

Field applicability of self-recovering sustainable liner as landfill final cover

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Abstract Preventing the penetration of rainwater into a landfill site is the main purpose of the final cover in landfill sites. Conventional designs of landfill covers use geotextiles, such as geomembrane and geosynthetic clay liners, and clay liners to lower the permeability of the final cover of landfill sites. However, differential settlement and climatic effects in landfill sites instigate crack development or structural damage inside the final cover. This study therefore investigates the field applicability of a self-recovering sustainable liner (SRSL) as an alternative to the landfill final cover. The SRSL utilizes the precipitation reaction of two chemical materials to form precipitates that fill the pores and thereby lower the overall permeability of the liner. To examine the field applicability of the SRSL system, uniaxial compression tests and laboratory hydraulic conductivity tests were performed under various climatic effects such as wet/dry and freeze/thaw processes. Furthermore, field-scale hydraulic conductivity tests were performed with intentionally induced cracks to demonstrate the self-recovery performance for practical applications. Extensive laboratory and field test results confirmed the capability of the SRSL final cover system to fulfill the strength and hydraulic conductivity requirements, even in harsh field conditions.

Keywords SRSL · Permeability · Landfill final cover · Self-recovery performance

Introduction

The main purpose of landfill final cover is to avoid contact of waste with people and the surrounding environment, and minimize water penetration into the landfill site so that an increased amount of leachate and does not threaten the stability of the landfill structure and facilities. In many applications, the final cover system consists of compacted, fine-textured soil, either with or without a geomembrane depending on the regulations. Synthetic liners are practically impervious but are prone to damage or puncturing during/after installation since they are located at the top of the landfill, often exposed to the air and subjected to the ambient environment, including wet and dry or freeze and thaw cycles. On the other hand, compacted clay liners are more durable but have a finite permeability that can be increased by differential settlement, desiccation and so on.

Therefore, a number of studies have focused on developing an alternative method to overcome the drawbacks of the conventional liner system for landfill final cover. Some studies examined the use of cementing agents or grouting to stabilized waste, and others that of precipitation and adsorption reactions to chemically immobilize hazardous constituents (Heide et al. 1984; Frey et al. 1984; Rosar et al. 1988; Gouvenot et al. 1986; McLaren et al. 1988, 1991). Côté et al. (1996) suggested a ‘self-sealing, self-healing liner’, capable of self-repair in situ when damaged, that surrounds the mass of waste with two layers of porous material. The two layers, each containing a sufficient amount of interactive reagents, act as a waste-encompassing interface. Upon placement, the reagents in the two

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layers form precipitates that fill the pores at the interface of the two layers, and finally form a waste-encompassing layer with reduced permeability. The special benefit of this method is that the interactive reagents form a new seal if seal rupture occurs, thus preventing loss of noxious substances through the rupture.

Kwon and Park (2006) demonstrated the high performance of a self-recovering sustainable liner (SRSL) through laboratory permeability tests. The SRSL maintained a low hydraulic conductivity ($<1.0 \times 10^{-6}$ cm/s) against the cracks due to climatic stress effects such as freeze/thaw and wet/dry processes by the reaction of the two layers. Furthermore, the low hydraulic conductivity was maintained even with the introduction of intentional cracks, thereby demonstrating the high performance against various types of crack. Nevertheless, all these tests were performed in a laboratory and therefore suffered limitations such as the relatively small specimen size, which may not represent actual field conditions, and the inevitable errors introduced during lab testing, such as formation of voids during sample preparation, introduction of air into the saturated samples and growth of microorganisms on long-term tests (Olsen and Daniel 1981). Thus, most waste management projects require the performance of field hydraulic conductivity tests to establish the relationship between field and laboratory hydraulic conductivity test results for a project.

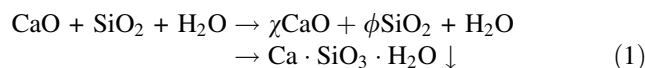
This study focuses on the practical application of an SRSL as a landfill final cover. Thus, this research examines the hydraulic conductivity and strength of the SRSL materials. The strength characteristics of the SRSL are investigated by unconfined compression tests under various conditions. The hydraulic conductivities of the SRSL are evaluated not only in the laboratory under various conditions, but also in a field application with the introduction of intentional cracks through field-scale tests to ensure the practical applicability of the SRSL. The field tests results are compared with the laboratory tests results.

Self-recovering sustainable liner

An SRSL is defined as a chemical liner that reduces the increased permeability arising from cracking by forming impermeable precipitates of chemicals contained in the liner (Kwon and Park 2006). When there occurs a crack and the rainfall is infiltrated, the self-recovery process is triggered. The self-recovery process (Fig. 1a) involves a transport stage where the constituents migrate along the concentration gradients and a reaction stage where the precipitates are formed at the boundary layer. These precipitates fill up the pores and form a layer, which differs in physical and chemical characteristics from the parent chemical itself. Any mechanical damage to the interface

will cause further diffusion and precipitation, thereby repairing the layer, which is the principal advantage of this technique (Fig. 1b, c).

In this study, diatomite and slaked lime were used for the recovery reaction. Diatomite is a soft, powdery, sedimentary mineral rock of fossilized remains that is mainly composed of SiO_2 . Slaked lime is a fine white powder that is mainly composed of $\text{Ca}(\text{OH})_2$. The sodium ash of Na_2CO_3 was used as a catalytic agent to catalyze the pozzolan reaction between the diatomite and slaked lime and so generate calcium carbonate. Thus, the general reaction for precipitation is described in Eqs. 1 and 2.



For visual confirmation of the reaction, spectroscopic analysis was performed with scanning electron microscopy (SEM, JSM-5600, Japan). The SEM image of Joomunjin standard sand and the interface of two layers, each mixed with the reactants of this study, are shown in Fig. 2a, b. The image shows that the precipitation covers the soil particles and forms a liner at the interface of the two layers.

Based on leaching tests, Kwon and Park (2006) reported negligible secondary contamination by the material used in the SRSL. The test results revealed major contaminant concentrations, such as arsenic (As), cadmium (Cd) and lead (Pb), at below detection limits.

Materials and methods

Field soils and SRSL layers

The upper layer of the twin-layer SRSL is a mixture of field soils and diatomite with sodium carbonate as a catalytic agent. In the lower layer, the field soil is mixed with slaked lime, which acts as a chemical additive in the field soil for the recovery reaction with diatomite.

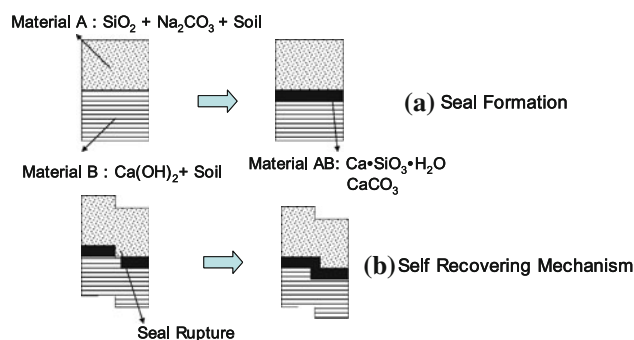


Fig. 1 Concept of SRSL: **a** seal formation and **b** self recovering mechanism (Kwon and Park 2006)

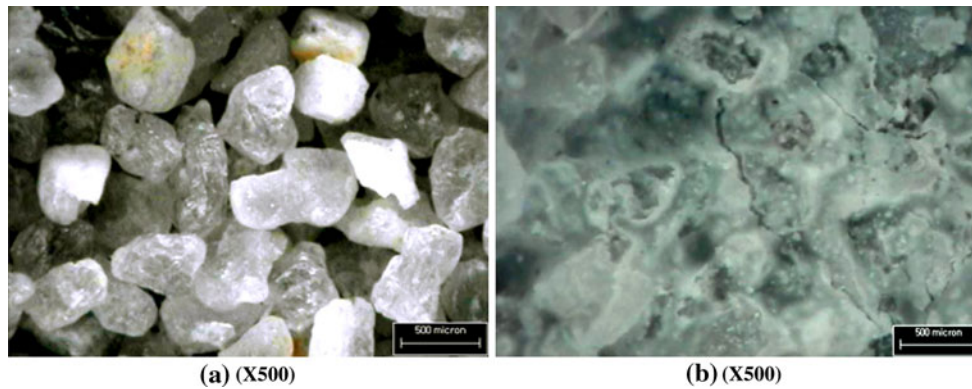


Fig. 2 SEM images of **a** Joomunjin standard sand, and **b** SRSL with sand

Table 1 shows the basic characteristics of the field soil. The natural moisture content was 9.9%, specific gravity 2.66, and hydraulic conductivity 1.5×10^{-5} cm/s. The liquid and plastic limits were non-plastic (NP), and the USCS soil classification was SW–SM soil (well graded sand and containing 8% of fine-grained (passed a No. 200 sieve). Figure 3 shows the gradation curve of the field soil.

In field, the SRSL layers were prepared in a batch plant in a powder form controlling the percentage of the chemical additives and the field soils. Each layer was compacted with an optimum water contents. The mixing ratios of the chemical additives in the specimens were determined from a previous study performed by Kwon (2006). The hydraulic conductivity tests were performed with various chemical contents on each single layer and mixed layer to find a minimum chemical contents to satisfy the hydraulic conductivity regulation ($<10^{-6}$ cm/s). Since the hydraulic conductivity of each layer of the SRSL must fulfill the Korean regulations (10^{-6} cm/s), the diatomite content must be more than 8% by weight with 2% of sodium ash as the catalytic agent in the upper layer, and the slaked lime content must be more than 12% by weight in the lower layer. In this study, the lower limit of each chemical additive was used: 90% soil, 8% of diatomite and 2% of sodium ash in the upper layer and 88% soil and 12% of slaked lime in the lower layer.

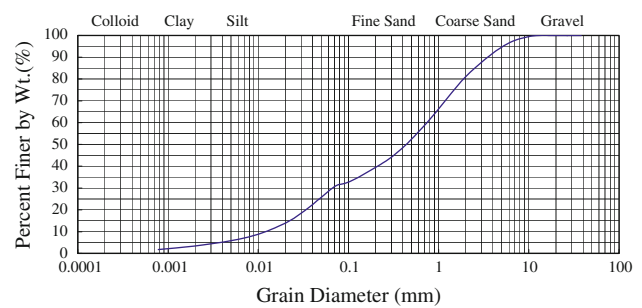


Fig. 3 Particle size gradation curve of field soil

Testing program

The testing programs were focused on the verification of the self-recovery behavior and field applicability of the SRSL. Thus, the testing program presented in Table 2 was operated because the strength and hydraulic conductivity are the two major concerns. Laboratory unconfined compression tests were performed to test the strength of the material, laboratory hydraulic conductivity tests the durability against climatic stress effects, and field hydraulic conductivity tests the self-recovery performance against large-scale cracks.

The optimum moisture contents of the SRSL were obtained from laboratory compaction tests. The specimens for the unconfined compression tests were prepared with

Table 1 Basic characteristics of the field soil

Test	USCS	Permeability (k , cm/s)	G_s	Atterberg Limit	D_{50} (mm)	D_{10} (mm)	
Value	SM–SW	1.5×10^{-5}	2.66	NP	0.45	0.013	
Test	C_u	C_c	W_n (%)	OMC (%)	γ_d (min, t/m^3)	γ_d (max, t/m^3)	q_u (kg/cm ²)
Value	34.6	1.2	15.5	13.5	1.20	1.89	4.2

Table 2 Test contents and field test methods

Test contents	Test methods
Basic characteristics	Soil classification, specific gravity, liquid and plastic limit, permeability of field soil
Compaction	Max. dry unit weight (t/m^3), optimum moisture content (%) SRSL material (field soil + diatomite/sodium ash or slaked lime)
Lab. compression tests	Measurement after curing time (7, 14, 28 days) Uniaxial compressive strength of SRSL with freeze/thaw and dry/moisture cycling
Lab. hydraulic conductivity	Hydraulic conductivity of SRSL in laboratory test (field soil + SRSL material) Hydraulic conductivity tests after various cycles of freeze/thaw and dry/moisture cycles: comparison with field soil
Field hydraulic conductivity	Field hydraulic conductivity tests were performed after intentional crack instigation

modified compaction mold (inside diameter of 50 mm) and 2.5 kg rammer with 30 cm falling height. Compaction with four layers with six blows per layer produces similar energy with the standard Proctor compaction.

Unconfined compression tests were performed to analyze the strength characteristics according to curing days and climatic changes. The hydraulic conductivities of the SRSL were investigated both in the laboratory under various conditions and in field with large cracks.

Laboratory tests against climatic effects

Compressive strength

In previous research on the final cover system, the main concern has generally focused on the hydraulic conductivity. However, strength should also be treated as another major issue as the final cover system is prone to damage during construction and is made of geo-materials. Thus, the compressive strength of the SRSL specimen was measured to evaluate the field workability and durability against climatic effects. The SRSL specimens were produced with a specified mixing ratio between the soil and the SRSL chemicals, and compacted at the optimum moisture content derived from the Proctor soil compaction test (ASTM D698). After the specimen production, the SRSL specimens were cured in a thermo-humidistat at 20°C and 40% humidity for 7, 14, and 28 days before the compression tests.

In addition, since the final cover is subjected to climatic changes and weathering processes such as freeze/thaw and wet/moisture that are reported to change the engineering properties of geo-materials considerably (Qi et al. 2006; Ogata et al. 1985), uniaxial compression tests were performed to evaluate the durability of the SRSL specimen against multiple cycles of freeze/thaw and wet/moisture. The SRSL specimens were subjected to different freezing temperatures (−30 and −40°C), freeze/thaw cycle durations

(6 and 24 h) and cycle numbers (3 and 10 cycles) and the variation of the compressive strengths was investigated. The dry/moisture process was examined by modifying the conventional test regulation of the American Society of Testing and Materials (ASTM D559). The specimen was placed in a drying oven at 70°C for 24 h. For the wetting process, the sidewalls of the specimens were wrapped with plastic film to maintain the form of the specimen, which were then saturated in a bucket of water for 24 h. The length of a single dry/moisture cycle was 48 h. The variation in permeability for the SRSL specimens was observed after 1, 3 and 5 dry/moisture cycles.

Hydraulic conductivity

Similar to the uniaxial compression tests, laboratory hydraulic conductivity tests were performed to verify the self-recovery performance against the climatic effects of the freeze/thaw and dry/moisture cycles.

Previous researchers reported a two-order of magnitude increase in hydraulic conductivity of clay due to freeze/thaw cycling in laboratory studies (Chamberlain et al. 1990; Othman and Benson 1993; Kim and Daniel 1992). Therefore, the freeze/thaw process was used to evaluate the self-recovery performance of the SRSL specimen at the crack occurred. The freeze/thaw test method was carried out according to the modified testing regulations published by the American Society of Testing and Materials (ASTM D6035, D560). A total of 48 h (freezing 24 h at −23°C, and thawing 24 h at 21°C) was considered to a single freeze/thaw cycle. The same amount of freeze and thaw durations applied as the strength tests were considered as a single freeze/thaw cycle. First, the hydraulic conductivity of the SRSL after 1–15 freeze/thaw cycles was estimated in order to evaluate the degree of cracking as a function of the number of cycles. However, the conventional freeze/thaw process results did not represent the SRSL self-recovery performance. Therefore, the SRSL self-recovery

performance was subsequently confirmed by observing the variation in conductivity of the SRSL specimens at different freezing temperatures (-40 , -30 and -20°C), freeze/thaw cycle durations (6 and 24 h) and cycle numbers (3 and 10 cycles).

Since final cover systems are subjected to periods of drying, usually immediately after construction, desiccation cracks may develop in a liner. In a laboratory study, the conductivity of desiccated samples increased by one order of magnitude or more (Dunn 1986). Therefore, the wet/dry process was used to evaluate the SRSL self-recovery performance at the crack occurred as another climatic effect. The effect of desiccation cracking caused by wet/dry cycling was examined by modifying the conventional test regulation (ASTM D559) because the main material of the specimens is the weathered soil.

Field tests: self-recovery performance against large cracks

The test site was an abandoned unsanitary landfill located in Chung Cheong Nam-Do, Korea, with an average annual temperature and precipitation of 11.6°C and 1,229 mm, respectively. The SRSL was installed in June, 2005, when the average monthly temperature and precipitation are 24°C and 174.5 mm, respectively (1971–2006 Daejeon Regional Meteorological Administration, <http://www.kma.go.kr>). The dimensions of the installed SRSL were 10 m (length) \times 5 m (width) \times 0.34 m (depth).

To investigate the self-recovery performance in the field, cracks were intentionally developed in the SRSL by raising a steel pipe (10 cm diameter, 6 m length) that was embedded along the edge side of the SRSL and then returning the pipe to its original position, as shown in Fig. 4a. Figure 4a also shows the three points (A 6 mm, B 4 mm and C 2 mm) where the field hydraulic conductivity tests were performed. After 28 days to allow the SRSL to recover, a field hydraulic conductivity test was conducted at these three points to evaluate the SRSL performance. In order to exclude the effect of evaporation loss during the tests, a control test was carried out with a bottom-closed pipe for calibration, as shown in Fig. 4c (the field hydraulic conductivity test mold at the very left).

Figure 5 shows the installation diagram and procedure of the field hydraulic conductivity tests. To prevent horizontal flow through the cracks, a hole was made to allow installation of an acryl mold, and bentonite and shotcrete were injected into the gap between the SRSL and the mold. In order to prevent the uplift pressure of water in the acryl mold, the initial height of water was 50 cm to the end of the acryl pipe, the bentonite and mortar block were installed, and the test was performed after 24 h for full saturation.

Test results and discussion

Laboratory tests against climatic effects

Compressive strength

Uniaxial compression tests were performed using the field SRSL material. Figure 6 shows stress–strain curves of typical unconfined compression tests on field soil only and SRSL materials before the self-recovery action for the preliminary comparison. The unconfined compressive strength of the SRSL specimen before the chemical reaction shows almost twice greater than that of field soil only. Furthermore, the strain at the peak strength of the SRSL material is larger than that of the field soil only showing that the mixture of SRSL material make the specimen becomes more ductile. Table 3 summarizes the variation of compressive strengths according to curing duration (7, 14 and 28 days). After 28 curing days, the compressive strengths of the upper layer, lower layer and two-layered specimens were above the regulation limit ($>5 \text{ kg/cm}^2$). Moreover, the compressive strength of the one-layered system mixed with upper and lower layer material after 28 curing days was increased by between 2.72 and 3.77 times compared to the other three SRSL specimens, due to the filling of the existing pores with the precipitates from the chemical reactions.

The uniaxial compression tests were performed to evaluate the durability of the specimens subjected to freeze/thaw and dry/moisture cycling. After 28 curing days, the freeze/thaw and dry/moisture processes were performed to exclude the effect of cementation with each SRSL material.

Figure 7a, b shows the uniaxial compression test results. The tests were performed by observing the variation in conductivity of the SRSL specimens at different freezing temperatures (-30 and -40°C), freeze/thaw cycle durations (6 and 24 h) and cycle numbers (3 and 10 cycles). The compressive strengths of all specimens at all conditions were maintained above a minimum of 18 kg/cm^2 , well above the regulation limit ($>5 \text{ kg/cm}^2$). The compressive strength was little affected by the number and duration of freeze/thaw cycles or the different freezing temperatures (-30 and -40°C). Note that all the specimens were carefully prepared and stored to maintain homogeneity between specimens, but there might be non-uniformity in the specimens, or procedural deviation, or the changes in the environmental conditions.

Figure 8 presents the variation of the compressive strength with different dry/moisture cycles. One day after the 28-day curing period (29 days in Fig. 7), the number of dry/moisture cycles affected the compressive strength but no regular tendency was evident. Interestingly enough, the overall compressive strength increased with more dry/

Fig. 4 Schematic diagram of SRSL in landfill final cover: **a** plane view and sectional view and **b** crack inducing system

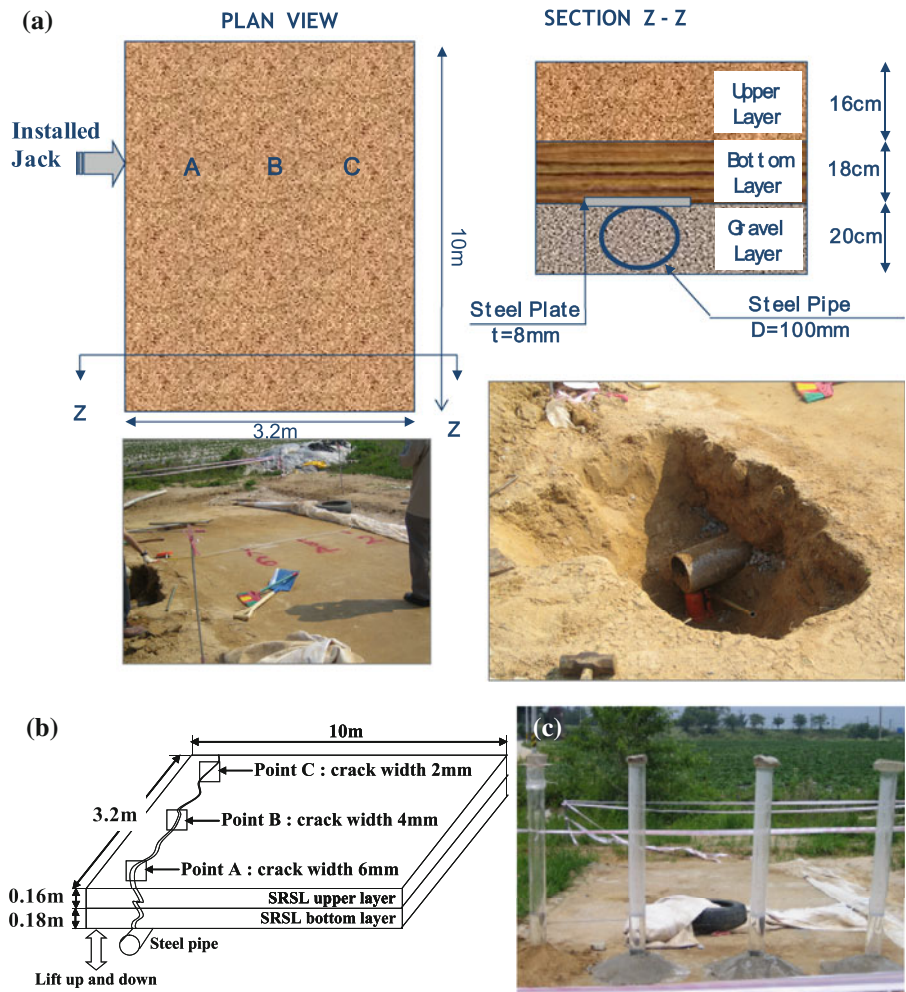
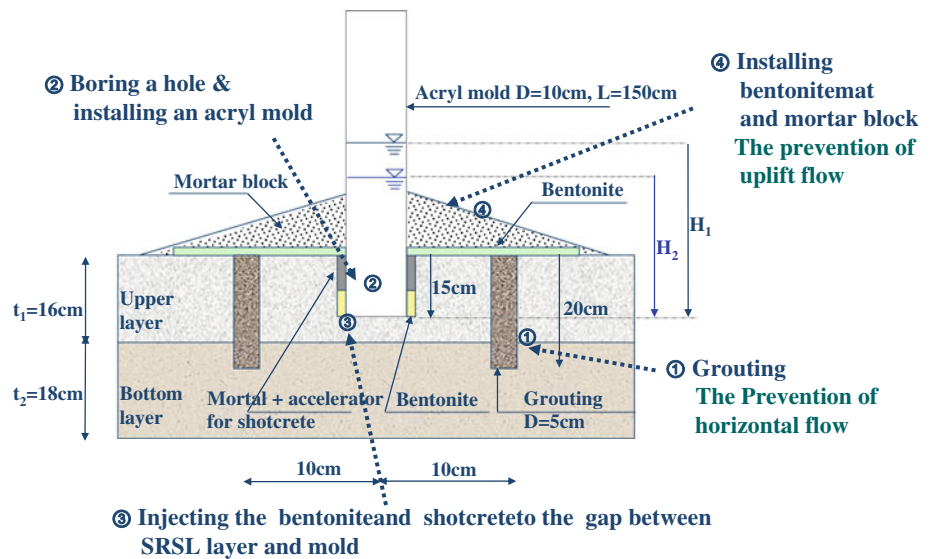


Fig. 5 Installation diagram and procedure of field hydraulic conductivity tester: (1) grouting, (2) installing an acryl mold, (3) injecting bentonite and shotcrete, and (4) installing bentonite mat and mortar block to prevent uplift flow



moisture cycles. This was attributed to the cementation effects arising from the addition of water, so that the dry/moisture effects were overcome by the curing effects of the

SRSL materials. All specimens showed a compressive strength higher than 10 kg/cm^2 , which is twice the regulation limit.

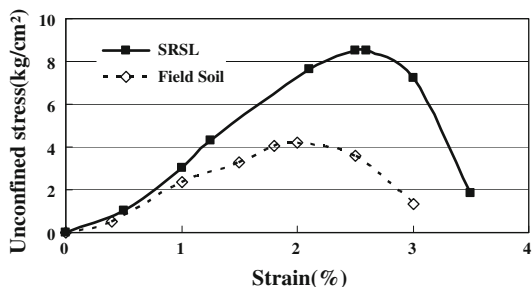


Fig. 6 Stress–strain curves of typical unconfined compression tests on field soil only and SRSL material

Table 3 Test results for uniaxial compression strength of SRSL

Specimen types	Uniaxial compression strength (kg/cm ²)			
	Initial	7 curing days	14 curing days	28 curing days
Upper layer: A (Na ₂ CO ₃ 2%)	10.37	13.08	19.63	18.22
Lower layer: B	5.77	7.03	7.67	17.91
Two-layered system	6.30	8.93	10.63	13.16
One-layered system (mixed with A, B)	12.47	31.45	44.71	49.55

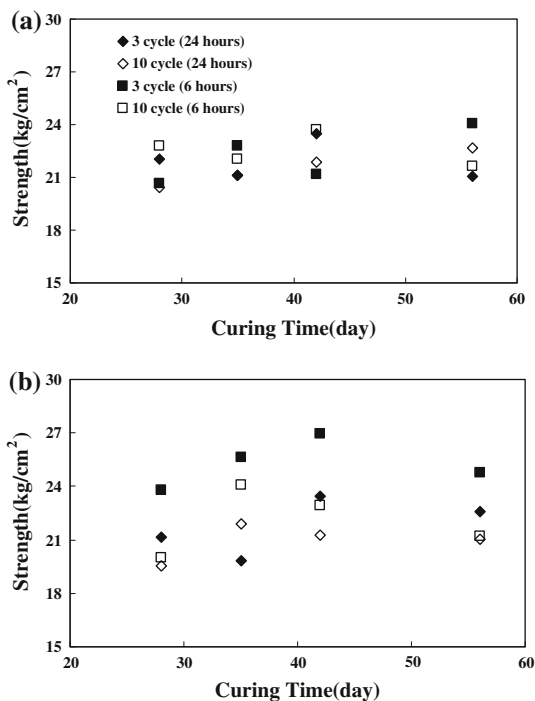


Fig. 7 Uniaxial compression strength test results after freeze/thaw process with a freezing temperature of **a** -40°C and **b** -30°C

Hydraulic conductivity

Laboratory hydraulic conductivity tests were performed using the field SRSL material. The variation of hydraulic

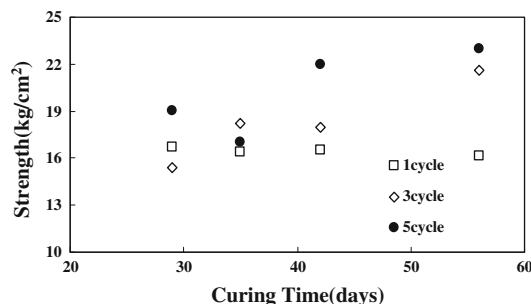


Fig. 8 Uniaxial compression strength test results after wet/dry process

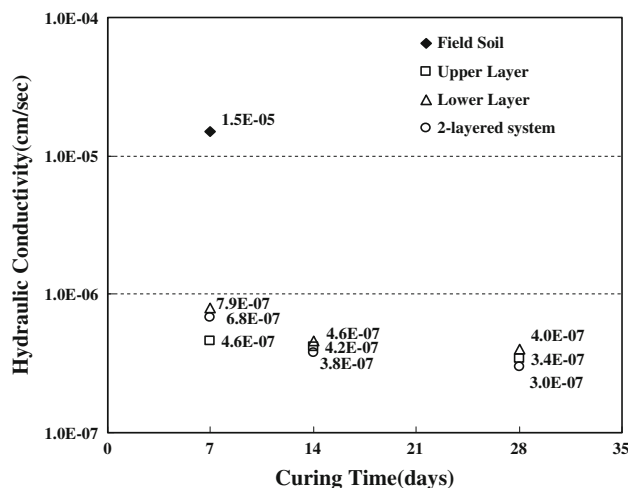


Fig. 9 Laboratory hydraulic conductivity test results using field SRSL materials

conductivity was measured with different curing durations (7, 14, and 28 days) and the results are shown in Fig. 9. The hydraulic conductivities of all SRSL materials were an order of magnitude smaller than those of the field soil. As we may expect all layers (upper, lower and two-layered systems) show similar k values, because the layer with smaller permeability will control the vertical conductivity of the overall system. The two separate SRSL materials by themselves showed sufficiently low hydraulic conductivities for the landfill final cover and the hydraulic conductivity of the two-layered SRSL material also fulfilled the regulation limit. The hydraulic conductivities of all three SRSL materials were decreased to below 10^{-6} cm/s after 7-day curing and continued to decrease with increasing curing time to half of the value at 14-day curing duration. The hydraulic conductivity of the two-layered SRSL specimen decreased from 6.8×10^{-7} to 3.0×10^{-7} cm/s at 21-day curing. The hydraulic conductivity of the two-layered system was less than the harmonic mean conductivity of the upper and lower layers (14 days: 4.39×10^{-7} cm/s, 28 days: 4.67×10^{-7} cm/s), which suggested the action of self-recovery during this procedure.

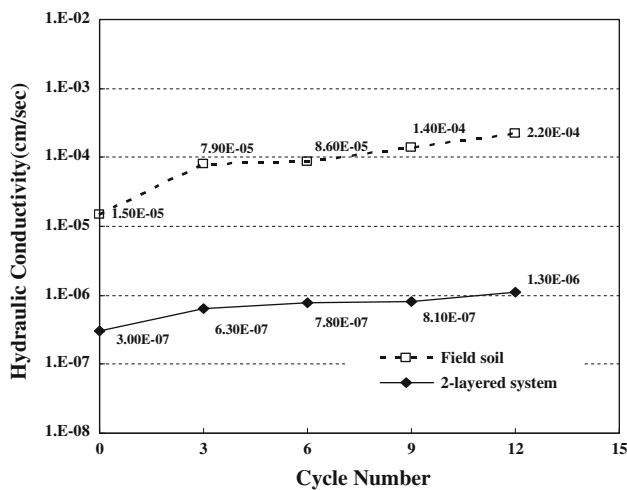


Fig. 10 Hydraulic conductivity results after 3, 6, 9, and 12 freeze/thaw cycles

The hydraulic conductivity of the SRS� and the field soil-only specimens after 3, 6, 9 and 12 freeze/thaw cycles was estimated in order to evaluate the degree of cracking as a function of number of freeze/thaw cycles and to confirm the self-recovery performance, as shown in Fig. 10. As compared with the hydraulic conductivity of the field soil-only specimen after freeze/thaw processing, the two-layered specimen of the field SRS� exhibited a two-order of magnitude decrease of the hydraulic conductivity after 12 cycles (2.2×10^{-4} vs. 1.3×10^{-6} cm/s, respectively). This large decrease confirmed the resistibility of the field SRS� against freeze/thaw effects. Although the SRS� exhibited some resistibility to climatic effects, the hydraulic conductivity of the two-layered specimen after 12 freeze/thaw cycles exceeded the regulated level for landfill final cover in Korea ($>1.0 \times 10^{-6}$ cm/s). However, the hydraulic conductivity of this process was checked on only 2 days, so the hydraulic conductivity of the SRS� specimen after freeze/thaw processing may have been continuously decreased below the hydraulic conductivity regulation for landfill final cover by the self-recovery performance.

Similar to the investigation of the freeze/thaw effects on the SRS� materials, both the field soil-only specimens and the SRS� materials were subjected to different dry/moisture cycles. The hydraulic conductivity of the two-layered SRS� system and the field soil-only specimen after 3, 6, 9 and 12 dry/moisture cycles was estimated in order to evaluate the degree of cracking as a function of number of dry/moisture cycles and to confirm the self-recovery performance of the field SRS�.

Figure 11 shows the hydraulic conductivity after dry/moisture processing. Similar to the freeze/thaw cycles, the two-layered SRS� specimen exhibited a two-order of magnitude decrease of the hydraulic conductivity

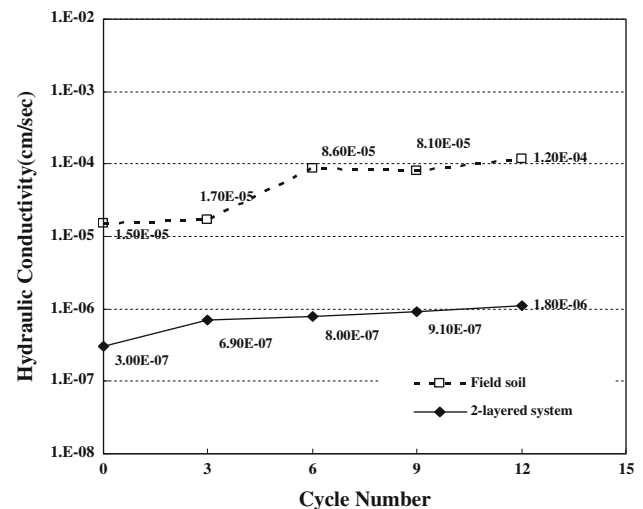


Fig. 11 Hydraulic conductivity results after 3, 6, 9, and 12 dry/moisture cycles

compared with the hydraulic conductivity of field soil-only specimen (1.8×10^{-6} vs. 1.2×10^{-4} cm/s, respectively), even with the dry/moisture process. This large decrease, even with the dry/moisture cycling, revealed the resistibility of the field SRS� against both the freeze/thaw effects and the dry/moisture effects. However, despite the two-order of magnitude difference in hydraulic conductivity between the field soil and SRS� system, the hydraulic conductivity of the two-layered specimen after 12 dry/moisture cycles exceeded the regulated level for landfill final cover in Korea ($>1.0 \times 10^{-6}$ cm/s).

However, again, the hydraulic conductivity in this test was only measured on 2 days, which was insufficient to measure the full SRS� recovery performance. Therefore, the hydraulic conductivity of the SRS� specimen was continuously decreased below the regulated level of hydraulic conductivity for landfill final cover by the self-recovery performance.

Field test results: self-recovery performance against large cracks

Field hydraulic conductivity tests were performed after intentional crack processing as previously explained. The field permeability (k) was calculated using the modified Boutwell field hydraulic conductivity equation suggested by Hvorslev (1949) and Daniel (1989) due to the relatively thin SRS� thickness (34 cm).

$$k = \frac{\pi D}{11(t_2 - t_1)} \ln \frac{H_1}{H_2} \quad (3)$$

where D represents the diameter of the pipe (cm), H the water level (cm) and t the time (s) at which the level was measured.

Table 4 Hydraulic conductivity measured at different points in the SRSL field testing (the amount of water evaporated was considered)

Point	Test No.	Δt (s)	Water level (cm)		Field permeability (cm/s)
			H_1	H_2	
A	1	84,600	49.3	48.7	4.13×10^{-7}
	2	91,800	48.7	48.2	3.21×10^{-7}
	3	252,000	48.2	47.0	2.86×10^{-7}
B	1	75,600	50.5	49.8	5.27×10^{-7}
	2	91,800	49.8	48.6	7.59×10^{-7}
	3	252,000	48.6	46.3	5.49×10^{-7}
C	1	75,600	52.4	51.9	3.62×10^{-7}
	2	91,800	51.9	51.3	3.62×10^{-7}
	3	252,000	51.3	50.1	2.68×10^{-7}

Table 4 shows the hydraulic conductivity measured in the field tests, in which the water evaporated during the test was considered. The water levels were measured over three different durations for up to 70 h. The hydraulic conductivity of the SRSL system remained below 1×10^{-6} cm/s under all conditions, even upon the development of a large crack sized from 2 to 6 mm. The average hydraulic conductivity was below 1×10^{-6} cm/s at every testing point (A: 2.86×10^{-7} cm/s, B: 5.49×10^{-7} cm/s and C: 2.68×10^{-7} cm/s). This indicated that the self-recovery performance was well maintained even at crack size up to 6 mm. Interestingly, the hydraulic conductivity at point A with the largest crack was lower than that at point B with a smaller crack. The larger hydraulic conductivity values of the separate SRSL materials than those of the mixed SRSL prevented confirmation of the self-recovery reaction. The hydraulic conductivity values measured from the field tests were very similar to those obtained from the laboratory tests.

Discussions on field hydraulic conductivity tests

As mentioned in the previous section, the field hydraulic conductivity was calculated using the modified Boutwell permeameter method. The original Boutwell method consists of two stages to evaluate the relative effect of vertical and horizontal conductivities. Nevertheless, the two stages of the Boutwell test were not successively performed at a borehole because the liner thickness of the SRSL sealing material, which was required to calculate hydraulic conductivity, was estimated at less than 1 cm in this test. Consequently, it was hard to obtain an accurate evaluation of the vertical hydraulic conductivity of the SRSL through the original Boutwell method. Thus, the hydraulic conductivity measured in the field tests included both the

vertical and horizontal directions. However, as the horizontal conductivity is generally 5–10 times greater than the vertical one in compacted clays (Daniel 1989), the hydraulic conductivity measured herein successfully fulfills the requirement of less than 1×10^{-6} cm/s.

Furthermore, temperature is another factor that influences the hydraulic conductivity. In general, the temperature standard is 15°C and the hydraulic conductivity is corrected due to the variation of the dynamic viscosity of water due to the temperature change, as expressed in Eq. 4.

$$k_{15^\circ\text{C}} = k_{T^\circ\text{C}} \times \frac{\mu_{T^\circ\text{C}}}{\mu_{15^\circ\text{C}}} \tag{4}$$

where $k_{15^\circ\text{C}}$ is the hydraulic conductivity at 15°C (standard hydraulic conductivity) and $\mu_{T^\circ\text{C}}$ the dynamic viscosity of water at $T^\circ\text{C}$.

As the outside temperature in this field test was maintained in the range 25–29°C, an additional decrease of 21.8–28.6% was expected from the hydraulic conductivity values reported in Table 4. Therefore, no temperature correction needed to be applied as all the field permeability results were already below the regulated maximum hydraulic conductivity for landfill final cover in Korea of 10^{-6} cm/s.

The hydraulic conductivity of the SRSL sealing layer was calculated in order to confirm the explicit self-recovery performance of the SRSL sealing layer under the assumptions of a 1 cm-thick, SRSL sealing layer and a field water flow (field hydraulic conductivity) in the vertical direction. The hydraulic conductivity of the SRSL sealing layer can be estimated with Eq. 5.

$$k_{\text{field}} = \frac{18 \text{ cm}}{\frac{1 \text{ cm}}{k_{\text{seal}}} + \frac{17 \text{ cm}}{k_{\text{bottom-crack}}}} \tag{5}$$

The range of k_{field} (field hydraulic conductivity) was from 1.91×10^{-7} to 5.94×10^{-7} cm/s. The hydraulic conductivity of the lower layer with crack, $k_{\text{bottom-crack}}$, was reported as 5.5×10^{-3} cm/s (Kwon 2006). The calculated hydraulic conductivity of the created SRSL sealing layer ranged from 1.11×10^{-8} to 2.28×10^{-8} cm/s. In practice, the hydraulic conductivity of the created SRSL sealing layer might be lower because field hydraulic conductivity, k_{field} , might be lower than the actual vertical hydraulic conductivity and because the SRSL sealing layer might be thinner than 1 cm.

Conclusions and further study

Based on the results of extensive experimentation, the following conclusions can be drawn regarding the field applicability and self-recovery behaviors of SRSL as a landfill final cover.

1. In the uniaxial compaction test, the compressive strengths of the upper layer, lower layer and two-layered SRS� specimens after 28 curing days were well above the regulation limit ($>5 \text{ kg/cm}^2$). Moreover, the compressive strength of the SRS� system was maintained even after freeze/thaw and dry/moisture cycling, demonstrating its high durability against climatic effects.
2. The SRS� exhibited good performance in terms of hydraulic conductivity under both intact final cover conditions and climatic effects. The cracks induced by the climatic effects (freeze/thaw and wet/dry processes) were repaired by the reaction in the SRS�, and the final hydraulic conductivity was stabilized below the regulated level for landfill final cover in Korea.
3. In field tests, cracks up to 6 mm were intentionally developed in the SRS� by raising a steel pipe that was embedded along the edge side of the SRS� and then returning the pipe to its original position. Even upon the development of a large crack sized from 2 mm to 6 mm, the hydraulic conductivity of the SRS� system remained below $1 \times 10^{-6} \text{ cm/s}$ under all conditions. This indicated that the self-recovery performance was well maintained even at crack size up to 6 mm.

These experimental results for the basic characteristics, hydraulic conductivity and compressive strength of field SRS� material verified the potential field applicability of SRS� in landfill final cover. However, the long-term performance for years of the self-recovery is not guaranteed in this study. Particularly, the precipitates from the self-recovery reaction might be dissolved in the acidic rains. Further work is needed about the effects of environmental changes in the long-term performance and properties of SRS�.

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