Large-scale laboratory testing of the performance of geosynthetic mine waste covers

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ABSTRACT

The low permeability of geomembranes has made them a useful material for preventing contaminant leakage from many containment facilities, such as landfills and lagoons. This same characteristic also makes them an attractive choice for cover applications, particularly in the mining industry. However, geomembrane covers have not been widely adopted due to a lack of published research on their effectiveness. To address this lack of research, a large-scale laboratory study was done to quantify the amount of leakage obtained through a defect in a geomembrane cover. The leakage rate was assessed for a variety of slope angles, rainfall rates, surface microtopography, and defect sizes, shapes, and locations. The leakage rate was found to depend on all of these factors to varying degrees.

RÉSUMÉ

La faible perméabilité des géomembranes en fait un matériau utile pour empêcher les fuites de contaminants de nombreuses installations de confinement, telles que les décharges et les bassins de lagunage. Cette même caractéristique en fait également un choix intéressant pour les applications de recouvrement, en particulier dans l'industrie minière. Cependant, les recouvrements par géomembrane n'ont pas été largement adoptés en raison d'un manque de publication de recherches sur leur efficacité. Pour remédier à ce manque de recherches, une étude en laboratoire à grande échelle a été réalisée pour quantifier la quantité de fuite due à un défaut dans le recouvrement par géomembrane. Ce taux de fuite a été évalué pour diverses inclinaisons, pluviométries, microtopographies de surface, ainsi que différentes tailles, formes et emplacements des défectuosités. On a constaté que le taux de fuite dépendait de tous ces facteurs à divers degrés.

1 INTRODUCTION

A geomembrane is a very low permeability synthetic membrane typically formed of thin sheets of a polymer material. Because of their low permeability, geomembranes are often used to control fluid migration in many geotechnical applications. However, installed geomembranes are never perfectly impermeable, mainly due to defects caused by manufacturing, transportation, handling, and installation. These defects allow some amount of fluid leakage, which must be quantified so that it can be considered during the design process.

The most common application of geomembranes is as liners in lagoons, landfills, and other waste impoundment facilities. These geomembranes are effective at reducing liquid and contaminant migration into underlying soils. Defects in geomembrane liners have been extensively studied in order to quantify the expected amount of leakage. In many cases, quantifying this leakage is a fairly straightforward problem of fluid flow through a defect on a flat surface under hydrostatic conditions.

Another potential use for geomembranes is in cover systems for mining waste. These waste materials often contain pyrite or other sulfide minerals that can oxidize when exposed to air and water. This results in a phenomenon known as acid mine drainage (ARD), which is detrimental to the environment. Water flow can also leach other contaminants from waste rock, creating a wide range of environmental issues that can persist for decades or centuries after a mine is closed. Mine waste is often capped with a low permeability soil cover to prevent water infiltration. Soil covers are also well studied and effective; however, they can become expensive when there is no suitable material nearby. The nearly-impermeable nature of geomembranes suggests they would be an ideal alternate cover material, with the potential for cost savings over typical soil covers in some situations.

Despite their suggested advantages, geomembrane covers have not been widely adopted due to a lack of published research on their effectiveness. While geomembrane liners have been extensively studied, geomembrane covers present a more challenging problem. The flow over a geomembrane cover is highly dependent on transient hydraulic conditions as well as physical factors such as slope inclination, location of defects, and the microtopography of the geomembrane surface.

2 BACKGROUND

Mining is a large and important part of Canada's economy. In 2020, the minerals and metals sector made up 5% of Canada's GDP, or $107 billion through direct and indirect contributions (Natural Resources Canada, 2018). As mining activities increase, so too does the amount of mining waste that needs to be managed or rehabilitated. Mining waste that is improperly managed can cause environmental problems for decades or centuries after the mine is no longer in use. Acid rock drainage (ARD) is a problem in Canada, particularly in waste that contains pyrite and other sulfide minerals. These minerals can

oxidize when exposed to air and water, creating acidic conditions that are harmful to aquatic ecosystems.

To reduce the risk of ARD and leaching of other contaminants, mine closure usually involves capping waste piles with a barrier designed to stop the inflow of water and/or oxygen. Soil covers are often used for this purpose. A well-designed soil cover with a sufficiently low hydraulic conductivity can greatly reduce water influx to the mine waste. Soil covers and cover systems have been well studied by various researchers and consultants. These cover systems may store and release moisture or divert it using structures such as capillary barriers. Ross (1990) developed bounding values on the diversion capacity and maximum effective width of capillary barriers. Parent and Cabral (2006) expanded on this research to develop a design procedure for optimizing the water diversion length of a capillary barrier.

The primary shortcoming of soil covers is that they require a ready supply of suitable material, usually a low permeable clay, for construction. Many mine sites do not have such a supply nearby. In addition, many mines are located in remote areas that would make hauling in proper material extremely cost prohibitive.

A potential alternative to soil covers is geomembrane covers or cover systems. As long as they have no defects, geomembranes are essentially impermeable to water, with a hydraulic conductivity in the order of magnitude of 10^{-15} m/s for HDPE (Giroud and Bonaparte, 1989a). This means that, when water permeation is the primary concern, geomembrane covers could be used to reduce the amount of soil materials needed, while also potentially performing better than a soil cover.

However, geomembranes are rarely installed without any defects occurring. Damage can happen during manufacture, transport, placement, seam welding, or placement of cover material. In a survey of more than 300 sites of geomembrane failures, Nosko and Touze-Foltz (2000) found that 71.17% of geomembrane defects were caused by stones within the protection layer, with a further 15.59% caused by heavy equipment. When discussing leakage rates through geomembrane defects, Giroud and Bonaparte (1989a) focused on seam defects, as they were the most frequent defect found by forensic analyses at the time. In contrast, McQuade and Needham (1999) found that the frequency of defects at seams had greatly decreased, likely due to improved welding methods and better quality control and assurance of welds. Indeed, quality control has proven to be crucial in detecting and limiting defects in installed geomembranes. McQuade and Needham (1999) found an average frequency of 4.2 holes per hectare in 111 surveys, while those surveys with a thorough quality assurance program often found no holes at all.

The expected leakage rate through defects in a geomembrane has been extensively studied and many equations proposed. Some of these equations are purely empirical, while others are based on a combination of experimental results and analytical or numerical models. Brown et al. (1987) performed permeameter testing on flaws in various types and thicknesses of flexible membrane liners (FML). They found that the size and shape of the flaw was a controlling factor when the

subbase had a higher conductivity (10^{-3} m/s). The subbase conductivity had a greater effect when the conductivity was low (10^{-6} m/s and 10^{-8} m/s)

Giroud and Bonaparte (1989a) were among the first to propose equations to quantify leakage. Their equations were based on Bernoulli's equation for free flow through an orifice. In Giroud and Bonaparte (1989b) they looked at composite geomembrane liners, developing a series of equations depending on the contact conditions between the geomembrane and the underlying soil. A series of papers by Giroud et al. (1997a, 1997b, 1997c) studied leakage through geomembrane defects depending on the permeability of the overlying and underlying media.

Rowe and Booker (1998) also used an analytical approach, while Touze-Foltz and Giroud (2003 and 2005) added to an ever-growing list of empirical equations. The uniting factors for all of these proposed equations is that they require a known head of liquid above a defect, and the defect is located on a flat surface. The slope is only taken into account when determining the hydraulic head above the defect.

This approach works well for geomembranes in basal applications, such as lagoon liners. Current equations do not take into account the highly transient hydraulic conditions that would develop on a geomembrane used as a cover. Slope angles, rainfall rates, and surface microtopography are all factors that make geomembrane covers a more complicated problem to analyze.

The following research attempts to address these factors in order to quantify leakage through defects in a geomembrane on a slope.

3 MATERIALS

The cover system that was tested consisted of mine waste rock, a geomembrane, and a drainage geocomposite. Two cover profiles were considered: one with and one without a cover soil. Testing has been completed on the exposed geomembrane and is still in progress on the cover soil system. The two cover systems are shown in Figure 1.

The mine waste rock was a run of mine material sourced from a Canadian mine in order to better represent field conditions. It was a variable material consisting of shale particles ranging from <1mm to >200mm. These particles were brittle and friable, breaking down easily when wetted. The material also contained harder limestone and other materials in pieces up to 0.6m in diameter. Figure 2 shows a grain size distribution for the material passing the 25mm sieve. The same waste rock was used as the cover material in the trials with a cover soil.

The geomembrane used for all trials was a 1.5mm thick LLDPE material. The geomembrane was textured on both sides and had a texture asperity of 16mil. A 1.5mm textured HDPE geomembrane was also considered; however, the geomembrane material, thickness, etc. were not considered the focus of these trials. Specific defects were cut into the geomembrane covers using a rotary cutting tool.

The final component of cover soil trials was a drainage geocomposite, made up of perforated minidrains placed between two nonwoven geotextile sheets. The geotextile
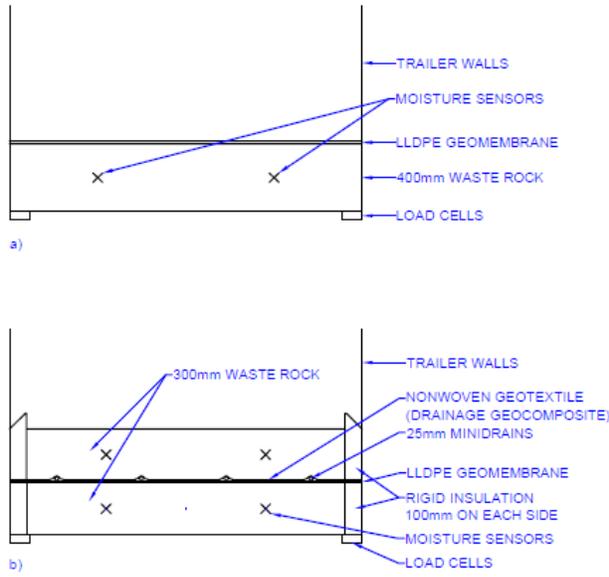
Figure 1. Cover system profiles with a) exposed geomembrane and b) cover soil, geomembrane, and drainage geocomposite

Figure 2. Grain size distribution from sieve analysis for screened waste rock passing the 25mm sieve

provides some protection to the geomembrane from cover soil being placed on top. It was also intended to help with drainage by carrying water to the minidrains and thus draining off of the cover system. The minidrains were 0.25mm in diameter and spaced at 0.5m intervals. The drainage geocomposite was only used during the cover soil trials.

4 METHODOLOGY

4.1 Large-Scale Laboratory Testing

Testing for this project took place in the Multi-purpOse Slope Testing (MOST) facility at the University of Saskatchewan. The MOST facility specializes in slope and cover system testing and was equipped with a large scale hillslope apparatus that was used for this project. The large-scale test bed consisted of a modified tri-axle dump trailer. The trailer system was designed and tested by Pratt and McDonnell (2017), and a full description of its modifications and advantages is given in their paper.

The dump trailer allowed for testing at a range of slope angles using the trailer's incorporated hydraulic scissor lift. It could be raised to a maximum slope of 45°, which exceeded the expected maximum testing slope of 3:1 (18.4°). The interior dimensions of the trailer were 4.53m length, 2.08m width, and 1.1m depth. Although it is far from a full scale mine waste cover, this size allowed for testing at a much larger scale than is generally practicable in a laboratory.

The facility was also equipped with a rainfall simulator that was used to simulate rainfall at a range of intensities. The simulator consisted of two peristaltic pumps that supplied water to a manifold suspended over the test bed.
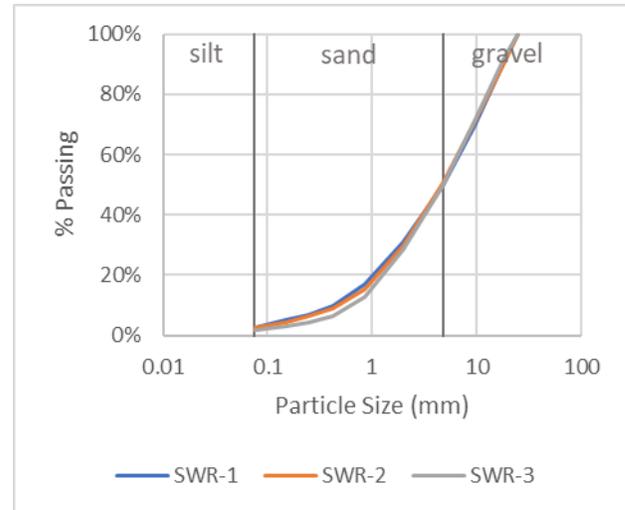
The manifold contained rows of hypodermic needles, spaced at approximately 75mm, that formed water droplets. The manifold was raised to a sufficient height to allow the raindrops to reach terminal velocity before impacting the test bed. The water supplied to the simulator was purified using reverse osmosis to remove any minerals that may precipitate and clog the manifold pipes.

4.2 Design and Instrumentation

4.2.1 Exposed Geomembrane Cover

Utilizing the large-scale test bed and the rainfall simulator, the cover systems were constructed as a water balance problem:

$$Q_{in} = Q_{out} + \Delta Storage \qquad [\#]$$

where Q_{in} and Q_{out} are water flow rates.

The flow into the system was controlled by the precipitation rate from the rainfall simulator. This rate was measured by two or three tipping bucket rain gauges placed on the slope surface.

Flow out of the system was divided into surface flow and baseflow for the exposed geomembrane. Surface flow comprised the majority of the flow for the exposed geomembrane and was measured using an orifice bucket. The orifice bucket used the principles of orifice flow to determine the flow rate at any head of liquid.

$$Q = C_d A \sqrt{2gh} \qquad [\#]$$

where A is the area of the orifice, h is the head above the orifice, and C_d is the coefficient of discharge. Three different orifices areas were used, each calibrated to the expected runoff from a predetermined rainfall intensity. The head in the orifice bucket was measured with an ultrasonic level sensor positioned above the tank.

Baseflow was allowed from the bottom layer of waste rock to avoid oversaturating the system. It was collected through an opening at the base of the slope, as shown in Figure 3, and measured with a tipping bucket.

The change in storage represented the water that leaked through the geomembrane defect and was retained in the waste rock. This leakage was measured using four low-profile load cells, one at each corner of the trailer. The trailer was raised off of the ground and supported by the load cells, allowing the weight of the trailer to be measured to within approximately 1.5 kg, or 1.5L of water added (0.03% of 10,000lb capacity).

The load cell readings were also verified using 5TM soil moisture and temperature sensors. Six sensors were placed in a 2x3 grid within the waste rock to measure the soil's dielectric permittivity. These values could then be converted to volumetric water contents.

Together, all of these measured flows were used to confirm the water balance of the cover system. The leakage rates for these trials were primarily calculated from the measured change in storage as water flowed through the defect. The baseflow was also added to this rate to account for the water leaving the mine waste at the base.
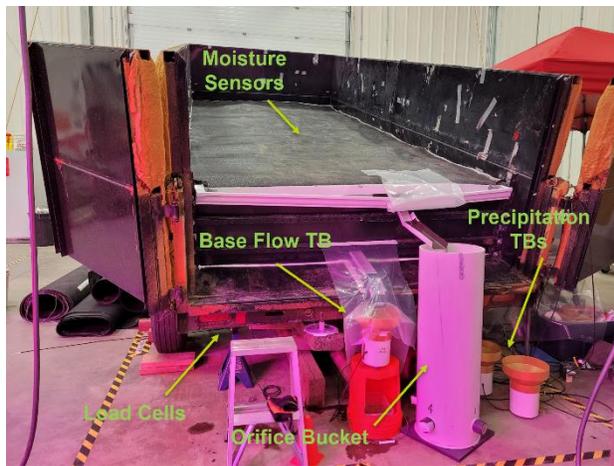

Figure 3. Hillslope system with instrumentation in place

4.2.2 System with Cover Soil

The cover soil trials also utilized the water balance approach, with a few differences. The surface flow was greatly reduced by the cover soil, and so could be more easily measured with a tipping bucket instead of the orifice bucket.

In addition to the baseflow, flow was also collected through the drainage geocomposite. The geotextile and minidrains collected water that flowed through the cover soil and over the top of the geomembrane. Flow was collected separately from each of the four minidrains and measured with tipping buckets.

The change in storage, measured by the weight change of the trailer, now had to be divided between the base soil and cover soil. Six more moisture sensors were installed in

the cover soil in order to measure the moisture content changes in the two layers.

Finally, the second layer of waste rock would have brought the weight of the system over the capacity of the trailer's hydraulic scissor hoist. To avoid this, the size of the test bed was reduced by lining the trailer sides and upstream end with rigid foam insulation. This kept the total weight approximately the same as the exposed geomembrane trials and also moved the center of mass closer to the pivot point to ease the burden on the scissor hoist.

4.3 Defect Trials

A series of trials were conducted to test the effects of defect size, shape, and location, slope angle, and rainfall intensity on the resulting leakage rate.

Three different defect shapes were considered: a horizontal tear, a vertical tear, and a circular hole. Three sizes of horizontal tear were tested – 150mm, 300mm, and 500mm – and two sizes of circular hole – 20mm and 40mm diameters. The vertical tear was 300mm in length, for a total of six defect types. The different defects are illustrated in Figure 4.
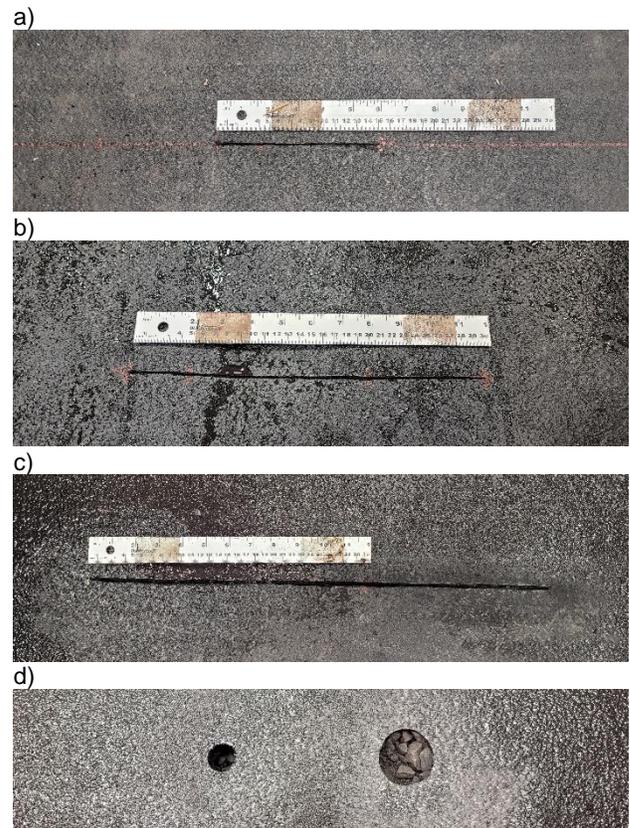
a)

b)

c)

d)

Figure 4. a) 150mm horizontal defect, b) 300mm horizontal defect, c) 500mm horizontal defect, and d) 20mm and 40mm circular defects

Defect location was of particular interest for the exposed geomembrane trials. Defects were tested in two locations: upstream and downstream on the slope. The upstream defects were located approximately 1m from the top of the hillslope. The downstream defects were between 3m and 3.5m from the top of the slope.

The microtopographic location was also considered for the downstream defects. Although the waste rock surface was smoothed and compacted prior to placing the geomembrane cover, the geomembrane surface was still subject to small variations that created microtopographic highs and lows. In many cases these elevation differences were less than 1cm and usually occurred over rocks or larger particles that could not be fully compacted into the waste rock surface. It was of interest to determine how this microtopography affected the leakage rate, i.e., would a defect on a topographic high receive measurably less leakage than a defect in a topographic low spot? The three defect locations that were tested were downstream microtopographic high, downstream microtopographic low, and upstream microtopographic low.

The leakage rate was assessed at two different slope angles of 10:1 and 3:1. The 10:1 slope was selected to be nearly flat, while still angled enough to allow flow down the slope. The 3:1 slope was chosen to reflect the maximum slope a mine waste pile could typically be built at in the field.

Finally, tests were run at three different rainfall intensities: approximately 2mm/hr, 10mm/hr, and 20mm/hr. For some of the earlier tests, only a high (~15mm/hr) and low (~2mm/hr) rainfall rate were used. The rainfall intensities and test durations were based on the limitations of the rainfall simulator and a typical intensity-duration-frequency curve.

Between the six different defect types, three defect locations, two slopes, and three rainfall rates, there were a total of 108 possible combinations. Considering the tests where only two rainfall rates were used, only 70 of these combinations were tested.

5 RESULTS AND DISCUSSION

5.1 Effect of Defect Size and Shape

The effects of the defect size and shape on the leakage rate for the exposed geomembrane are shown in Figure 5. The results were as expected, with larger defects generally seeing more leakage than their smaller counterparts.

The two sizes of circular defects received approximately the same amount of leakage, suggesting that the smaller size was sufficiently large to receive all of the leakage available at a given location. The three defect shapes showed similar leakage rates, with horizontal tears receiving slightly less than the circular holes, and the vertical tears receiving slightly more.

The 500mm horizontal defect was a notable exception, receiving significantly more leakage at higher rainfall rates. A possible explanation for this is discussed in a later section.

5.2 Effect of Defect Location

The effects of the defect location are also as expected. They are illustrated in Figure 6, which shows the three different locations for each of the three horizontal defects.

For all three sizes, the defects located downstream received more leakage than the same defect in an upstream location. This is due to a greater accumulation of surface flow collecting further down the slope.

The actual length of slope above these defects (1m – 3.5m) was relatively small compared to waste rock slopes that would typically be built in the field (>60m). A more accurate test could thus be designed with a baseline of surface flow representing the precipitation falling on a longer upstream slope. This was beyond the scope of the current research.

The other result shown in Figure 6 is that defects located in microtopographic lows generally received more leakage than those in microtopographic highs. This was likely due to flow paths that tended to follow the microtopographic lows. This is discussed in section 5.4.

5.3 Effect of Slope Angle and Rainfall Intensity

The effects of slope angle can be seen in Figure 7. Defects on the lower 10:1 slope generally received more leakage than their counterparts on the steeper 3:1 slope. On the 10:1 slope, the surface flow took longer to flow down the slope, travelled a more tortuous path, and had more opportunities to intercept with a defect, especially one in a microtopographic low point.

As is evident in every trial, greater rainfall intensities also led to greater leakage rates. In most cases, there is also evidence of a decreasing slope as the rainfall intensity increases. This is possibly due to a given defect reaching a "saturation point" where it is accepting as much leakage as possible. This trend could be further explored by testing at higher rainfall intensities; however, the intensities used for these trials were limited by the capabilities of the rainfall simulator.

5.4 Microtopography and Flow Paths

As alluded in the previous sections, the microtopography of the geomembrane surface had a significant effect on the leakage rate each defect received. Figures 8 and 9 illustrate the flow paths that formed on the surface as a result of this microtopography. On the gentle 10:1 slope, these flow paths clearly followed the microtopographic lows, creating winding paths down the slope and pooling in low spots. On the steeper 3:1 slope, the microtopography affected the flow paths to a smaller degree. Many of the flow paths instead travelled in a straighter line directly down the slope.

These straight flow paths are also a possible explanation for the very high rate of leakage received by the 500mm horizontal defects at higher rainfall intensities. Since the 500mm defects stretched across nearly 25% of the 2.07m trailer width, it was almost impossible to place a defect such that it did not intercept at least one flow path. As such, most of the 500mm defects could be considered
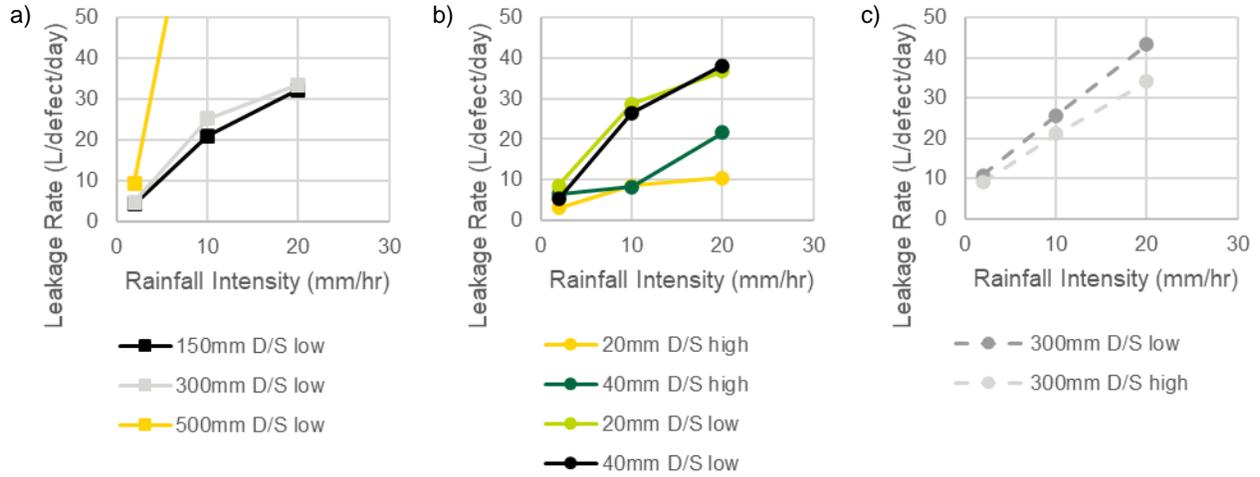
Figure 5. Effects of defect size and shape for a) horizontal tears, b) circular holes, and c) vertical tears
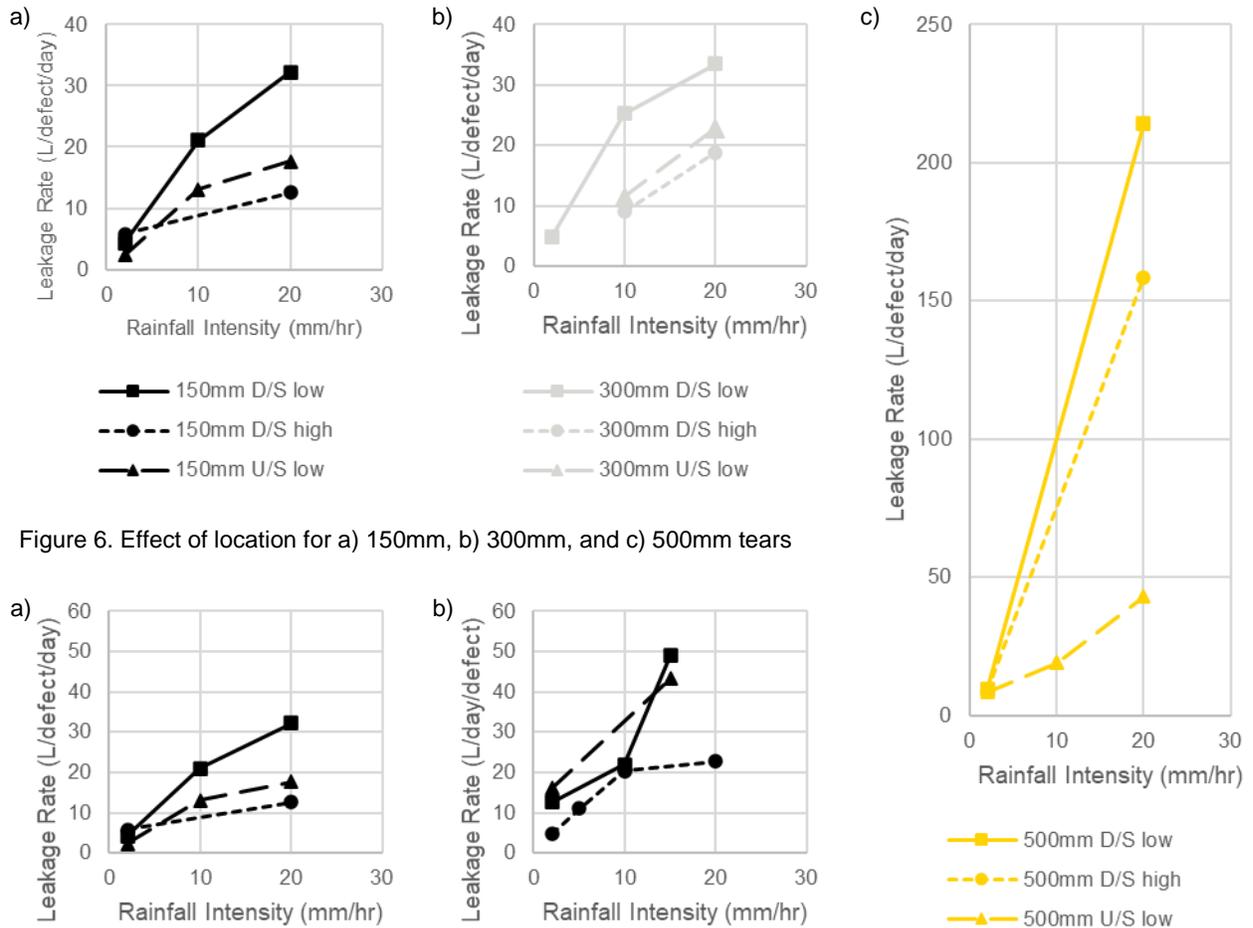

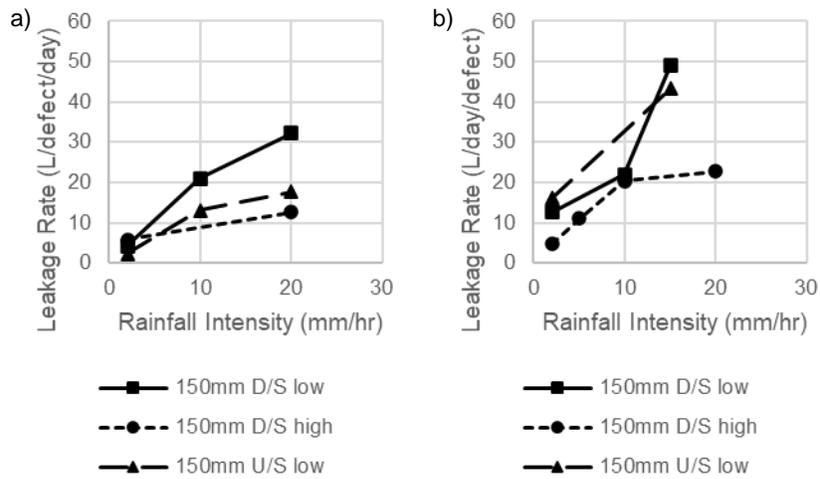Figure 6. Effect of location for a) 150mm, b) 300mm, and c) 500mm tears

Figure 7. Effect of slope angle for a) 3:1 slope and b) 10:1 slope

at least partially located in a topographic low, and thus received greater amounts of leakage.

Figure 8. Winding flow paths on 10:1 slope

Figure 9. Straight flow paths on 3:1 slope

6 CONCLUSION

Large-scale laboratory testing was used to quantify the performance of an exposed geomembrane mine waste cover. The leakage rate through a defect was assessed based on defect size and shape, defect location, surface microtopography, slope angle, and rainfall intensity. All of these factors influenced the leakage rate to some degree. The microtopography had a particular effect, with defect located in microtopographic low points, or flow paths, receiving greater leakage than similar defects located in microtopographic high points. Further research will be done to consider the effects of a cover soil and drainage geocomposite overlying the geomembrane.

7 ACKNOWLEDGEMENT

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