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THE EFFECT OF CHEMICAL EXPOSURE ON THE BURST STRENGTH OF A GEOMEMBRANE

by

Tyson Haedrich

B.Eng. (Civil Engineering)

B.Sc. (Biology)

A thesis submitted
to the Faculty of Graduate Studies and Research
in partial fulfilment of the requirements
for the degree of
MASTER OF ENGINEERING*

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Burst Strength of a Geomembrane"**

submitted by
Tyson Haedrich

in partial fulfilment of the requirements for the degree of
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Thesis Supervisor

Professor A.P.S. Selvadurai

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ABSTRACT

The burst behaviour of a polyvinyl chloride (PVC) geomembrane, designated for use as a landfill liner, was studied using an experimental apparatus designed at Carleton University. The experimental apparatus was an axi-symmetric, tension test which stressed the samples out-of-plane. The apparatus simulates the conditions created during landfill settlement or internal gas accumulation.

The stress-strain behaviour of the geomembrane was analyzed after exposure to air, water, 5% acetone, 10% acetone and 20% acetone solutions. The samples were exposed on both sides, single sided and partial single sided. The results showed; (i) the experimental apparatus was reliable and produced consistent results, (ii) the geomembrane burst strength decreased with exposure to increasing acetone concentrations, and (iii) tensile and puncture tests conducted on the same material confirmed that increasing acetone concentration decreased the geomembrane strength for both types of tests.

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1.0 INTRODUCTION

1.1 General

Geomembranes were first used in civil engineering applications in the early 1950's. The potential applications of these materials in different fields rapidly developed and by the 1970's geomembranes in widespread use throughout the world. The rapid introduction of geomembranes was paralleled by the similar rapid growth in the variety of geotextiles available for civil engineering purposes.

Both geomembranes and geotextiles are classified under the umbrella of geosynthetics. In this thesis the term geosynthetics will refer to the general classification of any synthetic material that is used in a geotechnical application. Geotextiles refer to materials that have a woven or repeating pattern weave which in most cases allows the free flow of gases and liquids through them. Geomembranes refer to materials that can act as a barrier to solids, liquids or gases.

1.2 Uses of Geomembranes

Geomembranes are employed in a wide variety of applications with civil geotechnical engineering being one of the major users. The extensive applications of geosynthetics such as geomembranes stem from the particular characteristics of soils in relation to their strength and permeability. Geomembranes are employed both as a reinforcing element and as an impermeable barrier to the transport of fluids through soils. These combined advantages make geosynthetics a useful addition to the geotechnical engineer's list of tools.

1.2.1 Types of Geomembrane Applications

The practical applications of geomembranes range from soil reinforcement to liners of canal systems providing irrigation water to landfill liners. The development of this thesis originates from applications of geosynthetics as landfill liners and investigates the effectiveness of geomembranes as durable barriers. The following section presents a brief summary of the most important uses of geomembranes as barrier systems.

As barrier systems, geomembranes are commonly used in landfills. Until the early 1970s landfills both in Canada and the United States were very loosely regulated. The design requirements were simple and many older landfills were constructed without any guidelines. The environmental consequences of such unregulated or poorly designed landfills resulted in the development of more stringent requirements for landfill containment. The major regulations in the United States were the Solid Waste Disposal Act in 1965, the Resource Conservation and Recovery Act in 1976 and the 1984 Hazardous and Solid Waste Amendments (Tchobanoglous et al.,1993). This legislation protected the surrounding environment from the harmful effects of the landfill. The stricter regulations coincided with the increased use of geomembrane landfill liner systems.

The use of a geomembrane as an engineered barrier in the design of landfills is a natural match. Besides providing a potentially impermeable barrier, the geomembrane (usually a millimetre or two in thickness) can be used to replace a 1 to 2 meter thick clay layer greatly increasing the landfill capacity. In a perfectly functioning system, shown in Figure 1, the geomembrane is expected to contain all the leachate within the landfill

providing protection to the external environment. Current technology uses a multi-layer landfill containment system that uses two layers of geomembrane, a thick clay underlayer, a filter layer on the geomembrane surface and a leak detection system beneath each geomembrane layer (Koerner, 1994). While the new landfill technology virtually

Figure 1 Typical Landfill Liner System (Koerner 1994)

guarantees an isolated system many landfills evolved before the regulations were in place and these landfills can not be upgraded except by excavating the entire landfill and installing an approved containment/liner system.

Another important use of geomembranes is in landfill closure cover systems as shown in Figure 1. The geomembrane is placed over the landfill providing a relatively impermeable cover which reduces infiltration and leachate production.

Another common use of geomembranes, shown in Figure 2, is as a liner for sludge

lagoons. Sludge lagoons are open ponds used to settle out particulate matter present in processed sludge. A typical sludge lagoon typically consists of a sand bed underlain by a leak monitoring system placed on the surface and a geomembrane liner placed on the surface of the sand bed. The geomembrane prevents the movement of the sludge effluent and particles into the external environment. The settled sludge is cleaned from the

Figure 2 Typical Sludge Lagoon Liner System (Koerner 1994)

bottom of the tank as the lagoon fills.

A third application of geomembranes as a barrier layer is in the construction of mining tailings dams (Figure 3). Mining tailings are small particles of material, often toxic, that are produced during the mining process. These particles are frequently used to build dams to contain the water used in the mining operations. Containment of these particles is necessary to prevent the contamination of the external environment. To prevent the migration of mining tailings from the dam a geomembrane/geotextile system is used that prevents pollutants from the tailings from moving into the outside water and also prevents external water pressure from causing instability in the tailings resulting in

Figure 3 Typical Tailings Dam Liner System (Koerner 1994)

a general failure of the dam.

A fourth use of geomembranes, as a barrier system, is in the construction of irrigation canals that carry large volumes of water (Figure 4). With canals, a barrier system is necessary to prevent both the loss of water from the canal and to reduce the damage caused by soil erosion. A major loss of water from the canal would result in substantial increases in the cost of delivering the water and the reduction of the total amount of water available at the delivery end of the system. A substantial infiltration

Figure 4 Typical Canal Liner System (Weimer 1985)

from the canal system would also result in large wet areas near the canal which could be a threat to areas adjacent to the canal. The infiltration could also result in a migration

and concentration of minerals as they are leached from the soil and transported to other areas. Geomembranes are ideally suited for canal liners because they act as good barrier systems which occupy a very small volume and causes minimum friction resistance to the water flow. This results in substantial cost savings for the operator of the canal system.

1.3 Geomembrane Damage

The increasing use of geomembranes makes it important to understand the potential for damage to the geomembrane which could severely reduce its effectiveness. The following sections discuss the types of geomembrane damage that can occur, the causes of the damage and the potential consequences of the damage.

1.3.1 Types and Causes of Geomembrane Damage

Under field conditions, the most common type of damage to geomembranes is puncture damage. Puncture damage occurs when the geomembrane is subjected to a localized force resulting in the development of a hole through the geomembrane. The size of the hole depends upon the size of the object causing the puncture. Puncture damage commonly occurs during the installation of the liner and the construction of the liner (Koerner, 1994). Since geomembranes are laid on the ground and then covered by a top layer of protective material it is necessary to drive heavy earthmoving equipment over top the geomembrane. The weight of the equipment, combined with the frequent use of wheel treads, creates an ideal environment for puncture damage. Construction puncture damage can also be caused by the protective filter layer placed on top of the

liner. The protective cover may be a gravel layer which can produce puncture damage with its angular shape. The current practice is to place a geonet between the geomembrane and the gravel filter layer to prevent gravel contact with the geomembrane.

The second type of liner damage is due to tearing action. Tear damage occurs when the geomembrane is subjected to a force sufficient to exceed the tensile limit of the geomembrane and pulls it apart. Tear damage is restricted only by the tensile strength of the geomembrane and the force applied. Once a tear is initiated, the geomembrane loses its load carrying capacity. The tear can continue to progress with continued loading. The main cause contributing to tearing damage in a landfill liner system is high tensile stresses caused by uneven short term and long term differential settlement.

Differential settlement of a landfill, as depicted in Figure 5, is a problem that occurs when the subsoils are loaded by the accumulated weight of the waste material. Since landfills usually occupy a large area the soil layers of variable thickness can

Figure 5 Differential Settlement of a Landfill

settle unevenly (Hoekstra, 1991). The differential settlements of the site can induce tensile stresses in the geomembrane. If these stresses exceed the tensile strength of the geomembrane the result will be a tear which will continue until the stresses reduce to values consistent with either the tensile capacity or fracture toughness capacity of the geomembrane.

Long term differential settlement at variable rates can occur over a site as a result of the variability of the consolidation characteristics of the underlying soil layers. Such differential consolidation settlements can also induce stresses in the geomembrane due to the development of tensile forces (Koerner et al., 1990). These forces can vary with the amount of settlement.

Burst damage is another type of damage. Burst damage is also caused by local forces but it results from a more rapid increase in stress than local settlement which causes tear damage. Burst damage occurs when the geomembrane suddenly ruptures due to a rapid increase in local stress. Burst damage can be caused by the expansion of a geomembrane liner exposed to the effects of gas migration. The damage can occur as a result of gases, generated within the landfill, migrating upwards, as shown in Figure 6, and remaining trapped under the geomembrane liner.

Chemical damage is another type of geomembrane damage. Chemical damage results when the geomembrane is exposed to a single chemical or combination of chemicals that result in a change to the mechanical properties of the geomembrane. The damage usually results in a change in the mechanical properties of the geomembrane (Haxo et al., 1985). For example, after chemical exposure, a geomembrane may have an

Figure 6 Gas Migration within a Landfill

increase or a decrease in its tensile strength. Typically chemical action will result in an increased likelihood that the geomembrane will suffer puncture, tear or burst damage as a result of the change in its mechanical properties (Koerner et al., 1988).

Chemical damage in landfill liners is difficult to assess because landfill leachate is a diverse mixture of chemicals which constantly changes over the lifetime of the landfill. The problem is further compounded because the chemicals are in a mixture and the effects of the chemicals in their combined condition is not known. The chemical damage is also affected by the pH of the leachate which varies over time and is known to affect geomembrane liners.

Ultraviolet (UV) damage is another type of geomembrane damage. UV damage is caused by the exposure of the geomembrane to light in the ultra-violet spectrum

(Koerner, 1994). The exposure causes degradation of the chemical bonds which hold the geomembrane polymer structure together and results in a change to the mechanical properties of the geomembrane. The effects of UV damage in a landfill can be reduced if the geomembrane liner is covered by a protective sand layer as soon as possible.

1.4 Rationale for Measuring Effects of Chemical Exposure

The use of geomembranes requires that certain properties of the geomembrane are known. These properties include the tensile strength, the puncture resistance, the tear resistance and the durability properties. In the case of landfill design the most important durability property is chemical resistance. The chemical resistance is of prime importance since, in most cases, the geomembrane is in direct contact with the landfill leachate and its primary function is to prevent the leachate from moving through the geomembrane barrier to the external environment.

1.4.1 Potential for Geomembrane Damage

The potential for chemical damage to the geomembrane liner is high since the geomembrane is in direct contact with the landfill leachate. Although the functional life of a landfill for receiving waste may only last 10 to 15 years the isolation requirements are indefinite. This creates a situation where long term effects of geomembrane exposure to the leachate's chemical mix need to be thoroughly examined.

Also, since the landfill by virtue of its design is securely enclosed it is extremely difficult to make repairs on a liner system that suffers damage. For this reason it is

important to attempt to construct a containment system that will resist any physical and chemical damage to the natural and synthetic barrier systems.

The situation in a landfill is further complicated by the composition of the stored waste. Many different chemicals are contained in the waste placed in municipal landfills. Table 1 lists the most common chemical containing household wastes found in a typical

Household and Cleaning Products

Bleach
Drain opener
Window cleaners
Metal Polish
Oven cleaners
Charcoal lighter fluid
Glue

Automotive Products

Motor oil
Oil filters
Radiator sealers
Anti-freeze
Brake fluids

Paint Products

Paint
Paint thinner

Personal Items

Butane fuel
Hair spray
Suntan oil
Deodorants
Peroxide

**Insecticides, Herbicides and
Pesticides**

Insect sprays
Germicides
Weed killers

Table 1 Common Household Hazardous Wastes (Reinhart 1993)

landfill. While these chemicals are prohibited from municipal landfill sites they commonly are found in the landfill waste (Reinhart, 1993). This mix of chemicals is

constantly changing as new waste is placed in the landfill. The chemicals involved may act in a synergistic manner and cause damage that would not result from the separate actions of the chemicals. The pH of the leachate also changes over time and this may also affect the chemical action. For example some chemicals may increase in potency as the pH decreases. Further factors include thermal effects on the chemical actions. The temperature inside a landfill can be much higher than the ambient temperature due to heat generation by biological decay of the waste. The internal landfill temperatures usually range from 25-45°C (Crawford and Smith, 1985). The elevated temperature can have the effect of increasing the rate of chemical degradation of the geomembrane.

While each of the above effects are important the most crucial aspect of the concept of landfill design is the time frame for the design of landfills. It is difficult to replicate the extremely long term effects of chemical damage on the particular geomembrane selected for use in a landfill. Over very long time periods very slight amounts of damage undetectable in a laboratory setting can ultimately result in a failure of the geomembrane. The EPA Method 9090 uses standard exposure times of 30, 60, 90 and 120 days which attempt to measure the effect of time on chemical compatibility (Tisinger et al., 1991).

In summary, the influences of chemical damage are difficult to predict and measure due to the varied nature of the leachate, the thermal effects and the requirements for long term exposure of the geomembrane to the chemical mix. Because of these difficulties it is important to evaluate the potential for chemical damage taking all possible sources of damage into account.

1.4.2 Potential for Geomembrane Leakage

Owing to the high risk of geomembrane damage it is necessary to examine the influence of damage on the leakage or flow rate across the geomembrane barrier. The main concern is that damage to the geomembrane will result in movement of the leachate into the surrounding environment resulting in contamination of ground water sources being utilized by nearby populations. In a recent study of hazardous waste landfills conducted in the United States (Pavelka et al., 1993) it was found that the landfills contained significant levels of compounds hazardous to human health. The most common constituents included *methyl-ethyl ketone, acetone, methyl isobutyl ketone, methylene chloride, phthalic acid, phenol, arsenic, nickel, zinc and barium*.

Research work has found that holes and perforations in a geomembrane can allow high flow rates through the geomembrane. Recent studies by Brown and Thomas (1988) have shown that leakage rates through a PVC (polyvinyl chloride) geomembrane with a 6.4 mm diameter hole and a head of 0.5 m will be 2300 litres/day and that the leakage rate will increase to 3500 litres/day with a head of 1.0 m. Such leakage rates can pose a significant threat to the ground water system in adjacent areas. Koerner (1994) states that a 6.3 mm diameter hole in a 75,000 litre underground storage tank will dangerously pollute the drinking water supply of a 100,000 person community. The cost of reversing this type of damage is high; consequently it is important to develop engineered barrier systems which can function satisfactorily under adverse conditions.

The main problems with leakage in a geomembrane system are; (i) detecting the presence of a leak, (ii) locating the position of the leak and (iii) repairing the

geomembrane system. Until recently the best method of detecting a leak was to monitor the groundwater downstream of the landfill. This method is effective but unfortunately once the leak is detected the pollutants have already been introduced into the environment and the groundwater is contaminated. However with the increasingly sophisticated design of landfill containment systems it is now possible through a network of leak detection monitors placed around and within the landfill containment system to detect a leak in the containment system before the leachate is able to breach the secondary liner.

The detection of the position of a leak is difficult to determine because of the large areas covered by a typical landfill. The use of a network of leak detectors will allow the general location of the leak to be determined but the precise location is very difficult to pinpoint once the bottom layer is covered with waste. Newer methods, which use electrical resistivity methods, have been developed that allow more precise location of leaks (Furuichi and Tanaka 1993). Additional research should continue to produce more refined methods that can pinpoint the location of a leak.

Once leakage is detected and the source is localized it is necessary to develop a control strategy. The strategies to control a leaking landfill range from excavating the landfill and repairing the defect to pumping out the water downstream of the landfill and treating it to remove the toxins. These methods all require considerable resources and planning.

The potential for leakage is quite high because of the variety of ways a geomembrane liner system can be damaged. It is important to attempt to prevent any damage to the geomembrane and if such damage cannot be prevented and a leak is

detected then it becomes important to contain the leak because of the high leakage rates that are possible with small holes and typical hydraulic heads.

1.5 Objectives and Scope of the Thesis

The objective of this thesis is to develop a simple method of examining quantitatively the effects of chemical exposure on the mechanical properties of a typical geomembrane liner. The test method will attempt to simulate realistic burst loading patterns encountered in a landfill. The chemical exposure portion of the test will be able to be performed in a reasonable amount of time and will thus be an accelerated type of test.

The scope of the thesis consists of a review of the work done on this problem, the development of a test apparatus and documenting the results of the experimental research program.

2.0 LITERATURE REVIEW

2.1 General

The literature review uses a case history to illustrate the chronological history of geomembrane use. Research on chemical compatibility testing and the mechanical properties of geomembranes are also discussed. Previous research conducted by the author are presented. The last section discusses the development of the burst test program in relation to other researchers work.

2.2 Chronological History of Geomembrane Use in Landfills

The development of landfill design and the use of geomembranes is best illustrated using a case history. Woods (1994) traces the development of a typical landfill from the 1950's to the present in the state of Pennsylvania. Originally the landfill was an open pit with only natural soil as a bottom liner. This condition was maintained through the 1960's due to lack of any regulations regarding landfill design. In 1978 plans were made for an expansion at the site using a double liner system. This design was very innovative for the time as most other landfills were only beginning to implement a single liner system. The expansion was completed in 1983 and consisted of a primary liner of 30 mil PVC geomembrane and a secondary liner of a thin layer of asphalt. In 1987 the landfill was again expanded using a new double liner system. The asphalt secondary liner was replaced in the new design with 30 mil PVC geomembrane. A further expansion in 1988 saw an increase in the thickness of the primary PVC liner to 50 mil. In 1992 the decision was made to replace the PVC liners with HDPE (High Density Polyethylene) in any

future expansions.

This case history provides a general time frame of geomembrane use in the design of landfills. The use of geoliners in landfills is a relatively recent innovation and while the regulations and design are increasingly being improved there exist many landfills which were built with little or no regulations and are depending upon a landfill liner which may not provide the containment barrier required over the potential lifetime of the system.

2.3 Discussion of Chemical Testing Research

Chemical resistance testing and chemically induced degradation of polymers and specifically geomembranes has been examined by many different researchers. The conclusions that have been developed are universal but the methods and techniques for measuring the effects of chemical degradation are not agreed upon. While it is agreed that chemical degradation is perceived as a major problem the current state of knowledge is ranked as only moderate (Koerner et al., 1988). This shows that there is a need for continued geomembrane chemical compatibility testing.

The design of a chemical compatibility testing program should employ worst-case exposure conditions. In order to create these conditions a standard leachate solution may have to be altered in order to create an aggressive chemical mix (Cassidy et al., 1992). The results of the worst case test are discussed by Fluet, Badu-Tweneboah and Khatami (1992) who state that the results of chemical compatibility testing have to be carefully evaluated when approving a geomembrane for a project. Their discussion is based on a

pass or *fail* system for the chemical exposure test. If the geomembrane is exposed to a actual leachate from the installation site then a fail result is accepted as a fail and a pass result is accepted as a pass. However if the exposure solution is a synthetic leachate or a similar natural leachate, a fail result is accepted as a fail but a pass result is no guarantee of a suitable material. The pass with no guarantee is important because if the geomembrane is not tested with actual leachate then no assurance can be made of the compatibility of the liner.

This problem is further explored by White and Verschoor (1990) who discuss the life span predictions of geomembranes under chemical degradation. They make the point that life predictions are impossible to verify because there are several assumptions made that can not be verified. These assumptions are as follows: degradation is caused solely by chemical reaction at a measurable rate, the reaction mechanism is the same at all test and service temperatures, leachate tested is the same as in the installation environment, temperatures and environmental conditions will remain the same during the service life of the geomembrane and that liner failure will result from aging induced chemical degradation. Due to these assumptions, which can not be confirmed, the authors recommend that chemical resistance testing must include testing of more than one geomembrane property and to examine trends in the data taking into account the inevitable variability between the properties of individual samples.

The current standard test method for measuring geomembrane chemical compatibility is the EPA Method 9090 (Tisinger, 1991). This test method exposes the geomembrane to a chemical mix over time intervals of 30, 60, 90 and 120 days. At each

interval the physical and mechanical properties of the geomembrane are measured. The different sample exposure times allow the progression of the chemical effects to be quantified. The geomembrane is exposed to the chemical mix in an airtight chamber which keeps the mix circulating. The geomembrane is also exposed to the chemical mix at temperatures of 23°C and 50°C. These temperatures provide a typical landfill operating temperature (23°C) as well as an elevated temperature (50°C) which can be used to estimate chemical degradation under accelerated conditions.

The physical and mechanical properties measured include the physical dimensions of the geomembrane, tensile strength, tear resistance, puncture resistance and the hardness.

The ASTM D543-87 Standard Test Method for Resistance of Plastics to Chemical Reagents (ASTM, vol. 08.01, 1995) also provides parameters for chemical compatibility testing. The test uses a seven day immersion time period and measures the mechanical and physical properties of the plastic after immersion. The test is specified for a temperature of 23°C but also recommends that tests can be conducted at 50°C and 70°C.

2.4 Discussion of Mechanical Properties Research

The concept of index tests and their limitations as opposed to performance tests in the testing of geomembranes is introduced by Koerner, Koerner and Hwu (1990). An index test is one that measures a single property such as a uni-axial tensile test. Index tests generally do not simulate in-situ conditions but rather provide a benchmark that can be compared with other samples with accuracy. Performance tests on the other hand attempt to simulate real conditions that a test sample would encounter in the field.

Performance tests generally give a more realistic answer to the potential in-situ behaviour of the test sample.

The discussion of using standardized index tests to measure the burst strength of a geomembrane are raised by Verschoor, White and Allen (1990) who recommend that the Mullen burst test which specifies that a 100 mm diameter sample be used because it is both reliable and repeatable. However Cassidy et al. (1992) recommend that this index test not be used because the small sample size makes the test unreliable. This disagreement points out the difficulty in selecting a test to accurately measure the burst strength of a geomembrane.

The apparatus designed by Koerner et al. (1990) is a performance test designed to evaluate the stress applied to a geomembrane at the bottom of subsiding landfills. The proposed apparatus is a three dimensional axi-symmetric tension test. The test consists of a 500 mm diameter circle opening over which the sample to be tested is placed. The pressure is applied with water. The researchers tested a 20 mil (0.51 mm) thick PVC membrane. The results of the PVC testing showed that the membrane achieved a stress of 15 MPa at a strain of 80%. The researchers also present the theoretical background to convert pressure versus deflection readings into stress versus strain values. This is the basic philosophy advocated in the research work associated with this thesis.

The research of Haxo et al. (1984) and Haxo et al. (1985) investigates the long term effects of chemical exposure on the physical and mechanical properties of different geomembranes. One of the geomembranes used was PVC. The samples were exposed to ten different chemical solutions and the various properties were measured at set time

intervals. The results showed that the PVC geomembranes experienced both weight increases and decreases and that the PVC also showed embrittlement as well as severe softening. The researchers also found that acid and alkaline wastes caused stiffening of the geomembrane which they attributed to the loss of plasticizer from the geomembrane structure. Further research showed that the weight increase was from 1-6% and that the tensile strength experienced a variation in strength from 87-117% of the original strength.

Ozsu and Acar (1992) studied the "apparent hydraulic conductivity" or liquid transmission through a geomembrane under a hydraulic pressure difference. They tested a 20 mil PVC geomembrane with acetone solutions of 10%, 50%, 90% and 100% by weight. Their results showed a significant increase in the conductivity of the PVC geomembrane for all solutions. The increase in conductivity was linear from the 10% acetone solution to the 100% acetone solution. The authors assumed that this increase in the conductivity was the result of acetone attack on the plasticizers used in the PVC.

The experimental research performed by Haedrich (1993) was conducted in connection with an undergraduate project supervised by Professor A.P.S. Selvadurai at Carleton University. The results of this project led to the developments reported in this thesis. The project examined the effect of chemical exposure on three mechanical properties of a PVC geomembrane. The geomembrane used for the experiment was the same geoliner used in the thesis research. The project also examined the effects of keeping the samples under a tensile load during exposure to the chemical bath. The mechanical properties measured were tensile strength, tear strength and puncture strength. The chemical used was acetone at concentrations of 0%, 10% and 100% by volume with

exposure times of 1,7,14,42 and 70 days.

The results of the experimental work are summarized in Figures 7, 8 and 9. Figure 7 shows the effect of acetone concentration on the normalized tensile strength. Figure 8 shows the effects of chemical exposure on the normalized puncture strength of the geomembrane and Figure 9 shows the effects of chemical exposure on the normalized

Figure 7 Normalized Tensile Test Results

tear strength of the geomembrane. The mechanical properties measured all showed a drop in strength with exposure to the acetone. The results of this research show that there is a direct correlation between the acetone concentration and the effects on the mechanical properties of the geomembrane. These results were used to determine the acetone concentrations required to get measurable results for the current research.

Figure 8 Normalized Puncture Test Results

Figure 9 Normalized Tear Test Results

2.5 Discussion of Parameters of the Burst Test Program Design

The use of PVC geomembranes in landfill design is widely documented. Examples are provided by Schevon and Damas (1986), Furuichi and Tanaka (1992), Ikeguchi (1993) and Woods (1994). PVC geomembranes have been commonly used as landfill liners in North America (Bagchi, 1990) and while PVC has been replaced by HDPE liners in current practice there exist many older landfills with PVC as the primary liner.

This research approaches the problem by examining those landfills that were built with less than the state of the art technology and may have a greater possibility of sustaining chemical damage. The use of PVC as a landfill liner has been largely discontinued as newer materials such as HDPE have been introduced (Koerner, 1994). However landfills do exist that have PVC as the primary liner (Woods, 1994). These older landfills, due to their lack of sophisticated monitoring systems and multi-layer barriers, will have a greater chance of failure. This thesis examines the possibility of failure in a less favourable landfill liner represented by PVC rather than the current industry choice of HDPE (Koerner, 1994).

Acetone is a common chemical that is found in many landfills. In a study by Pavelka et al. (1993) acetone is one of the top three organic compounds found in hazardous and mixed hazardous/municipal waste landfills.

The burst test apparatus design used a combination of ideas from several researchers. Koerner et al. (1990) had designed a large multi-axial tensile test apparatus that tested a sample of 500 mm diameter and used water pressure to deform the specimen.

Rollins (1985) recommends that the specimen be at least 150 mm in diameter for a burst test. He also recommends that air pressure be used to deform the specimen and that the pressure be applied in 50 kPa pressure increments. These were the basic parameters that were established for the design of the test apparatus. The completed design had a specimen diameter of 250 mm and used air pressure to apply stresses to the specimen.

The test time frame is discussed by Park and Nibras (1993) who studied the absorption of leachate by geomembranes. The results for both HDPE and PVC showed that the weight gain from absorption reached equilibrium after approximately four days. After the four days the weight gain was insignificant. The exposure time in the current research was based on this time frame.

The test program was influenced by several parameters discussed by other researchers. The first is the use of control samples which should be placed in deionized or tap water (Allen and Verschoor, 1990). These authors also recommend that chemical compatibility testing take into account variations in the physical dimensions of the samples which can vary both within a roll and between rolls. They also recommend using error bars when presenting the data to show the extent of variation for each of the tests.

3.0 THEORETICAL DEVELOPMENT

3.1 General

This chapter presents the basic chemical and mechanical properties of polyvinyl chloride (PVC) and acetone. It follows with an introduction to the mechanical and chemical stability of geomembranes and how the mechanical stability of a geomembrane can be affected by the chemical degradation of the geomembrane. This discussion provides a background to the experimental program which examines the effects of chemical attack on the mechanical properties of the geomembrane.

3.2 Polyvinyl Chloride

The polyvinyl chloride (PVC) geomembrane used in the experimental work is a sheet with a grey colour and a thickness of 0.5 mm (specified as 20 mil) manufactured by Canadian General Tower Ltd. in Cambridge, Ontario. The exact composition of the geomembrane is proprietary to the manufacturer but in general PVC geomembranes are composed of approximately 35% resin, 25% filler, 5-10% carbon black, 2-3% additives and 30-35% plasticizer. The resin is composed of vinyl chloride monomers strung together to form the polymer. The chemical formula of the vinyl chloride monomer is CH_2CHCl and is shown in Figure 10. The average number of monomers in a single chain is $80^{\wedge}$. The number of molecules in the chain represents the degree of polymerization of the PVC. The large number of joined monomers results in a material with molecules large in comparison to other materials. For example, if a single iron atom in the steel matrix were compared to a PVC molecule the relative size of the PVC would be 2500

Figure 10 Chemical Composition of Vinyl Chloride Monomer

times greater.

There are two types of chemical bonds that hold the geomembrane structure together. The first are primary bonds which link the individual monomers together in a chain. These bonds are covalent or electron sharing bonds formed by the interactions between electrons shared by the two monomers. These types of bonds are quite strong compared to the second type of bonds which hold the chains of monomers to other chains. These bonds are called secondary bonds and provide the intermolecular force required to hold the chains together. These types of bonds do not use electron sharing as a means of bonding but rather attractive forces that are based on the distance between the chains. The closer the chains, the stronger the secondary bonds.

The assembly of PVC proceeds through three steps which build up the polymer chain. The steps are initiation, propagation and termination. The initiation step begins with a single molecule of vinyl chloride which is bonded with a free radical with an unpaired electron which seeks to bond with another molecule forming a stable molecule.

The free radicals are usually formed from peroxides which have an oxygen double bond. The vinyl chloride molecule with the free radical then bonds to another vinyl chloride to form a stable structure between the two vinyl chloride monomers. This is the propagation phase of the reaction. The end of the chain with the free radical then seeks out another vinyl chloride and the reaction continues. The chain will continue to propagate until the reaction is terminated and the chain construction ends. Termination occurs when the reactive end of the chain encounters the end of another propagating chain or an unbonded free radical. These three steps form the chains of PVC which are held together by secondary forces to form the PVC structure. Additives are then introduced to give the PVC its required properties.

3.3 Acetone

The chemical selected for subjecting the geomembrane to chemical exposure is acetone. Acetone is a colourless, volatile, flammable liquid with the chemical formula CH_3COCH_3 . It is a member of the ketone family which is characterized by the presence of a carbon-oxygen double bond called a carbonyl group. It is also miscible in water in all proportions.

Acetone is a widely available chemical that is used in the manufacture of other chemicals, as a solvent, a paint thinner and nail polish remover (Montgomery and Welkom, 1989).

The chemical and physical properties of acetone are shown in Table 2. The values are taken from Howard (1990) and Montgomery and Welkom (1989).

Boiling Point: 56.2°C at 760 mm Hg

Melting Point: -95.35°C

Molecular Weight: 58.09

Density: 0.7899 at 20/4°C

Dielectric Constant: 293.2

Water Solubility: Miscible in all proportions

Vapor Pressure: 231 mm Hg at 25°C

Henry's Law Constant: 3.67×10^{-5} atm-m³/mole

Table 2 Chemical and Physical Properties of Acetone

3.4 Mechanical Stability of Geomembranes

The mechanical stability of a geomembrane depends on the mechanical properties of the geomembrane. The mechanical properties of the geomembrane are in turn dependent upon the molecular arrangement and intermolecular strength of bonds between the chains. The following sections discuss the effects of chemical degradation on the mechanical properties of a geomembrane. The properties discussed are the modulus of elasticity, the strength and the general stress-strain behaviour.

In the small strain range the modulus of elasticity or Young's modulus for geomembranes is dependent upon the strength of the intermolecular bonds or those bonds which hold the individual atoms together and intramolecular bonds which hold the

molecular chains together (Figure 11). The degree of strain placed on the bonds due their physical arrangement is also important in determining the modulus of elasticity. The strains are due to twisting or bending of the chains and the ability of the molecules to rotate around their chains. The chemical composition of the geomembrane will affect the

Figure 11 Intramolecular and Intermolecular Bonds in PVC Molecules

ability of the molecules to rotate at the bonds. Another factor determining the modulus of the geomembrane is the degree to which the chains are intertwined.

The strength of the geomembrane is also determined by the strength of the intramolecular and intermolecular bonds. The intramolecular bond strength is defined by the following relationship given in Moore and Kline (1984):

$$F = \frac{E}{d} \quad (3.1)$$

where: **F** = force required for bond breakage (N)
 E = bond disassociation energy (J/bond)
 d = bond distance (nm)

The force required to break the bond will ultimately determine the strength of the geomembrane. The higher the bond disassociation energy the higher the strength of the geomembrane. The bond distance is determined by the type of bond between the atoms and is constant for a particular type of bond.

The mechanical behaviour of a geomembrane is also determined by its molecular structure. Geomembranes are viscoelastic materials which exhibit both elastic and viscous effects. In the small strain range, elastic materials are defined as materials which obey Hooke's Law. The behaviour of these materials ignores the influence of time in the constitutive relationship. Alternatively, the rate of strain is assumed to have no influence on the stress-strain behaviour. Purely viscous materials, on the other hand, ignore any elastic behaviour and the constitutive relationship is expressed in terms of the stress and the rate of strain with viscosity being a constitutive parameter identified with Newtonian viscous fluids. Geomembranes exhibit properties of both types of responses. By virtue of the structure of the molecules and their positions within the geomembrane different force reactions can be created. One chain can be pulled apart from another chain with a resistive force equal to the strength of the secondary bonds between the two chains as shown in Figure 11. The required force is affected by the degree of chain twisting around

each other. The speed at which the force is applied will also influence this reaction. A low strain rate will allow the chains to gradually untangle and will require less force than a higher strain rate which will tend to rip the chains apart rather than untangle them. The chains monomers also have to be pulled apart and requiring enough force to break the primary bonds. These force reactions all occur at the same time creating a complex system of reactive forces.

The arrangement of the polymer chains will be altered by the application of a force due to the untangling and twisting behaviour. When the force is released the chains will attempt to return to their original position but inevitably a different configuration will be formed. This type of behaviour is elastic in the sense that the material is attempting to return to its original shape.

The strength and durability of a geomembrane are dependent on the strength of the bonds at the molecular level. The strength of these bonds is determined by the chemical composition of the geomembranes which determines the bond type and proximity of the chains to each other. The mechanical properties are also influenced by the degree of cross-linking and distortions of the chains.

3.5 Chemical Stability of Geomembranes

The chemical stability of geomembranes depends upon three main factors. These factors are the chemical composition of the geomembrane, the chemical composition of the surrounding medium and the environmental conditions that govern the system. These factors determine the type of reaction, the speed of the reaction and the limits to the

reaction. These factors can be closely controlled in a laboratory environment and work has been done to produce predictions for the degradation of geomembranes under chemical exposure (reviewed in Moiseev and Zaikov, 1987). It is difficult to directly translate these results to a real exposure situation in a typical reaction because of the variability in the chemical composition of the surrounding medium and the environmental conditions. The chemical composition of the geomembrane can also change over time as various chemical reactions take place both on and within the geomembrane.

3.6 Relationship between Chemical and Mechanical Properties of Geomembranes

The relationship between the chemical degradation and the mechanical properties of polymers is reviewed by Moiseev and Zaikov (1987). A summary of their review is described in the following section.

The relationship between chemical degradation and strength of a polymer was first proposed by Orowan (as cited in Moiseev and Zaikov, 1987). Using a model based on the energy available at the surface of the polymer Orowan derived the following relationship:

$$\sigma_{th} = \sqrt{\frac{(\gamma_{surface} - \Gamma)E}{a_0}} \quad (3.2)$$

where:

σ_{th} = theoretical strength of the polymer (MPa)

$\gamma_{surface} - \Gamma$ = free surface energy of the solid polymer (J/m²)

E = modulus of elasticity (MPa)

a_0 = twice the distance from the energy equilibrium position to the maximum quasi-elastic force (m)

The basic conclusion is that the strength of the solid polymer depends upon the surface energy at the polymer-surrounding medium interface. From this result it can be concluded that the free surface energy will change when the polymer is exposed to a reactive medium.

The second approach to assessing the influence of chemical degradation on the strength of a polymer is that presented by Kobeko (as cited in Moiseev and Zaikov, 1987). This research examined the strength of individual molecular chains of the polymer and the disassociation energy needed to break the chains. Kobeko's research produced the following equation for the theoretical strength:

$$\sigma_{th} = \frac{NB_0D}{2} \quad (3.3)$$

where :

- σ_{th} = theoretical strength of the polymer (MPa)
- N = number of chains belonging to unit area of the cross section of the unstressed specimen of orientated polymer
- D = bond disassociation energy (J/bond)
- B_0 = constant relating the frequency and amplitude of the oscillation of the particles

This equation infers that the strength of a polymer depends on the density of chains in the polymer as well as the energy required to separate the molecular bonds. If either the density of connected chains is decreased or the energy of the bonds is reduced then the strength of the polymer will be reduced. This situation would be expected if the polymer was exposed to a chemical medium which reacted with the polymer and affected either of the two parameters.

A third approach to chemical degradation and its effects on polymer strength is that developed by Gubanov and Chebychelov (as cited in Moiseev and Zaikov, 1987).

These researchers proposed the following equations:

$$M_n < 10^5 \quad \sigma_0 = \frac{3}{2} \left[\frac{(\gamma_{\text{surface}} - \Gamma)E}{d_0} \right]^{\frac{1}{2}} (1 - \gamma_p) \quad (3.4)$$

$$M_n > 10^5 \quad \sigma_0 = \frac{3}{2} \left[\frac{(\gamma_{\text{surface}} - \Gamma)E}{d} \right]^{\frac{1}{2}} \quad (3.5)$$

where :

- σ_0 = tensile strength of the polymer (MPa)
- $\gamma_{\text{surface}} - \Gamma$ = free surface energy of the polymer (J/m²)
- $(1 - \gamma_p)$ = probability of scission in polymer chain
- $d = 2 (S / \pi)^{1/2}$
- $d_0 = 2 (S_0 / \pi)^{1/2}$
- S = surface area of the defect (m²)
- S_0 = cross-sectional area of the polymer chain (m²)
- E = modulus of elasticity (MPa)
- M_n = number average molecular weight of the polymer

From this work the authors determined that the strength of the polymer in uniaxial tension depends upon three parameters, the surface energy of the polymer-medium surface, the energy of the chemical bonds in the polymer molecules and the number average molecular weight of the polymers. Again as shown in the previous work by Orowan (as cited in Moiseev and Zaikov, 1987) and Kobeko (as cited in Moiseev and Zaikov, 1987) interaction with an aggressive medium will lower the surface energy at the interface as well as decrease the energy of the polymer bonds. Additionally as defects begin to

enlarge the polymer strength will decrease.

The role of plasticizers is also important to the relationship between the chemical and mechanical properties in polymers. Plasticizers are added to plastics to make them flexible which greatly increases the potential uses. PVC in its unplasticized form is a rigid plastic. The addition of plasticizer makes the PVC flexible.

Plasticizers are compounds of low molecular weight which are absorbed into the molecular structure of the PVC. The plasticizers reduce the intermolecular bond strength of the geomembrane by occupying space between the chains and increasing the distance between the chains. This reduces the strength of the secondary bonds which are dependent upon the distance between chains. The plasticizers also increase the movement between the chains by creating extra space in the polymer structure. This tends to reduce the physical cross-linking of the chains and reduces the strength of the geomembrane. The reduction in bond strength and untangling results in a lower strength but also gives the geomembrane its flexibility. In effect, the plasticizer reduces the geomembrane strength in order to provide flexibility which is an important functional requirement for a geomembrane.

The increase in geomembrane flexibility is based on the glass transition temperature (T_g). The glass transition temperature is the critical temperature below which the geomembrane becomes rigid and brittle and above which the geomembrane becomes rubbery. The T_g of unplasticized PVC is 87°C. The addition of plasticizer reduces the glass transition temperature to a point where the geomembrane will continue to remain flexible under most operating conditions. This property is illustrated by PVC garden

hoses which are flexible in the summer and rigid in the winter.

The effects of acetone on the geomembrane are based on the same principles as the addition of plasticizer. The effects of the plasticizer and the acetone are shown in the following diagrams. Figure 12 shows the polymer spacing of the unplasticized PVC. The

Figure 12 Molecular Spacing of Unplasticized PVC

solid lines represent the bonds between the PVC monomers which are represented by the PVC symbol surrounded by a rectangle. The spacing represented by L_{PVC} at a minimum and the PVC is rigid. The effects of the plasticizer, represented by the P, are shown in Figure 13. The plasticizer which is a solvent moves into the molecular structure of the PVC and the physical space that it occupies moves the PVC molecules apart a distance of dP . The average distance between the PVC molecules now becomes $L_{PVC} + dP$. The increase in distance between the PVC molecules reduces the bonds between the molecules and reduces the effects of intertwined molecules. The result is a flexible material with many new uses. The exposure of the geomembrane to acetone, CH_3OHCH_3 , results in a further increase in the distance between the PVC molecules. The new spacing now

Figure 13 Molecular Spacing of Plasticized PVC

Figure 14 Molecular Spacing of Plasticized PVC with Acetone

becomes $L_{PVC} + dP + dCH_3OHCH_3$. The effects of acetone exposure are shown in Figure 14. The acetone is also a solvent which enters the geomembrane structure and moves the geomembrane chains further apart which decreases the secondary bond strength which in turn decreases the overall strength of the geomembrane.

4.0 EXPERIMENTAL DEVELOPMENT

4.1 Basic Concepts

The use of geomembranes in waste containment systems presents a set of design challenges to the engineer. One of the main challenges is evaluating the effects of chemical exposure on selected geomembranes. The primary chemical source is the leachate generated from the waste which usually comes in direct contact with the geomembrane barrier. Coupled with the chemical exposure is the possibility of induced stresses in the geomembrane which can increase the potential for damage.

The geomembrane can be subjected to stresses both during construction and after the completion of the landfill. Settlements, both total and differential, are important in the design of the liner system; they induce forces that are instrumental in stressing the geomembrane. The total and differential settlements can be calculated using standard geotechnical analysis as well as settlement models specific to waste in landfill sites. The stresses from settlement will be carried primarily by the geomembrane lining the sides of the landfill. The bottom liner will not be exposed to these stresses unless there is local settlement. Local settlement can occur when there is a variation in the soil layers beneath a certain area (Hoekstra, 1991). The rate of settlement below the bottom liner will depend on the consolidation or creep characteristics of the soils. The rate of settlement within the landfill will depend on the speed of waste degradation and compaction (Tchobanoglous, 1993).

The main objective of the thesis is to develop an experimental procedure, with simple experimental concepts, which can be used to evaluate the strength characteristics

of geomembranes which are subjected to chemical exposure.

The experimental program involves the exposure of a geomembrane liner to a single chemical found in landfills and then testing the samples with a loading pattern simulating local settlement under a landfill. The experimental program will offer the following features as part of its overall design and implementation.

First the test apparatus, the chemical exposure tank and the sampling equipment will be kept as simple and user friendly as possible. This will reduce the possible factors of error and will make the procedure both easy to replicate and simple to operate.

The second feature of the program will be the use of accelerated chemical exposure tests. Accelerated tests refer to tests that simulate the effects of damage due to a prolonged exposure by increasing the concentration of the exposure medium. The results obtained can then be used to predict the long term effects of the damage without recourse to testing which involves an extended time frame. In this test program the percentage of chemical in the mix is increased to levels that produce changes in the geomembrane properties over a period of 100 hours. The standard time frames used by the EPA Method 9090, as discussed earlier, are 30, 60, 90 and 120 days. The choice of 100 hours or approximately four days was selected for two reasons. The first reason is that previous research (Haedrich, 1993) and preliminary tests showed that a change in the mechanical properties of the geomembrane could be observed after time intervals of 1 day and 3 days. The second reason is that the project had to be completed within a reasonable time period. The effect of the 100 hour time frame will be that longer term results will not be measured and that patterns of degradation will not be observed. There

are no convenient procedures which allow for testing on time scales of typical landfill use; consequently accelerated tests are both convenient and necessary.

Another feature of the experimental program is the use of a single chemical exposure medium. Using one chemical reduces the different effects that can occur when mixing different chemicals together. Because each landfill leachate is different it is only possible to truly test the chemical compatibility of a landfill liner system by testing the leachate present in a specific landfill. However, as the leachate ages and new waste is placed in the landfill, the chemical composition of the leachate also changes. The variability of the chemical mix makes it very difficult to accurately test a proposed landfill liner. Therefore the proposed test uses a single chemical compound that is usually found in landfill leachate (Pavelka et al. 1993). Typical acetone concentrations have been measured at 3.5 ppm and 46.6 ppm (Howard, 1990). These concentrations are very low when compared to the concentrations of 5 to 20% by volume that are used in the experimental program. However it was decided that a single chemical found in landfills would be selected and that the chemical would be used in high enough concentrations in order to produce chemical degradation. The high concentrations of acetone produce a type of accelerated test.

Another feature of this experimental program is the loading system (Figure 15). In this research program a burst test is used which simulates the effects of localized settlement. The test uses a large circular membrane that is deformed by a localized force while the edges are held stationary. This loading has two purposes. Firstly it simulates a condition that can occur in landfills (Veldhuijzen Van Zanten, 1986) and secondly it

Figure 15 In-situ and Experimental Apparatus Geomembrane Deformation

allows a visual observation which can demonstrate how the chemical exposure alters the mechanical properties of the geomembrane. These loading patterns typically are found in the top cover geomembrane but can also be found in the bottom layers (Koerner, 1990). The loading system subjects the geomembrane to three dimensional loading of the geomembrane which will detect any anisotropic behaviour that the geomembrane might exhibit before or after exposure to the chemical mixture.

4.2 Design Criteria

The design of the experimental test apparatus had to meet several criteria in order to facilitate the features discussed in the previous section. These factors are as follows:

- **Ease of Use**

The experiment was designed from the outset to be simple to set up and operate. This will allow for multiple tests without long periods of set up time.

The entire test apparatus is situated on one platform with the exception of the data acquisition system which is contained on board the computer system. The loading force is supplied by compressed air which eliminates the need for specialized gas cylinders and pressure regulators. The pressures required are less than 50 psi which makes the system accessible to any laboratory with a compressed air source. The computer system requires an Intel 386 based computer.

The test system also allows for convenient changing of test specimens. This aspect is required because each test category involves multiple tests in succession. The variability associated with tests can be minimized by making the test procedure as simple as possible.

This ease of use criteria will allow the system to be set up quickly and also allows operation by an individual with a minimum of experience.

- **Size of Test Specimen**

The size of the test specimen was an important consideration in design of the test apparatus. The size of the test specimen attempts to realistically simulate the effects of localized settlement. To develop a realistic test it is necessary to have as large a sample size as practically possible. The geomembrane sample size chosen for this experiment had a diameter of 250 mm. This sample size is substantially larger than the ASTM D3786-87 Burst Resistance Test (ASTM, vol. 07.02, 1995) sample diameter of 100 mm as recommended by Verschoor et al. (1990).

Another consideration concerning the size of the geomembrane sample was

the configuration it would achieve under conditions of inflation. Since PVC geomembranes are highly flexible at room temperature the size of the inflated membrane would be considerably larger. This expansion was demonstrated in the preliminary tests when the samples were inflated to volumes of 15 litres.

A third factor in the choice of the size of the samples was the effect of the bursting action on the surrounding environment and the safety of the operator. This effect was difficult to assess a priori; in general, however, the larger the sample the greater the release of energy during bursting action. The preliminary tests showed that while the samples did "explode" with a loud noise and the geomembrane shattered into fragments there was minimum risk of damage to the room or occupants provided care was taken to protect the operator (e.g. safety glasses, ear protection, etc.)

The last factor in the size of the test specimens was the requirement for the immersing of the samples in a chemical bath. In order to limit the size of the chemical immersion tank the maximum size of the sample had to be kept within reasonable limits.

- **Chemical Selection**

The selection of the chemical exposure environment which would interact with the geomembrane had several requirements. The first requirement is that the chosen chemical had to be one present in leachate from existing landfills. This requirement would accurately simulate a situation that could occur in an existing landfill.

The second requirement is that the chemical had to be easily available and safe to handle in a laboratory setting. This was necessary because the samples would be exposed to the chemical and then handled in order to conduct the testing. The samples are also ruptured during the test and there would be some danger of the chemical being distributed around the laboratory. The chemical bath would also have to sit for some time unattended and thus had to be relatively safe.

The third requirement is that the reaction of the chemical and the geomembrane should not result in the releasing of any hazardous substances.

The fourth requirement is that the chemical be ubiquitous. That is a chemical that is widely used both in its pure form and in other products. This would ensure that the chemical would have a good chance of being distributed to a waste containment site.

- **Chemical Compatibility of Experimental Apparatus**

The choice of the chemical was also restricted by the availability of experimental apparatus construction materials that were nonreactive with the chosen chemical. This is very important because the test sample could be contaminated if the test apparatus or the chemical immersion tank would react with the exposure chemical and thus change the chemical composition of the solution in contact with the sample.

Chemical compatibility is also necessary to ensure the long term durability of all the equipment.

- **Data Acquisition System**

The data acquisition system requirements are governed by several factors. The first factor is reliability. The loading of the sample consists of a rapid increase in the pressure followed by a sudden shock wave from the rupture and followed by a rapid decrease in the pressure. This pattern will be repeated many times during the duration of the test period. The burst test also requires that the design of the test rig provide protection for the load cells.

The second factor is the rate of sampling. The rate of sampling or scanning rate will have to be sufficient to capture the behaviour during the short duration of the loading event. Preliminary tests showed that 1 data sample every 2 seconds was fast enough to describe the event. This scanning rate was within the range of the data acquisition system.

The last factor required is that the data recording system be located a sufficient distance away from the test apparatus in order to protect the sensitive data recording equipment and the computer from the explosive nature of geomembrane rupture.

4.3 Proposed Design of the Experimental Facility

The proposed design of the experimental apparatus consists of three main components. These are the test specimens, the burst test apparatus and the data acquisition system. The last two components are used together to perform the testing of the samples. The three components are described in detail in the following sections.

4.3.1 Test Specimens

The test specimens used were from a 20 mil (0.51 mm) PVC Geoliner manufactured by Canadian General Tower Ltd.

The geomembrane was delivered as a single sheet with approximate dimensions of 3 metres by 20 metres. The sample sheet was kept covered to reduce any UV damage that might occur before the samples were tested. The individual samples were made by cutting the sheet into 300 mm by 300 mm square samples. This size would allow the sample to completely cover the test area and neoprene gasket allowing an airtight seal to be made between the two test plates and the geomembrane.

4.3.2 Burst Test Apparatus

The burst test apparatus consists of four components. These are the base plate, the test plates, the pressure tubing system and the test platform. These components are described in the following sections.

4.3.2.1 Base Plate

The burst test apparatus consists of three main components. The first is the universal base plate. The design of the base plate is shown in Figure 16. The base plate consists of a 50 mm thick piece of aluminum with a width of 400 mm and a length of 600 mm. The size of the base plate was selected to provide sufficient mass so that the test apparatus would remain stable during the burst tests. Aluminum was chosen as the material for the apparatus because it is easier to machine and less expensive to purchase

1. Material is aluminum.
2. Dimensions in millimeters.

DRAWING NOT TO SCALE

Universal base plate for geomembrane burst test	Drawn by: Tyson Haedrich	27 January 1994
	Checked by: APS Salvadurai	Drawing A-1
	Carleton University Dept. of Civil Engineering	

Figure 16 Universal Base Plate Design

than stainless steel. Aluminum is also resistant to rusting which is important considering the moist nature of the test samples.

The burst chamber is located in the centre of the base plate and has a diameter of 250 mm. The depth of the chamber is 25 mm. This depth was chosen to allow separation between the test sample and the inlet port. The thermocouple sensor tip will be located in this chamber beneath the sample. The edges of the burst chamber are filleted to reduce the possibility of sharp edges coming in contact with the geomembrane sample.

Circling the burst chamber is the O-ring groove that houses an O-ring supplying an airtight seal between the base plate and the lower test plate. The O-ring groove has a 300 mm inside diameter and an 315.6 mm outside diameter. The O-ring is a National 453 type made of Buna-N material. The O-ring thickness is 6.25 mm with an inside diameter of 300 mm and an outside diameter of 312.5 mm. The depth of the O-ring groove is 5.125 mm. The dimensions of the O-ring groove are determined by the O-ring specified which is designed to provide the maximum seal capacity.

Surrounding the O-ring groove on a 350 mm diameter are the bolt holes used to attach the upper and lower test plates to the base plate. The bolt holes are drilled for 9.375 mm bolts and are located at 45 degree intervals around the circle. The bolt holes are drilled through on all three plates. This design allows the use of different shaped test plates without any modifications to the base plate. Test plates with any sample shape can be used as long as the dimensions of the test shape remain within the boundaries of the 250 mm burst chamber.

The inlet port is located in the centre of the burst chamber and is a through hole tapped from the bottom to 6.25 mm NPT specifications. This type of fitting will allow an air tight seal to be securely fastened to the bottom of the base plate.

The base plate itself is supported on four 15.625 mm bolts with a length of 87.5 mm located in each corner of the plate. The position of the bolts is 37.5 mm from each side. The bolts are attached to the base plate with 15.625 mm tapped holes with a depth of 37.5 mm. The support bolt configuration allows the bolts to be adjusted to both level the base plate and to eliminate any imperfections in the placement of the test apparatus.

4.3.2.2 Upper and Lower Circular Test Plates

The upper and lower test plates consist of 9.4 mm thick aluminum with outside dimensions of 400 mm by 600 mm matching the base plate. The design of the upper test plate is shown in Figure 17 and the design of the lower test plate is shown in Figure 18. Both plates have a 250 mm diameter hole in the centre of the plate which corresponds to the base plate burst chamber. The edges of the circle are filleted all around to prevent any sharp edges from penetrating the geomembrane test sample. Both base plates also have eight 9.375 mm through bolt holes drilled on a 350 mm diameter circle around the circle test shape. These bolt holes correspond to the bolt holes drilled through the base plate.

The design of the test plates allows the test sample to be placed between the upper and lower plates and then the two test plates and the base plate are clamped together with the eight bolts. To prevent the geomembrane sample from moving during the burst test

Top plate

1. Material is aluminum.
2. Dimensions in millimeters.

DRAWING NOT TO SCALE

**Circular test plate
for geomembrane
burst test**

Drawn by: Tyson Haedrich

27 January 1984

Checked by: APS Salvadurai

Drawing A-2A

Carleton University Dept. of Civil Engineering

Figure 17 Upper Test Plate Design

1. Material is aluminium.
2. Dimensions in millimeters.

DRAWING NOT TO SCALE

**Circular test plate
for geomembrane
burst test**

Drawn by: Tyson Heedrich

27 January 1994

Checked by: APS Selvadurai

Drawing A-2B

Carleton University Dept. of Civil Engineering

Figure 18 Lower Test Plate Design

it was necessary to provide a non-slip surface between the two test plates. This was done using a neoprene gasket placed on the lower test plate around the circular test shape. The neoprene gasket had a thickness of 1.6 mm and an inside diameter of 268.8 mm and an outside diameter of 293.8 mm. The gasket was designed to sit between the edge of the burst chamber and the clamp down bolt circle.

4.3.2.3 Pressure Tubing System

The pressure transducer, thermocouple and mass flowmeter are connected to the burst test base plate through the pressure tubing system (Figure 20). The pressure tubing system is constructed of 6.25 mm stainless steel tubing and stainless steel Swagelok fittings.

The pressure tubing system begins at the connection to the air supply. The air supply is a 100 psi line from the laboratory system. The air supply connects to a short length of tubing which is connected to the input port of the mass flowmeter. The output of the mass flowmeter is connected by a short length of tubing to a T-joint. One branch of the T-joint connects to a bleeder valve which can be used to depressurize the system. The other branch of the T-joint connects to a longer piece of tubing which is also connected to a T-joint. This joint is the inlet for the thermocouple wire. The thermocouple wire is sealed into a coupling with silicone sealant. The silicone forms an air tight seal preventing pressure loss and the coupling allows the thermocouple to be easily removed for inspection. The other branch of the T-joint connects with a short piece of tubing to a T-joint with 6.25 mm NPT fittings. The top of the T-joint is screwed

into the other branch of the T-joint. The thermocouple wire is fed through the system and into the base plate through this inlet. All of the connections are wrapped with teflon tape before they are joined.

4.3.2.4 Test Platform

The base plate and pressure tubing system are located on a test platform which secures the test apparatus. The test platform is constructed of 16 mm thick plywood with dimensions of 675 mm by 900 mm. On either edge of the platform are two supports with a height of 37.5 mm, a width of 56 mm and a length of 400 mm. The supports have two holes drilled in each of them which correspond to the bolt heads protruding from the bottom corners of the base plate. The holes provide a secure support for the base plate and give a clearance of 130 mm beneath the base plate which creates room for tightening the clamp down bolts as well as adjusting the pressure transducer.

4.3.3 Data Acquisition System

The test program required that three parameters be recorded during the burst test. The parameters are the pressure inside the burst chamber, the temperature inside the burst chamber and the rate of air flow into the burst chamber. The three parameters were all sampled at a rate of 1 data sample every 2 seconds interval and the data points stored in one file.

4.3.3.1 Thermocouple System

The air temperature inside the burst chamber was recorded using a K type thermocouple positioned with the sensor tip 50 mm above the inlet port in the centre of the burst chamber. The thermocouple was constructed by TIG welding a connection between an alumel and a chromel wire. The weld was then protected by covering the exposed area with Devcon liquid aluminum epoxy. The thermocouple wire was then fed through the inlet port and outside through a T-joint and connected to the analog multiplexer.

4.3.3.2 Pressure Transducer System

The pressure in the burst chamber was measured using a DCT Instruments PZA100AC series port style pressure transducer. The manufacturers specifications for the pressure transducer are as follows:

Pressure range:	0-100 psia (0-690 kPa)
Input excitation:	10 VDC
Output signal:	5 mV/V
Linearity and hysteresis:	0.50% of full scale
Temperature range:	
compensated	70 to 170 °F
operating	0 to 180 °F
Safe overload:	200% of full scale
Calibration factor:	20.1557 mv/V

The manufacturer supplied a calibration certificate with the pressure transducer

that guaranteed the calibration factor listed in the transducer specifications. The calibration factor was assumed to be correct because the facilities to replicate the calibration procedure are not available at the Carleton University Geotechnical Engineering Laboratory. The performance of the pressure transducer was approximately evaluated for accuracy using a constant pressure apparatus over the pressure range of the transducer. The constant pressure apparatus tests confirmed that the pressure transducer was measuring pressure accurately. By running a series of preliminary tests it was also confirmed that the response time of the pressure transducer was rapid enough for the burst tests. These tests showed that the response time of the pressure transducer as well and the data acquisition system was sufficient to record the required data.

4.3.3.3 Mass Flow Controller System

The mass flow controller system is used to measure and regulate the flow of air pressurizing the sample. The mass flow controller used is model FMA-119 supplied by Omega Engineering Inc. The flow range is 0-10 litre/minute. The controller was interfaced with the LabWindows software which allowed precise monitoring and control of the mass flow. The flow was controlled by a 0-5 VDC signal and the output is also measured with a 0-5 VDC signal.

The mass flow controller was calibrated by Omega Engineering using air as the test gas. The calibration sheet supplied showed a maximum difference between indicated and actual flow of 0.04% which is within acceptable limits.

4.3.3.4 Data Acquisition and Control System

The data control portion of the data acquisition system consisted of three components, an analog multiplexer, a data acquisition board and a personal computer system. A flow diagram of the complete data acquisition system is shown in Figure 19. The analog multiplexer, supplied by National Instruments Corporation, was model number AMUX-64T. The analog multiplexer was installed in a custom designed box constructed at Carleton University and is capable of handling up to 64 channels of data. The data

Figure 19 Flow Chart of Burst Test Data Acquisition and Control System

acquisition board, also supplied by National Instruments Corporation, was model number AT-MOI-16F-5. The data acquisition board plugs directly into a 16-bit expansion slot on the computer system motherboard and is connected to the analog multiplexer with a 50 pin ribbon cable connector. The board is capable of supporting up to 16 channels of data with two of those being output control channels.

The computer system consists of a 486DX33 installed with the commercially available software package LabWindows. LabWindows allows the user to custom design and control the data acquisition system. For the experimental program the LabWindows user interface was designed to display the current rate of air flow into the burst chamber, the pressure in the burst chamber and the temperature in the burst chamber. The interface was also designed to allow the user to control the rate of air flow into the burst chamber and the data sampling time interval.

The signal leads from the mass flowmeter, pressure transducer and thermocouple were attached directly to the analog multiplexer.

The pressure transducer and the mass flowmeter both required input voltages. The 10 VDC input excitation voltage of the pressure transducer was supplied directly to the transducer from a DC power supply. The mass flowmeter required both an excitation voltage and an input flow rate control signal. The excitation voltage was supplied by a DC power supply. The input control voltage controlled was supplied from the data acquisition board and sent through the analog multiplexer.

4.4 Design Refinement

The process of design refinement involved discussion with colleagues and a series of preliminary tests which tested the design before the final configuration was selected. The final design schematic is shown in Figure 20. Plates 1 and 2 show the burst test apparatus and the overall test layout. During the design several issues were vital to the final test design.

The first issue was the fluid that could be used to inflate the geomembrane sample. The three choices considered were water, air or an inert gas. Water was the first choice because it can be considered incompressible and therefore it would be easy to measure the volume of the inflated geomembrane. However a preliminary inflation test showed that because of the large volume of water needed to inflate the geomembrane the resulting burst would create a large problem with cleanup and the instrumentation would have to be waterproofed. The choice of a pure gas was considered because it is available and safe. However no obvious advantage for using gas could be found as opposed to compressed air and therefore air was selected as the inflation fluid.

Another issue considered was the air tight sealing of the geomembrane sample. The original design used an O-ring between the upper and lower test plates to provide a seal with the test sample. However after conducting some clamping tests and loading the sample it was determined that an O-ring did not provide enough frictional grip to prevent the sample from slipping under load. Two custom made neoprene gaskets with thicknesses of 1.6 mm and 3.2 mm were tested and it was found that while both gaskets provided an adequate surface area the thicker gasket resulted in a slight warping of the

Figure 20 Schematic of Burst Test Apparatus Configuration

Plate 1 Burst Test Apparatus

Plate 2 Overall Test Layout

top test plate as it was clamped down. From this observation the 1.6 mm thick gasket was selected to clamp the geomembrane sample.

The positioning of the thermocouple and the pressure transducer also presented a design problem. The original design had three inlets into the base plate for the thermocouple, the pressure transducer and the inflation medium. However once air had been selected as the inflation medium the number of inlets was reduced to one and the position of the pressure transducer and the routing of the thermocouple wire were designed. The use of one inlet simplifies the design as well as reducing the number of connections required to be air tight.

The design was tested in stages as it was constructed and the final design was subjected to a series of preliminary tests described in the following chapter.

5.0 EXPERIMENTAL PROGRAM

5.1 General

The experimental program used three different tests. The first test was the burst test, the second test was the tensile test and the third test was the puncture test. The tensile and puncture tests were used to provide a method for both confirming the results of the burst tests and for providing a comparison for the burst tests. The burst test work was divided into four different sample exposure methods. The methods were no exposure, partial single sided exposure, single sided exposure and two sided exposure. The tensile and puncture tests were conducted only with samples subjected to a two sided exposure environment.

The experimental program used five different exposure environments. These were air exposure, water exposure, and 5%, 10% and 20% concentration by volume acetone exposure environments. The samples for the three different tests were exposed to the same test solutions.

The samples for the three tests were also placed in the exposure environments for the same length of time and were handled in the same manner to minimize any differences between the sample exposure of the different test methods.

5.2 Test Samples

The test specimens were prepared from a 20 mil geomembrane manufactured by Canadian General Tower Ltd. The geomembrane has a thickness of 0.51 mm, is grey in colour and has plasticizer added for flexibility. The geomembrane was delivered in one

piece. The geomembrane was kept covered at all times to limit the exposure and potential damage from UV light.

5.2.1 Test Sample Preparation

5.2.1.1 Burst Test Samples

The burst test samples were prepared by cutting the geomembrane sheet into 300 mm x 300 mm squares. The samples were taken from the portions of the geomembrane that had not been folded in order to reduce the error from stresses or damages created by folding. The geomembrane samples were then weighed.

The testing program required that the burst test specimens be exposed to the test environments in three configurations. The exposure configurations were partial one sided exposure, one sided exposure and two sided exposure.

The one sided partial exposure samples were prepared by marking an area in the centre of the geomembrane of 120 mm x 38 mm. The area outlined was approximately 10% of the circular area subjected to loading in the burst test. The sides of the area were formed by applying a thick bead of silicon around the edge with a height of approximately 10 mm. An overlapping top made of Lexan with a hole drilled in the middle was then gently pressed onto the silicon outline and the sample was left to dry for 48 hours. The result was an enclosed area with the required dimensions and a small access hole providing a means of injecting the exposure medium. The sample is shown in Plate 3. The cavity was then filled and the access hole sealed with tape. As with the one sided test the silicon was easily peeled away before testing.

The one sided samples were prepared in the following manner. A sample had a bead of silicon sealant placed around its edges. A second sample was then placed on top

Plate 3 Burst Test Partial One Sided Exposure Sample

of the first sample and the edges were smoothed down to create a water tight bond with the silicon around the entire perimeter of the two samples. This created a pocket of air between the two samples with only one side exposed to the outside environment. The silicon was placed so it did not touch the area of the geomembrane that would be pressurized during the burst test. The samples were allowed to dry for a minimum of 48 hours before being immersed in the exposure medium. During immersion the samples were carefully observed for any signs of bubbles which would indicate a leak in the silicon seal. When the samples were removed from the exposure medium they were again

checked for any signs of liquid between the two samples. The silicon was easy to remove from the sample and peeled away in one piece once peeling was initiated.

The two sided exposure samples were placed directly in the exposure medium with no additional preparation necessary.

5.2.1.2 Tensile Test Samples

The tensile test samples were formed by cutting strips of geomembrane 175 mm long and 12.5 mm wide in the centre portion. The samples were tapered slightly to the 12.5 mm width to prevent breakage at the ends (Plate 4). The samples were cut from

Plate 4 Tensile Test Sample

areas which did not contain the folded areas of the geomembrane. The samples were placed in their respective exposure environments after they were cut.

5.2.1.3 Puncture Test Samples

The puncture test samples were prepared by cutting 75 mm x 75 mm square pieces of the geomembrane from the unfolded portions of the geomembrane (Plate 5).

Plate 5 Puncture Test Sample

The samples were then placed in their respective test environments.

5.2.2 Chemical Exposure Program

The chemical exposure program subjected the geomembrane to the effects of acetone exposure over a period of 100 hours. The acetone concentrations used in the tests were 5%, 10% and 20% acetone by volume. The acetone was mixed with tap water to produce the desired concentration. The acetone which is less dense than water (refer to

Table 2) does not float in water because it is hydrophilic and miscible with the water in all proportions (Montgomery and Velkom, 1989). The mixing ratio is defined on the basis of by total volume so that a 10.0 litre 20% acetone bath would have 2.0 litres of acetone and 8.0 litres of tap water.

The chemical exposure program required that the samples be placed in different exposure environments for 100 hours. Two chemical baths were used to keep the geomembrane samples immersed in the exposure environments. The first was a large two chamber tank constructed of Lexan. Each chamber had a volume of 50 litres. The tank had a custom mounting system that held the samples suspended in the medium. The second method used commercial tanks with 12 litre volumes.

Both systems were used for exposing the samples to a 5% acetone solution. Comparing the burst results of the samples from the two types of tanks it was found that there was no difference in the results. This led to the use of the smaller tanks to immerse the samples in acetone concentrations of 10% and 20% acetone. The smaller tanks have the advantage that they reduce the amount of acetone required and reduce the surface area of the tank thus reducing the rate of evaporation of the solution. The tanks were also filled to the top of the tank and the lids were sealed tightly. These steps reduced the rate of evaporation of the acetone which has a Henry's constant of 3.67×10^{-5} making volatilization an important consideration (Montgomery and Velkom, 1989).

5.3 Preliminary Results

The experimental work was preceded by a series of preliminary tests which

established the parameters for the test program. The results of the preliminary tests are summarized in Table 3. The preliminary results established that the experimental facilities were functioning correctly and also established the limits of the test parameters expected during the testing program. The exposure time period of 72 hours showed that

Exposure Environment	Exposure Time	Normalized Burst Pressure
	(hours)	(%)
Air	72	100.0
Water	72	102.1
10% Acetone	72	79.2
20% Acetone	72	66.7
40% Acetone	72	52.1

Table 3 Summary of Preliminary Results

the samples exposed to acetone showed a drop in burst strength of up to 48% for the samples exposed to the 40% acetone concentration by volume and 33% for the samples exposed to the 20% acetone concentration by volume. These results showed that the experiment could be conducted successfully with the designed test apparatus.

The preliminary tests were conducted before the mass flow controller was installed. The air flow was regulated manually with a valve on the air line. This resulted in varying volume flow rates for each sample. This did not appear to significantly alter the burst strength results although it is acknowledged that widely varying rates of strain will alter the failure strength of a geomembrane due to their viscoelastic behaviour.

5.4 Test Description

5.4.1 Burst Test Description

The design and setup of the burst test apparatus is described in Chapter 4. The basic layout consists of a mass flow controller regulating the volume of air allowed to enter the test plates holding the geomembrane sample. The geomembrane sample is then inflated at a controlled rate of 5.0 litres per minute and the pressure, volume and temperature of the air contained by the geomembrane sample were monitored during the test. The operation of the mass flow controller and the monitoring instruments were integrated into a graphically controlled software interface that allows real time display of the results.

5.4.2 Tensile Test Description

The tensile tests were performed using the Instron testing machine located in the Carleton University Civil Engineering Laboratory. The samples were clamped into small jaws placed 110 mm apart. The samples were tested under a tensile load at a strain rate of 50 mm/minute. The load, displacement and time parameters were recorded every 2 seconds. The control of the machine and data recording were provided by the CMT200 software package installed on the machine.

5.4.3 Puncture Test Description

The puncture tests were performed using the Instron testing machine according to a test method based on the ASTM D4833-88 Standard Test Method for Index Puncture

Figure 21 Puncture Test Sample Mounting Fixture

Resistance of Geotextiles, Geomembranes, and Related Products (ASTM vol. 04.09, 1995). A sample mounting fixture, shown in Figure 21, and a test probe, shown in Figure 22, were fabricated for the test.

The sample mounting fixture consists of a mounting bracket with two circular plates. The bottom plate is welded to the mounting bracket and has an O-ring groove in it. The top plate is detachable. Both plates have 45 mm holes cut out in the centre and six matching bolt holes. The sample is placed on the bottom plate, the top plate is placed over the sample and the six bolts are tightened. The result is a doughnut shaped clamp with the geomembrane placed across the open centre.

Figure 22 Puncture Test Probe

The test probe is centred on the sample and pushed inwards against the geomembrane until puncture. The test speed of the probe is 50 mm/minute.

The load, displacement and time were recorded every 2 seconds. The control of the machine and data recording were done with the CMT200 software package.

5.5 Test Schedule

5.5.1 Burst Test Schedule

The burst test program, summarized in Table 4, performed tests on samples exposed to 5 different environments. The samples within each exposure environment were further divided into three different types of exposure. The five different exposure environments were air, water, 5% acetone, 10% acetone and 20% acetone. The three different exposure types were two sided exposure, one sided exposure and partial one sided exposure. The samples that were exposed to air were not tested with one sided and partial one sided because the air was a baseline measurement and there would be no behavioral difference between the samples exposed to the other two methods.

The water samples were exposed only to two sided and one sided exposure areas because it was decided that further tests with the water exposure would be redundant and that the one sided exposure would be sufficient to describe any changes in the behaviour of the geomembrane due to a partial one sided exposure.

The sample, were all exposed for 100 hours and four samples were tested for each test configuration.

Exposure Environment	Exposure Area
Air	Two sided
Water	Two sided
Water	One sided
5% Acetone	Two sided
5% Acetone	One sided
5% Acetone	Partial one sided
10% Acetone	Two sided
10% Acetone	One sided
10% Acetone	Partial one sided
20% Acetone	Two sided
20% Acetone	One sided
20% Acetone	Partial one sided

Table 4 Burst Test Schedule

5.5.2 Tensile Test Schedule

The tensile test program tested samples exposed to five different environments.

The samples were only exposed to the two sided area.

The samples were exposed for 100 hours and four samples were tested for each test configuration.

5.5.3 Puncture Test Schedule

The puncture test program tested samples exposed to five different environments. The samples were only exposed to the two sided area.

The samples were exposed to the test environment for 100 hours and four samples were tested for each test configuration.

6.0 EXPERIMENTAL RESULTS AND ANALYSIS

6.1 Test Results

6.1.1 Results of Burst Tests

The results of the burst tests are presented as average stress-strain curves for the two sided, the one sided and the partial one sided tests. The stress and strain values for the samples were calculated using the analysis of Koerner (1994). The complete analysis is presented in Appendix B.

The calculations were done by determining the volume of air contained by the geomembrane at each data point using the combined gas law:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \quad (6.1)$$

where: P_1, P_2 = pressures at time t_1 and t_2 (kPa)
 V_1, V_2 = volumes at time t_1 and t_2 (litres)
 T_1, T_2 = temperatures at time t_1 and t_2 (°C)

The unknown volume of air pressurizing the sample could then be directly calculated. The sample volume was then used to calculate the vertical displacement of the geomembrane sample. At this point in the calculations the assumption was made that the inflated shape of the geomembrane corresponds to a hemisphere. This assumption introduces an error at low volumes when the geomembrane is beginning to inflate but for the critical portion of the data at the rupture point the geomembrane had a profile close to that of a hemisphere. This assumption will result in slightly lowered stress and strain values because the true shape of the geomembrane, as shown in Figure 23, is slightly

Figure 23 Geomembrane Sample Shape at Rupture

elliptical and has a larger vertical displacement than calculated. The vertical displacement is calculated using the equation for the volume of a sphere:

$$V = \frac{4}{3} \pi r^3 \quad (6.2)$$

where: V = volume of the sphere (litres)
 r = radius of the sphere (vertical displacement) (mm)

The stress values for the geomembrane are then calculated using Koerner's (1994) analysis with the assumption that the vertical displacement is greater than or equal to the initial radius:

$$\sigma_B = \frac{Lp}{4t} \quad (6.3)$$

where: σ_B = geomembrane burst stress (MPa)
 L = initial diameter of geomembrane (mm)
 p = applied pressure to geomembrane (MPa)
 t = initial geomembrane thickness (mm)

The engineering strain values were calculated using the following relationship developed by Koerner (1994) with the same assumption as above:

$$e_B(\%) = \frac{AB - L}{L} (100) \quad (6.4)$$

where: ϵ_B = geomembrane burst strain (%)
 AB = profile length of geomembrane (mm)
 L = initial diameter of geomembrane (mm)

The results of the two sided exposure samples are shown in Figure 24. The results of the one sided exposure samples are shown in Figure 25 and the results of the partial one sided exposure are shown in Figure 26. The average stress-strain curves were calculated by averaging the stresses for a given strain of the individual tests in Appendix C.

Figure 24 Burst Test Average Stress-Strain with Two Sided Exposure

Figure 25 Burst Test Average Stress-Strain with One Sided Exposure

Figure 26 Burst Test Average Stress-Strain with Partial One Sided Exposure

The peak burst stress values are summarized in the three tables in Appendix C. The high, low and average values refer to the highest peak burst stress measured among the four geomembrane samples, the lowest peak burst stress and the average peak burst stress of the four samples.

The five exposure environments are labelled on the graphs. The air exposure curve is the same for each of the graphs because, as explained in Section 5.5.1, only one set of samples were tested with the air exposure and the water exposure for the strip test was the same as the one sided test.

The results of all the tests are shown in Figure 27. The curves show the burst stresses, normalized to air exposure, for the five exposure environments. The three

Figure 27 Normalized Peak Burst Stress vs. Exposure Environment

exposure methods, two sided, one sided and partial one sided, are presented on the same Figure. The error bars show the range of values measured for each set of tests. The data for the curves is presented in tabular form in Appendix C.

6.1.2 Observations of Burst Tests

The samples for each test were observed before and after each test and any visible changes were noted. The observations are summarized in the following sections. The average weights of the samples before and after testing are in Appendix C. The average weight before immersion varies from 61.7 to 64.5 grams because each set of four samples had some variation in the size of the sample. The higher weights represent a sample set that has an average size larger than 300 mm x 300 mm and a lower average weight set has a smaller average size. The comparison between the weights before and after immersion is based on the percentage weight change within each set and will not be affected by the different average weights of the sample sets.

6.1.2.1 Air Exposure Samples

The geomembrane samples exposed to air showed no change between sample preparation and the sample test. There was no change in the sample weight.

6.1.2.2 Water Exposure Samples

The geomembrane samples exposed to water showed no change between sample preparation and the sample test. The weight of the samples showed little change during

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PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

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exposure to the water.

6.1.2.3 5% Acetone Exposure Samples

The geomembrane samples exposed to 5% acetone were discoloured after exposure. The discoloration consisted of a slightly fading of the geomembrane sample from the original colour. The samples exposed on two sides had the fading on both sides while the samples exposed on one side had the discoloration only on the side exposed to the acetone environment. The partial one sided exposure samples showed the discoloration only in the test exposure area.

The two sided and one sided exposure samples also felt slightly more rubbery than the original samples. The partial one sided exposure samples were more rubbery in the area where they were exposed to the test environment.

The weight of the samples increased an average of 1.1% after two sided exposure and an average of 1.3% after one sided exposure.

6.1.2.4 10% Acetone Exposure Samples

The geomembrane samples exposed to the 10% acetone environment showed the same behaviour as the 5% acetone exposure samples. The discoloration pattern was similar and the samples were slightly more flexible than the 5% acetone samples.

The weight of the samples increased an average of 2.2% after two sided exposure and 2.4% after one sided exposure.

6.1.2.5 20% Acetone Exposure Samples

The geomembrane samples exposed to the 20% acetone environment showed the same behaviour as the 5% acetone exposure samples. The discoloration was similar and the samples were more rubbery than the 10% acetone exposure samples.

The weight of the samples increased an average of 4.2% after two sided exposure and 4.0% after one sided exposure.

6.1.3 Results of Tensile Tests

The results of the tensile tests are presented in the average stress-strain curves shown in Figure 28. The average stress-strain curves were calculated by averaging the

Figure 28 Tensile Test Average Stress-Strain

stresses for a given strain of the individual tests contained in Appendix D. The five

exposure environments are labelled on the graph. The tensile stresses were calculated using the standard formula applicable to the engineering stress:

$$\sigma_t = \frac{F}{A} \quad (6.5)$$

where: σ_t = geomembrane tensile stress (MPa)
 F = applied force (kN)
 A = initial cross-sectional area (mm²)

The engineering tensile strains were calculated using the following relationship:

$$\epsilon_t = \frac{L - L_0}{L_0} \quad (6.6)$$

where: ϵ_t = geomembrane tensile strain (%)
 L = length of sample (mm)
 L_0 = original length of sample (mm)

These results are summarized in Figure 29. The graph shows the normalized tensile stress for the five exposure environments. The data for the graph is presented in tabular form in Appendix D.

The observations of the tensile test samples were the same as those observed with

Figure 29 Normalized Tensile Stress vs. Exposure Environment

the burst test samples including discoloration and increased flexibility.

The tensile samples were not weighed during the test program.

6.1.4 Results of Puncture Tests

The results of the puncture tests are shown in the average stress-strain curves in Figure 30. The average stress-strain curves were calculated by averaging the stresses for a given strain of the individual tests contained in Appendix E. The five exposure environments are labelled on the graphs.

Figure 30 Puncture Test Average Load vs. Displacement

Figure 31 Normalized Puncture Load vs. Exposure Environment

These results are summarized in Figure 31. The graph shows the normalized puncture load for the five exposure environments. The data for the graph is contained in tabular form in Appendix E.

The observations of the puncture test samples were the same as the burst test sample observations including discoloration and increased flexibility.

The puncture samples were not weighed during the test program.

6.2 Analysis of Results

6.2.1 General

The results of the experimental program demonstrated that the burst strength, the tensile strength and the puncture strength of the geomembrane were reduced by exposure to the acetone environments. The amount of strength reduction is a function of the concentration of acetone in the exposure environments. The higher the concentrations of acetone, the lower the measured strength for each of the tests. The tests also showed that while the reduction in strength varied depending upon the type of test performed, the percentage reduction between the different acetone exposure environments can be described by a linear progression from the no acetone environment to the 20% concentration by volume acetone environment. Analysis of the results of the three tests are described in the following sections.

6.2.2 Analysis of Burst Tests

The average results of the burst tests in Figures 24, 25 and 26 show a similar

pattern for the three exposure methods. The two sided exposure samples show similar results for the samples exposed to water and those exposed to air. This is expected because there is no evidence of interaction between the tap water and the geomembrane. The acetone results show the effects of the chemical exposure on the geomembrane. The 5% concentration by volume acetone, 10% concentration by volume acetone and 20% concentration by volume acetone exposure samples all show a reduction in burst stress. The reduction is approximately the same between the water and air samples and the 5% acetone samples as between each of the increasing acetone concentration samples.

The one sided samples show a similar pattern of burst stress reduction. The differences are less than the two sided samples and the gap between the 5% concentration by volume acetone exposure environments and the water and air is slightly larger, approximately 15%, compared to the differences between the acetone exposed samples of 8-10%.

The partial one sided samples show the same pattern as the preceding two test methods but the gap between the acetone exposed samples is less than the previous two tests, approximately 5%, while the differences between the acetone samples and the water and air sample of 5% is proportionally larger than the other tests.

The results are presented in a single graph shown in Figure 27. The curves show the effects of the different exposure environments as well as the effects of different exposure areas. The normalized results show no difference between the air and water exposed samples. The normalized results also show the decrease in peak burst stress of the geomembrane samples exposed to higher concentrations of acetone. The peak burst

stress at 5% concentration by volume acetone exposure is 84-93% that of original, at 10% concentration by volume acetone exposure it is 76-88% and at 20% concentration by volume acetone exposure it is 62-67% for the two and one sided samples and 83% for the partial one sided samples.

There is a little difference in the burst stress reduction between the samples exposed on two sides and those exposed on one side. The samples exposed to a partial one sided area show an increase in strength compared to the other two methods. These results show there is a little difference between exposing the entire area on one side or on two sides.

The reduction in strength of the acetone exposed samples compared to the original samples in the three methods is evidence of the effects of the acetone exposure on the geomembrane. The loss in strength is approximately linear for the two sided and one sided samples.

It is assumed that acetone will enter the geomembrane by diffusion until the system reaches equilibrium at the outside acetone concentration. This assumption is made because the permeability or hydraulic conductivity of a PVC geomembrane is in the order of 10^{-13} to 10^{-15} m/s (Haxo, 1990 and McBean et al., 1995) while the diffusion coefficient of rigid PVC and water is 10^{-6} cm²/s (Brandrup and Immergut, 1989). The rate of diffusion is governed by Fick's Law and is dependent upon the diffusion coefficient of one substance into another. The diffusion coefficient is dependent upon the size and shape of the molecules of the permeating species as well as the molecular characteristics and structure of the geomembrane (Haxo, 1990). Before and after an equilibrium

condition is reached the samples exposed to higher concentrations of acetone will have higher levels of acetone within the geomembrane.

It was also noted that there is an acetone concentration reached at which the PVC geomembrane begins to harden and crack. This was demonstrated using a 40% concentration by volume acetone environment which after 72 hours of exposure resulted in cracks in the geomembrane sample. The sample also became brittle after drying for several hours and appeared to be similar in consistency to unplasticized PVC. Some work was also done with 100% acetone which produced similar results in a period of 24 hours.

The sample weights before and after exposure are shown in Appendix C. The increase in weight shown by the geomembrane samples exposed to than acetone indicate that the samples may be absorbing the acetone/water mixture. The weight differences between the samples exposed on two sides opposed to those exposed on one side are 0.2%. This slight difference can be attributed to the variability of geomembrane test results as noted by White and Verschoor (1990).

6.2.3 Analysis of Tensile Tests

The average stress-strain results of the tensile test are shown in Figure 28. The graph shows the stress-strain relationship for the five exposure media. The results show there are differences in the tensile strengths of the samples exposed to the different environments. As with the burst tests the higher the acetone concentration the lower the geomembrane tensile strength.

The main difference between the burst test and the tensile test is the strength of

the water exposed samples and the air exposed samples. The curves show that the water exposed samples are significantly lower than the air exposed samples. There is no clear explanation for this behaviour and it was not correlated with the burst test results. The ductility of the samples also increased with the exposure to acetone.

The explanations for the sample behaviour is the same as those explained in the burst test analysis. The one anomaly is the difference in tensile stress between the water and air exposed samples.

The stress-strain behaviour of the burst test and the tensile test can be compared directly using the values from the graphs in Figures 24 and 28. The comparison shows that the stress values are fairly similar for the two tests. The values for the tensile tests are generally higher by 10-20% than the values of the burst tests. The differences in stress values between the two tests can be attributed to two factors.

The first is that the strain rates between the two tests are different and the viscoelastic behaviour of the geomembrane, which means that the rate of loading has an influence on the stress-strain behaviour of the sample. In general, the lower the strain rate the lower the stress at failure.

The second factor is that the calculations for the stress of the burst test samples is based on the assumption that the geomembrane always forms the same uniform shape. This is not the case as shown by the shape of the samples in the photographs in Appendix C. The stress analysis of the burst tests is based on the height of the samples above the reference configuration. If this height is lower than calculated from the total air volume in the sample then the stresses calculated will be lower than the true values.

The strain rates between the two tests cannot be compared because they are described by two different types of behaviour. The first type of behaviour is the uniaxial strain of the tensile test and the second type of behaviour is the multi-axial strain of the burst test.

6.2.4 Analysis of Puncture Tests

The average puncture load versus displacement curves in Figure 30 shows the same results as the other two tests of a reduction in strength with increased acetone concentrations. The difference with the puncture tests is that the load for the water exposed samples is higher than the air exposed samples. This is opposite to the results of the tensile test and differs from the results of the burst test which showed no difference between the air and water exposed samples. No clear explanation for this differing behaviour between the water and air exposed samples of the three tests.

The normalized puncture load for the five different exposure environments shown in Figure 31 has a drop in the puncture strength of 10% between the air and water samples and the 5% concentration by volume acetone environment, a 22% drop to the 10% concentration by volume acetone environment and 37% drop to the 20% acetone concentration by volume exposure samples. This relatively linear drop in the strengths of samples is consistent with the burst and tensile tests. The drop in strength between the exposure environments is greater for the puncture test than the other two tests but this analysis is based on the load measured by the testing machine and is not as a result of a calculation of the stress on the geomembrane. The displacement measurements are also

not directly comparable to either of the other two test because there is no calculation of the strain values reached in the geomembrane during the puncture test.

The results of the puncture test are used to provide an additional indexing type testing method to confirm the results of the burst test. The measured results provide this evidence.

6.3 Summary of Results and Analysis

The results of the burst, tensile and puncture tests showed a similar pattern for the measured failure strengths. The air and water exposed samples were higher in strength than the acetone exposed samples. The acetone exposed samples showed a drop in strength with the 5% concentration by volume acetone exposure samples having the lowest reduction in strength and the 20% concentration by volume acetone exposure samples having the highest reduction.

The burst test also investigated the effects of exposing different areas of the geomembrane to the chemical medium. The results showed that there was little difference between the two sided and the one sided exposure samples but that the partial one sided samples had a slightly higher burst strength.

A comparison between the results of the burst test stresses and the tensile test stresses showed that the two tests produced relatively similar results. The stresses measured by the burst test were slightly lower than the tensile test results. The comparison of the results also confirmed the validity of the burst test stress analysis. This analysis can be further improved by using numerical methods of stress analysis.

The reduction in strength of the samples exposed to the acetone environments for all three tests was a result of the acetone diffusing into the geomembrane structure and forcing the molecules farther apart reducing the strength of the intermolecular bonds. The distance between the molecules is a function of the acetone concentration within the geomembrane structure. The acetone concentration within the geomembrane is a function of time and the gradient across the geomembrane surface. The higher the outside acetone concentration the higher the gradient and the more rapid the diffusion into the geomembrane structure. Eventually an equilibrium state will be reached at which point the gradient across the geomembrane surface will be zero.

7.0 CONCLUSIONS

The purpose of the research work was to develop a method of simulating the effects of large areas of pressure applied to a landfill geoliner exposed to a chemical leachate. This was accomplished by designing and constructing a computer controlled burst test apparatus. The experimental work consisted of a series of burst tests on geomembranes exposed to different concentrations of acetone and varying the area of the geomembrane exposed. Secondary tests were also conducted using tensile and puncture tests to compare the results to the burst test.

The main contribution of the thesis research was the development of the test apparatus which was used to simulate out of plane loading conditions. The advantage of the developed test over the use of tensile tests is that the geomembrane is subjected to multi-axial loading conditions instead of being restricted to uni-axial loading. The test apparatus also tests a larger sample size reducing the effects of variability between geomembrane test samples. The results measured from the burst test and the puncture test can complement each other. The puncture test provides data for a concentrated load and the burst test provides data for a more distributed load.

The results of the experimental tests showed that exposure to increasingly higher concentrations of acetone produces a corresponding reduction in the peak strengths and the failure strengths of the three tests. The strength reductions are linear in shape implying the acetone concentration within the geomembrane directly affects its strength.

The implication of these results is that the exposure of landfill geomembranes to the leachate can cause a reduction in the ability of the geomembrane to resist loading and

a reduction in the failure strength of the geomembrane. The research focused on one type of PVC geomembrane exposed to a single chemical. This would not be the case within a landfill where the leachate is composed of a mixture of hundreds of different chemicals at much lower concentrations. However, the exposure time of these chemicals could potentially be decades if the landfill exists intact for its complete design life. The reaction between the acetone and the PVC appeared to be based on the concentration of the acetone solution but other reactions may be time dependent or reaction material dependent.

The results of the experimental work are very preliminary and serve only as an indication that there is a potential problem concerning the chemically enhanced degradation of geomembrane landfill liners. The long term design of landfills should not be accepted without consideration of this type of damage which can occur in even the most carefully designed landfills where damage to conventional geological barriers such as clay can eventually expose the geosynthetic liner to chemically induced degradation.

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APPENDIX A PRELIMINARY BURST TEST RESULTS

Figure A.1 Preliminary Air Exposure Test Results

Figure A.2 Preliminary Water Exposure Test Results

Figure A.3 Preliminary 10% Acetone Exposure Test Results

Figure A.4 Preliminary 20% Acetone Exposure Test Results

Figure A.5 Preliminary 40% Acetone Exposure Test Results

APPENDIX B BURST TEST STRESS AND STRAIN CALCULATIONS

Strain Calculations

- (1) For $\delta \geq L/2$, assume the geomembrane test specimen to be deformed in an elliptical shape as shown below.

Here,

$$AB = \pi \sqrt{\frac{(L/2)^2 + \delta^2}{2}}$$

$$AB = \pi \sqrt{\frac{L^2 + 4\delta^2}{8}} \quad (1)$$

$$e(\%) = \frac{AB - L}{L} (100), \text{ the desired value of strain} \quad (2)$$

Stress Calculations

- (1) For $\delta \geq L/2$, take force summation in the vertical direction;

$$S \cdot p = C \cdot \sigma \cdot t \quad (3)$$

where

S = surface area of geomembrane

p = applied pressure

C = circumference

σ = vertical component of geomembrane stress

t = geomembrane thickness

thus,

$$[\pi (L/2)^2] \cdot p = \pi L \cdot \sigma \cdot t$$

$$\sigma = \frac{[\pi (L^2/4)]p}{\pi (L)t}$$

$$\sigma = \frac{Lp}{4t} , \text{ the desired value of stress} \quad (4)$$

APPENDIX C BURST TEST RESULTS

C.1 Two Sided Sample Exposure

Exposure Environment	Peak Burst Stress		
	High	Low	Average
	(MPa)	(MPa)	(MPa)
Air	6.6	6.3	6.4
Water	6.6	6.2	6.4
5% Acetone	5.7	5.4	5.6
10% Acetone	5.0	4.8	4.9
20% Acetone	4.1	3.9	4.0

Table C.1 Peak Burst Stresses for Two Sided Exposure Samples

Exposure Environment	Normalized Peak Burst Stress		
	High	Low	Average
	(%)	(%)	(%)
Air	103.1	98.4	100.0
Water	103.1	96.9	100.0
5% Acetone	89.1	84.4	87.5
10% Acetone	78.1	75.0	76.6
20% Acetone	64.1	60.9	62.5

Table C.2 Normalized Peak Burst Stresses for Two Sided Exposure Samples

Figure C.1 Burst Test Results with Two Sided Air Exposure

Figure C.2 Burst Test Results with Two Sided Water Exposure

Figure C.3 Burst Test Results with Two Sided 5% Acetone Exposure

Figure C.4 Burst Test Results with Two Sided 10% Acetone Exposure

Figure C.5 Burst Test Results with Two Sided 20% Acetone Exposure

C.2 One Sided Sample Exposure

Exposure Environment	Peak Burst Stress		
	High	Low	Average
	(MPa)	(MPa)	(MPa)
Air	6.6	6.3	6.4
Water	6.6	6.3	6.4
5% Acetone	5.4	5.3	5.4
10% Acetone	5.0	4.8	4.9
20% Acetone	4.4	4.2	4.3

Table C.3 Peak Burst Stresses for One Sided Exposure Samples

Exposure Environment	Normalized Peak Burst Stress		
	High	Low	Average
	(%)	(%)	(%)
Air	103.1	98.4	100.0
Water	103.1	98.4	100.0
5% Acetone	84.4	82.8	84.4
10% Acetone	78.1	75.0	76.6
20% Acetone	68.8	65.6	67.2

Table C.4 Normalized Peak Burst Stresses for One Sided Exposure Samples

Figure C.6 Burst Test Results with One Sided Water Exposure

Figure C.7 Burst Test Results with One Sided 5% Acetone Exposure

Figure C.8 Burst Test Results with One Sided 10% Acetone Exposure

Figure C.9 Burst Test Results with One Sided 20% Acetone Exposure

C.3 Partial One Sided Exposure

Exposure Environment	Peak Burst Stress		
	High	Low	Average
	(MPa)	(MPa)	(MPa)
Air	6.6	6.3	6.4
Water	6.6	6.3	6.4
5% Acetone	6.0	5.9	5.9
10% Acetone	5.7	5.5	5.6
20% Acetone	5.5	5.2	5.3

Table C.5 Peak Burst Stresses for Partial One Sided Exposure Samples

Exposure Environment	Normalized Peak Burst Stress		
	High	Low	Average
	(%)	(%)	(%)
Air	103.1	98.4	100.0
Water	103.1	98.4	100.0
5% Acetone	93.8	92.3	92.3
10% Acetone	89.1	85.9	87.5
20% Acetone	85.9	81.3	82.8

Table C.6 Normalized Peak Burst Stresses for Partial One Sided Exposure Samples

Figure C.10 Burst Test Results with Partial One Sided Water Exposure

Figure C.11 Burst Test Results with Partial One Sided 5% Acetone Exposure

Figure C.12 Burst Test Results with Partial One Sided 10% Acetone Exposure

Figure C.13 Burst Test Results with Partial One Sided 20% Acetone Exposure

C.4 Burst Test Sample Weights

Exposure Environment	Exposure Area	Average Weight Before Immersion	Average Weight After Immersion	Weight Increase
		(g)	(g)	(%)
Air	Two sided	61.5	61.6	0.2
Water	Two sided	64.0	64.0	0.0
Water	One sided	64.4	64.5	0.2
5% Acetone	Two sided	64.5	65.2	1.1
5% Acetone	One sided	61.9	62.7	1.3
10% Acetone	Two sided	64.4	65.8	2.2
10% Acetone	One sided	61.7	63.2	2.4
20% Acetone	Two sided	62.1	64.7	4.2
20% Acetone	One sided	61.8	64.3	4.0

Table C.7 Burst Test Sample Weights Before and After Exposure

APPENDIX D TENSILE TEST RESULTS

Exposure Environment	Tensile Failure Stress		
	High	Low	Average
	(MPa)	(MPa)	(MPa)
Air	19.4	18.6	19.0
Water	18.4	17.8	18.1
5% Acetone	17.0	16.1	16.9
10% Acetone	15.8	15.2	15.6
20% Acetone	14.8	13.4	13.6

Table D.1 Tensile Test Failure Stresses

Exposure Environment	Normalized Tensile Failure Stress		
	High	Low	Average
	(%)	(%)	(%)
Air	102.1	97.9	100.0
Water	96.8	93.7	95.3
5% Acetone	89.5	84.7	88.9
10% Acetone	83.2	80.0	82.1
20% Acetone	77.9	70.5	71.6

Table D.2 Normalized Tensile Test Failure Stresses

Figure D.1 Tensile Test Results with Air Exposure

Figure D.2 Tensile Test Results with Water Exposure

Figure D.3 Tensile Test Results with 5% Acetone Exposure

Figure D.4 Tensile Test Results with 10% Acetone Exposure

Figure D.5 Tensile Test Results with 20% Acetone Exposure

APPENDIX E PUNCTURE TEST RESULTS

Exposure Environment	Puncture Failure Load		
	High	Low	Average
	(N)	(N)	(N)
Air	158.3	154.9	156.9
Water	166.2	153.5	160.0
5% Acetone	145.5	140.5	142.5
10% Acetone	124.0	121.3	122.8
20% Acetone	99.7	95.0	97.3

Table E.1 Puncture Failure Loads

Exposure Environment	Normalized Puncture Failure Load		
	High	Low	Average
	(%)	(%)	(%)
Air	100.9	98.7	100.0
Water	105.9	97.8	102.0
5% Acetone	92.7	89.5	90.8
10% Acetone	79.0	77.3	78.3
20% Acetone	63.5	62.0	62.0

Table E.2 Normalized Puncture Failure Loads

Figure E.1 Puncture Test Results with Air Exposure

Figure E.2 Puncture Test Results with Water Exposure

Figure E.3 Puncture Test Results with 5% Acetone Exposure

Figure E.4 Puncture Test Results with 10% Acetone Exposure

Figure E.5 Puncture Test Results with 20% Acetone Exposure

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