ジオシンセティックス論文集
第 32 巻(2017. 12)

Effect of Shape of Damage Hole on Self-Healing Capacity of GCL

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The effect of the shape of a damage hole on the self-healing capacity and permittivity of geotextile encased-geosynthetics clay liner (GCL) was investigated through a series of constant head leakage rate tests. Three different damage shapes, circle, rectangle and square were tested with different size. Hydraulic radius (R_h) (damage area/periphery length of a damage) has been used to analyze the effect of the shape of a damage hole. The test results indicate that the self-healing ratio (α = healed area/total damage area) was influenced by the shape of a damage. For a rectangular or a square damage under the same damage area condition, α tends to decrease with increase of R_h. In case of a circular damage, it has a larger R_h, but had a higher value of α compared with a square damage of the same area. It has been explained that for a square or a rectangular damage, at corner locations, the amount of the bentonite entered the damage hole will be reduced due to so called "corner effect".

Keyword：GCL, self-healing capacity, hydraulic radius, permittivity

1．Introduction

Geosynthetic clay liners (GCLs) are widely used in the liner and cover systems of landfills because its low permeability, easy installation and cost effectiveness. A GCL consists of a thin layer of granular sodium bentonite sandwiched between a woven and a non-woven geotextiles. Normally the two layers of the geotextile are bonded together by needle-punch technics. However, in the field, GCL can be damaged during the installation (Fox et al., 1998). The damage may be due to stress concentration, such as GCLs placed over a sharp stone (Koerner 2012). Further, after installation and if only covered by a layer of geomembrane, day-night temperature variation induced vapor-water drops of groundwater into the GCL, can cause down-slope erosion of bentonite in a GCL to form spots without bentonite (Rowe et al., 2014). Mazzieri and Pasqualini (2000) conducted series of permeability test of damaged GCL samples and the result shows that permeability of a damaged sample decreases with elapsed time. This phenomenal arise due to the hydrated bentonite squeezed into the damage hole and partially healed the damage, and the phenomenon is called self-healing (Babu et al., 2001).

In past decades, many researchers investigated the factors influencing the self-healing capacity of a GCL, such as overburden pressure, cation concentration in the leachate, size of damage, etc. Sari and Chai (2013) reported that the overburden pressure has two effects on self-healing capacity. The overburden pressure can squeeze the hydrated bentonite into the hole resulting in improving the self-healing capacity. While higher overburden can restrain the expansion of the bentonite. The self-healing capacity can be reduced by increasing cation concentration in the leachate (Jo et al., 2005 and Chai et al., 2013). By increasing of cation concentration, the osmotic repulsion force between clay particles is reduced, which resulting in decrease of swelling of the bentonite (Mitchel and Soga 2005). A GCL with a damage hole up to 30 mm can be fully healed in case the liquid used is tap water (Sari and Chai 2013; Mazzieri and Pasqualini 2000). However, previous researches generally considered a circular damage hole (Touze-Foltz et al., 1999; Sari and Chai 2013; Mazzieri and Pasqualini 2000). In the field, the damage hole can be any shape. Therefore, this research aims to investigate the effect of the shape of damage holes on the self-healing capacity of a GCL. A parameter, hydraulic radius (R_h), which is the ratio of area/periphery length of a damage hole, has been employed to analyze the test results. Eleven GCL samples with different damage shape and size were tested and the results are discussed.

2. Leakage rate tests

(1) Device and test procedure

A rigid-wall constant head permeability cell was used to measure the leakage rate of GCLs with a damage hole. The equipment is mainly composed of a piston loading system, and an acrylic cell with an inner diameter of 150 mm. The overburden pressure was applied using compressed air through a bello-frame cylinder system. A porous stone was inserted into the piston and the piston was perforated. The vertical displacement was measured by a dial gauge. The schematic view of the equipment is shown in Figure 1(a) and the picture is given in Figure 1(b).

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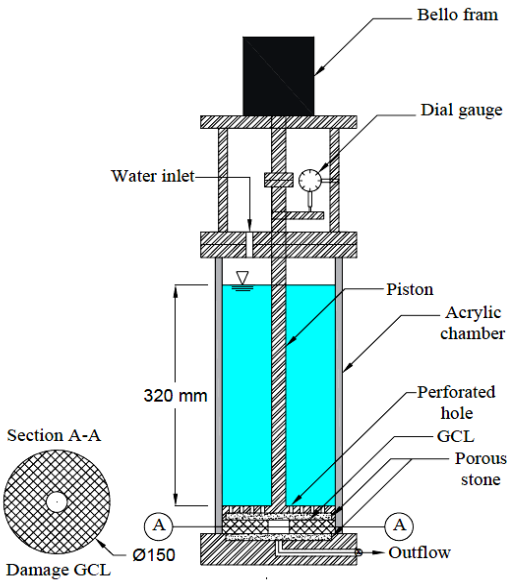
The tests were conducted under an overburden pressure of 40 kPa. Tap water was used as permeation liquid, and a constant water head of 320 mm was adopted. During the test, the amount of water flow was recorded, and then the flow rate and permittivity were calculated. The test procedure is as following:



(a) Sketch

(b) Picture

Figure 1 Rigid wall permeability test apparatus

a) A square GCL sheet with dimension of about 200 × 200 mm was trimmed to a circle specimen with a diameter of 150 mm. A HDPE sheet with a model damage hole was made and put it on the GCL sample and cut the GCL along the boundary line of the HDPE model by a sharp cutter.
b) The weight and the initial thickness of the specimen were measured and recorded.
c) The porous stones at the bottom and in the piston were saturated by boiling for 30 minutes and kept submerged before using. The filter paper was placed on the bottom porous stone first and then the GCL specimen was set. After that the piston was placed on the top of the specimen.
d) The tap water was filled into the cell to the desired level and the bottom drainage valve was closed. After that the loading system was setup.
e) A pressure of 40 kPa was applied on the top of the specimen and the displacement was recorded. The setup was keep for 24 hours before leakage rate test.
f) Open the bottom drainage valve and started the leakage rate test.
g) The amount of water flow and displacement were recorded periodically.
h) After steady state flow was reached, the leakage rate test was stopped, and the mass and water content of the hydrated bentonite entered the hole were measured.

Table 1. Properties of GCL (The data are provided by the manufacturer)

Properties	Standard	Value
Mass	ASTM D5993	0.25
Grab strength	ASTM D4632	0.40
Grab elongation	ASTM D4632	100%
Tensile strength	ASTM D6768	9.8 kN/m
Peel strength	ASTM D6496	1751.3 N/m
Index flux	ASTM D5887	$<1\times10^{-8}$ m^3/m^2/sec
Permeability	ASTM D5084	$<5\times10^{-11}$ m/s

(2) Geosynthetic clay liner (GCL)

The GCL comprises of a granular sodium bentonite sandwiched between a woven and a nonwoven geotextiles. The properties of the GCL are listed in Table 1. The index properties of the bentonite are summarized in Table 2.

Table 2. Index properties of the granular bentonite.

Test	Value
Liquid limit (%)	581
Plastic limit (%)	64
FSI* (ml/2g)	43
Specific gravity G_s	2.52
Compression index, C_c	2.84
Swelling index, C_s	1.36

*FSI is free swelling index

(3) Test program

Eleven (11) cases were tested as listed in Table 3. The 11 cases can be divided into three series and the tests were conducted for three damage shapes, i.e. circular, square and rectangular. The first series had damage area of 1787.0 mm^2 with only two damage shapes, i.e. square and rectangular. The second series had damage area of 2578.7 mm^2 with six cases, i.e. circular, square and four rectangular. The last series had a damage area of 3500.0 mm^2 with three damage shape, i.e. circle, square and rectangle.

Table 3. Summaries of testing program

Case	Shape	Width (mm)	Length (mm)	Diameter (mm)	Area (mm^2)	Perimeter (mm)	R_h (mm)	m/A[a] (kg/m^2)	t_i[b] (mm)
1	Rectangle	25.5	80.0	-	1787.0	191.1	9.4	6.29	6.45
2	Square	42.3	42.3	-	1787.0	213.7	10.6	6.48	6.75
3	Rectangle	32.2	80.0	-	2578.7	224.5	11.5	6.65	6.25
4	Rectangle	34.4	75.0	-	2578.7	218.8	11.8	6.59	6.55
5	Rectangle	36.8	70.0	-	2578.7	213.7	12.1	6.68	6.65
6	Rectangle	39.7	65.0	-	2578.7	209.3	12.3	6.57	6.55
7	Square	50.8	50.8	-	2578.7	203.1	12.7	6.60	6.50
8	Circle	-	-	57.3	2578.7	180.0	14.3	6.63	6.55
9	Rectangle	50.0	70.0	-	3500.0	240.0	14.6	6.88	6.75
10	Square	59.2	59.2	-	3500.0	236.6	14.8	6.83	6.65
11	Circle	-	-	66.8	3500.0	209.7	16.7	6.52	6.85

Note: [a]m/A = bentonite mass per unit area (exclude unit weight of geotextiles), [b]t_i = initial thickness

3. Test results and discussion

(1) Permittivity of damage hole (ψ_{hole})

Figures 2(a) to 2(c) show the flow rates (Q) versus time curves of different damage shapes with damage area of 1787.0, 2578.7 and 3500.0 mm^2, respectively. The steady flow rate of the intact sample of GCL is also indicated in the figures. For the sample with a damage hole, the values of Q reduced with elapse time and it is considered due to the self-healing of the GCL specimen. At the steady state, the value of Q increases with increasing of size of damage hole for a given damage shape.

From the flow rate, the permittivity (ψ_{hole}) of the damage hole can be calculated by Equation (1) .

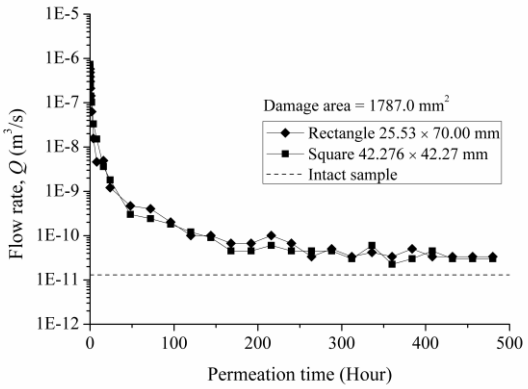
$$\psi_{hole} = \frac{Q_{damage} - Q_{intact}}{A_{damage} \cdot \Delta h} \qquad (1)$$

where Q_{intact} is the steady flow rate of the intact sample, Q_{damage} is the steady flow rate of the damage sample, A_{damage} is the damage area and Δh is the water head difference.

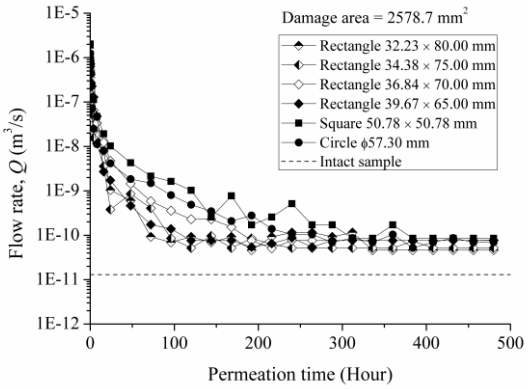
The hydraulic radius, R_h is defined as:

$$R_h = \frac{A}{L} \qquad (2)$$

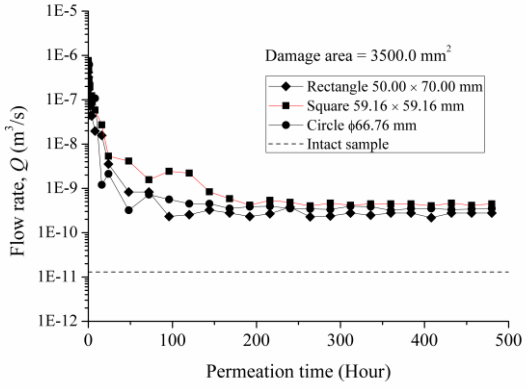
where A is the damage area and L is the periphery length of a damage hole. A comparison of ψ_{hole} for the different damage shapes are shown in Figure 3(a) and 3(b) for damage area of 2578.7 mm^2 and 3500.0 mm^2, respectively. For the damage area of 1787.0 mm^2, the GCL specimens are fully healed for all cases. Therefore, the relationship between R_h and ψ_{hole} for this case was not shown. Under the condition of a given damage area, conceptually, the value of ψ_{hole} is controlled by the volume of hydrated bentonite entered the hole. Lager the volume of the hydrated bentonite entering the hole, more area of damage hole can be covered by the bentonite and result in smaller value of ψ_{hole}.



(a) Damage area of 1787.0 mm^2



(b) Damage area of 3500.0 mm^2

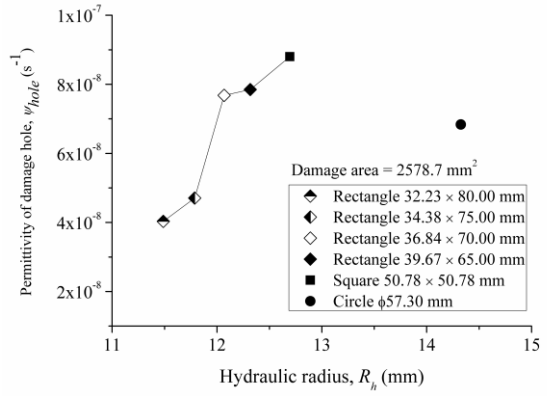


(c) Damage area of 3500.0 mm^2

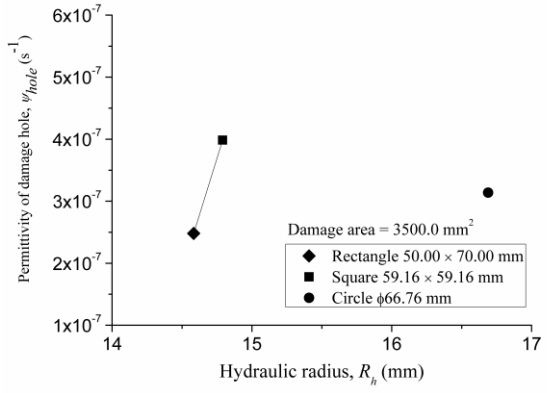
Figure 2 Flow rate versus time curves for given damage areas

Under a given damage area, longer the periphery length of a hole, more bentonite can enter the hole, and larger the value of R_h, relatively more space for the bentonite entered the hole to expand. For the results in Figure 3(a) and 3(b), in case of the rectangular and square damage shapes the ψ_{hole} increase with the increase of R_h. While for a circular damage, it has largest R_h under the same damage area condition, but resulted in lower ψ_{hole} compared with the square damage of the same

area. The reason will be further investigated by the mass of bentonite entered the damage hole as well as the water content of the bentonite.



(a) Damage area of 2578.7 mm^2



(b) Damage area of 3500.0 mm^2

Figure 3 Relationship of ψ_{hole} with R_h

(2) Self-healing ratio (α)

a) Method to determine the healing ratio (α)

The healing ratio (α) is calculated as:

$$\alpha = \frac{A_1}{A} \tag{3}$$

where A is the initial damage area, and A_1 is the healed area. For measuring the value of A_1, the final shape of the damage hole was photographed with a scale, and an AutoCAD program was used to determine the value of A_1 as shown in Figure 4.

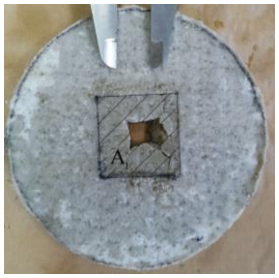


Figure. 4 Shows the photo of the tested specimens.

b) Results of self-healing ratio (α)

For damage area of 1787.0 mm^2, the rectangular and square damage specimens had the same α of 1 (fully healed) as shown in Figure 5(a). For damage area of 2578.7 mm^2 and damage area of 3500.0 mm^2, different shape resulted in different healing ratio (α). The shape of the holes after the leakage rate test are shown in Figure 5(b) and 5(c), and the calculated values of α are shown in Figure 6(a) and 6(b). It shows the same tendency as the value of ψ_{hole} in Figure 3.

For a rectangular damage to have the same self-healing capacity, the value of $R_{h\text{-}r}$ will be smaller than that $R_{h\text{-}c}$ of a circular damage with the same area, i.e.

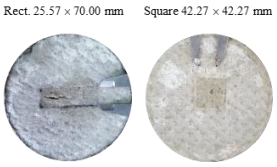
$$R_{h\text{-}r} = \beta R_{h\text{-}c} \tag{4}$$

where $\beta < 1.0$. From the test results in Figure 6 (a) and (b), $\beta \approx 0.88$ can be evaluated. Under the condition of the same damage area and the same self-healing ratio (α) (i.e. $R_{h\text{-}r} = 0.88R_{h\text{-}c}$). It can be easily derived that:

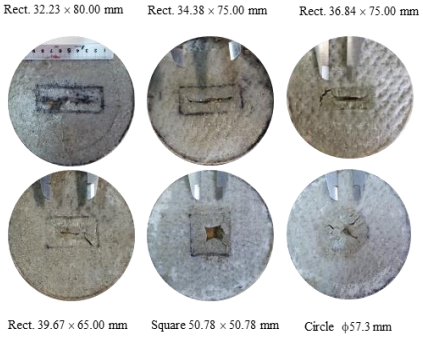
$$w = 2.00R \tag{5}$$

$$t = 1.57R \tag{6}$$

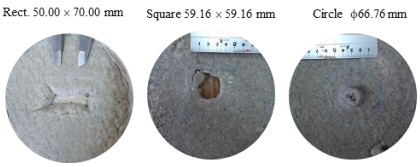
where, w and t are the width and the thickness of the rectangular damage hole and R is the radius of the circular damage hole. In this case the ratio of $w/t \approx 1.27$.



(a) Damage area of 1787.0 mm^2



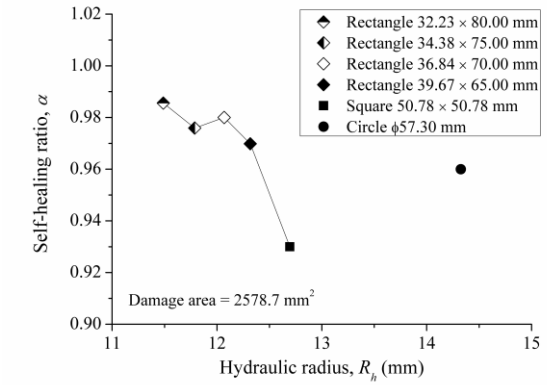
(b) Damage area of 2578.7 mm^2



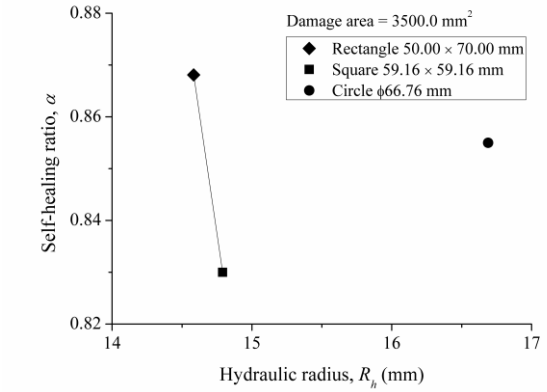
(c) Damage area of 3500 mm^2

Figure 5 GCL specimens after leakage rate test

The relationship between the mass (m_b) of the bentonite entered the damage holes and R_h and the relationship of the water content (w) of the bentonite entered the hole versus R_h are plotted in Figure 7(a) to 7(b) and Figure 8(a) to 8(b), respectively.



(a) Damage area of 2578.7 mm^2



(b) Damage area of 3500.0 mm^2

Figure 6 Results of α with R_h

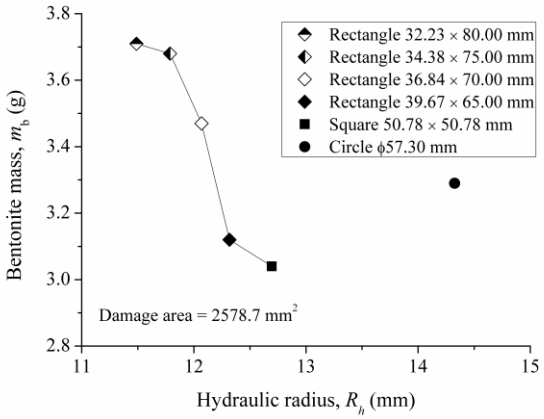
The relationships in Figure 7 and Figure 8 follow the general trend of Figure 3 and Figure 6 for both damage areas (2578.7 mm^2 and 3500 mm^2), i.e. lower the ψ_{hole}, higher the α and higher the value of m_b and w. Therefore, it is considered that (1) for a given damage area, for a square or rectangular shaped damage hole, the lower value of R_h, the higher the value of α, and (2) for a circular damage, it has a larger value of R_h, but a higher value of α compared with a square damage. As shown in Figure 4 for a square damage, there is a "corner effect". At the corners of a square damage hole, when the bentonites at adjacent two sides tends to enter the hole, they will influence each other and result in smaller mass entered the hole.

4. Conclusion

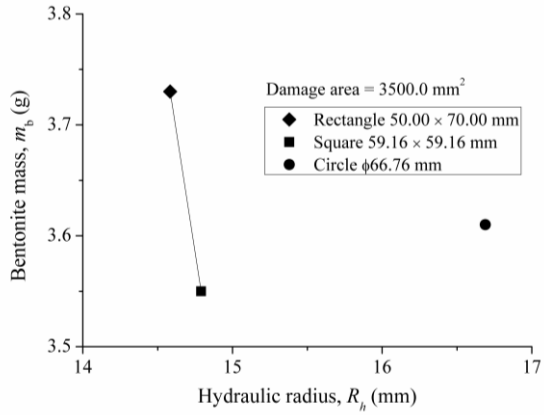
Effect of the shape of a damage hole on the self-healing capacity of a geosynthetic clay liner (GCL) with a damage hole has been investigated by a series of constant head leakage rare tests. Based on the test results, following conclusions can be drawn:

(1) The shape of a damage hole has a significant effect on the self-healing ratio (α = healed area/total area of a damage hole). Under the same damage area condition, a circular damage had higher value of α compared with a square damage. The reason considered is the "corner effect" of the square damage, i.e. at corners, in term of the hydrated bentonite entering the hole, adjacent perpendicular sides will influence each other and reduce the amount of hydrated bentonite entered the hole.

(2) For rectangular (including square) damages, the smaller the hydraulic radius (R_h = area/periphery length of a damage hole), the higher the value of α



(a) Damage area of 2578.7 mm^2

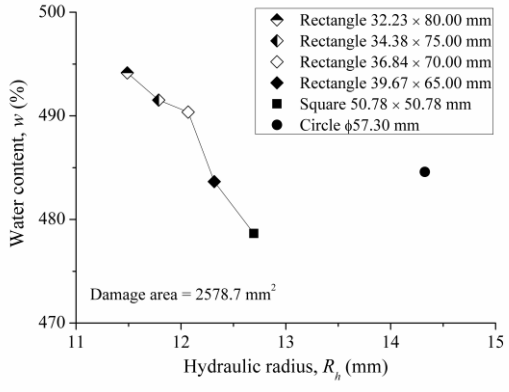


(b) Damage area of 3500.0 mm^2

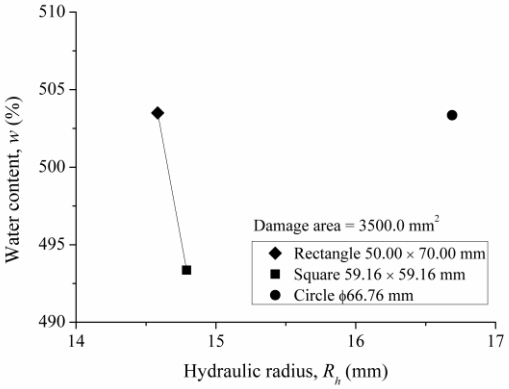
Figure 7 Relationship of m_b and R_h

Acknowledgement

This work has been supported by Grants-in-Aid for Scientific Research (KAKENHI) of Japan Society for the Promotion of Science (JSPS) with a grant number of 17K06558. Mr. Y. Togo, undergraduate student at Saga University, Japan prepared specimens and conducted leakage rate tests.



(a) Damage area of 2578.7 mm^2



(b) Damage area of 3500.0 mm^2

Figure 8 Relationship between w and R_h

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損傷がある GCL の自己修復能力に及ぼす損傷部形状の影響

Nutthachai Prongmanee・柴　錦春

損傷があるジオシンセンティックスクレイライナー(GCL)の自己修復能力および損傷部の透水量係数における損傷部形状の影響について、定水位透水（漏水）試験によって調べた。三つの損傷部形状、即ち円、長方形と正方形および異なる損傷の大きさを用いて試験を行った。径深（R_h = 損傷面積/損傷周長）を用いて、自己修復能力における損傷部形状の影響を検討した。試験結果から、修復率（α = 修復した面積/全損傷面積）は損傷部の形状に大きく影響していることが分かった。正方形・長方形損傷の場合、一定の損傷面積において、α は R_hの増加に伴って減少した。しかし、円形損傷と長方形損傷とを比べると、同じ損傷面積、同じ R_hでは円形損傷のα値が高い。これは長方形・正方形の場合、角の部分で損傷部二つの垂直の辺から損傷部にベントナイトが進入する際、お互いに影響し、結果として全体的に損傷部に進入したベントナイトの量が減少し、自己修復能力が低下したと考えている。この現象を“角の影響”と定義している。

キーワード：GCL、自己修復能力、径深、透水量係数