Viscosity of PDM3

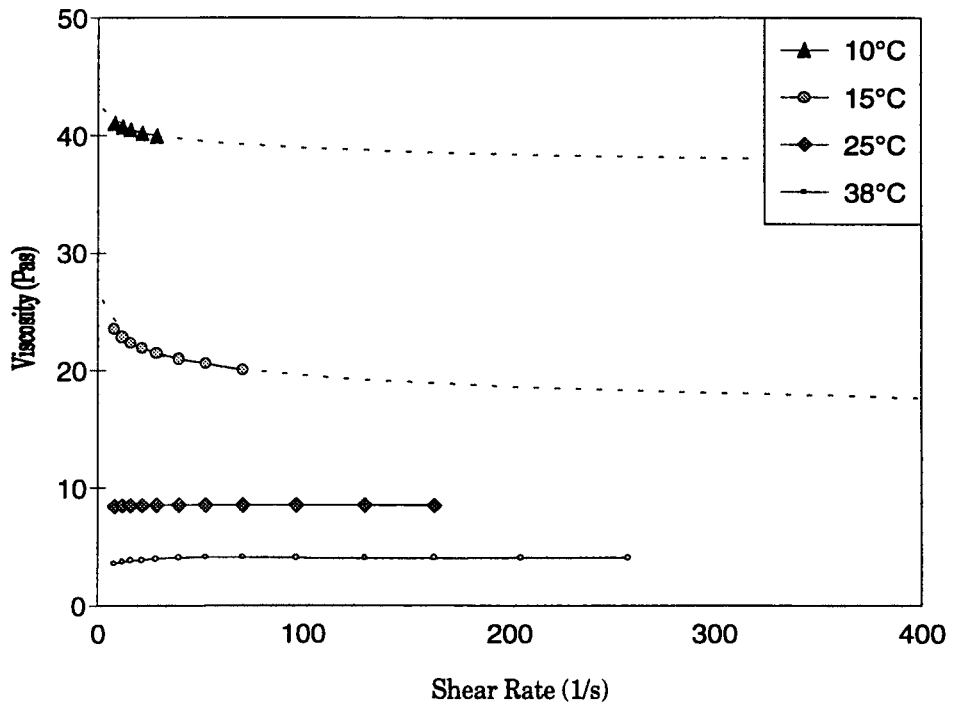


Figure 60. Effect of Temperature on Viscosity of PDM4

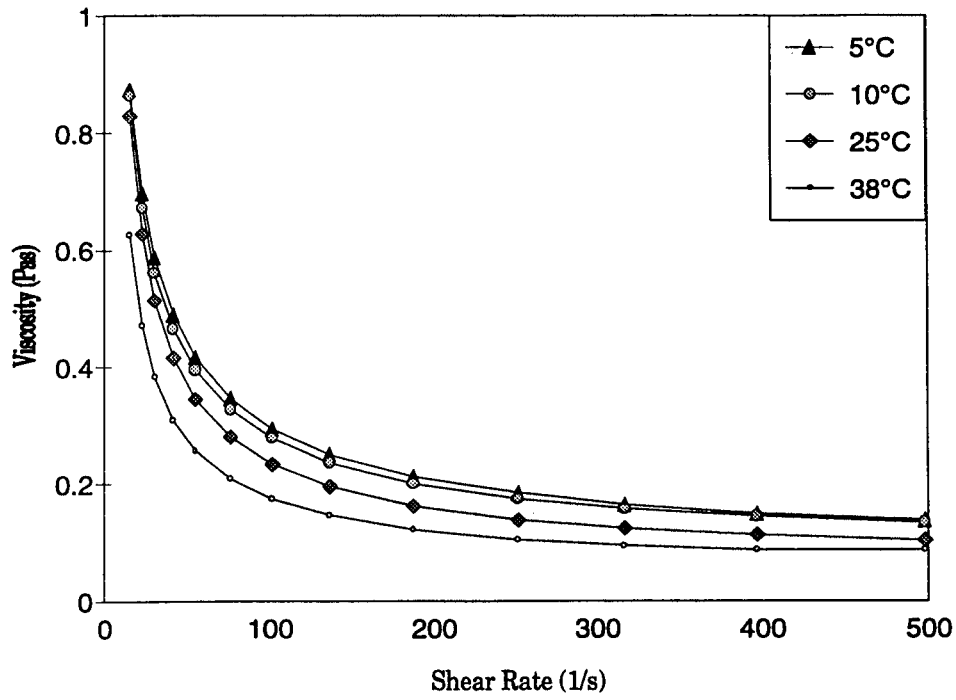


Figure 61. Effect of Temperature on Viscosity of PDM5

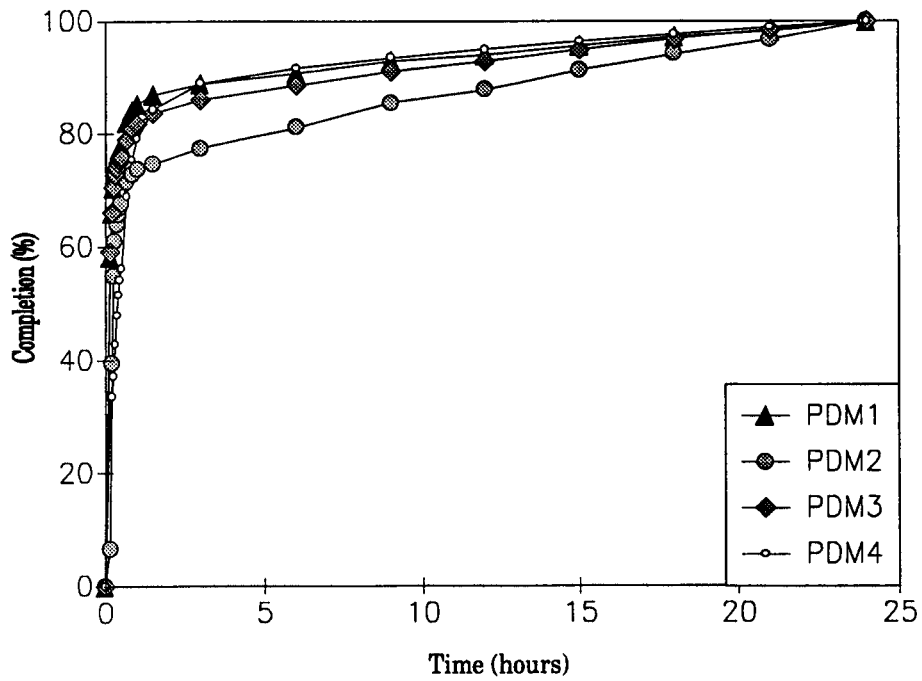


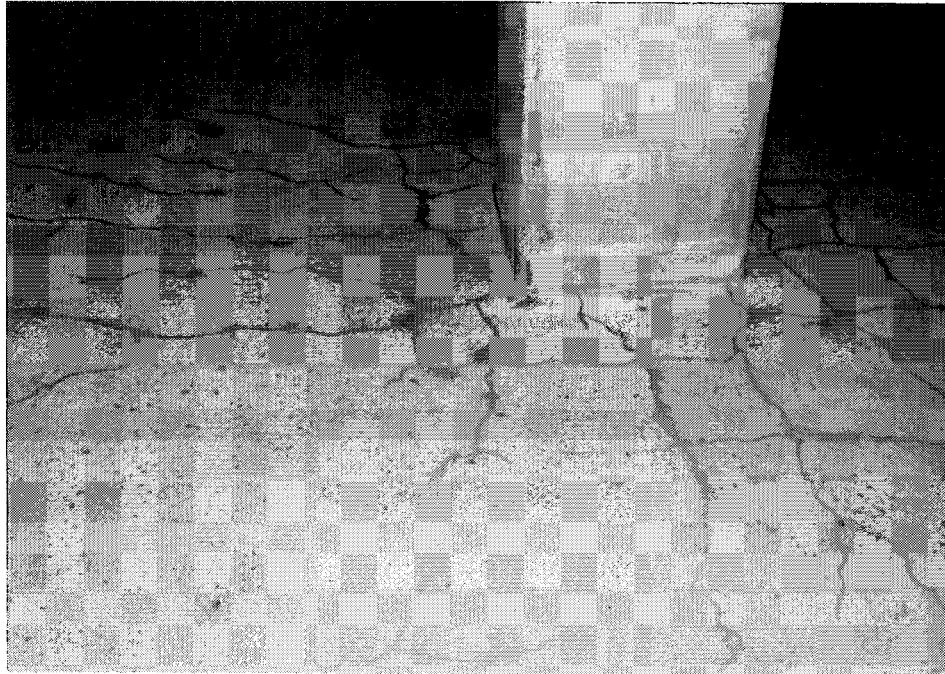
Figure 62. Reaction Completion of Parking Deck Membranes



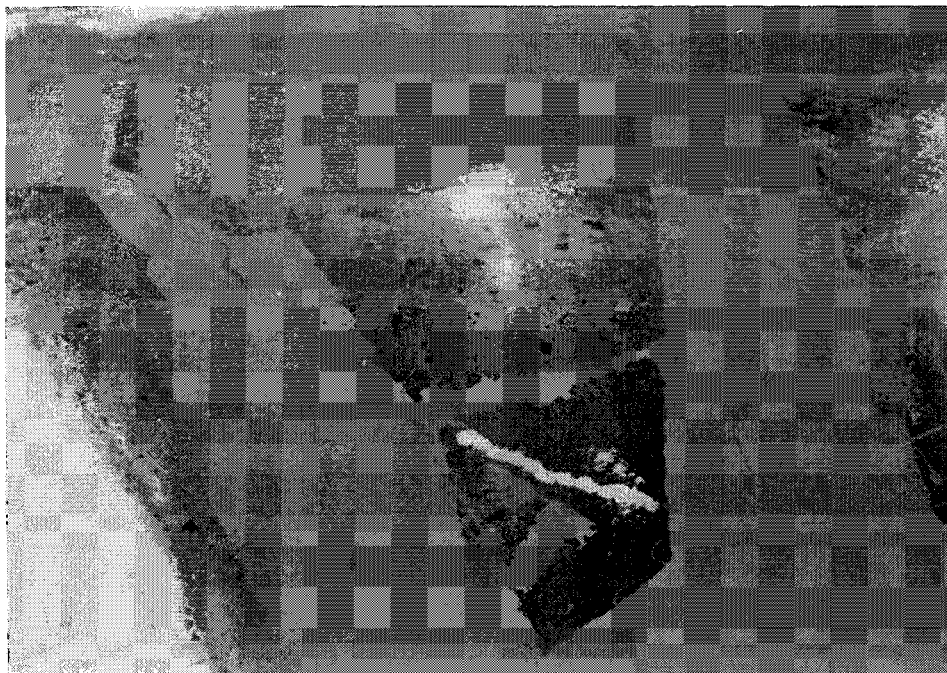
Photograph 1. Patching of shotblasted deck , level P2 at Ottawa City Hall, with an epoxy patching material.



Photograph 2. Filling of routed crack with urethane joint sealant, level P2 at Ottawa City Hall.



Photograph 3. Typical example of cracking around column on level P2 at Ottawa City Hall. Cracks have been routed and filled.



Photograph 4. Illustration of the crack repair process. After routing and filling, sections are primed and a swath of membrane is applied along the crack. Note, however, that this photograph indicates that not all cracks were routed and filled, as crack on right hand side is reflecting through the membrane.



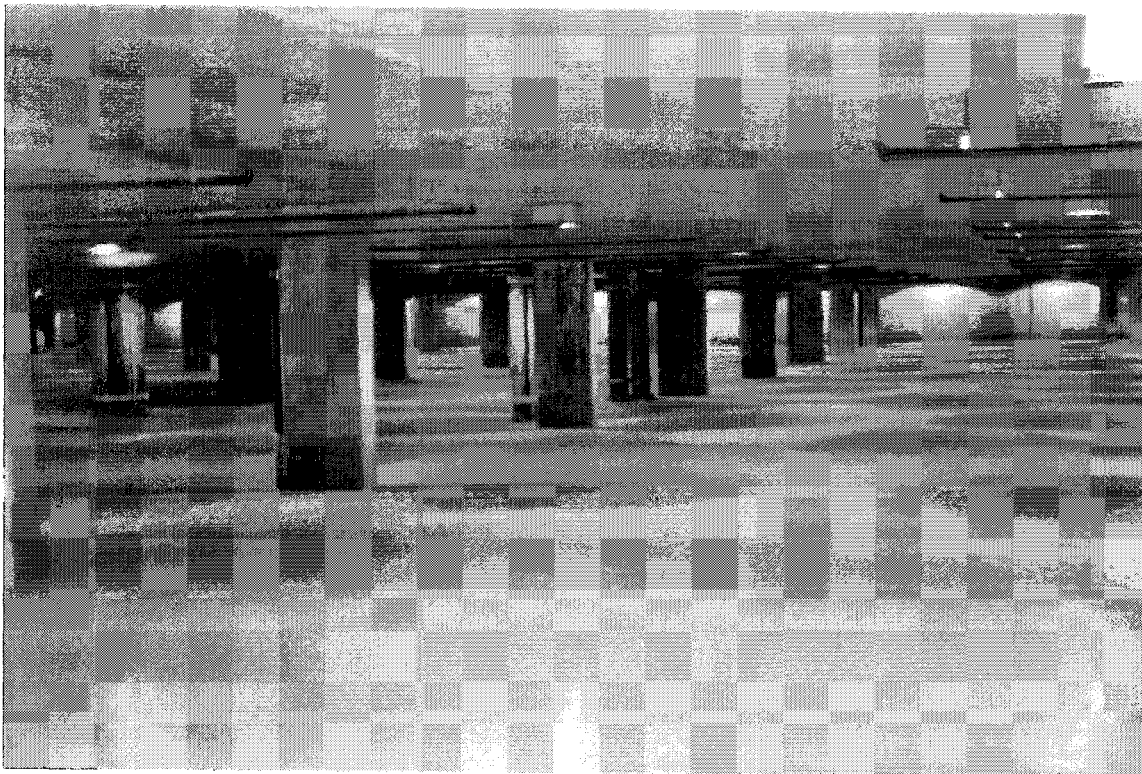
Photograph 5. Application of primer by spray at Ottawa City Hall.



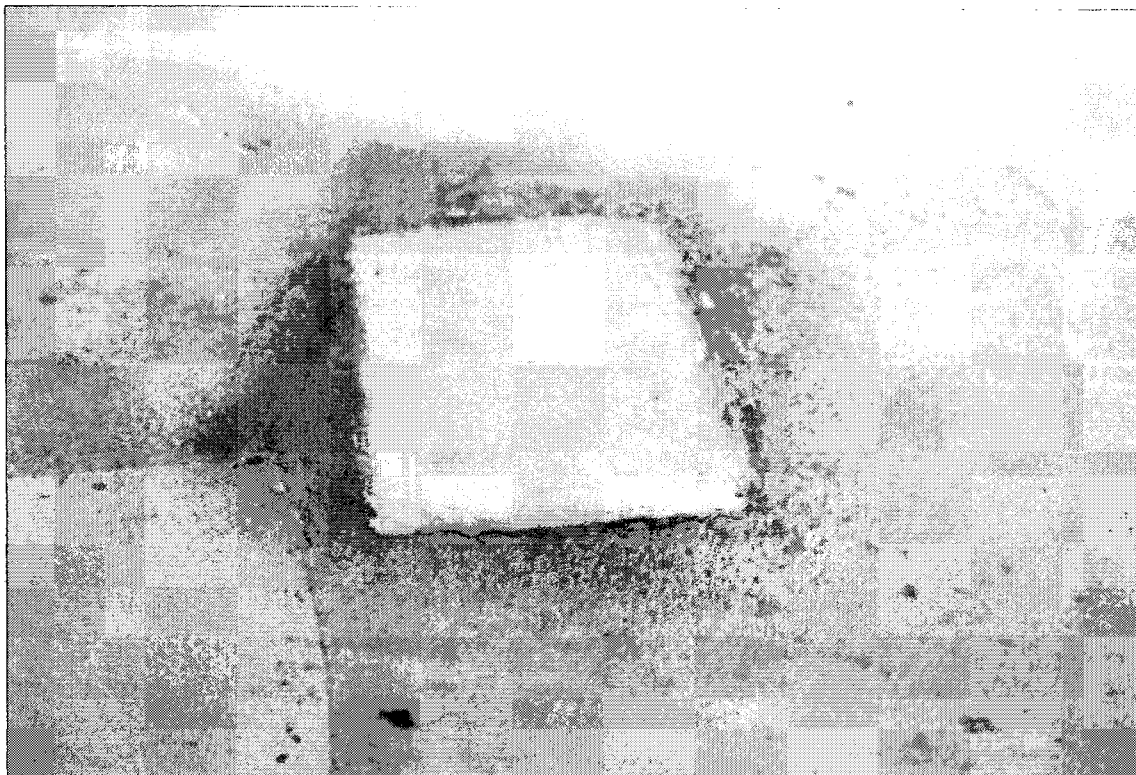
Photograph 6. Application of PDM3 by spray and back rolling at Ottawa City Hall.



Photograph 7. Newly finished membrane at Ottawa City Hall.



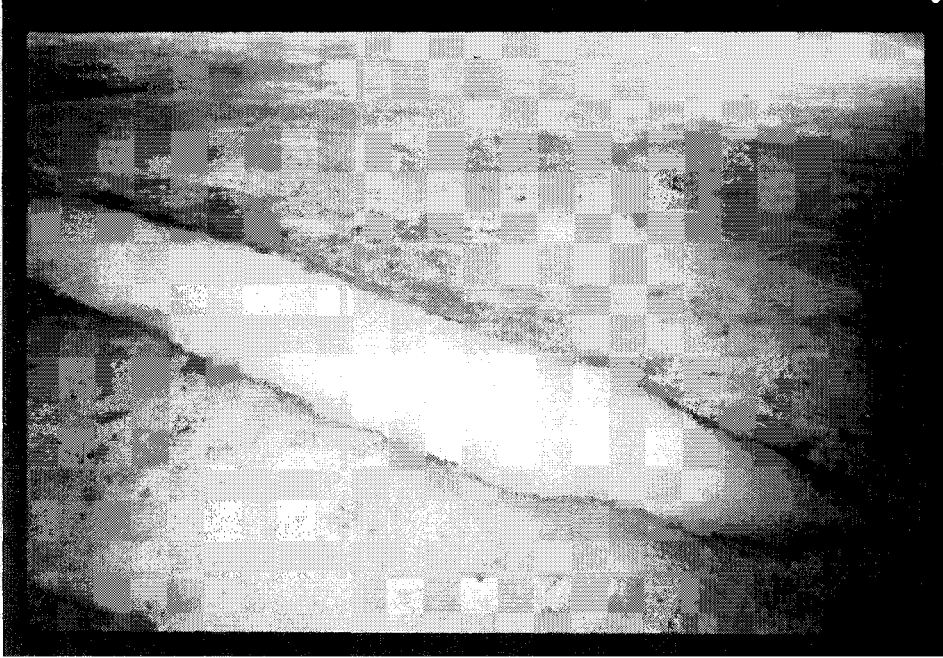
Photograph 8. Membrane after 24 hours at Ottawa City Hall.



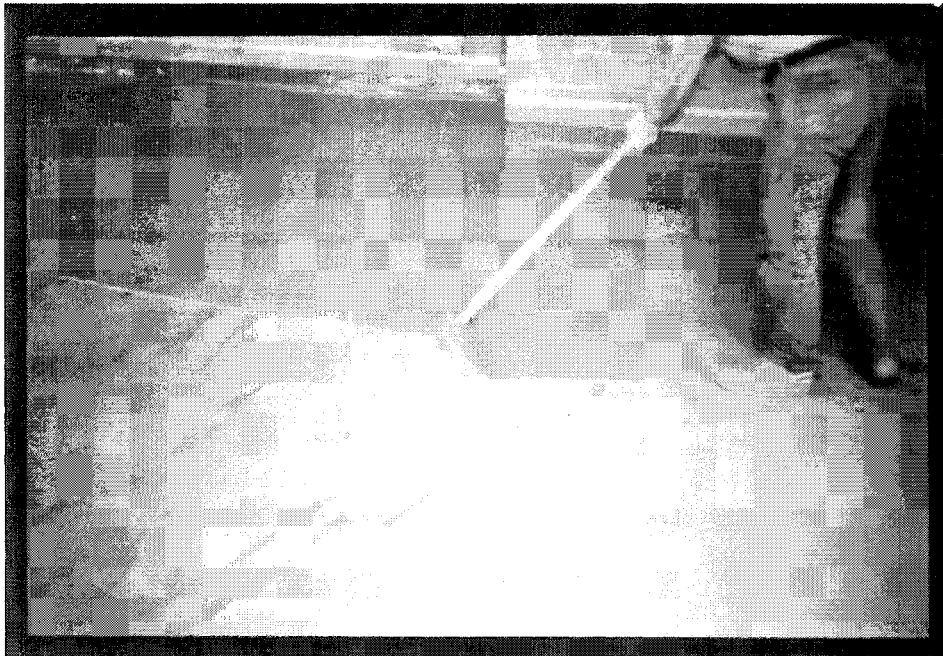
Photograph 9. Typical repair of Islington Tower in Toronto.



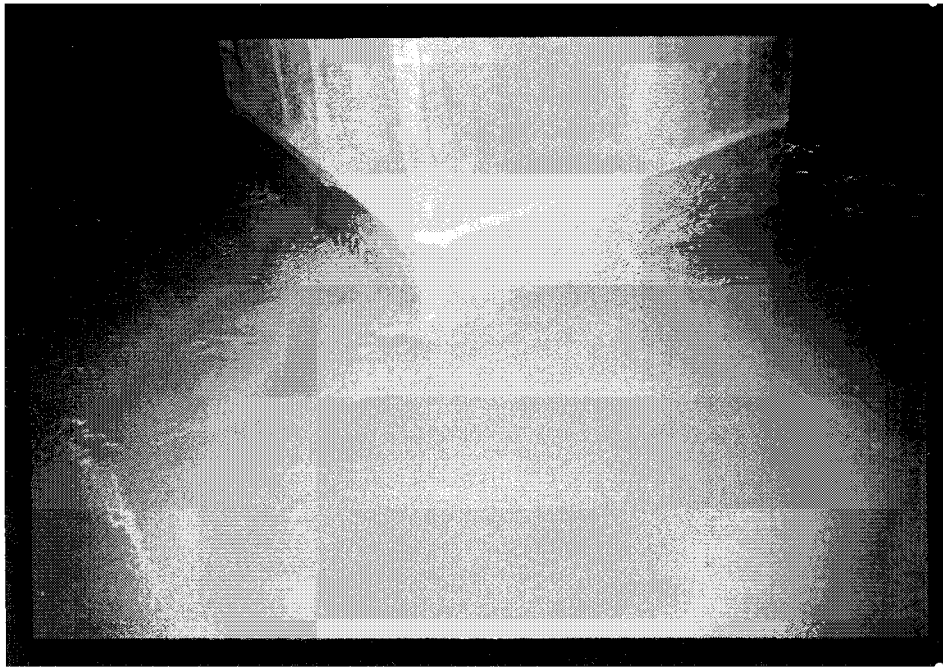
Photograph 10. Application of PDM5 by spray at Islington Tower in Toronto.



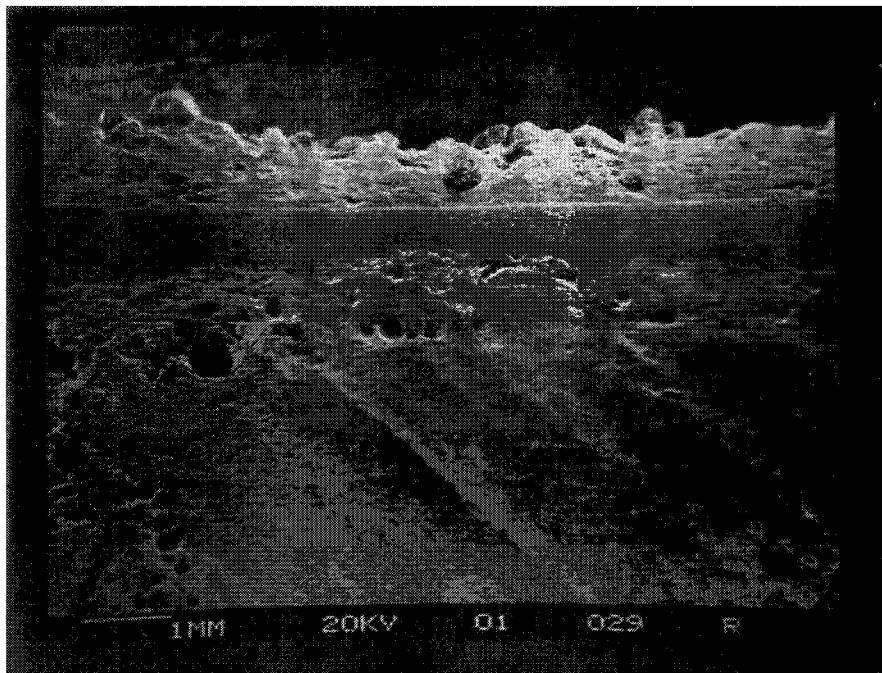
Photograph 11. Repairs to shot blasted deck at MacArthur Plaza in Ottawa.



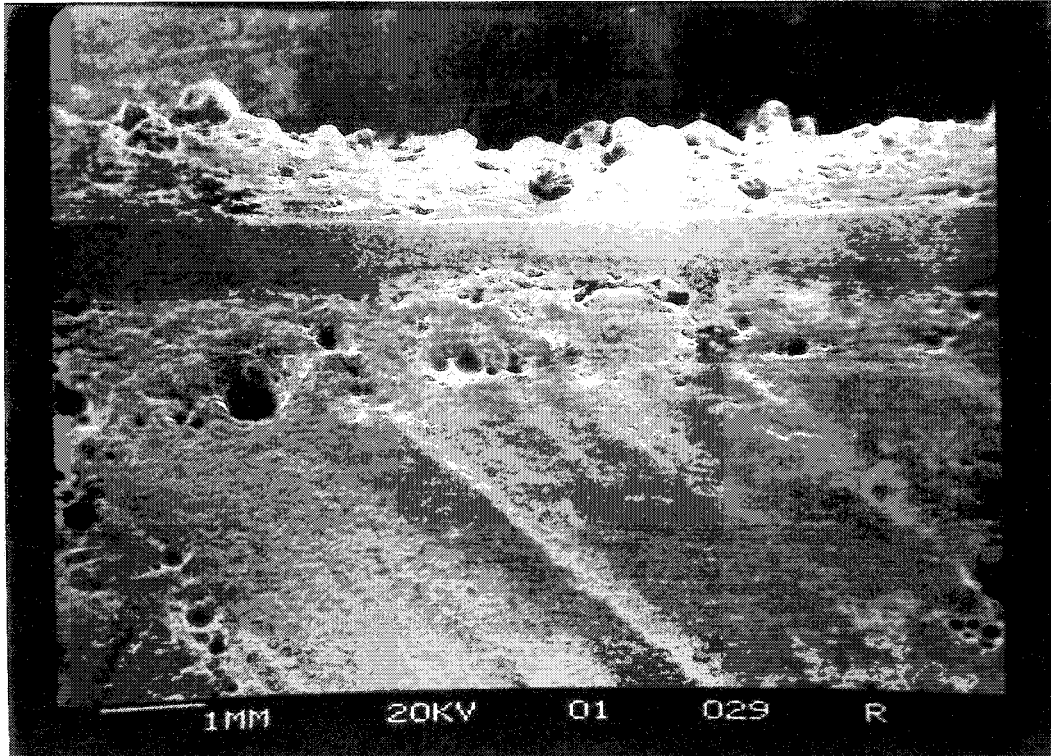
Photograph 12. Application of PDM6 by squeegee at MacArthur Plaza in Ottawa.



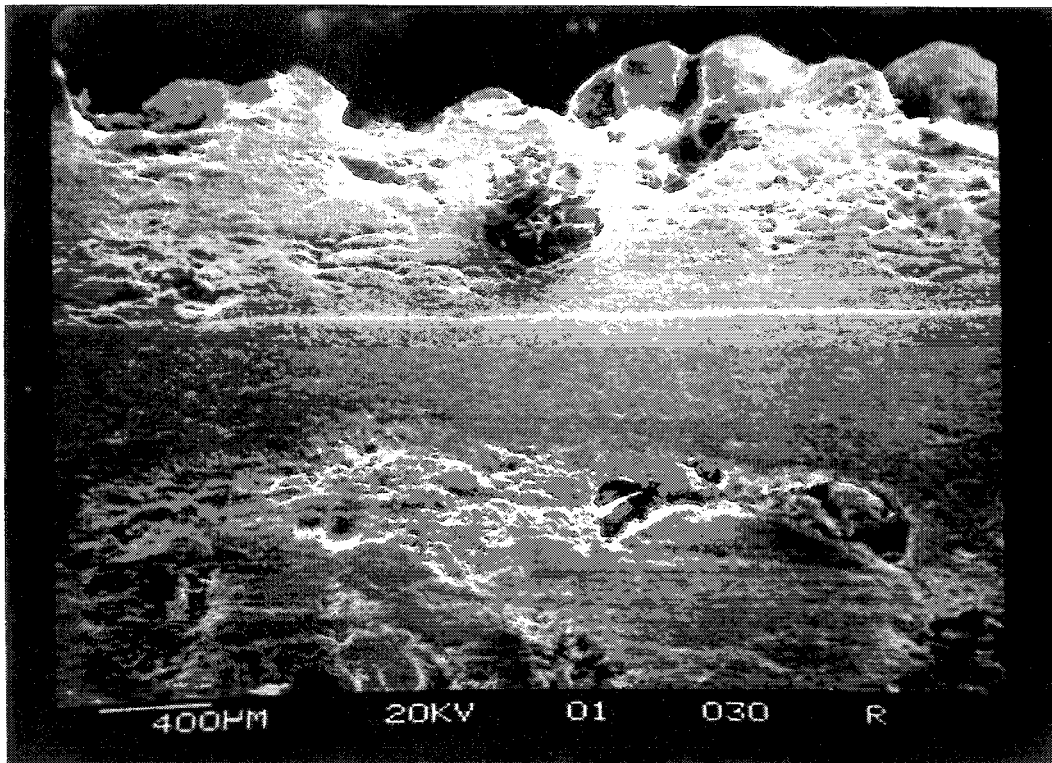
Photograph 13. Detail of application of PDM6 around column at MacArthur Plaza in Ottawa.



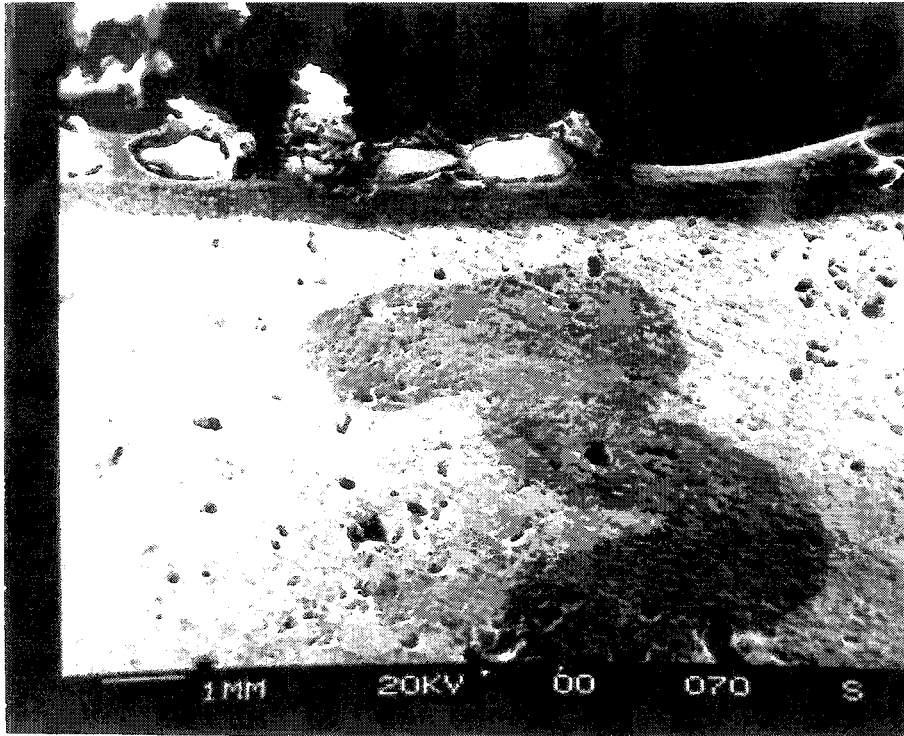
Photograph 14. Cross sectional view (40X magnification) of PDM1.



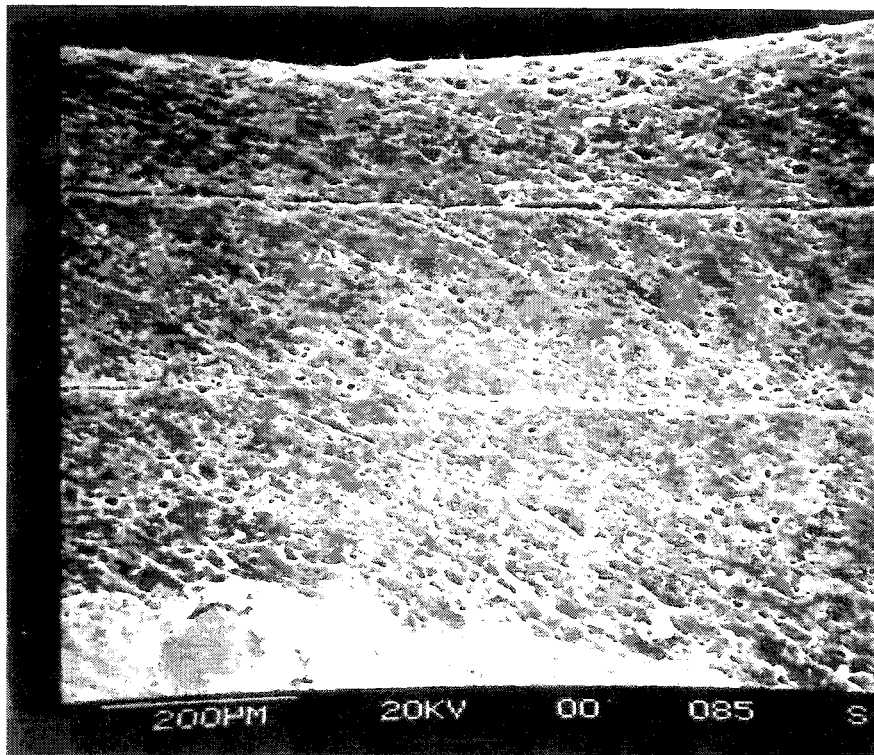
Photograph 15. Cross sectional view (10X magnification) of PDM2.



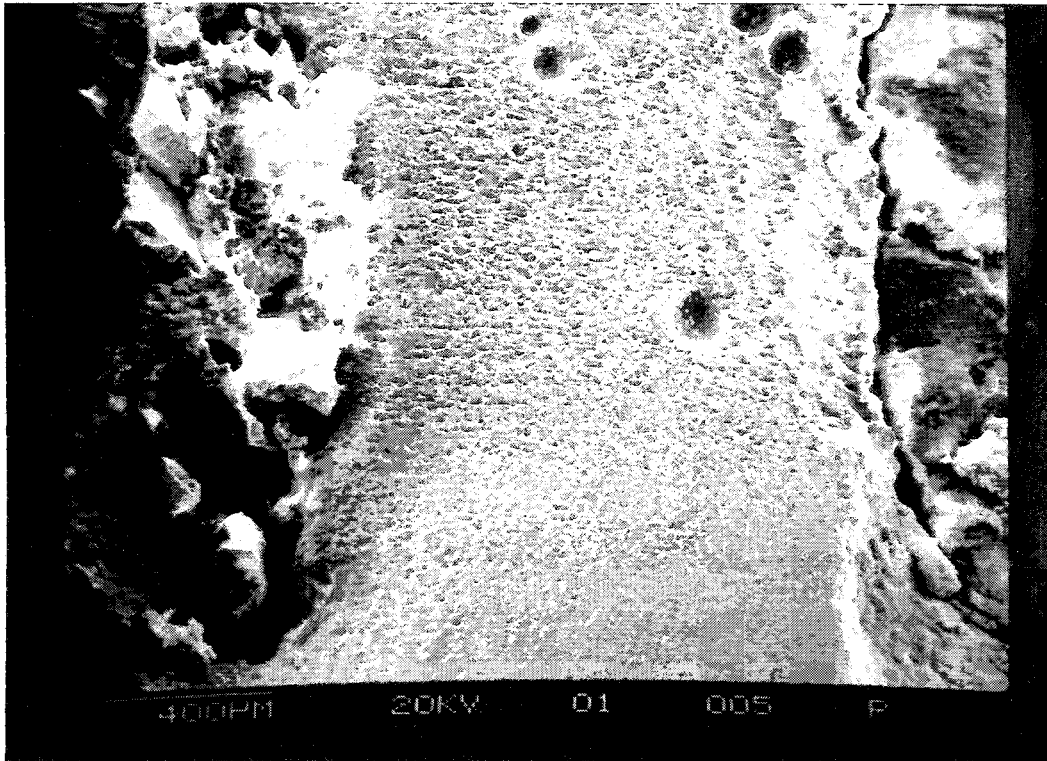
Photograph 16. Cross sectional view (30X magnification) of PDM2.



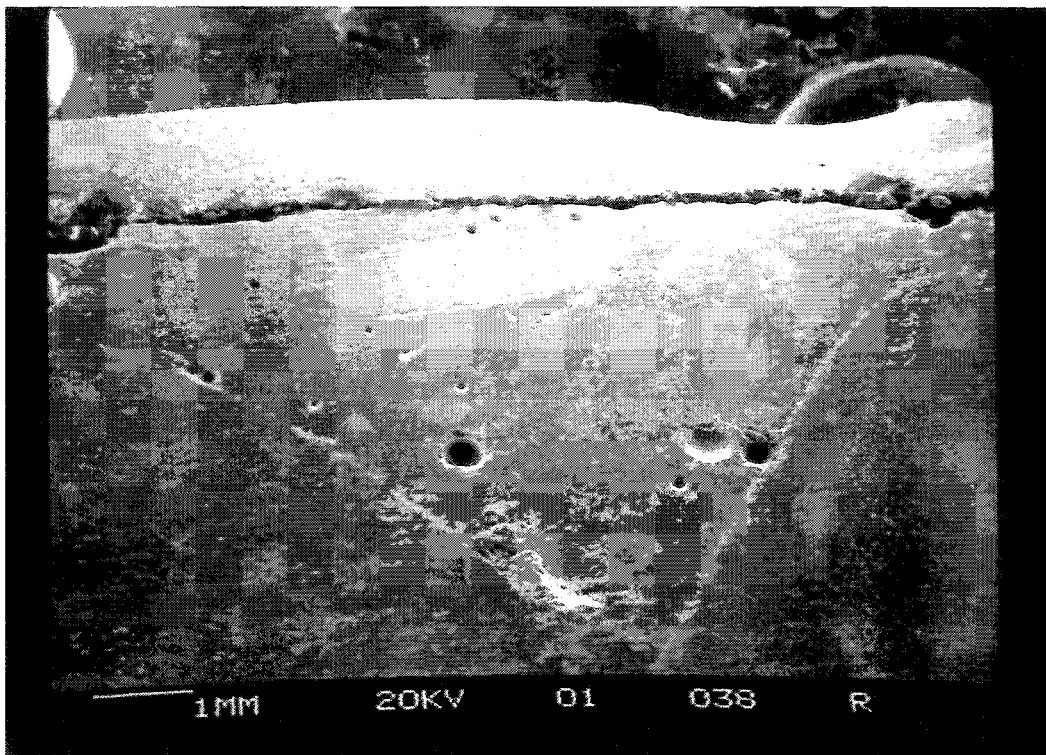
Photograph 17. Cross sectional view (8X magnification) of PDM3.



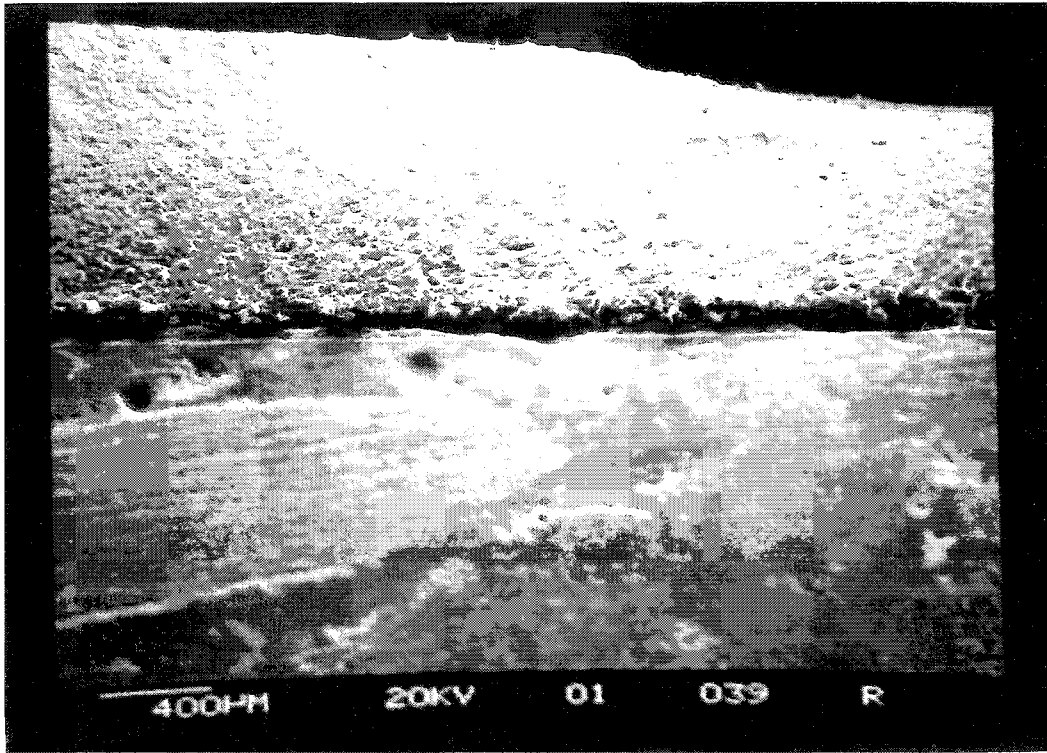
Photograph 18. Cross sectional view (100X magnification) of PDM3.



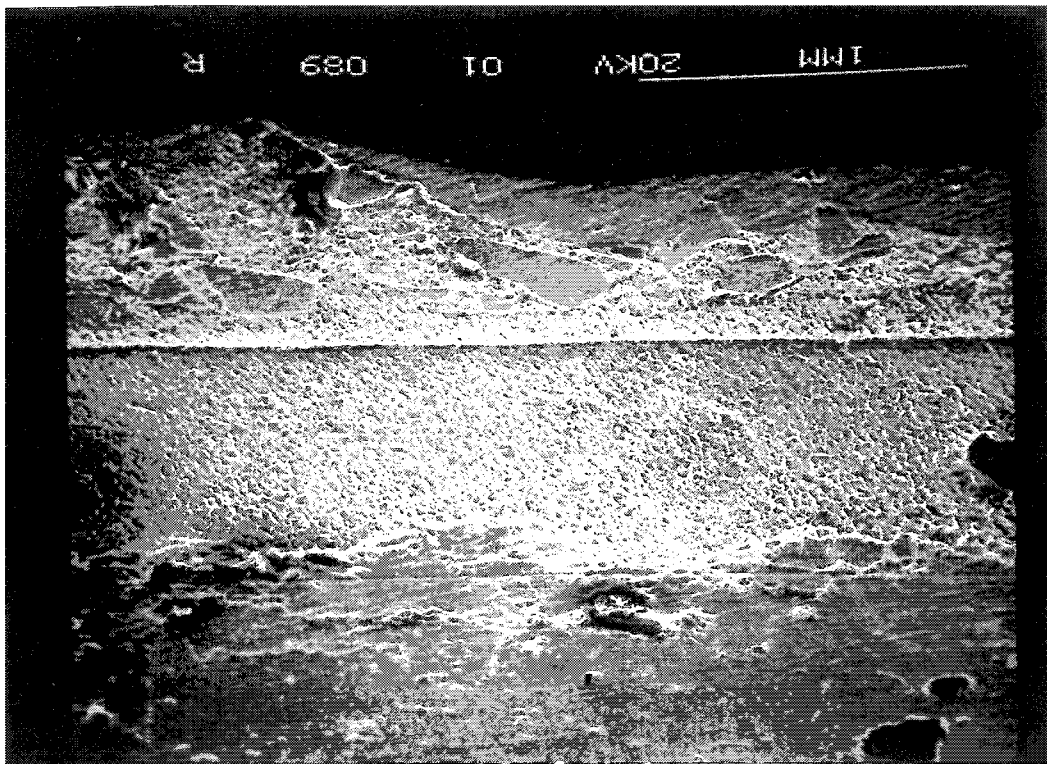
Photograph 19. Cross sectional view (43X MacArthur) of PDM4.



Photograph 20. Cross sectional view (10X magnification) of PDM5.



Photograph 21. Cross sectional view (30X magnification) of PDM5.



Photograph 22. Cross sectional view (30X magnification) of PDM6.

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APPENDIX I

Mixing Ratios

The following mixing ratios were used for incorrect proportioning

Membrane	Excess Resin	Correct Proportions	Excess Hardener
PDM1 (v/v)	3.45:1	3:1	3:1.15
PDM2 (v/v)	2.30:1	2:1	3:1.15
PDM3 (v/v)	63.25:1	55:1	55:1.15
PDM4 (w/w)	156.40:1	136:19.4	136:23.81