Evaluation of Tensile Properties of HDPE Geomembranes with Temperature under Exposure to Chemical Solutions

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Abstract: In most conventional applications, geosynthetics are exposed to highest mechanical stress during installation. A series of laboratory simulation test for installation damage of geomembrane (GM) was carried out at different loading cycles on HDPE GMs where ISO 10722:2007 was used as a guide. The tensile properties of the samples were tested. The result of the test is reported and it has been found that number of loading cycle has irregular influence on installation damage. It is known that the service life of a GM depends on the exposure conditions, which in a landfill may involve adverse chemical exposure, elevated operating temperatures, and potentially large physical stresses. New equipment was developed and the installation damaged GM samples were exposed to pH solutions under different stress at elevated temperature for hours. Tensile tests was performed to get the residual strength and analyzed. It has been noticed that as the applied stress on GM samples increases, residual tensile strength decreases and they showed higher tolerance to acidic condition than alkali condition.

Keywords: laboratory simulation test, loading cycles, HDPE GMs, installation damage, chemical exposure, damaged GM

1. Introduction

High density polyethylene (HDPE) geomembranes (GM) are used as a part of liner systems in modern landfills [1]. The primary function of GM is to provide barrier to adjective and diffusive migration of contaminants [2]. Field and laboratory data suggest that the properties of GM change with time due to ageing. Thus it is important to assess the long-term performance and to assess the service life of the GM for typical exposure conditions. The installation may represent the hardest stress on a geosynthetic during its service life. Over the last years numerous field studies regarding the installation survivability of geosynthetics have been performed [3,4]. They have shown that, in addition to the type of geosynthetic, the level of damage will depend on weight, type, and the number of passes of the construction and compaction equipment [5], the graduation, angularity and condition of fill material [6,7] and the lift thickness [8].

The ideal way of assessing the service life of GM would be by examining actual field samples over the service life. However this is not feasible because it would take too long to obtain results under field conditions. Thus the service life is generally assessed using laboratory-accelerated ageing tests. Therefore, it is necessary to simulate field condition in the laboratory test as best as possible. Otherwise, laboratory test result would have no use to determine service life of the material. The service life of a GM depends on the exposure conditions, which in a landfill may involve adverse chemical exposure, elevated operating temperatures, and potentially large physical stresses [1]. Even a GM that is properly manufactured, designed and installed may be expected to experience some degradation or ageing over its lifetime. HDPE GM are most commonly used for landfill barrier systems given their excellent resistance to a wide range of chemicals [1].

The key parameters to be considered in geosynthetics applications with regard to long-term degradation include temperature, moisture, UV radiation, thermal stress, chemical environment, mechanical stress, microbiological activity and atmospheric pollution. These parameters may - or may not, depending on the type of polymer and presence of synergetic effects - be influenced by the polymer structure, and eventually the functionality of the product given occurrence of additional synergetic effects [1].

The first objective of this paper is to detail the design of new laboratory equipment to simulate the ageing of geosynthetics under chemical exposure, elevated temperatures and applied stresses. The second objective is to get an idea of tensile properties change of HDPE GM after exposure to different
pH condition under stress at elevated temperature.

In this paper, at first newly designed equipment for exposure to chemical solution is described and then experiments and results are discussed to maintain the flow of presentation. In the experimental, HDPE GM were exposed to pH solution under stress at elevated temperature for hours after laboratory installation damage and residual strength was measured, same specimen were also used for stress cracking resistance observation at pH solution and also tensile strength of notched of different depth specimens were tested to see effects of notch on strength of HDPE GM.

2. Design of Test Equipment

A new equipment for exposure to chemical solution is designed and this equipment may be useful to conduct experiments with geosynthetics in the laboratory by simulating the field environment where three key parameters (stress, temperature, chemicals) can work together on the specimen. The equipment is designed in such a manner that three parameters can be changed or controlled individually. They are stress, temperature and chemical solution where they affect the geosynthetics simultaneously. The equipment has three modules; 1) main frame and loading system, 2) bath, 3) control unit. Figure 1 shows the photograph of the entire equipment mentioning the units using arrows. The entire equipment has to be made of stainless steel and especial care should be taken on hanging frame that holds the specimen and immersed into chemical solution, and the bath that is full of the chemical solution during the experiments to avoid degradation by rust and corrosion.

2.1. Main Frame

Figure 2 shows the design of the main frame. The outer dimension of the frame is 150×50×110 cm. For dimensional stability and safety, the main frame was designed widely. The hanging frame with two clamps holds a test a specimen of geosynthetics. Among the two clamps of the hanging frame, one is fixed at the lower part of the frame and the other movable one is connected with the overhead pulling cord. The pulling cord passes over two pulleys located above. Load is applied at the cord so that geosynthetics stay under stress between the clamps.

2.2. Bath

Bath is a chamber with a dimension of 40×25×50 cm. Testing material under stress is immersed into the bath at elevated temperature. The heating system consists of an electric heater that is located at the bottom of the bath and that is connected to a control system. A thermometer is also installed in the bath to know instant temperature.

2.3. Control Unit

A control unit controls the temperature of solution in the bath. If the temperature reaches at desired level, heater is stopped by the control unit. Again heater is powered on when the temperature falls. To measure the elongation or displacement, an extensometer is also introduced in the control unit. Thus the control unit displays instant temperature.
and displacement. This unit is connected to a computer to have graphical output such as elongation vs. time curve.

2.4. Scope
In the laboratory, there is no useful equipment that stress, temperature and chemical exposure can work on geosynthetics together at a time. Although a geosynthetic liner longevity simulator (GLLS) has been developed to simulate the chemical, temperature, and physical exposure conditions that are expected for a landfill basal liner system in the field, that is expensive and complicated. This newly designed equipment, described above, is cheaper to make and easy to control. It can be very useful tools to conduct experiments with geosynthetics to provide an estimate of the service life. Here should be noted that no laboratory simulation can perfectly substitutes actual field environment. All the simulation may give an idea before mass application in the field. HDPE GM were exposed to pH solution using this equipment which is discussed later in this paper.

3. Experimental

3.1. Materials
Commercially available HDPE geomembranes of two kinds were tested: smooth (2.0 mm) and textured (2.0 mm).

3.2. Installation Damage and Soil Particle Distribution
A hydraulic cyclic loading system with a maximum capacity of 80 kN and a maximum loading rate of 2.5 Hz was used in the present study. ISO 10722:2007 (Geosynthetics-Index test procedure for the evaluation of mechanical damage under repeated loading-Damage caused by granular material) was used as a guide. Figure 3(a) shows the photograph of the equipment used for laboratory installation damage. One still rigid box of 350 mm long, 350 mm wide and 100 mm high was used to contain the fill material (soil) and GM for the test. A steel loading plate of 300 mm long, 200 mm wide and 30 mm thick was placed at the center of the rigid box. Loading cycles were 200, 400, 600 and 800 with a loading frequency of 0.5 Hz.

Figure 3(b) explains the soil particle distribution curve of soil used as fill material for installation damage of GM. The yield strength of HDPE GM (smooth and textured) at both direction (MD and CMD) due to laboratory installation damage at different loading cycle (intact, 200, 400, 600, 800) is presented by ASTM D6693-04(2010) (Standard Test Method for Determining Tensile Properties of Nonreinforced Polyethylene and Nonreinforced Flexible Polypropylene Geomembranes).

3.3. Exposed to pH solution
As the installation damaged GM sample with 800 loading cycle is expected to have highest damage (yield strength 30 kgf, thickness 2 mm), that was used for pH solution exposure. It was exposed to pH 4 and pH 12 buffer solutions under their different yield stress at 50°C for hours using the newly designed equipment described earlier section. Table 1 shows exposure parameters. pH 4 buffer solution was prepared with acetic acid (CH₃-COOH) and sodium acetate (CH₃-COONa). pH 12 buffer solution was prepared with sodium hydroxide (NaOH) and potassium chloride (KCl).

Tensile tests was performed in accordance with ASTM D6693-04(2010) using dumbbell-shaped specimens in a tensile testing machine at a strain rate of 50 mm/min. Three replicate samples were tested and the average is reported.

Table 1. Exposure parameters

<table>
<thead>
<tr>
<th>pH</th>
<th>Applied stress (yield%)</th>
<th>Temp. (°C)</th>
<th>Duration (hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>25%, 30%, 35%, 40%</td>
<td>50</td>
<td>1200</td>
</tr>
<tr>
<td>12</td>
<td>25%, 30%, 35%, 40%</td>
<td>50</td>
<td>1000</td>
</tr>
</tbody>
</table>
3.4. Notch for Stress Cracking

ASTM D5397-07 (Test method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test) was used as a guide to conduct the stress crack resistance test. HDPE smooth and HDPE textured GMs are cut into dumbbell shape and notched using the notch maker. The depth of the notch produced a ligament thickness of 90% to 10% of the nominal thickness of the specimen at 10% interval. Yield stress and elongation was measured of those samples and plotted on graph that is shown in results and discussions later. Again, HDPE smooth and HDPE textured GMs were cut into dumbbell shape. Both installations damaged and intact GMs were used to understand stress crack behavior. Intact sample were notched in such a manner that the depth of notch produced a ligament thickness of 80% of the nominal thickness of the specimen. Installation damaged samples were not notched. Figure 4 shows the dimension of dumbbell shape specimen with notch. Stress crack resistance behavior was observed using notched constant tensile load (NCTL) test of virgin notched sample and installation damaged sample at 50±1°C at different yield stresses immersing pH 4 and pH 12 buffer solutions. Figure 5 shows NCTL test equipment. Residual strength after stress cracking observation of one thousand hours is reported in the result and discussion section.

4. Result and Discussion

4.1. Yield Strength at Different Loading Cycles

Figures 6 and 7 show the yield strength of HDPE GM (Smooth and textured) at both machine direction (MD) and cross-machine direction (CMD) due to laboratory installation damage at different loading cycle (intact, 200, 400, 600, 800). In the tensile behavior measurement, the stress initially increases proportionally to elongation according to Hook’s law before passing through a maximum known as the yield point. It provides to be extensively ductile up to the elongation of 11%. The samples failed at approximately 700% of strain.

In Figures 6 and 7, both smooth and textured HDPE GMs showed gradual decrease in yield strength with the increase in loading cycle with some fluctuations in the case of the cross machine direction. It seems that the decrease is not so significant as even after 800 loading cycle decrease in yield strength is less than 2% for both samples except textured samples in CMD (7.4%). In general, it seems that the increase in loading cycle caused more damage on the GM.
samples. However, any significant changes are not observed that any specific correlation can be drawn. Therefore, we can just say the higher the number of loading cycle, the higher the damage that causes declination in yield point. More intensive experiments are needed to obtain better knowledge on installation damage on GMs considering not only particle size and number of loading cycle but also shape or angularity of the particles.

### 4.2. Tensile Strength after Chemical Exposure

The residual strength of samples after pH solution exposure was compared in Figures 8 and 9. It would help to get an idea of tensile strength in the real field for long time use where three parameters work simultaneously. In this experiment, stress was variable. It has been noticed that as the applied stress increases, residual tensile strength decreases. It can be said that residual tensile strength is inversely proportional to exposed stress. As the temperature was constant, it is difficult to explain the effect of temperature clearly. But it is obvious that a GM will degrade faster at higher temperatures than lower temperatures. However, although it is hard to say confidently, it seems that HDPE GM (both smooth and textured) shows better performance to acidic condition than alkali condition.

In the simulated landfill conditions, the crystallinity and tensile yield strain increased in the early stages of ageing and then remained relatively constant over the testing period [1]. In our experiment, residual strength was only tested after a fixed period of time. That’s why changes over exposed period were not obtained.

GMs are polymeric material. Therefore, no significant change in the tensile properties doesn’t imply no degradation in the material. It is rather more important to know the polymeric degradation and anti-oxidant depletion of GM for the understanding of the service life of GM. Usually, service life of HDPE GM can be divided into three stages where Stage I represents the time for antioxidant depletion, Stage II refers to induction time to the onset of polymer degradation, and Stage III is the polymer degradation involving the decrease in a GM property to an arbitrary level often taken to be 50% of the original value or half-life. Hence, the service life of a GM is the sum of the three stages. A small amount of antioxidant (typically 0.5-1%) is added to the GM to retard oxidation and increase their service life. The long-term performance of GM in landfill is initially controlled by the rate of antioxidant depletion in Stage I. Oxidation of polymer takes place without any measurable decline in mechanical properties in Stage II. In Stage III oxidative degradation of polymer continues and the mechanical properties (e.g. tensile strength at break) change to the end of service life. From the result of the conducted experiment, it can be easily infer that the GM specimen was still in Stage I.

### 4.3. Yield Stress and Elongation at Different Notch Depth

Due to notch, GM lose strength like other materials. The yield stress and elongation at yield point decreases gradually as the notch depth is increased. Figure 10 states the notch percentage at 10% interval across the thickness of GM and their yield stresses. It explains the traditional experience that yield stress depends on the thickness of materials if the width is constant. It does not show any exception in the figure. It can be concluded that yield stress is proportional to the thickness of material at constant width without any significant difference. Rate of decrease in yield stress is almost constant after 20% depth of notch. Figure 11 shows the elongation at yield point of different thickness of GM at constant width. Here, elongation at yield point of GM is proportional to their thickness without significant fluctuations.
4.4. Stress Cracking Resistance

Stress cracking of HDPE smooth and textured GM were measured at pH 4 and pH 12 where ASTM D5397-07(2012) (Standard Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test) was used as a guide. Notched GM means intact samples with 20% notch of its thickness and damaged sample means laboratory installation damaged sample after 800 loading cycle without any further notch. In this Stress Cracking test, some samples failed and some of them did not fail even after one thousand hours. It seems that residual strength decreases as applied load increases. After data analysis, it seems that at 25% and 30% tensile load GM can withstand more than one thousand hours whereas over 35% tensile load GM become vulnerable to stress cracking where both damaged and notched GM follow the same trend. It is also observed that notched GM possess less strength than installation damaged GM at every stage. It clarifies that 20% notch is an overestimate to understand stress cracking resistance due to installation damage of GM that further intensive investigation considering all relevant factors.

Figure 12, 13, 14 and 15 shows the residual strength after stress cracking observation. Some symbols should be interpreted as NF=Not failed after one thousand hours, F(t)=Failed (at time in hour) and B(t)=Broken (at time in hour).
5. Conclusion

In general, it seems that increase in loading cycle caused higher damage on the GM samples. However, as any significant changes are not observed, any specific correlation cannot be drawn from the experiments. Therefore, it can be concluded that the higher the number of loading cycle, the higher the damage that causes declination in yield point. More intensive experiments should be conducted to obtain improved knowledge on installation damage on GMs considering not only particle size and number of loading cycle but also shape or angularity of the particles.

A newly developed experimental equipment that is capable of simulating the ageing of geosynthetics under the combined effects of chemical exposure, elevated temperatures and applied stresses is described. Experiments were performed to provide an estimate of the tensile strength of HDPE GM after exposed to pH 4 and pH 12 and at different stress conditions at elevated temperature. HDPE GM is more resistant to acidic condition than alkali condition. Residual tensile strength is inversely proportional to exposed stress. More intensive research is required to make any concrete statement.

After the study of tensile strength at different depth of notch, it can be concluded that the yield stress is proportional to the thickness of material at constant width without any significant difference. In the stress cracking observation, it is understood that residual strength decreases as applied load increases.

After data analysis, it seems that at 25% and 30% tensile load GM can withstand more than one thousand hours without any significant damage whereas over 35% tensile load GM become vulnerable to stress cracking where both damaged and notched GM follow the same trend. It is also observed that notched GM possess less strength than installation damaged GM at every stage. It clarifies that 20% notch is an overestimate to understand stress cracking resistance due to installation damage of GM that requires further intensive investigation considering all relevant factors.

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References