

Geosynthetics applied in waste landfills and containment facilities

Katsumi, T. & Inui, T.

Graduate School of Global Environmental Studies (GSGES), Kyoto University, Sakyo, Kyoto, Japan

Ishimori, H.

National Institute for Environmental Studies (NIES), Tsukuba, Ibaraki, Japan

Kamon, M.

Kagawa National College of Technology, Takamatsu, Kagawa, Japan

Keywords: hydraulic conductivity, chemical compatibility, coastal landfills, abandoned wastes, remediation

ABSTRACT: Among the recent challenges related to developments and applications of the geosynthetics in landfill engineering, three issues on geomembranes and geosynthetic clay liners (GCLs) are discussed in this paper, including (1) chemical resistance of GCLs against synthetic chemical solutions and waste leachate, (2) performance of geosynthetic materials applied to the coastal waste containment facilities, and (3) application of geosynthetic barriers to remedial actions at abandoned waste disposal sites. To evaluate the chemical compatibility of bentonitic barrier materials including GCLs, the chemical equilibrium is necessary, and therefore the long-term hydraulic conductivity tests have been conducted on GCLs against chemical solutions and waste leachates. Heterogeneity is also an important issue to discuss the hydraulic barrier performance, particularly when the prehydration prior to the permeation of waste leachate is expected. These aspects have been discussed in the first part of this paper. Due to the limitation of inland space available to waste disposal, coastal landfills and the associated containment systems are important considerations, particularly for metropolitan areas. Barrier performances of several types of side barrier systems using geosynthetic materials have been numerically analyzed in the second part of this paper. Remediation of the sites where the wastes have been abandoned and/or wastes have been disposed of without engineered containment systems under old regulations has been a critical issue. An analytical study to evaluate the cost-effective remedial option for a dumped waste site located along a landslide area, where cut-off wall keyed into the aquitard might elevate groundwater level and thus may not be employed, is presented.

1 INTRODUCTION

Numerous challenges have been made on the development of geosynthetic materials and their applications to landfill engineering, partly because of the social demand to environmental issues. Among these challenges, evaluation of the long-term performances of geosynthetic materials including geomembranes and geosynthetic clay liners (GCLs) has been a great issue. Many works have been conducted on the long-term durability and chemical compatibility of geomembranes and GCLs. The applications of geosynthetic materials to harsh environments such as coastal landfills and abandoned waste disposal sites have also been discussed particularly in the authors' country, due to the limitation of inland space available to waste disposal and the necessity of construction over the abandoned sites.

Based on these backgrounds, three issues are presented in this paper, that are (1) chemical resistance of GCLs against synthetic chemical solutions and waste leachate, (2) performance of geosynthetic ma-

terials applied to the coastal waste containment facilities, and (3) application of geosynthetic barriers to remedial actions at abandoned waste disposal sites. Chemical compatibility of GCLs is evaluated using hydraulic conductivity test with and/or without prehydration conditions, considering the chemical equilibrium and heterogeneity in Chapter 2. Since coastal landfills and the associated containment systems are important considerations particularly for metropolitan areas in Japan, barrier performances of several types of side barrier systems using geosynthetic materials have been numerically analyzed in Chapter 3. Remediation of the sites where the wastes have been abandoned and/or wastes have been disposed of without engineered containment systems under old regulations has been recent a critical issue in Japan. An analytical study on contaminant transport to evaluate the cost-effective remedial option for a dumped waste site located along a landslide area is presented in Chapter 4.

2 CHEMICAL RESISTANCE OF GCL

Geosynthetic clay liners (GCLs) are manufactured clay liners, which consist of a thin layer of bentonite glued to a geomembrane or encased by geotextiles. GCLs are considered effective barrier materials that can be used as alternatives or combined with previous barrier materials, due to their relatively low cost, easy installation, long-term stability, deformability, and excellent barrier performance to water. The barrier performance of GCLs to permeant solutions is significantly dependent on the swelling volume of bentonite in them. The swelling is the crystal interlayer expansion of montmorillonite in the bentonite by the intercalation of water molecules. Pure water is easily intercalates between the crystal interlayers, and expands them. The bentonite in the pure water exhibits the sufficient swelling and barrier performance. In contrast, electrolytic chemical solutions such as waste leachates limit the crystal interlayer expansion, because cations in the solutions attract the crystal interlayers charged with a negative potential. Therefore, bentonite in electrolytic chemical solutions exhibits the insufficient swelling and barrier performance (Norrish 1954; Norrish and Quirk 1954; Lutz and Kemper 1958; Posner and Quirk 1964; McNeal et al. 1966; van Olphen 1977; Alther et al. 1985; McBride 1994; Egloffstein 1995; Prost et al. 1998). Many researchers have pointed out the deterioration of the swelling capacity and barrier performance of bentonites and GCLs against electrolytic chemical solutions, and have examined their chemical compatibility and improvement.

This section describes the following three factors affecting the barrier performance of GCLs: (1) type and concentration of electrolytic chemical solutions permeating the GCLs, (2) prehydration effects by hydrating bentonite in the GCLs with water, before the bentonite is exposed to the permeant solutions, and (3) effects of confining pressures due to weight of landfill wastes.

2.1 Long-term hydraulic conductivity of GCLs against chemical solutions and waste leachates

An increase in the hydraulic conductivity by the permeation of electrolytic solutions is of great concern to use GCLs in the sea areas or waste containment facilities. When the electrolytic solution containing exchangeable cations permeates into GCLs, the space of crystal interlayers of clay minerals (in particular, montmorillonite) is narrowed by the attraction force of the cations, and the swelling volume and the barrier performance of bentonite are decreased. In the cases of the electrolytic solution having the multivalent exchangeable cations, moreover, the multivalent cations replace the monovalent cations occupied in the exchange sites of montmorillonite so that the barrier performance are further de-

creased. Many researchers have conducted the hydraulic conductivity tests of nonprehydrated GCLs using single-species or multi-species solutions of sodium chloride and calcium sodium etc., and have shown that the hydraulic conductivity of GCLs became higher for the electrolytic solution with the higher ionic valence and concentration of the permeant solution (Gleason et al. 1997; Petrov and Rowe 1997; Ruhl and Daniel 1997; Shackelford et al. 2000; Jo et al. 2001; Shan and Lai 2002; Katsumi et al. 2004 and 2007; Kolstad et al. 2004a). In addition, they have also shown that the hydraulic conductivity correlates the swelling volume which the bentonite in the GCL exhibits in the permeant solution (Jo et al. 2001; Katsumi et al. 2008b).

The following subsections summarize the characteristics of the swelling volume and hydraulic conductivity of not only general nonprehydrated GCLs, but also two manufactured chemical resistance materials that one is multiswellable bentonite developed by Onikata et al. (1996) and the other is dense-prehydrated GCL.

2.1.1 Swelling volume

Swelling volume of bentonite in a GCL has been considered an effective indicator to estimate the barrier performance of the GCL for a permeant solution. It is because the swelling volume can be easily evaluated for about a day according to ASTM D 5890 while the hydraulic conductivity test according to ASTM D 5084 spends a long-term duration like several months. The difference in swelling volume to various permeant solutions indicates the chemical compatibility as the barrier material against each solution.

Figure 1 shows the swelling volume of sodium bentonite to each chemical solution. The bentonite is obtained from needle-punched GCL and it has a powdered form. The permeant solutions consist of single-species or multi-species components of sodium chloride (NaCl), calcium chloride (CaCl₂), and potassium chloride (KCl). The ionic strength for cations, I , and the ratio of monovalent cations to divalent cations, RMD, are defined as

$$I = \frac{1}{2} \sum_{j=1}^N c_j z_j^2, \quad RMD = \frac{M_m}{2\sqrt{M_d}}$$

where c_j = the concentration of "j"-th cation of the aqueous solution, z_j = the valence or charge of "j"-th cation of the aqueous solution, N = the number of all cations in the solution, M_m and M_d = the concentration of monovalent and divalent cations, respectively. In this study, the ionic strength is calculated from the concentration of only cations, because the swelling and barrier performance of bentonite are significantly dependent on the exchangeable cations. The ratio of monovalent to divalent cations is also calculated as mentioned above although another defini-

tion not including factor of "2" is proposed (Kolstad et al. 2004a; Shackelford 2007).

As shown in Fig. 1, the swelling volume became smaller for the solution with the stronger ionic strength. In addition, the divalent cation of calcium had an influence on the decrease in the swelling volume more than the monovalent cation of sodium as to the solution with the ionic strength of 0.1 M. However, the difference hardly appeared in a strong ionic strength of 0.5 M. The bentonite hardly swells in a solution having such a concentration level. Hence, the barrier performance as well as the swelling volume has been considered remarkably changed by electrolytic solutions having ionic strength of < 0.5 M.

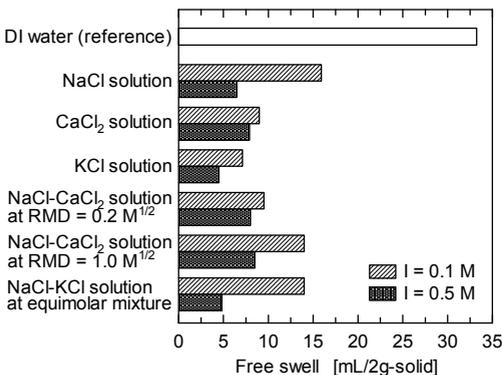


Figure 1. Swelling volume to electrolytic solutions

2.1.2 Long-term hydraulic conductivity

The hydraulic conductivity test of GCLs was conducted using flexible-wall permeameters according to ASTM D 5084. A GCL specimen, which had a 60 mm in diameter, was placed in the permeameter, and then a permeant solution was directly permeated from the influent point without prehydration. The flow volumes, the thickness, and the hydraulic conductivity of the specimen were measured over the testing duration. The hydraulic conductivity when termination criteria described in ASTM D 6766 was satisfied was regarded as a representative value.

The hydraulic conductivity of nonprehydrated GCLs against electrolytic chemical solutions is shown in Fig. 2. The hydraulic conductivity values were measured in testing conditions of a cell pressure of 20-30 kPa, an average hydraulic gradient of 90, and a constant temperature of 20 °C. The GCL exhibited an excellent barrier performance of $k = 2.2 \times 10^{-11}$ m/s to the deionized water. However, the barrier performance of GCLs deteriorated to electrolytic chemical solutions. The hydraulic conductivity became larger to electrolytic chemical solutions with stronger ionic strength, because the swelling volume became smaller to the stronger solutions (see Fig. 1).

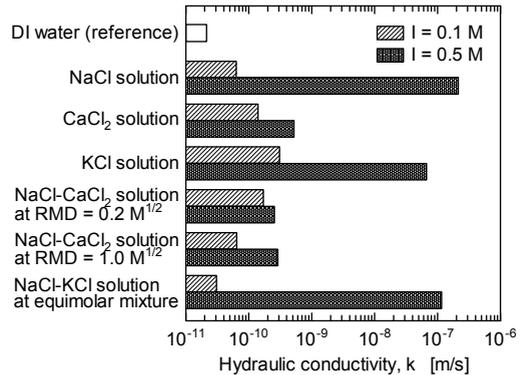
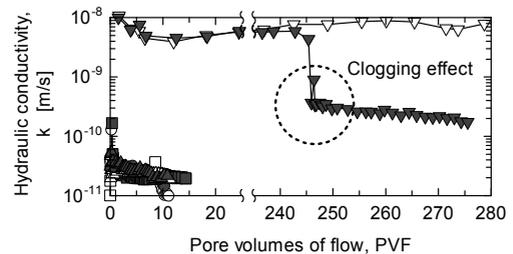


Figure 2. Hydraulic conductivity to electrolytic solutions



Open: filtered waste leachate, Closed: raw waste leachate
 ○—● Waste leachate A (pH = 6.50, EC = 0.023 S/m)
 □—■ Waste leachate H (pH = 7.97, EC = 0.090 S/m)
 △—▲ Waste leachate S (pH = 11.8, EC = 0.404 S/m)
 ▽—▾ Waste leachate K (pH = 7.75, EC = 2.842 S/m)

Figure 3. Long-term hydraulic conductivity of GCLs against four waste leachates and their filtered solutions

Figure 3 shows the long-term change in the hydraulic conductivity of GCL against waste leachates with time. The x-axis is the pore volumes of flow regarding the elapsed time, and this parameter is a value in which the accumulated flow volume is divided by the porous volume of the specimen. The permeant solutions were four waste leachates, A, H, S, and K, and their solutions filtered with 6 μm mesh filter paper. The GCLs permeated with waste leachates of A, H, and S exhibited a good barrier performance of about $k = 2.0 \times 10^{-11}$ m/s. They could exhibit a good barrier performance even to waste leachate S which had a high pH value of 11.8. However, waste leachate K seriously deteriorated the barrier performance. It was because waste leachate K had an enough electrolytes so that bentonite in the GCL exhibited an insufficient swelling. The filtration of the waste leachates hardly affected the hydraulic conductivity value of GCLs. However, the hydraulic conductivity of GCL was abruptly much decreased from PVF > 245 in the testing case to use waste leachate K without filtration. The reason was because the GCL pore specimen might be blocked by the colloidal matters contained in the waste leachate. GCLs permeated with simulated electrolytic

chemical solutions such as NaCl and/or CaCl₂ solutions also showed a similar profile that their hydraulic conductivities hardly changed with time (Katsumi et al. 2007). One of the differences in between the real waste leachates and the simulated chemical solutions as permeant solutions is whether colloidal matters are included or not to block the pore of GCLs. The colloidal matters may work to decrease the hydraulic conductivity as shown in Fig. 3.

Figure 4 shows the long-term change in the hydraulic conductivity of GCL against waste leachate K and its diluted solutions. The results pointed out that the hydraulic conductivity was different even if the solutions permeating GCLs had the same electric conductivity. The GCL exhibited the hydraulic conductivity of $k = 5.2 \times 10^{-10}$ m/s to old waste leachate K left alone for a year after its sampling, although the GCL exhibited $k = 6.2 \times 10^{-9}$ m/s to fresh waste leachate K immediately after its sampling. Probably, the organic substances contained in the waste leachate may be deteriorated by leaving them alone for a year. It will be necessary to evaluate the effects of organic substances or colloidal matters on the barrier performance of GCLs.

The dilution of the waste leachate K decreased the hydraulic conductivity, because the electrolytic concentration of permeant solutions was decreased by the dilution. The long-term hydraulic conductivity to the $\times 4$ diluted waste leachate K showed an impressive profile. The hydraulic conductivity of the GCL was evaluated as approximately $k = 2.0 \times 10^{-11}$ m/s in $PVF < 7$, but the hydraulic conductivity increased gradually over time in $PVF > 7$ and it reached $k = 8.7 \times 10^{-11}$ m/s in two years. Such a slow increase in the hydraulic conductivity sometimes occurred for permeation solutions with a low electrolytic concentration (Shackelford et al. 2000). It was necessary to be careful for a long-term change of barrier performance when a GCL was permeated with an electric solution having a low concentration.

Figure 5 shows the relationships between the hydraulic conductivity and the electric conductivity of permeant solutions. The hydraulic conductivity was increased with the electric conductivity. The difference between the single-species solutions and the multi-species solutions appeared in the range of $EC > 2$ S/m, although the difference did not appear in the range of $EC < 2$ S/m. When the electric conductivity was equivalent, the hydraulic conductivity to monovalent single-species solutions of NaCl and KCl was highest as shown in dash line in Fig. 5, and the hydraulic conductivity to multi-species solutions including CaCl₂ became lower than that shown in the dash line. Here, it is noted that the electric conductivity is not equivalent even when the ionic strength is equivalent. Electric conductivity which can be easily measured will be an effective indicator to estimate the barrier performance of a GCL. For example, the hydraulic conductivity of the GCL has

been considered $k < 1.0 \times 10^{-9}$ m/s according to Fig. 5 when the electric conductivity of a sampled waste leachate is less than 2 S/m.

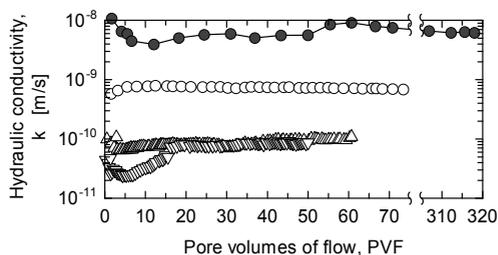


Figure 4. Long-term hydraulic conductivity of GCLs against waste leachate K and its diluted solutions

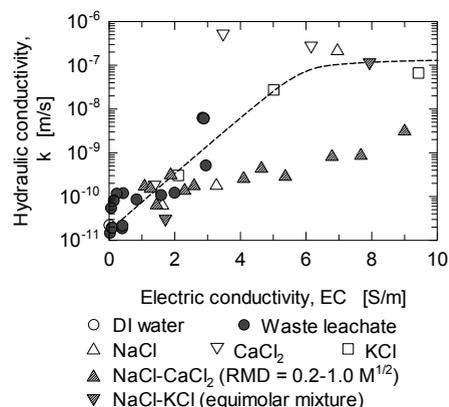


Figure 5. Relationship between the hydraulic conductivity and the electric conductivity of permeant solutions

2.1.3 Performance of chemical resistance materials

To improve the deterioration of GCLs against chemical attacks, some chemical resistance materials has been developed. In this subsection, the characteristics and the barrier performance of two manufactured chemical resistance materials, (1) multiswellable bentonite (MSB) and (2) dense prehydrated GCL (DPH-GCL), are described as follows.

Onikata et al. (1996) discovered that propylene carbonate (PC) can be utilized as a swelling activation material to natural bentonite (NB). The MSB which is a complex of NB and PC can swell enough for electrolytic solution and fresh water (Onikata et al. 1996; Shackelford et al. 2000; Katsumi et al. 2004, 2008b; Katsumi and Fukagawa 2005). Also, hydrating the bentonite before exposed by electrolytic solutions is effective method to enhance the chemical compatibility. Dense prehydrated GCLs

(DPH-GCLs) are factory-manufactured materials that GCLs containing the prehydrated bentonite are compressed. Kolstad et al. (2004b) investigated the hydraulic conductivity of DPH-GCLs for three permeant solutions, which were deionized water, NaCl solution and CaCl₂ solution having the concentrations of 1.0 M, and showed that the hydraulic conductivity to the three solutions was lower than $k = 1.0 \times 10^{-12}$ m/s.

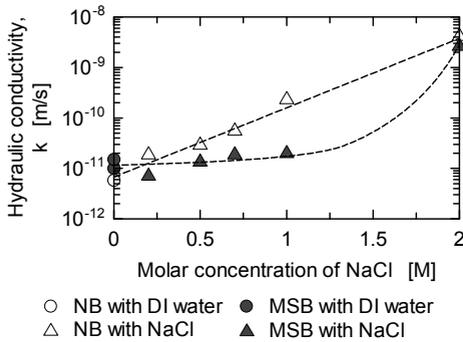


Figure 6. Hydraulic conductivity of NBs and MSBs permeated with NaCl solutions

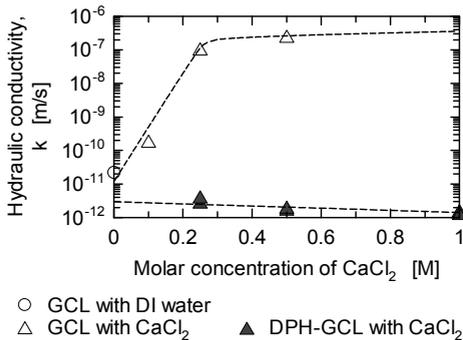


Figure 7. Hydraulic conductivity of GCLs and DPH-GCLs permeated with CaCl solutions

Figure 6 shows the hydraulic conductivity of NBs and MSBs permeated with NaCl solutions. Although the NB had a good barrier performance to deionized water, it was seriously deteriorated by permeation of NaCl solution. The hydraulic conductivity of the NB was increased with the concentration of NaCl solution. In contrast, the MSB could exhibit a low hydraulic conductivity of about $k = 1.0 \times 10^{-11}$ m/s even to NaCl solution with the molar concentration of < 1.0 M. However, the MSB could not exhibit such a low hydraulic conductivity to NaCl solution with too strong molar concentration of 2.0 M. The MSB exhibited almost the same hydraulic conductivity as the NB for the permeation of NaCl solution with the molar concentration of 2.0 M. Figure 7 shows the hydraulic conductivity of GCLs and DPH-GCLs

permeated with CaCl₂ solutions. The hydraulic conductivity of the GCL was also increased by the permeation of electrolytic solution of CaCl₂. In contrast, the DPH-GCLs had an extremely good barrier performance of about $k = 1.0 \times 10^{-12}$ m/s to any CaCl₂ solutions tested. It is concluded that MSBs and DPH-GCLs are effective barrier materials to the permeation of electrolytic chemical solutions without an unrealistic concentration level.

2.1.4 Relationship between swelling volume and hydraulic conductivity

Figure 8 shows the relationship between the hydraulic conductivity and the free swell (Katsumi et al. 2008b). The plotted data include previously reported results for nonprehydrated bentonite materials (Jo et al. 2001; Katsumi et al. 2007 and 2008b; Kolstad et al. 2004a; Lin et al. 2000; Shan and Lai 2002). The data consists of the hydraulic conductivity values for 89 single-species solutions including deionized water, for 54 multi-species solutions, and for 18 waste leachates. The hydraulic conductivity of a bentonite can be approximately given as a simple function of the free swell, in spite of the type and concentration of the permeant solution, and the type of the bentonite. The hydraulic conductivity of GCLs confined with 20-30 kPa is represented as

$$\log\left(\frac{k}{c}\right) = \exp(a(FS - b))$$

where k = the hydraulic conductivity (m/s) and FS = the free swell of the bentonite (mL/2g-solid). As to each fitting parameter, a is -0.21, b is 13.1 mL/2g-solid, and c is 1.00×10^{-11} m/s, which is the hydraulic conductivity at FS to infinity. It should be noted that these fitting parameters are dependent on the effective stress confining the bentonite. This relationship can be used within the limitations of non-prehydrated bentonites confined with the effective stress of 20-30 kPa. This relationship may have a problem in accuracy for estimating the hydraulic conductivity from the free swell of < 15 mL/2g-solid, but will be able to show that bentonite materials have an excellent barrier performance of $k < 1.0 \times 10^{-11}$ m/s when the free swell of the bentonite is larger than 15 mL/2g-solid.

The type and concentration of the chemical permeant solutions has significantly an influence on the barrier performance of GCL. However, it is too difficult to predict the type and concentration of the permeant solution before GCL is applied to a site, because the solution permeated into GCL is unspecified. Thus, to evaluate the hydraulic conductivity of GCL from the ionic strength is not practicable. Figure 8 is expected to practically estimate the barrier performance of GCLs which had been installed. Even if the type and concentration of the permeant solution cannot be specified, the free swell to sampled leachates will derive the hydraulic conductivity.

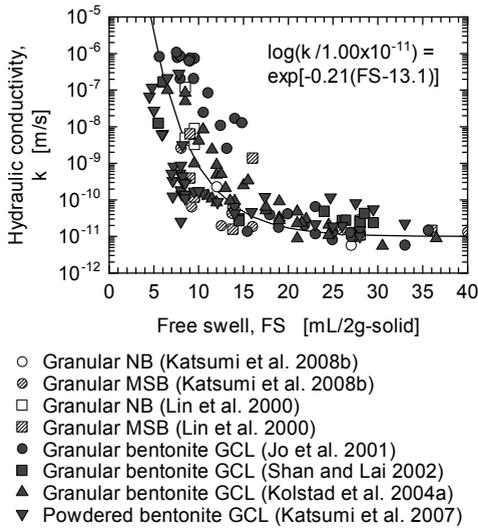


Figure 8. Relationship between the hydraulic conductivity and the free swell (modified Katsumi et al. 2008b)

2.2 Hydraulic conductivity of GCLs naturally prehydrated on base layer soil

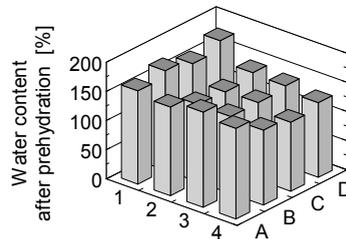
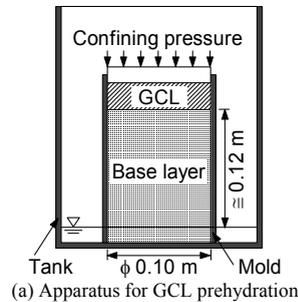
Hydrating bentonites before being exposed to chemical solutions is called "prehydration". It is one of the factors that might affect the barrier performance of GCLs in actual sites, because the GCLs are naturally prehydrated by absorbing moisture in the underlying base layer on which the GCLs are installed as bottom liners. Bentonites prehydrated with water have been considered to have a lower hydraulic conductivity than nonprehydrated ones. The barrier performance of the prehydrated bentonites is dependent on the magnitude and distribution of their water content (Daniel et al. 1993; Katsumi et al. 2008a; Lee and Shackelford 2005; Vasko et al. 2001).

There are some reports that represent the necessary water contents to satisfy the required barrier performance. For example, Bonaparte et al. (1996) have considered that the prehydration water content of GCLs exhibits 40-100% in actual sites, but they did not show the hydraulic conductivity values of the prehydrated GCLs. Lee and Shackelford (2005) systematically investigated the hydraulic conductivity of prehydrated GCLs against several chemical solutions. Their prehydrated GCLs were prepared by directly permeating the fresh water into them in the apparatus for the hydraulic conductivity tests before permeating the chemical solutions. Katsumi et al. (2008a) and Vasko et al. (2001) have investigated the water content and its distribution of GCLs hydrated under an actual process that the GCLs absorb moisture from their underlying base layer, and then evaluated their hydraulic conductivity values. The following subsections described the water content of

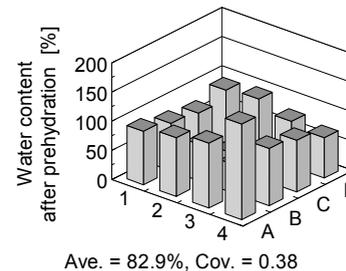
GCLs naturally prehydrated on base layer soil and their hydraulic conductivity to chemical solutions.

2.2.1 Prehydration water content

Prehydrated GCLs were prepared using the apparatus as shown in Fig. 9 (a). A soil was compacted at an optimum water content of 15% using a compaction test mold, which had a 0.1 m in diameter and a 0.13 m in height. The compacted soil was removed to an acrylic mold, which had a 0.1 m diameter and 0.15 m height, and was used as the base layer in the prehydration test. Next, a GCL was trimmed to a 0.1 m diameter and then it was placed on the base layer with a confining pressure of 5 kPa. The mold with the base layer was placed in a water tank, which size is a 0.6 m width × 0.3 m depth × 0.35 m height, with a water level of 0.01 m as water supply source, and the tank was closed. Then this tank was placed in a constant temperature room controlled at 20 °C, and the GCL was cured for 7-31 days.

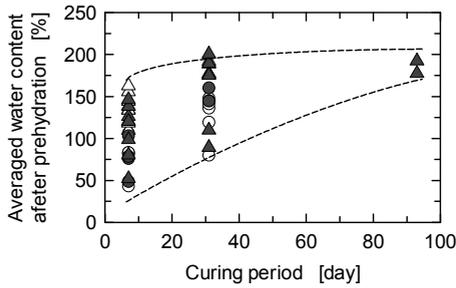


(b) Water content distribution with powdered bentonite



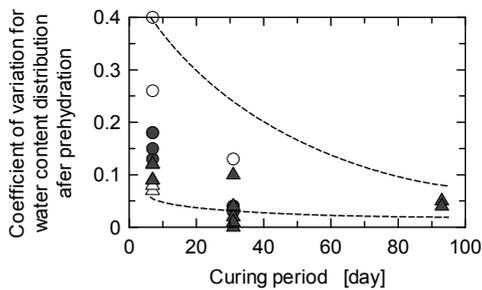
(c) water content distribution with granular bentonite

Figure 9. Apparatus to prepare prehydrated GCLs and their water content distribution after prehydration for seven days



- Open: granular bentonite GCLs
- Closed: powdered bentonite GCLs
- Base layer is a fine sand
- △ Base layer is a decomposed granite soil

Figure 10. Effect of curing period on averaged prehydration water content



- Open: granular bentonite GCLs
- Closed: powdered bentonite GCLs
- Base layer is a fine sand
- △ Base layer is a decomposed granite soil

Figure 11. Effect of curing period on heterogeneity of prehydration water content distribution

Figures 9 (b) and (c) show the water content distribution of a prehydrated GCL with powdered bentonite or granular bentonite, respectively. The water content distribution was evaluated by measuring the water content of each specimen when the prehydrated GCL was divided into 16 rectangular specimens (Namely, each specimen had an area of about $0.025 \times 0.025 \text{ m}^2$). The average and the variance of the water content distribution were shown as "Ave." and "Cov." in the figure. The curing period for prehydration was 7 days. The prehydrated GCL with powdered bentonite had a higher water content (144.6% in average) and a more homogenous water content distribution (0.12 in coefficient of variance) than that with granular bentonite. The prehydrated GCLs with the more homogenous water content distribution as well as the higher water content have been considered to have the superior barrier performance. In contrast, the prehydrated GCLs with heterogeneous water content distribution may not exhibit a good barrier performance even if they had a high water content on average. Although the suffi-

ciently swollen parts included in the heterogeneously prehydrated GCL can exhibit the low hydraulic conductivity, the insufficiently swelled parts exhibit the high hydraulic conductivity so that the hydraulic conductivity of the entire GCL with the heterogeneous water content distribution becomes high.

Figures 10 and 11 show the effects of the curing period on the average and the variance of the water content distribution after prehydration. The GCLs with powdered bentonite could be more homogeneously prehydrated with a higher water content than those with granular bentonite. The base layer consisting of decomposed granite soil worked to more homogeneously prehydrate the GCLs with a higher water content than that consisting of fine sand. In addition, increasing of the curing period improves the prehydration water content and the heterogeneity of its distribution in all the prehydration conditions tested. However, a curing period greater than certain days did not cause a significant change in either the prehydration water content or heterogeneity. The curing period is dependent on the soil properties of the base layer, the GCL properties, and the actual depth from the ground surface where the GCL is installed to the water table; In this experiment, a curing period longer than 31 days did not cause a significant change in either the prehydration water content or heterogeneity. In conclusion, prolonging the curing period and employing GCLs with the powder bentonite are effective measures for enhancing the prehydration water content and for homogenizing the water content distribution.

2.2.2 Hydraulic conductivity of prehydrated GCLs

Twenty-five specimens of the GCLs prepared in the above prehydration tests were used for the hydraulic conductivity test in order to discuss the prehydration effect on the barrier performance of GCLs against the permeation of chemical solutions. To prepare the specimen, the prehydrated GCL, which had a 0.1 m in diameter, was cut into a diameter of 0.06 m. Here the average of the water content of the GCLs was indirectly estimated from the water content values of the remaining bentonite pieces after this trimming. Next, the prepared specimen was placed in the flexible-wall permeameters, and then the hydraulic conductivity test was conducted according to ASTM D 5084. Calcium chloride solutions with a molar concentration of 0.1-0.5 M were used as the permeant solutions. This concentration level had an influence to deteriorate nonprehydrated GCLs as shown in Fig. 7. The testing conditions for the hydraulic conductivity tests were a cell pressure of 20-30 kPa, an average hydraulic gradient of 90, and a constant temperature of 20 °C. The testing duration was at least more than a year to investigate the long-term change in the hydraulic conductivity.

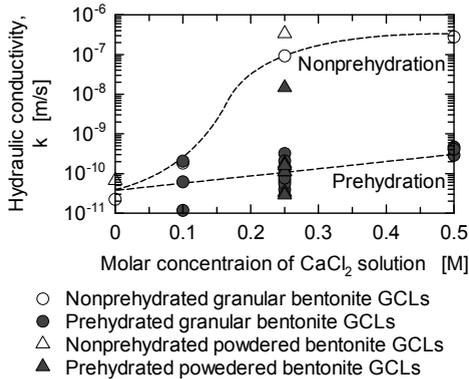


Figure 12. Hydraulic conductivity of nonprehydrated GCLs and prehydrated GCLs against CaCl_2 solutions

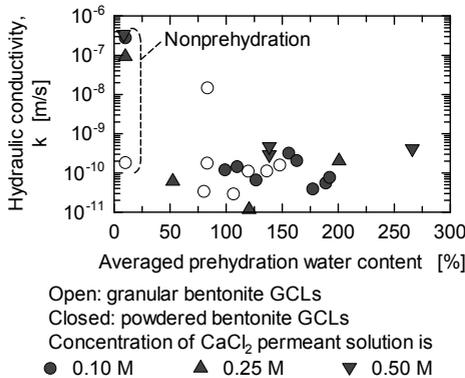


Figure 13. Relationships between the hydraulic conductivity and the water content of prehydrated GCLs

Figure 12 shows the hydraulic conductivity of nonprehydrated and prehydrated GCLs. The prehydration treatment maintained an extremely low hydraulic conductivity even to the permeation of the aggressive chemical solutions such as CaCl_2 solutions. In particular, the effect of the prehydration treatment greatly appears in the hydraulic conductivity when the CaCl_2 solution with a high concentration permeates into the GCL. The nonprehydrated GCL was deteriorated by the permeation of a CaCl_2 solution with a molar concentration of 0.5 M so that the hydraulic conductivity increases up to $k = 2.8 \times 10^{-7}$ m/s, while the prehydrated GCLs against the 0.5 M CaCl_2 solution exhibited the low hydraulic conductivity of $k \approx 1.0 \times 10^{-10}$ m/s.

Figure 13 shows the effects of the prehydration water content on the hydraulic conductivity of prehydrated GCLs against 0.1–0.5 M CaCl_2 solutions. When the water content was over 50%, the hydraulic conductivity of the prehydrated GCLs was $k \approx 1.0 \times 10^{-10}$ m/s even to CaCl_2 solutions tested, which significantly affects the decrease in the hydraulic conductivity of nonprehydrated GCLs. All the prehy-

drated GCLs with powdered bentonite indicated such a low hydraulic conductivity. In contrast, one of prehydrated GCLs with granular bentonite indicated the high hydraulic conductivity of $k = 1.5 \times 10^{-8}$ m/s, although the others indicated the low hydraulic conductivity. It might be concluded that GCLs with granular bentonite do not necessarily obtain the low hydraulic conductivity by the prehydration. It is because the water content distribution of the prehydrated GCLs with granular bentonite became easily heterogeneous as shown in Fig. 9 (c). Even if the sufficiently swollen parts included in the heterogeneously prehydrated GCL can exhibit the low hydraulic conductivity, the insufficiently swollen parts exhibit the high hydraulic conductivity. The hydraulic conductivity of the entire GCL with the heterogeneous water content distribution becomes high.

Prehydration is an effective measure for improving the chemical resistance of GCLs. The GCLs are expected to be naturally prehydrated by absorbing moisture in the underlying base layer on which the GCLs are installed as bottom liners. Most of the prehydrated GCLs exhibit a low hydraulic conductivity of $k \approx 1.0 \times 10^{-10}$ m/s against CaCl_2 solutions with concentrations between 0.1 and 0.5 M. This hydraulic conductivity value is about 1,000 times lower at the maximum than that of the nonprehydrated GCLs. However, the prehydrated GCLs have been considered not to exhibit such a low hydraulic conductivity when the water content distribution of the prehydrated GCLs was strongly heterogeneous. In particular, it was easy for GCLs with granular bentonite to be heterogeneously prehydrated.

2.3 Effects of the over-burden pressure on hydraulic conductivity of GCLs

In most of the previous studies including the above sections, the barrier performance of GCLs has been conducted using flexible-wall permeameters under a low confining pressure of 20–30 kPa. However, the GCLs which are applied as bottom liners are confined by the load of the landfill wastes so that the bentonite in the GCLs is consolidated and their void ratio and hydraulic conductivity are decreased. Such a consolidation effect has been considered remarkable because the bentonite has a high compressibility. The confining pressure of the buried wastes is also one of the factors that affect the barrier performance of GCLs at real sites.

In previous study, the data were limited to GCLs confined with < 120 kPa against deionized water or NaCl solutions (Petrove and Rowe 1997). Hence, this study conducted the consolidation and hydraulic conductivity tests using NaCl or CaCl_2 solutions, and showed the effects of the type and concentration of permeant solutions on the void ratio and hydraulic conductivity of GCLs confined with an effective pressure of < 314 kPa.

2.3.1 Relationships between hydraulic conductivity, void ratio, and confining pressure

The consolidation and hydraulic conductivity tests were performed in oedopermeameters. The procedure was as follows. First, a filter paper and geotextile which had a 6 mm diameter were placed in the permeameter. The granular NB was loosely put in the permeameter so that the thickness became approximately 10 mm, and then the surface of the granular NB was covered with the geotextile and filter paper. The granular NB sandwiched with two geotextiles were almost the same as GCL (Hereafter, the test specimen is regarded as GCL). The prepared GCL was fully saturated with a permeant solution, and then the GCL was consolidated with a confining pressure for 24 hours in the permeameter. If the degree of the consolidation reached over 90%, the consolidated GCL was permeated with the same permeant solution. If not, the consolidation was continued until the degree of the consolidation was over 90%. After that, the hydraulic conductivity test started according to ASTM D 5084 and D 6766. The void ratio and the hydraulic conductivity were calculated from the final thickness measured by displacement gauge.

Figure 14 shows the relationship between the hydraulic conductivity and the confining pressure. The hydraulic conductivity was more decreased when the confining pressure was increased. In a low confining pressure such as 20-30 kPa which is a general-used pressure level for the hydraulic conductivity test for GCLs, the hydraulic conductivity was remarkably dependent on the type and concentration of the permeant solution. The hydraulic conductivity to NaCl solutions was larger than that to CaCl₂ solutions when the ionic strength was equivalent. However, the difference in the hydraulic conductivity to each permeant solution having a different ionic species and concentration was suppressed when the confining pressure was increased. The hydraulic conductivity was $k \cong 1.0 \times 10^{-11}$ m/s to any solutions tested when the confining pressure was 316 kPa.

Figure 15 shows the relationship between the hydraulic conductivity and the void ratio. In a low concentration level, the void ratio was large and the hydraulic conductivity was low because the bentonite can sufficiently swell. The permeant solution with the high concentration, however, decreases the swelling capacity of the bentonite so that the bentonite permeated with the solution with such a high concentration level exhibited the low void ratio and the high hydraulic conductivity at a low confining pressure. When the confining pressure is increased from 29.4 kPa to 314 kPa, the hydraulic conductivity is decreased with the void ratio. The degree of this change was remarkable in the high concentration level. For example, only one-order of the hydraulic conductivity decreased for the NaCl solution with the ionic strength of 0.2 M. In contrast, three-order

of the hydraulic conductivity decreased for the NaCl solution with the ionic strength of 1.0 M. In conclusion, when GCLs are consolidated by a high confining pressure, they can exhibit a low hydraulic conductivity even to chemical solutions with the strong concentration.

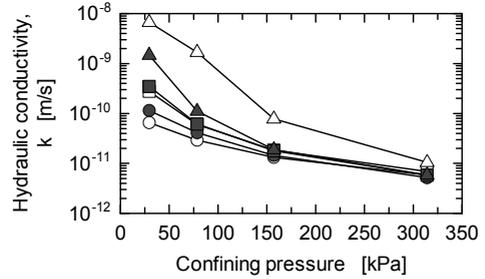


Figure 14. Relationship between the hydraulic conductivity and the confining pressure

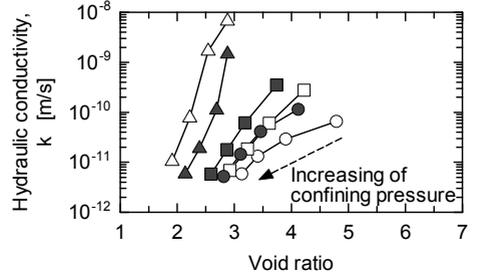


Figure 15. Relationship between the hydraulic conductivity and the void ratio

3 COASTAL LANDFILLS

3.1 Containment systems

In Japan, coastal landfills and the associated containment systems are important considerations, particularly for metropolitan areas such as Tokyo and Osaka due to the limitation of inland space available to waste disposal. Coastal landfill sites account for only 2% of the total number of disposal sites in Japan, but receive 28% of the waste produced because of their relatively large capacity (Tanaka et al. 2005). In addition, subsequent beneficial use of reclaimed/closed landfills of these facilities is an important consideration, since these coastal landfills are

constructed close to metropolitan areas and provide the new land for development. Coastal landfills may be found to be preferable to inland landfills for several reasons, including (1) the large area require for inland landfill may not be available or may be prohibitively expensive, (2) the groundwater beneath a typical coastal site may not be suitable for beneficial uses, (3) many coastal sites are isolated, with few inhabitants nearby (or fewer than inland sites), and (4) environmental concerns related to coastal landfills may be less controversial compared to inland fills. Disadvantages of coastal landfills include difficulties in monitoring and the possibility for bio-accumulation of toxic substances. Therefore, containment systems for coastal landfills are equally important to those of inland fills.

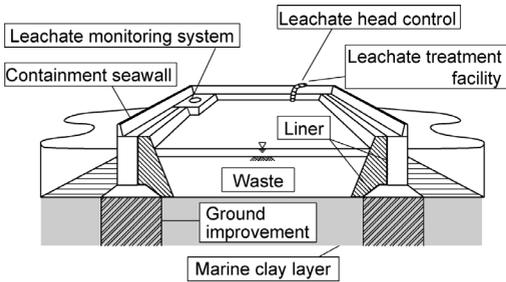


Figure 16. Typical configuration of coastal waste landfills

Typical configuration of coastal waste disposal site is shown in Figure 16. Most coastal areas in Japan often have thick clay layers that satisfy the Japanese regulation for landfill bottom liners, which prescribes a hydraulic conductivity value lower than 1.0×10^{-7} m/s and a thickness more than 5 m, or equivalent for the hydraulic barrier layer for the waste disposal facilities (Prime Minister's Office and Ministry of Health and Welfare in Japan 1998). Thus, the critical issues are design, construction, and performance of the seawall which acts as vertical barriers. The Japan Ministry of Land, Infrastructure, and Transport, which regulates issues related to ports, harbors, and coastal development, published revised guidelines for containment systems in coastal waste landfill sites in 2008. Typical barrier systems to be used in coastal landfill sites were shown in Figure 17. Japanese regulations for these lateral containment systems require a composite barrier system composed of two geomembranes, or alternative barrier materials, with some sort of stabilized backfill material placed in between (WAVE 2000). The gravity caisson seawall system shown in Figure 17 (a) and the rubble mound seawall systems shown in Figure 17 (c) both employ two geomembranes separated by backfill materials that serve as a cushion. The backfill may also function as part of the barrier

if they have low hydraulic conductivity and sufficient ductility to resist service loads.

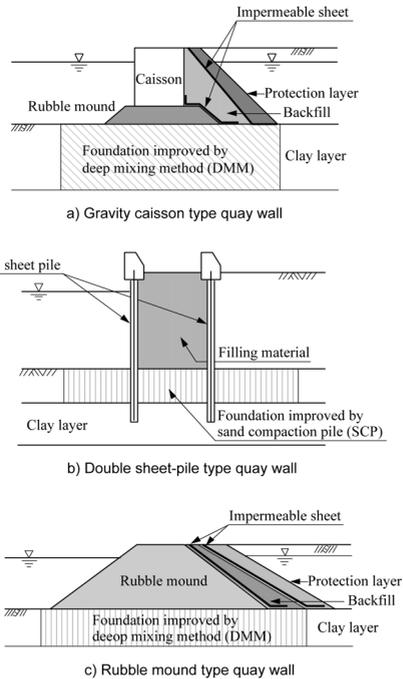


Figure 17. Typical seawall systems at coastal landfills

3.2 Fate and transport of heavy metals

Bottom clay liners are the most important barriers used in solid waste disposal facilities. For coastal landfill facilities that have been constructed to contain municipal and industrial types of waste in Japan, natural marine clay layers are thought to be the best clay liners for preventing the migration of pollutants. Bottom clay layers at coastal landfill sites may be under moderate to strong reduction conditions. In addition, leachate from landfills is rich in dissolved organic matter that can be used by microorganisms as a source of carbon for energy. The biochemical processes may lead to reduction-oxidation (redox) reactions and form a sequence of redox zones in the landfill leachate plume. Redox reactions strongly affect the behavior of pollutants leached from the landfills (Lyngkilde and Christensen 1992; Rugge et al. 1995). Among the different pollutants occurring in leachate, heavy metals can be of particular concern, which can be attenuated primarily by sorption and precipitation in addition to dilution (Christensen et al. 1994). The authors have also conducted the researches on the effects of redox potential on the heavy metals mobility in coastal landfill sites (Zhang et al. 2004; Kamon et al. 2006; Plata et al. 2008 and 2009; Inui et al. 2009).

Plata et al. (2008) reported a large column test (190 mm in inner diameter and 1,500 mm in height, shown in Figure 18) carried out during 502 days to simulate the conditions of a coastal landfill site and to evaluate the mobility of heavy metals within the incinerator ash layer and bottom clay layer, influenced by pH, Eh, TOC and microbial activities. The marine clay ($\rho_s = 2.61 \text{ Mg/m}^3$, $w_L = 41.1\%$, $w_P = 26.7\%$) sampled from Osaka Bay, Japan, was consolidated in the column under a consolidation pressure of 200 kPa, representing an approximate overburden pressure of disposed solid waste at a 20 m depth, until its void ratio reached 0.92, to form a clay layer with 150mm in height. Then, a layer of 850 mm height of municipal solid waste incinerator ash (MSWIA), a mixture of bottom and fly ashes collected at a MSW incinerator plant, was placed with the wet density of 1.35 Mg/m^3 above the clay layer. The artificial sea water was employed as an influent, enhanced with 2,000 mg/L of ZnCl_2 as target heavy metal, and 1,000 mg/L of $\text{NH}_4\text{H}_2\text{PO}_4$ and 1,000 mg/L of Na_2SO_4 which were added to favour reduced conditions. The column was continuously bubbled with N_2 gas during the time of the experiment under a pressure of 0.04 MPa. Zinc has been selected as target pollutant because it is generally found in the leachate from both hazardous and municipal solid waste (Kamon et al. 2000) and it shows a similar behavior to other heavy metals such as lead against the pH change.

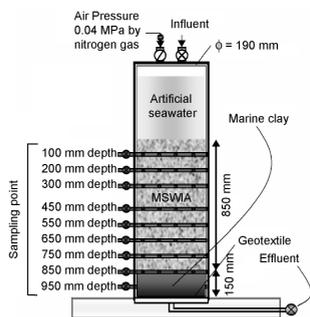


Figure 18. Large column to simulate the metal mobility in coastal landfill sites (Plata et al. 2008)

In the large column, the reduced-alkaline condition was dominant. Although 2000 mg/L Zn/Cl_2 were added to the influent, no significant soluble Zn was detected out of any of the sampling points along the column during the test except at the depth of 100 mm in the order of 100 mg/L. Figure 19 shows Zn concentrations as functions of pH and Eh along the column with the Zn forms expected for various pH and Eh values presented by Hem (1972). This result reveals that both pH and Eh influence the mobility of Zn in ash/clay-water system. As pH decrease and Eh increase, Zn is dissolved in water. In contrast, when pH increases and Eh decreases greatly, Zn is

effectively immobilized probably as insoluble hydroxides and carbonates. Previous studies also reported that Zn is effectively immobilized in soil as pH increases and Eh drops (Kamon et al. 2006). Figure 20 shows the distributions of Zn compositions in MSWIA layer with depth, which were determined according to the modified BCR sequential extraction method. The percentage of the exchangeable fraction, with regard to the total Zn, increased from 45% to values close to 60% after the test. An increase of the exchangeable fraction can pose a risk to the environment, since this one fraction is the most weakly bonded to the sediment and sudden changes in Eh or pH could mean the release of considerable quantities of heavy metals. Except at the depth = 100 mm, the amounts of exchangeable fraction were almost consistent regardless of the depth, however, the amounts of reducible fraction were increasing particularly at the depths shallower than 450 mm. From these observations, the mobility of Zn was basically very low and the water-soluble form was detected only around the surface (depth < 100 mm), where the neutral pH and relatively high Eh ranging from -200 to -100 mV were observed. Zinc is proved to be retained as 1) insoluble but exchangeable hydroxides and carbonates and 2) reducible form. These fractions, which could change their forms against variations in pH and oxygen concentrations, may be subjected to the re-release of metals. In the future, effects of these variations on the heavy metal mobility will be studied.

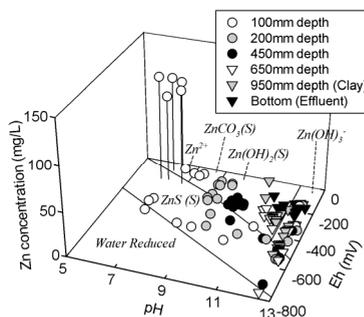


Figure 19. Zn concentration vs. pH and Eh with the pH-Eh diagram for Zn proposed by Hem (1972) (Plata et al. 2008)

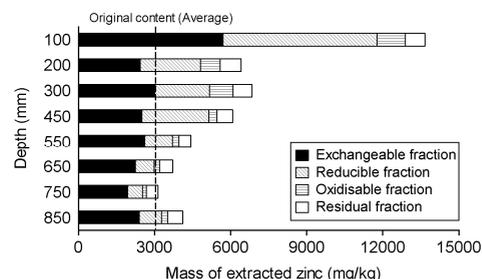


Figure 20. Distribution of Zn composition in MSWIA along the column (Plata et al. 2008)

3.3 Factors affecting containment performance

Polyvinyl chloride (PVC) geomembrane is widely used in the coastal waste containment facilities as barrier component in the gravity caisson type seawall and rubble mound type seawall systems (Figure 17 (a) and (c)). The containment performance of seawall systems is governed by a variety of factors including the durability of barrier component, integrity of the seawall system, installation quality of the barrier component, material properties of other components in the seawall systems. In this subsections, these factors affecting containment performance were reviewed and discussed based on previous research achievements mainly conducted in Japan.

3.3.1 Durability of PVC sheet

Installation of geomembrane sheet at the vast coastal landfill site has various technical and economical problems. Thus, PVC sheet is preferably employed due to its flexibility and economical advantage. Generally, PVC geomembranes contain approximately 30% plasticizer to enhance flexibility. Coastal seawall systems are easily subjected to large deformation due to subsoil settlement or earthquake. Thus, loss of plasticizers due to volatilization and/or leaching over time may have an adverse effect on the flexibility and tensile strength of sheet, and integrity of the seawall system will be concerned accordingly. Figure 21 shows the result of field exposure tests on PVC sheet (Japan chapter of International Geosynthetics Society 2009). In this test program, PVC sheet samples, which were exposed under field condition without any protection in different period, were collected at several inland landfill site in Japan, and subjected to the tensile test. PVC sheet sample after 27-year exposure was proved to retain only less than 30% tensile strength compared with that before the installation. As shown in Figure 21, thickness of the sheet was reduced and the tensile elongation retention reached less than 50% respectively in several cases including submerged condition. Compared with HDPE geomembrane sheet, changes in these physical properties were more significant in PVC sheet. These findings imply that physical properties of PVC sheet will significantly change even underwater condition if there is no protection layer constructed. Thus, PVC liner should be properly covered by some protection material immediately after the installation.

Concerning the chemical resistance of PVC geomembranes, previous studies have shown that the landfill leachate has no significant effect on PVC after 16 months (Artieres et al. 2001). However, Masada et al. (1994) reported that the clay-PVC geomembrane interface shear strength was more susceptible to the landfill leachate than that of the clay-HDPE interface. Thus, further studies on the long-term durability of PVC geomembrane and its

interface shear performance in coastal landfill are still required.

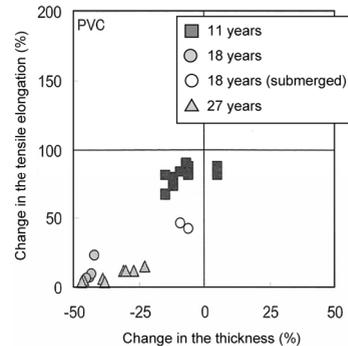


Figure 21. Changes in thickness and tensile elongation of PVC sheet after the long-term field exposure (Japan Chapter of IGS 2009)

3.3.2 Integrity of the seawall systems

Coastal seawall systems are easily subjected to large deformation, which is caused by subsoil settlement, lateral movement, earthquake motion, or uplift force due to wave and tidal fluctuation. Thus, integrity of the seawall against large deformation should be carefully considered in the design and construction stages. Kotake et al. (2004) measured the strains induced in PVC geomembrane sheet during the installation of the PVC sheet and the protection layer. It was observed that the strains were induced by the shear force due to the self weight of the protection layer and the deformation caused by the uneven conditions of subsoil. The maximum strain reached approximately 15%, which was influenced by the degree of unevenness of the subsoil. In addition, the protection layer acts as the counter weight against the hydraulic pressure acting on the geomembrane sheet due to tidal fluctuation. To protect the deformation of geomembrane due to the cyclic loading and uplift effect, specification of the protection layer should be carefully designed.

The seismic performance of the gravity caisson seawall system (Figure 17 (a)) through both experimental and analytical methods (Kano and Oda 2005; Oda et al. 2007). From a series of centrifuge model tests, the lateral movement of the gravity caisson seawall toward the waterfront side was induced by the earthquake motion and accordingly a large tensile strain occurred in the PVC sheet, although the maximum strain values observed at the top of the slope was less than 20%, which the typical PVC sheet was enough capable of. However, the integrity of seawall system against the large deformation due to the earthquake has been carefully considered in Japan, since the Hyogoken-Nanbu (Kobe) earthquake in 1995 caused significant damage to many seawall systems; particularly large displacement of some gravity caissons occurred due to the strong

10^{-4} to 1.0×10^{-7} m/s. Figure 25 clearly shows the influence of the saturated hydraulic conductivity of the backfill material on the constituent concentration of the seepage leaking through the seawall system. These analyses demonstrate that, even when the two geomembrane sheets were subjected to significant damages, backfill material with a low hydraulic conductivity material can effectively maintain the containment system performance.

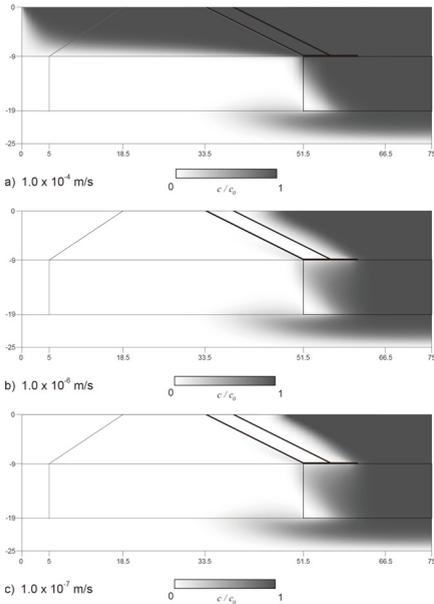


Figure 24. Effect of hydraulic conductivity of backfill material on the containment performance

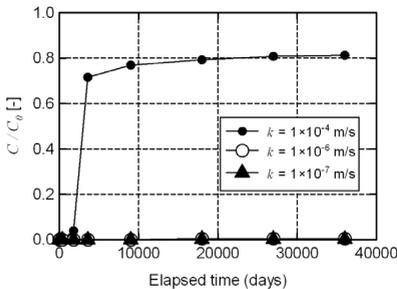


Figure 25. Influence of saturated hydraulic conductivity of backfill material on the contaminant concentration at the boundary between the seawall and the outer sea

Accordingly, in the guideline for containment systems in coastal waste landfill sites revised in 2008, the fail-safe design was introduced for the vertical hydraulic barriers, and two different hydraulic systems are installed in the seawall system (Watabe 2008). In the case that the main hydraulic barrier (two PVC geomembrane sheets) was damaged, additional low-permeable layer (backfill material) is able

to effectively minimize the contaminant transport, as proven in this analytical study.

4 REMEDIATION OF CLOSED AND/OR ABANDONED LANDFILLS

4.1 Redevelopment of closed landfills

After the closure of landfill sites, including coastal landfill sites, they are expected to be utilized as new land space, since new space is difficult to find in urban area of Japan. According to the regulation, the landfill site can be “closed,” only after the monitoring data proves that this landfill site will not provide any adverse effects on the surrounding environment even without any maintenance work. However, closed landfill sites are rarely utilized, or surface area of the landfill is utilized in the ways which do not require any foundation and excavation, such as park, green area and athletic ground. This is because 1) toxic gas and/or leachate may be generated if the waste begins to be decomposed again due to the intrusion of oxygen and water by excavation works or removal of cover soil, 2) engineering properties of the waste ground are unknown and of great heterogeneity, and 3) it cost a lot to dispose of the waste excavated.

In the Japanese law on the redevelopment of closed landfill, the area where the waste that is potentially harmful to the environment used to be disposed of must be registered to the prefectural governor. Redevelopment of the area of concern has to be also approved by the prefectural governor. Although the guideline has already been published to enforce this law (Committee on Technical Standards for the Redevelopment of Closed Landfill Sites, Ministry of Environment 2005), there are still a lot of technical issues to be solved. For example, the potential risk; generation of toxic gas and leachate, differential settlement of the waste layer, damage to the lining system, cannot be evaluated quantitatively, and detailed methods and technologies to manage and mitigate these risks have not been established.

Redevelopment and utilization of the closed landfill can be categorized into (1) shallow-layer utilization, (2) middle-layer utilization and (3) deep-layer utilization as shown in Figure 26, from a viewpoint of the depth in which the construction works for the redevelopment are involved. In shallow-layer utilization, construction works are executed only on the surface and in the cover layer. Light-weight structures such as portable house, road and so on, are expected to be constructed. In middle layer utilization, waste layer acts as the bearing layer of footing and mat foundation for the relatively light-weight structure. In deep-layer utilization, pile foundations are installed to reach the bearing layer beneath the land-

fill to obtain the bearing capacity enough for the heavy structures. Thus, the facilities in the landfill site, such as gas/leachate collection systems, lining system, have to be modified. Generally, the waste layer is heterogeneous in its mechanical, geotechnical and biochemical properties. Waste materials contain organic matters so much that toxic gas, leachate and smell are generated. Continuous and differential settlement occurs with the decomposition of organic substances. In addition, bearing capacity of the waste ground is relatively small compared with the normal ground.

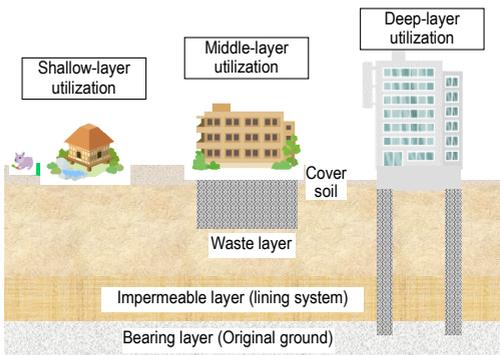


Figure 26. Categories of redevelopments of closed landfill sites with the depth where the construction works are involved (Kamon et al. 2007)

Considering these properties of the waste ground, the following risks should be carefully considered in the redevelopment of the closed landfill site. (1) settlement (particularly differential settlement), (2) insufficient bearing capacity, (3) gas generation (methane, bad smell), (4) leachate generation, (5) corrosion of steel and concrete in the ground, (6) negative influence on the vegetation, (7) pile installation prevented by the debris in the waste layer, (8) changes of properties of wastes with time and location, (9) treatment of waste and leachate, (10) spread of fine-particle waste during excavation and transportation. Figure 27 indicates the potential risks induced by the redevelopment of the closed landfill sites.

It is very difficult to evaluate these risks quantitatively prior to construction works, since (1) the waste ground has strong heterogeneity, (2) testing methods for the waste ground have not been established, (3) mechanism of the waste stabilization is still unclear and difficult to be estimated, for example, effect of the change from anaerobic to aerobic condition in the waste ground, which is considered to occur by excavation work, on the mobility of toxic substances immobilized, (4) geotechnical properties of the waste ground, particularly seismic performance, dynamic performance, earth pressure, are not clear, and (5) settlement is significant and complicated (induced by the decomposition of organics

as well as elastic and creep deformation). Thus, monitoring and mitigation of these risks are very important issues in redeveloping the closed landfill site. Kamon et al. (2007) introduced items and their criteria to be monitored during and after the redevelopment work, and reviewed the applicability of ground improvement techniques to mitigate these risks.

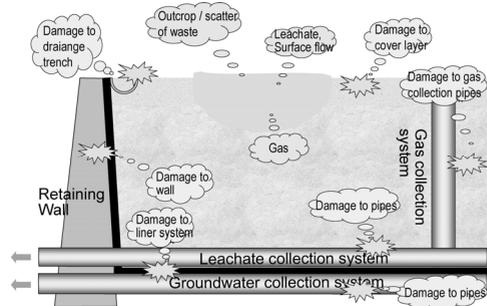


Figure 27. Risks induced by the redevelopment of the closed landfill site (Kamon et al. 2007)

4.2 Remediation of waste abandoned sites

There are many cases that the soil contamination due to the waste dumping was unintentionally detected during construction works or site investigation prior to the construction project. This type of soil contamination had a significant adverse effect on the process and economics of construction project. Thus, risk-based remediation design has gained great attention to assess the validity of the remediation program and choose the most cost-effective option (e.g., Kamon et al. 2003). In addition, the compatibility with the geotechnical properties of the contaminated site after the remediation is of another great concern, since some remediation programs may have some adverse effects on the geotechnical properties (e.g. change in the groundwater level, settlement, and deformation of the adjacent structures).

In general, soil and contaminant removal will be preferable particularly for the residents. However, there are some disadvantages for removal technology. This technology is usually expensive particularly when the volumes of removed materials are large. It is also difficult to find the landfill site or treatment plant which will receive these removed materials. Applications of containment technologies using vertical barriers such as cement bentonite, soil bentonite, steel-pipe sheet pile, etc. have been tried in many sites. One of the key issues to apply the containment technologies is to obtain the consensus of stakeholders. Risk analysis will be useful to explain the effectiveness of containment technologies (Kamon et al. 2003). Monitoring is also necessary to confirm the performance of the measure and the environmental safety. Some contaminated sites are located at mountainous areas because they are apart from the

residential areas. To design the remedial works at such sites, not only the environmental concerns but also the effects of the measures on the change in groundwater level and slope stability should be considered.

4.3 Remedial option for the waste abandoned site along a landslide area

The validity of a remediation program designed for a contaminated site based on the numerical advection-dispersion analysis has been examined by Tanaka et al. (2008). The site of concern is contaminated due to the dumping of waste. Polychlorodibenzo-p-dioxins (PCDDs) and heavy metals are the contaminants of potential concern. The area where this dumped site is located suffered the landslides historically, and has been still famous for the future potential of landslide; the national and local governments have conducted the remedial works for slope stability for many decades. These remedial works include the installation of concrete piles for reinforcement and horizontal and vertical water drainage tunnels to lower the groundwater table. Therefore, the remedial action against the contamination should not contradict the remedial actions against slope stability. At this site, the soil and contaminant removal is not preferable because the area is so wide and the cost is expected too expensive. The in situ containment technology using vertical barriers keyed into aquitard is concerned to affect the groundwater level and trigger the slope instability, and is not therefore acceptable either. Thus, the installation of the capping over the contaminated soil and/or the shallow vertical cutoff wall (not keyed into the aquitard) was designed as a remediation program to prevent the infiltration and groundwater flow into the contaminated zone. Contaminant transport in subsurface is examined using the finite element method for groundwater flow coupled with contaminant transport with and without the construction of these measures.

Groundwater flow at this site, based on the hydrogeological conditions, is numerically modeled using the finite element method. Hydrogeological conditions include the foundation profile, groundwater level, and hydraulic properties of foundation materials such as their porosities and hydraulic conductivities. The foundation layers of this site consist mainly of two layers; a residual soil layer with a relatively high hydraulic conductivity and an underlain base rock. Therefore, only a residual soil layer was modeled in the analysis and regarded as an aquifer. Considering that this site is located along the valley, groundwater flow parallel to the direction of the valley is most dominant. Thus, the cross section which is parallel to the dominant direction of groundwater flow was analyzed as shown in Figure 28. Constant water head conditions based on the groundwater levels investigated in geotechnical log boring were

given at the several points in the section. Since this site is located on the landfill area, drainage pipes and reinforcement piles were installed as the countermeasures against the landslide. In the analysis, the effects of these countermeasures on the geotechnical profiles (groundwater level and hydraulic conductivity) were considered.

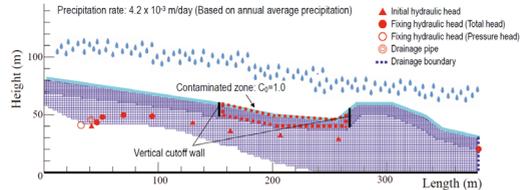


Figure 28. Cross section and finite element mesh used for 2-D advection-diffusion analysis (Tanaka et al. 2008)

Table 1. Material properties used in numerical analysis (Tanaka et al. 2008)

| Parameters | Unit | Values |
|------------------------------------|---------------------------|-----------------------|
| Hydraulic conductivity | k (m/s) | 2.9×10^{-5} |
| Effective porosity | n_e (-) | 0.2 |
| Longitudinal dispersivity | α_L (m) | 15 |
| Transversal dispersivity | α_T (m) | 1.5 |
| Coefficient of molecular diffusion | D_m (m ² /s) | 6.5×10^{-10} |
| Retardation factor | R_d (-) | 164 |

The finite element advection-dispersion chemical transport model, DTransu.2D EL (Nishigaki et al. 1995) was used to analyze the concentration and mass flux of a contaminant released from the contaminated zone in 50 years. The zone where the concentrations of dioxins were higher than the environmental criteria (1,000 pg-TEQ/g) is regarded as the contaminated zone. The parameters for an aquifer used in the analysis are shown in Table 1, based on the previous investigations. As the boundary conditions in the analysis, constant water heads and drainage conditions were assumed based on the groundwater level investigated as shown in Figure 28. At the node corresponding to the drainage tunnel, a constant drainage rate of $0.5 \text{ m}^3/\text{m/day}$ was assumed. Contaminant transport was analyzed under the unsteady-state hydraulic head distribution and unsaturated water flow condition. The precipitation intensity is fixed at $4.2 \times 10^{-3} \text{ m/day}$ according to the average value of the past 22 years in this region. Thirty percent of precipitation was considered to infiltrate into the ground. Unitless initial contaminant concentration, C_0 , of 1.0 was set for the contaminated zone, although the actual concentration of soluble dioxin was unknown.

Four cases were analyzed: (1) Case-A: No remedial action is conducted, (2) Case-B: A capping layer was installed at the surface of the contaminated area, (3) Case-C: A capping layer at the surface of the contaminated area and a shallow vertical cut off wall at upper side of the contaminated zone (14 m in depth, 0.5 m in thickness) were installed, and (4)

Case-D: A capping layer at the surface of the contaminated area and a couple of shallow vertical cut off wall at both upper and lower sides of the contaminated zone (upper side: 14 m in depth, 0.5 m in thickness, lower side: 8 m in depth, 0.5 m in thickness) were installed. Depths of the vertical cutoff walls correspond to the bottom of the contaminated zone, but not keyed into the aquitard. In Cases-B, C and D, a vertical cut-off wall and a capping layer are assumed impermeable.

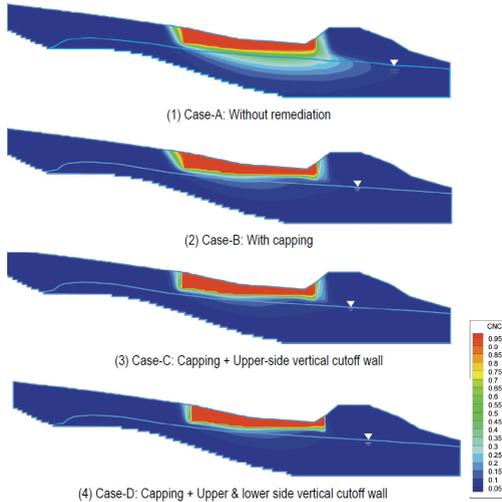


Figure 29. Distributions of the normalized contaminant concentration after 50 years (Tanaka et al. 2008)

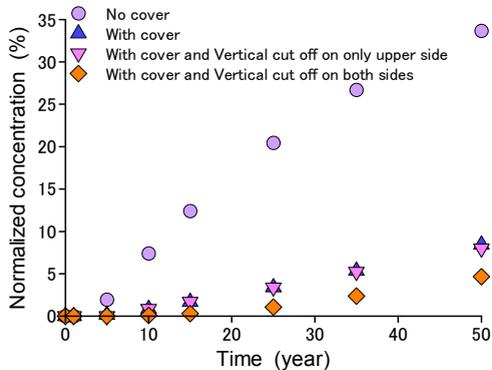


Figure 30. Changes in C_{264} , maximum concentration in the aquifer at the lower edge of the contaminated zone (Tanaka et al. 2008)

Figure 29 shows the groundwater level and distributions of contaminant concentration normalized by C_0 after 50 years for Case A to D. There is no difference in the groundwater level between Case-A and other cases. This confirms that the remedial action do not affect the groundwater level and accordingly the slope stability. By comparing with Case-

A and Case-B, the rainwater infiltration is a strong driver for the contaminant transport, and the infiltration cut by the capping is considered to be an effective remediation. From the results of Case-C and D, the vertical cutoff wall can reduce the lateral transport of contaminant effectively.

Temporal changes of C_{264} , which is the maximum concentration in the aquifer (below the groundwater level) at the length of 264 m, corresponding to the lower side edge of the contaminated zone, are shown in Figure 30. The C_{264} value after 50 years even for Case A is only 34% because dioxins are assumed strongly adsorbed to the organic matter in soil in the analysis. Cases B, C, and D resulted in the 8.5%, 8.0%, and 4.6% of C_{264} values after 50 years respectively. Capping over the contaminated zone will be considered very effective at this site. Further examinations such as the effects of the expansion of capping area and/or the depth of vertical wall are presented in Tanaka et al. (2008).

5 CONCLUSIONS

Three issues related to the application of geomembranes and geosynthetic clay liners (GCLs) are discussed in this paper, including (1) chemical resistance of GCLs against synthetic chemical solutions and waste leachate, (2) performance of geosynthetic materials applied to the coastal waste containment facilities, and (3) application of geosynthetic barriers to remedial actions at abandoned waste disposal sites.

The type and concentration of the chemical permeant solutions has significant influences on the barrier performance of GCL. From the relation between free swell and long-term hydraulic conductivity values obtained through experimental works, the free swell to sampled leachates will derive the hydraulic conductivity even if the type and concentration of the permeant solution cannot be specified. Prehydration is an effective measure for improving the chemical resistance of GCLs. The GCLs are expected to be naturally prehydrated by absorbing moisture in the underlying base layer. However, the prehydrated GCLs may not exhibit such a low hydraulic conductivity when the water content distribution of the prehydrated GCLs, particularly with granular bentonites, is heterogeneous.

Coastal landfills and the associated containment systems are important considerations, particularly for metropolitan areas, due to the limitation of inland space available to waste disposal. Not only barrier systems but also the nature of heavy metals in coastal landfills should be taken into consideration. A research project on heavy metals mobility using a larch column to simulate the redox potential at the coastal landfill sites was presented. Barrier performances of several types of side barrier systems using

geosynthetic materials were also numerically analyzed. In the case that the main hydraulic barrier (double PVC geomembrane sheets) was damaged, additional low-permeable layer (backfill material) is able to effectively minimize the contaminant transport.

Remedial option for a dumped waste site located along a landslide area should be designed under the consideration against contaminant transport as well as slope instability; cut-off wall keyed into the aquitard might elevate groundwater level and thus may not be employed. An analytical study on contaminant transport proves that the containment system using capping and shallow (not keyed) vertical barrier will be a cost-effective option.

6 ACKNOWLEDGEMENTS

The research presented in this paper was supported by multiple agencies, including the Japan Society for the Promotion of Science (JSPS) through Grant-in-Aid for Scientific Research (Grant Nos. 17206051, 19360212, and 20360211), the Japan Ministry of Environment through Grant-in-Aid for Scientific Research (Grant No. K1711), Osaka Bay Regional Offshore Environmental Improvement Center (Grant No. 210009), Steel Industry Foundation for the Advancement of Environmental Protection Technology (SEPT), National Institute for Environmental Studies, and Kyoto University Global COE Program on Human Security Engineering in Asian Megacities

7 REFERENCES

Alther, G., Evans, J. C., Fang, H. Y., and Witmer, K. 1985. Influence of inorganic permeants upon the permeability of bentonite, *Hydraulic Barriers in Soil and Rock*, ASTM STP 874, A. Johnson, R. Frobel and C. Petterson (eds.), ASTM, West Conshohocken, Pennsylvania, pp.64-73.

Artieres, O., Gousse, F. and Prigent, E. 1991. Laboratory aging and geomembranes in municipal landfill leachates, *Proc. 3rd International Landfill Symposium*, pp.587-603.

Bonaparte, R., Othman, M. A., Rad, N. R., Swan, R. H., and Vander Linde, D. L. 1996. *Evaluation of Various Aspect of GCL Performance, Report of 1995 Workshop on Geosynthetic Clay Liners*, EPA/600/R-96/149.

Christensen, T. H., Kjelsen, P., Hans-Jorgen, A., Heron, G., Nielsen, P. H., Bjerg, P. L., and Holm, P. E. 1994. Attenuation of landfill leachate pollutants in aquifers, *Critical Reviews in Environmental Science and Technology*, Vol.24, pp.119-202.

Committee on Technical Standards for the Redevelopment of Closed Landfill Sites, Ministry of Environment 2005. *Enforcement Guideline on the Redevelopment of Closed Landfill Sites* (in Japanese).

Daniel, D. E., Shan, H.-Y., and Anderson, J. D. 1993. Effects of partial wetting on the performance of bentonite component of a geosynthetic clay liner, *Geosynthetics '93*, Vol.3, pp.1482-1496.

Egloffstein, T. A. 1995. Properties and test methods to assess bentonite used in geosynthetic clay liners, *Geosynthetic*

Clay Liners, Balkema, Rotterdam, The Netherlands, pp.51-72.

Giroud, J. P., Badu-Tweneboah, T., and Soderman, K. L. 1994. Evaluation of landfill liners, *Proceedings of 5th International Conference on Geotextiles, Geomembranes and Related Products*, G.P. Karunaratne et al. (eds.), SEACIGS, pp.981-986.

Gleason, M. H., Daniel, D. E., and Eykholt, G. R. 1997. Calcium and sodium bentonite for hydraulic containment applications, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol.123, No.5, pp.438-445.

Hem, J. 1972. Chemistry and occurrence of cadmium and zinc in surface water and groundwater, *Water Resources Research*, Vol.8, No.3, pp.661-679.

Inui, T., Oya, Y., Plata, H., Katsumi, T., and Kamon, M. 2009. Speciation and mobility assessment of heavy metals in the coastal MSW incinerator ash landfill, *Journal of ASTM International*, Vol.6, No.8, Paper ID JA1102166.

Japan Chapter of International Geosynthetics Society 2009. *Handbook of the Durability Assessment of Geomembrane Sheets for Waste Containment*, p.87 (in Japanese).

Jo, H. Y., Katsumi, T., Benson, C. H., and Edil, T. B. 2001. Hydraulic conductivity and swelling of non-prehydrated GCLs permeated with single species salt solutions, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol.127, No.7, pp.557-567.

Kamon, M., Katsumi, T., and Sano, Y. 2000. MSW fly ash stabilized with coal ash for geotechnical applications, *Journal of Hazardous Materials*, Elsevier, Vol.76, No.2-3, pp.265-283.

Kamon, M., Inui, T., Endo, K., Ito, K., and Katsumi, T. 2002. Evaluating the effect of clay layer on the performance of composite liner having geomembrane defects, *Proceedings of the Seventh International Conference on Geosynthetics*, Ph. Delmas, J.P. Gourc, and H. Girard (eds.), Balkema, Lisse, The Netherlands, Vol.2, pp.519-522.

Kamon, M., Inui, T., Katsumi, T., and Doi, A. 2003. Environmental assessment of a contaminated site by use of risk based methodologies, *Proceedings of the 13th European Regional Conference on Soil Mechanics and Geotechnical Engineering*, Vol.1, pp.397-402.

Kamon, M., Zhang, H., Katsumi, T., and Inui, T. 2006. Biochemical effects on the long-term mobility of heavy metals in marine clay at coastal landfill sites, *Journal of ASTM International*, Vol.3, No.7, Paper ID JA113326.

Kamon, M., Inui, T., Katsumi, T., and Torisaki, M. 2007. Risk control in the redevelopment of closed landfill sites from geotechnical viewpoints, *GEE07 - Seventh Japanese-Korean-French Seminar on Geo-Environmental Engineering*, pp.19-24.

Kano, S. and Oda, K. 2005. Experimental study on seismic behavior of seawalls for controlled waste disposal, *Technical Note of National Institute for Land and Infrastructure Management*, No.256, (in Japanese).

Katsumi, T., Benson, C. H., Foose, G. J., and Kamon, M. 2001. Performance-based design of landfill liners, *Engineering Geology*, Elsevier, Vol.60/1-4, pp.139-148.

Katsumi, T. and Fukagawa, R. 2005. Factors affecting chemical compatibility and barrier performance of GCLs, *Proceedings of the Sixteenth International Conference on Soil Mechanics and Geotechnical Engineering*, Millpress Science Publishers, Rotterdam, Netherlands, pp.2285-2288.

Katsumi, T. and Kamon, M. 2002. Management of contaminated sites, *Environmental Geotechnics*, L.G. de Mello and M.S.S. Almeida (eds.), Balkema, Lisse, Netherlands, Vol.2, pp.1013-1038.

Katsumi, T., Ogawa, A., and Fukagawa, R. 2004. Effect of chemical solutions on hydraulic barrier performance of clay geosynthetic barriers, *Proceedings of the Third European Conference on Geosynthetics*, pp.701-706.

- Katsumi, T., Ishimori, H., Ogawa, A., Yoshikawa, K., Hanamoto, K., and Fukagawa, R. 2007. Hydraulic conductivity of nonprehydrated geosynthetic clay liners permeated with inorganic solutions and waste leachates, *Soils and Foundations*, Vol.47, No.1, pp.79-96.
- Katsumi, T., Ishimori, H., Ogawa, A., Maruyama, S., and Fukagawa, R. 2008a. Effects of water content distribution on hydraulic conductivity of prehydrated GCLs against calcium chloride solutions, *Soils and Foundations*, Vol.48, No.3, pp.407-417.
- Katsumi, T., Ishimori, H., Onikata, M., and Fukagawa, R. 2008b. Long-term barrier performance of modified bentonite materials against sodium and calcium permeant solutions, *Geotextiles and Geomembranes*, Vol.28, pp.14-30.
- Kavazanjian, Jr., E., Dixon, N., Katsumi, T., Kortegast, A., Legg, P., and Zanzinger, H. 2006. Geosynthetic barriers for environmental protection at landfills, *Geosynthetics - Proceedings of the 8th International Conference on Geosynthetics*, J. Kuwano and J. Koseki (eds.), Millpress Science Publishers, Rotterdam, Netherlands, Vol.1, pp.121-152.
- Kolstad, D. C., Benson, C. H., and Edil, T. B. 2004a. Hydraulic conductivity and swell of nonprehydrated geosynthetic clay liners permeated with multispecies inorganic solutions, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol.130, No.12, pp.1236-1249.
- Kolstad, D. C., Benson, C. H., Edil, T. B., and Jo, H. Y. 2004b. Hydraulic conductivity of a dense prehydrated GCL permeated with aggressive inorganic solutions, *Geosynthetics International*, Vol.11, No.3, pp.233-241.
- Kotake, N., Kitade, K., Tsurugasaki, K., Baba, S., Nishino, Y., and Tokubuchi, K. 2004. Induced strains in a Geosynthetics liner sheet installed in a controlled coastal disposal site, *Geosynthetics Engineering Journal*, Vol.19, Japan Chapter of IGS, pp.81-86 (in Japanese).
- Lee, J. M. and Shackelford, C. D. 2005. Concentration dependency of the prehydration effect for a geosynthetic clay liner, *Soils and Foundations*, Vol.45, No.4, pp.27-41.
- Lin, L., Katsumi, T., Kamon, M., Benson, C. H., Onikata, M., and Kondo, M. 2000. Evaluation of chemical-resistant bentonite for landfill barrier application, *Annals of the Disaster Prevention Research Institute, Kyoto University*, No.43 B-2, pp.525-53.
- Lyngkilde, J. and Christensen, T. H. 1992. Redox zones of a landfill leachate pollution plume (Vejen Denmark), *Journal of Contaminant Hydrology*, Vol.10, pp.273-289.
- Lutz, J. F. and Kemper, W. D. 1958. Intrinsic permeability of clay as affected by clay-water interaction, *Soil Science*, Vol.88, pp.83-90.
- Masada, T., Mitchell, G. F., Sargand, S. M., and Shashikumar, B. 1994. Modified direct shear study of clay liner-geomembrane interfaces exposed to landfill leachate, *Geotextiles and Geomembranes*, Vol.13, Issue 3, pp.165-179.
- McBride, M. 1994. *Environmental Chemistry of Soils*, Oxford University Press, New York.
- McNeal, B. L., Norvell, W. A., and Coleman, N. T. 1966. Effect of solution composition on the swelling of extracted soil clays, *Soil Science Society of America Proceedings*, Vol.30, pp.313-317.
- Nishigaki, M., Hishiya, T., Hashimoto, N., and Kohno, I. 1995. The numerical method for saturated-unsaturated fluid-density-dependent groundwater flow with mass transport, *Journal of Geotechnical Engineering*, JSCE, No.511, pp.135-144 (in Japanese).
- Norrish, K. 1954. The swelling of montmorillonites, *Discussions of Faraday Society*, Vol.18, pp.120-134.
- Norrish, K. and Quirk, J. 1954. Crystalline swelling of montmorillonite, use of electrolytes to control swelling, *Nature*, Vol.173, pp.255-257.
- Oda, K., Yoshida, M., Mitou, M., and Akimoto, T. 2007. Analytical study on seismic performance of seawalls for controlled waste disposal, *Geosynthetics Engineering Journal*, Japan Chapter of IGS, Vol.22, pp.159-166 (in Japanese).
- Onikata, M., Kondo, M., and Kamon, M. 1996. Development and characterization of multiswellable bentonite, *Environmental Geotechnics*, A. A. Balkema Publishers, Rotterdam, The Netherlands: 587-590.
- Petrov, R. J. and Rowe, R. K. 1997. Geosynthetic clay liner (GCL) - chemical compatibility by hydraulic conductivity testing and factors impacting its performance, *Canadian Geotechnical Journal*, Vol.34, pp.863-885.
- Plata, H., Katsumi, T., Inui, T., Oya, Y., and Kamon, M. 2008. Chemical partitioning of zinc in a coastal landfill site with MSW incinerator ash, *Global Waste Management Symposium: Promoting Technology and Scientific Innovation* (on CD).
- Plata, H., Katsumi, T., Inui, T., Oya, Y., and Kamon, M. 2009. Fractioning and mobility of zinc in a coastal landfill site with MSW incinerator ash, *Journal of Environmental Engineering*, ASCE (in review).
- Posner, A. and Quirk, J. 1964. Changes in basal spacing of montmorillonite in electrolyte solutions, *Journal of Colloid and Interface Science*, Vol.19, pp.798-812.
- Prime Minister's Office and Ministry of Health and Welfare in Japan 1998. *Ministerial Ordinance Determining Engineering Standards on Final Disposal Sites for Municipal Solid Wastes and Industrial Wastes* (in Japanese).
- Prost, R., Koutit, T., Benchara, A., and Huard, E. 1998. State and location of water adsorbed on clay minerals: Consequences of the hydration and swelling-shrinkage phenomena, *Clays and Clay Minerals*, Vol.46, No.2, pp.117-131.
- Rugge, K., Bjerg, P.L., and Christensen, T.H. 1995. Distribution of organic compounds from municipal solid waste in the groundwater downgradient of a landfill (Grindsted, Denmark), *Environmental Science and Technology*, Vol.29, pp.1395-1400.
- Ruhl, J. L. and Daniel, D. E. 1997. Geosynthetic clay liners permeated with chemical solutions and leachates, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol.123, No.4, pp.369-381.
- Shackelford, C. D. 2007. Selected issues affecting the use and performance of GCLs in waste containment applications, *21st Geotechnical Engineering Conference*, Politecnico di Torino, Torino, Italy, Nov. 27-28.
- Shackelford, C. D., Benson, C. H., Katsumi, T., Edil, T. B., and Lin, L. 2000. Evaluating the hydraulic conductivity of GCLs permeated with non-standard liquids, *Geotextiles and Geomembranes*, Elsevier, Vol.18, pp.133-161.
- Shan, H.-Y. and Lai, Y.-J. 2002. Effect of hydrating liquid on the hydraulic properties of geosynthetic clay liners, *Geotextiles and Geomembranes*, Elsevier, Vol.20, pp.19-38.
- Tanaka, Y., Inui, T., Katsumi, T., and Kamon, M. 2008. Analytical study on the remedial option for the dumped waste landfill located along the slope, *Geo-Environmental Engineering 2008 - Proceedings of the Eighth Japan-Korea-France Joint Seminar on Geoenvironmental Engineering*, pp.131-134.
- Tanaka, N., Tojo, Y., and Matsuto, T. 2005. Past, present, and future of MSW landfills in Japan, *Journal of Material Cycles and Management*, Vol.7, pp.104-111.
- Vasko, S. M., Jo, H. Y., Benson, C. H., Edil, T. B., and Katsumi, T. 2001. Hydraulic conductivity of partially prehydrated geosynthetic clay liners permeated with aqueous calcium chloride solutions, *Geosynthetics Conference 2001*, pp.685-699.
- van Olphen, H. 1977. *An Introduction to Clay Colloid Chemistry - 2nd Edition*, Wiley, New York.
- Watabe, Y. 2008. Seawalls of waste disposal facilities in Japan: Toward a revision of "Technical manual for desing, construction and management for coastal disposal facilities", *Geo-Environmental Engineering 2008 - Proceedings of the*

*Eighth Japan-Korea-France Joint Seminar on Geoenvi-
ronmental Engineering*, pp.253-258.

Waterfront Vitalization and Environmental Research Center
(WAVE) 2008. *Revised Manual of Design, Construction,
and Management at Coastal Disposal Sites* (in Japanese).

Zhang, H., Kamon, M., and Katsumi, T. 2004. Effect of acid
buffering capacity on the long-term mobility of heavy met-
als in clay liner, *Soils and Foundations*, JGS, Vol.44, No.6,
pp.111-120.