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실내 시공시 손상시험에 의한 HDPE 지오멤브레인의 기계적 특성 및 응력균열거동 해석

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Analysis of Mechanical Properties and Stress Crack Behavior of HDPE Geomembranes by Laboratory Installation Damage Test

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초록: 표면이 매끄럽고 돌기가 있는 2가지 HDPE 지오멤브레인 덤벨형 시료에 두께 10% 간격으로 10~90% 깊이의 노치를 가하여 실험에 사용하였다. ISO 10722에 의거하여 부가하중 횟수를 변화시켜 시공시 손상의 실내 모사시험을 HDPE 지오브레인에 실시하였으며, 부가하중 횟수가 시공시 손상에 미치는 영향을 비교하였다. 항복응력과 변형률은 노치 깊이가 커짐에 따라 감소하였다. 손상된 그리고 노치를 가한 지오멤브레인을 응력균열시험에 사용하였으며, 50±1 ℃에서 pH 4와 12 용액에 침지시켜 항복응력 변화에 따른 응력균열저항성을 NCTL 시험을 통하여 고찰하였다. 인장강도의 35% 이상에서 지오멤브레인은 응력균열에 취약함을 나타냈으며, 손상을 받은 그리고 노치를 가한 지오멤브레인 모두 같은 경향을 나타내었다. 특별히 노치를 가한 지오멤브레인의 경우 각각의 응력균열 시험조건에서 시공에 의해 손상된 지오멤브레인보다 낮은 강도를 나타내었다.

Abstract: Two smooth and textured surfaced HDPE geomembranes (GMs) were cut into dumbbell shape and notched where depth of the notch produced a ligament thickness of 10% to 90% of the nominal thickness with the specimen at 10% interval. A series of laboratory simulation test for installation damage were carried out at different loading cycles on HDPE GMs in accordance with ISO 10722 test method and the effect of number of loading cycle on installation damage was compared. It was found that yield stress and elongation at yield point decreased gradually as the notch depth was increased. Both installation damaged and notched, GMs were used to understand stress crack behavior and this behavior was observed through NCTL test at 50±1 ℃ at different yield stresses immerging in pH 4 and pH 12 buffer solutions. Over 35% tensile load, GMs became vulnerable to stress cracking. Both damaged and notched GMs showed the same trend. Especially, notched GMs showed less strength than installation damaged GMs at every stress cracking test condition.

Keywords: geomembranes, laboratory installation damage, loading cycles, stress crack behavior, NCTL test.

Introduction

Geomembranes (GMs) are very low permeability synthetic membrane liner or barrier used with any geotechnical engineering related material so as to control fluid (or gas) migration in a human-made project, structure, or system.[1,2] The past three decades, GMs have been extensively used in different civil engineering applications in many countries. The main applications include their use as liners for liquid or leachate ponds or as part of composite barrier systems for landfills. This extensive use is related to their low permeability to water and relative short-term high resistance to a wide range of

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chemicals. However, it is well known that polymeric materials, like GMs, may degrade and their properties may change over time.[3] In the polymer degradation stage of GMs changes in melt flow index (MFI), stress crack resistance (SCR) and tensile properties are of importance.[4] Among these, stress cracking is likely to have the greatest impact on the actual service life of HDPE GMs. Semi-crystalline HDPE GMs are known to be susceptible to stress cracking, which is external or internal cracking in plastic induced by a tensile stress less than its short-term mechanical strength.[5,6] Stress cracking occurs in a brittle manner with little or no elongation near to the crack surface.[5] One can anticipate that the oxidative degradation of HDPE with time will cause reduction in stress cracking resistance (SCR). The decrease in SCR combined with tensile stresses will lead to cracking in the GMs. Thus following extensive cracking GMs would no longer act as an effective contaminant barrier.[7] The application of a large external stress or loading on a polymer will result in a decrease in its useful lifetime, primarily via physical creep, although it is possible that chemical degradation mechanisms may also be enhanced.[8] Little has been reported regarding the effect of stress on the degradation of HDPE GMs. The installation may represent the hardest stress on a geosynthetics during its service life.[9] Over the last years numerous field studies regarding the installation survivability of geosynthetics have been performed. They have shown that, in addition to the type of geosynthetics, the level of damage will depend on weight, type, and number of passes of the construction and compaction equipment,[10] the gradation, angularity and condition of fill material[9,11] and lift thickness.[12] Durability of GMs is gaining increasing attention day by day because of new engineering and environmental applications of GMs. The resistance of GMs to installation damage is a great concern though sufficient investigated data is not available. Though laboratory simulation of installation damage is a way to have accelerated results, it requires correlation with the actual field installation. This paper presents findings regarding, i) Changes of mechanical properties on laboratory installation damage; ii) Tensile behavior at different notch depth; iii) SCR behavior for notched and damaged samples.

Experimental

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

Installation Damage. 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 (Figure 1). ISO 10722-1 was used as a guide. One steel rigid box of 350 mm long, 350 mm wide and 100 mm high was used to contain the fill material (soil) and GMs for the test.[13] 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 1. Laboratory installation damage test equipment.

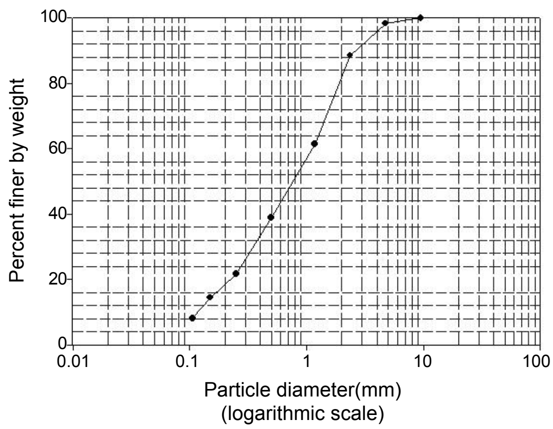

Figure 2. Grain size distribution.

Soil Particle Distribution. Figure 2 explains the soil particle distribution curve of soil used as fill material for installation damage of GMs.

Notch for SCR. 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 SCR Test.[14] HDPE smooth and 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 textured

GMs were cut into dumbbell shape. Both installations damaged and intact GMs were used to understand SCR behavior. Intact samples 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.

SCR behavior was observed using NCTL (notched constant tensile load) test of virgin notched sample and installation damaged sample at 50±1 ℃ at different yield stresses immerging pH 4 and pH 12 buffer solutions. Therefore pH 4 buffer solution was prepared with acetic acid (CH_3−COOH) and sodium acetate (CH_3−COONa). Again, pH 12 buffer solution was prepared with sodium hydroxide (NaOH) and potassium chloride (KCl). Tensile, tear and puncture resistance were evaluated and compared to intact material. However, tests were carried out according to ASTM standards: ASTM D 6693−04 (standard test method for determining tensile properties of non−reinforced polyethylene and non−reinforced flexible polypropylene GMs), ASTM D1004−08 (standard test method for tear resistance (graves tear) of plastic film and sheeting), ASTM D4833 (test method for index puncture resistance of geotextiles, geomembranes and related products).[15−17]

Results and Discussion

The following sub−sections highlight important discussion of measured results. The first sub−section focuses on analysis of mechanical properties of GMs considering laboratory installation damage. The second sub−section focuses on yield stress and yield elongation at different notch depth. In the third sub−section we illustrate SCR at pH 4 and pH 12 buffer solutions.

Analysis of Mechanical Properties of GMs Considering Laboratory Installation Damage.

Tensile Behavior: Figures 3 and 4 show the tensile behavior of HDPE GMs (smooth and textured) at both directions (MD and CMD) due to laboratory installation damage at different loading cycle (intact, 200, 400, 600, 800). 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 Figure 4, some changes in tensile behavior of HDPE textured GMs are observed. However, significant changes are not observed for HDPE smooth surfaced GMs (Figure 3) which implies that either executed laboratory installation damage is unsuitable to investigate strength reduction damage for the GMs due to installation or error occurred during testing period. Various comparisons and analyses are presented afterward based on tensile behavior of these GMs.

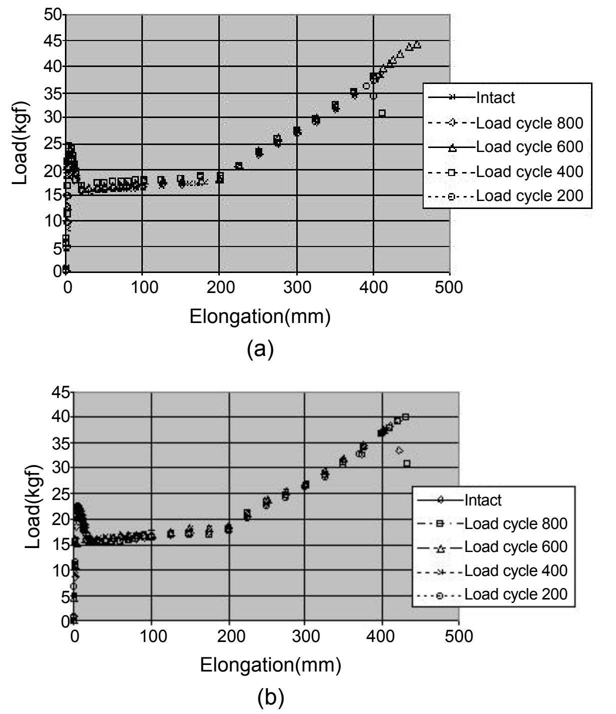

Figure 3. Tensile behavior of HDPE smooth GMs after installation at different loading cycle: (a) Machine direction (MD); (b) Cross machine direction (CMD).

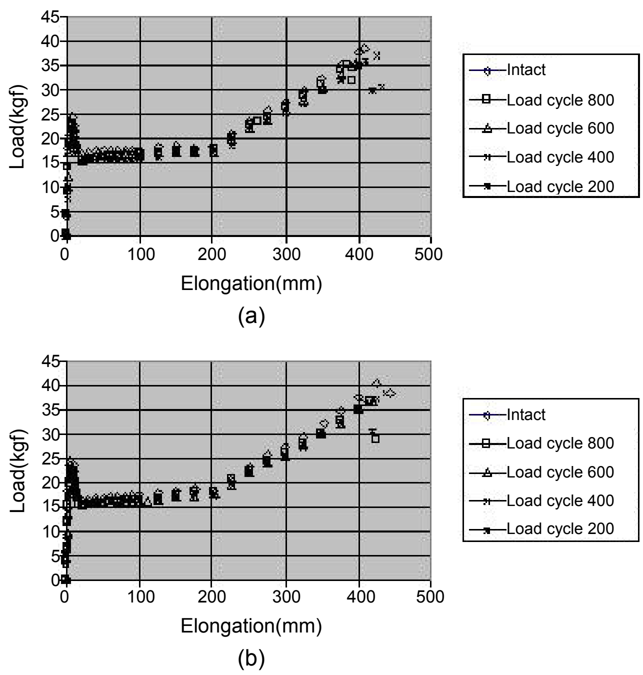

Figure 4. Tensile behavior of HDPE textured GMs after installation at different loading cycle: (a) Machine direction (MD); (b) Cross machine direction (CMD).

Yield strength and breaking strength of HDPE (smooth)

GMs increase significantly in machine direction and remain unchanged in cross machine direction with little fluctuations where breaking strength decreases. The reasons behind this attitude are unknown that suggests rechecking the process with intensive research. Contraction of plastic sheet due to load can be the reason for such increase. The same cause is applicable for other samples too. Yield strength and breaking strength of HDPE (textured) GMs declines in both directions with some fluctuations which implies that load causes reduction in tensile strength.

Tear Resistance: HDPE smooth and textured GMs do not present any significant change in tear behavior. Figures 5 and 6 illustrate the comparison of tear resistance of HDPE smooth and textured GMs respectively using bar graphs. Tear resistance of HDPE (smooth) GMs remains almost same after installation damage in machine direction where it fluctuates in cross-machine direction. Tear resistance of HDPE (textured) GMs goes up more in machine direction than that of cross-machine direction at 800 cycle: MD: 6.6%; CMD: 0.5%.

Puncture Resistance: According to GRI Report #10 (1993), failure of GMs due to puncture can be avoided only by a rational design method that considers the important variables that are involved. It is believed that the major variables with respect to the puncture resistance of GMs are: type and thickness of the GMs, nature of the puncturing medium, temperature of the GMs, magnitude of design loads, orientation of design loads, and required service lifetime.[18] Figure 7 shows the puncture resistance of GMs at different loading cycle. Puncture resistance of HDPE (smooth) GMs gradually rise to 6.7% at 800 cycles where HDPE (textured) GMs show fluctuations in values rather than gradual upward or downward trend. However, due to laboratory installation damage puncture resistance has not decreased because of the type of soil used i.e. angularity of particles. On the other hand, in most cases, puncture resistance has increased because of compaction by load applied. Further investigation is required to elucidate the phenomenon. However, as angularity of soil or installation medium is greatly important for the damage, highly angular sintered aluminum dioxide should have been used in this study. It is also important to keep in mind that GMs are viscoelastic in nature. This suggests that the failure pressure of these materials is a function of time. In this study, only pressure has been evaluated. The effect of time on the failure of GMs in the puncture mode has not been investigated. So, it is important to consider a creep related design for puncture resistance.

From this review, we cannot find the constant trend with compaction cycle for installation damage even though 10 samples were used for each SCR test. To explain this, it is only supposed that this fluctuation is uneven change in GM surface by compaction and more uneven surface change will be occurred by compaction increasing. Besides this, an-

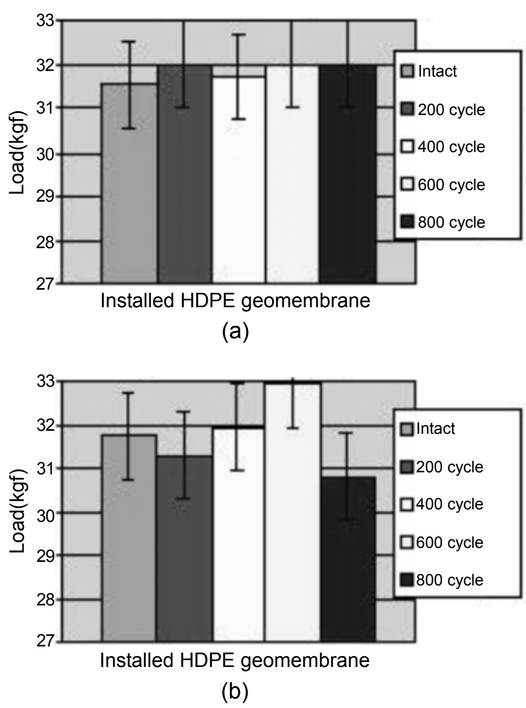

Figure 5. Comparison of tear resistance of HDPE smooth GMs at different loading cycles: (a) Machine direction(MD); (b) Cross machine direction(CMD).

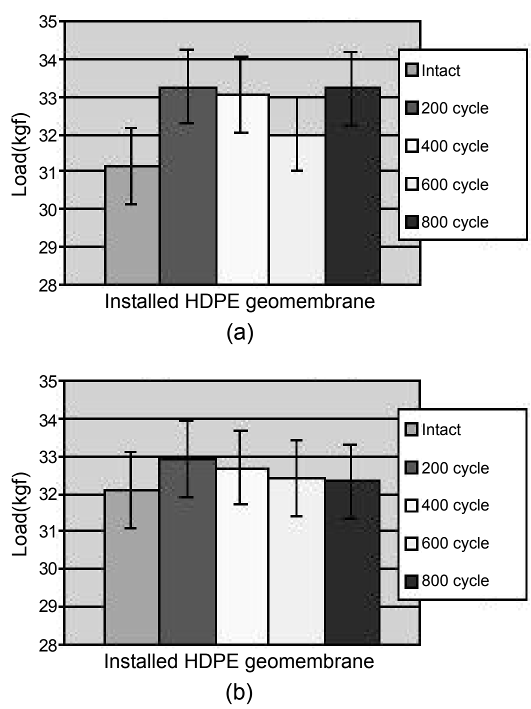

Figure 6. Comparison of tear resistance of HDPE textured GMs at different loading cycles: (a) Machine direction(MD); (b) Cross machine direction(CMD).

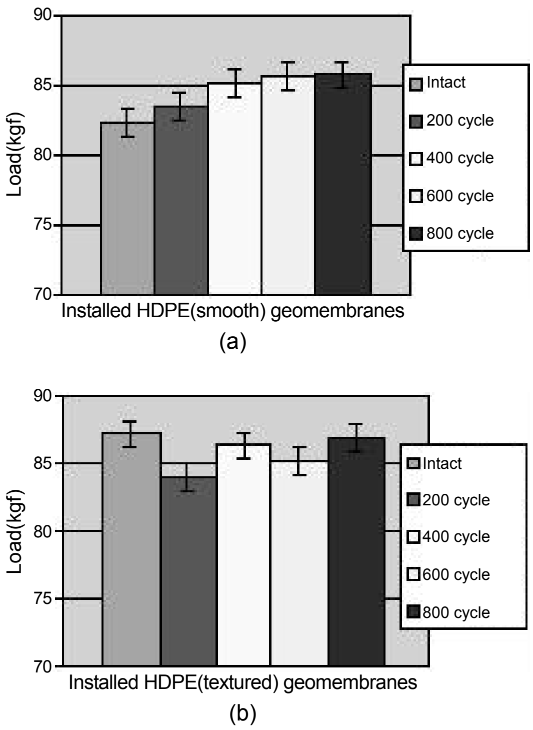

Figure 7. Comparison of puncture resistance of GMs at different loading cycles: (a) HDPE smooth GMs; (b) HDPE textured GMs.

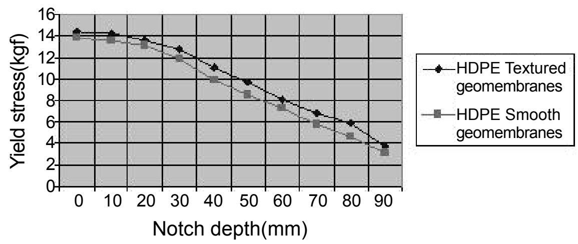

Figure 8. Yield strength of HDPE GMs at different notch depths.

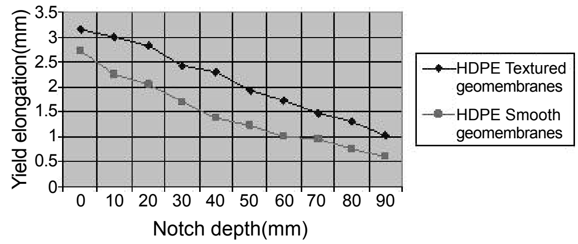

Figure 9. Yield elongation of HDPE GMs at different notch depths.

gularity of filled soils may also influence to surface damage and SCR of GMs.

Yield Stress and Yield Elongation at Different Notch Depth. Due to notch GMs lose strength like other materials. Yield stress and elongation at yield point decreased gradually as the notch depth was increased. Figure 8 states the notch percentage at 10% interval across the thickness of GMs and their yield stresses. It implies that yield stress depends on the thickness of materials if the width is constant. It doesn't show any major exceptions along 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 9 shows the elongation at yield point of different thickness of GMs at constant width. Here, elongation at yield point of GMs is proportional to their thickness without substantial change at constant width.

Stress Cracking Resistance (SCR). SCR of HDPE smooth and textured GMs were measured at pH 4 and pH 12 where ASTM D 5397-07 was used as a guide, respectively. Here, notched GM means intact samples with 20% notch of its thickness and damaged sample means laboratory installation damaged sample after 800 loading cycles without any further notch. In this SCR test, some samples failed and some of them didn't fail even after one thousand hours. However, from the obtained date, it seems that residual strength decreases as applied load increases. After data analysis, it shows that at 25% and 30% tensile load GMs can withstand more than one thousand hours whereas over 35% tensile load GMs become vulnerable to SCR where both damaged and notched GMs follow the same trend. It is also observed that notched GMs possess less strength than installation damaged GMs at every stage. It clarifies that 20% notch is an overestimate to understand SCR due to installation damage of GMs. So, further intensive investigation considering all relevant factors is required. Figures 10, 11, 12 and 13 show 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).

Conclusions

Yield strength and breaking strength of HDPE (smooth) GMs increase significantly in machine direction and remain unchanged in cross machine direction with little fluctuations where breaking strength decreases. The reasons behind this attitude are unknown that suggests rechecking the process with intensive research. Contraction of plastic sheet due to load could be the reason for such increase. The same reason is applicable for all other GMs. However, HDPE smooth and textured GMs do not present significant fluctuations in their tear behavior. However, puncture resistance due to laboratory installation damage has not decreased because of the type of used soil i.e. angularity of particles. On the other hand, in most cases, puncture resistance has increased because of compaction due to load applied. Further investigation is required to elucidate the phenomenon. After the study of

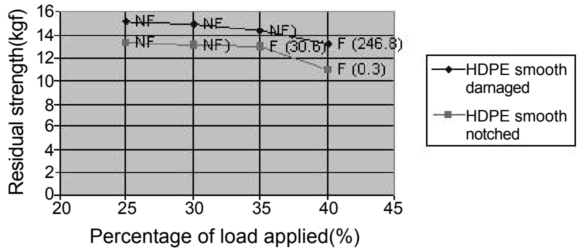

Figure 10. Residual strength of HDPE smooth GMs(notched and damaged) after stress cracking observation at pH 4.

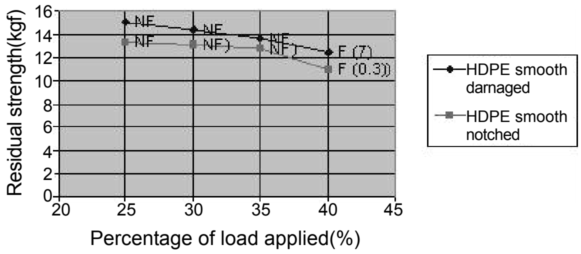

Figure 11. Residual strength of HDPE smooth GMs(notched and damaged) after stress cracking observation at pH 12.

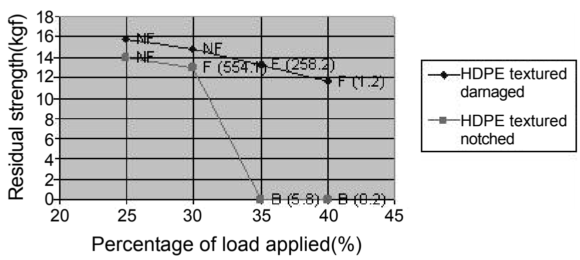

Figure 12. Residual strength of HDPE textured GMs(notched and damaged) after stress cracking observation at pH 4.

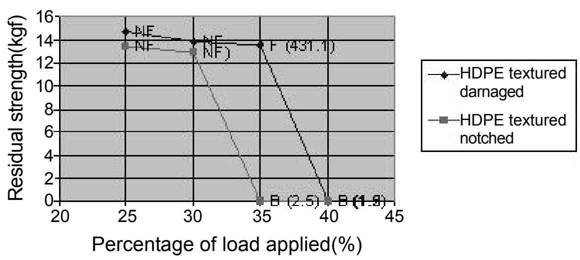

Figure 13. Residual strength of HDPE textured GMs(notched and damaged) after stress cracking observation at pH 12.

tensile strength at different depth of notch, it can be concluded that 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 GMs can withstand more than one thousand hours without any significant damage whereas over 35% tensile load GMs become vulnerable to stress cracking where both damaged and notched GMs follow the same trend. It is also observed that notched GMs possess less strength than installation damaged GMs at every stage. It clarifies that 20% notch is an overestimate to understand SCR due to installation damage of GMs that requires further intensive investigation considering all relevant factors. Through more intensive research is needed to find out acceptable correlation between changes in mechanical properties and laboratory installation damage along with the field installation. Finally, it is suggested that 20% notch is an overestimate to understand SCR due to installation damage of GMs.

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