AIR PERMEABILITY OF COMPACTED CLAYS AND GEOSYTHETIC CLAY LINERS

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ABSTRACT

Two of most important functions of a landfill cover are to minimize the infiltration of water and to control the emission of landfill gas. Compacted clay liner (CCL), geosynthetic clay liner (GCL), and geomembrane (GM) are the three major types of hydraulic barrier materials used in the bottom lining systems as well as cover systems of landfills. However, it is well recognized that clay liners crack upon desiccation. The cracked liner may enhance the capacity to conduct fluid, which not only increase the infiltration of the downward moving water but also the emission of upward moving gas. Laboratory air permeability tests were conducted to quantify the rate of air passing through desiccated clay liner specimens. In addition, the equilibrium water content of clay liners in the field condition is also studied. The results show that desiccated clay liners may allow considerable amount of landfill gas to pass through. In addition, the air permeability of desiccated GCLs are much higher than that of desiccated CCLs. Accordingly, it is suggested that geomembranes should be used to contain landfill gas for landfills located in areas where landfill gas emission are to be controlled effectively.

Keywords: Landfill, clay liner, air permeability, landfill gas emission

INTRODUCTION

In recent years, landfill gas emission has raised considerable concerns since methane is a major greenhouse gas. As a result, for closed landfills, the effectiveness of the cover system to control the emission rate of methane and non-methane organic compounds (NMOCs) needs to be assured. Gas passes through the landfill cover system by means of advection and molecular diffusion. In MSW landfills where large amount of gas is produced, the internal pressure is usually greater than atmospheric pressure such that landfill gas will be released not only by diffusion but also by pressure-driven advection. In the meantime, the natural fluctuation of atmospheric pressure can also cause gas to flow into or out of the landfill. Furthermore, a change in leachate/water table or difference of temperature across the cover system may also lead to gas migration. In many cases, the temperature within the landfill reaches higher than 40°C due to the heat generated by the anaerobic degradation process (Tchobanoglous et al. 1993).

Gas movement by diffusion is driven by gradient of concentration. When a gas is more concentrated in one region of a mixture more than another, it will diffuse into the less concentrated region. Thus the molecules move in response to a partial pressure gradient or concentration gradient of the gas. The present paper will focus only on advective transport.

Figueroa and Stegmann (1991) performed several field tests on a 0.6 m-thick soil cover (SC-SM) at a German landfill. They found that the landfill gas flow rates ranged from 5.2×10^{-6} to 9.6×10^{-5} $m^3/m^2/s$. They suggested that the dominant gas transport mechanism was advection.

In most of the modern landfills, compacted clay liner (CCL), geosynthetic clay liner (GCL), and geomembrane (GM) are the three major types of hydraulic barrier materials used in the bottom lining systems and cover systems.

Many landfills have used compacted clays as hydraulic barrier in the cover system since the hydraulic conductivity of well-constructed CCL can be as low as 1×10^{-10} m/s and can meet the regulatory requirements. However, the major disadvantage of compacted clay liner is that they will crack as a result of desiccation, freeze-thaw cycles, and differential settlement (Koerner and Daniel 1992, Daniel and Koerner 1993). For clay minerals with high swelling potential, the cracks may heal upon rehydration. Kraus et al. (1997), McBrayer et al. (1997), and Day (1998) have looked into the phenomenon of crack-healing of compacted clay. Furthermore, Day (1998) suggested that an important factor in the healing of cracks upon wetting is the type of clay mineral. He stated that for montmorillonite the desiccation cracks are completely healed upon wetting. The hydraulic conductivity of cracked Otay Mesa natural clay specimen decreased from 7×10^{-7} m/s to 3×10^{-10} m/s as a result of healing of cracks.

Geosynthetic clay liners have not only been used in bottom liners for landfills and surface impoundments (Schubert 1987; Daniel and Koerner 1991; Trauger 1991, 1992; Clem 1992), but also in final covers for landfills and remediation projects as well (Koerner and Daniel 1992, Daniel and Richardson 1995; Woodward and Well 1995). The main advantages and disadvantages of GCLs have been discussed by Boardman (1993) and Manassero et al. (2000) amongst many others.

Although GCLs are usually installed to limit advection of liquids (e.g., water through a cover system) they may also serve an important role in covers as a gas barrier. Theoretically, hydrated GCLs as well as wet compacted soils should hardly allow any gas to pass through (Daniel, 1991). Nevertheless, Trauger and Lucas (1995) did measure the rate of methane gas migrating through GCLs via diffusion. Their results show that the rate of gas transport through GCL was very low as long as its water content was greater than 90%. The permeance is about 2 x 10^{-6} m/s for GCL sample with a water content of around 50% and drops below 1 x 10^{-9} m/s when water content reached above 90%. This suggests that the gas permeability of GCLs is dependent on the water content.

GCLs are known to have a phenomenal ability to retain moisture such that they might have the potential to be effective barrier to gas migration. Research on GCLs buried in sands showed that they were able to absorb water from the environment very quickly why buried dry or hardly lose any water when buried saturated (Geoservice, 1989; Daniel et al., 1993).

With GCLs being increasingly used as part of the capping, their gas performance has come under a growing scrutiny. Recent work has shown that the gas permeability of GCLs is affected by the manufacturing process and the form of bentonite (Didier et al., 2000; Bouazza and Vangpaisal, 2000; Shan and Yao, 2000; Aubertin et al. 2000; Vangpaisal and Bouazza, 2001, 2003).

This paper presents a test method developed speci.cally to assess the gas permeability of GCLs. It is based on the method developed by Matyas (1967) for the measurement of air permeability in soils. The testing apparatus has been designed to accommodate the GCL sample and gas. Flowmeters are used to monitor gas outflow from the device. The test method offers the possibility of carrying out gas permeability tests at different pressure gradients and confining stresses.

EXPERIMENTAL PROGRAM

The air permeability of soil depends on factors such as the size and number of cracks, the air porosity (n_a), and the degree of saturation. Many of these factors are dependent on each other or on some other factors. For example, the degree of saturation depends on both the water content and the void ratio. Among these factors, the air permeability of soils is most sensitive to the variation of degree of saturation. On the other hand, the void ratio of a clay liner in the cover system will be almost constant, since effective stress is kept unchanged throughout the service period. Therefore, the degree of saturation solely depends on water content. Furthermore, the cracking of clay liners is also closely related to the water content. Therefore, in a cover system, the water content is the single most important factor that affects its air permeability of a clay liner. As a result, this research focused on determining the effect of water contents on the air permeability of the clay liners.

Materials

The three clays selected to represent the compacted liners were kaolinite, Hsin-chu clay, and Chung-li clay. The properties of the clays are listed in Table 1.

Table 1 Properties of soils samples.

Soil	Finer than #200 sieve (%)	LL*	PL*	PI*	G_s	USCS
Hsin-chu clay	48.88	25.4	21.1	4.3	2.58	SM-SC
Chung-li clay	92.51	58.5	22	36.5	2.65	CH
Kaolinite	100	56.5	41.1	15.4	2.71	MH

Note:*Portion Finer than #40 Sieve s

The CCL samples were compacted with 48% of the energy produced by standard Proctor compaction test. The results of the compaction tests are listed in Table 2 and the compaction curves are shown in Fig. 1. The shrinkage limits of the bentonite in the clays were determined according to standard test method ASTM D427-92 and are listed in Table 3. The results of hydraulic conductivity of the CCL specimens are listed in Table 4.

Table 2 Results of compaction tests.

Soil	$\gamma_{d,\,max}$ (g/cm^3)	Optimum water content (%)
Hsin-chu clay	1.72	18
Chung-li clay	1.48	27
Kaolinite	1.27	36

Note: Specimens were compacted with 48% of Standard Proctor compaction energy.

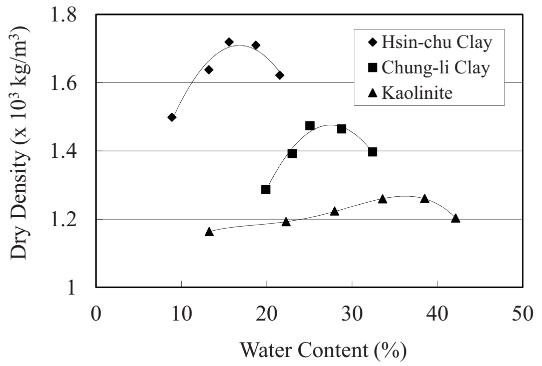


Fig. 1 Compaction curves of clays tested.

Table 3 Shrinkage Limit of Soils.

Soil	Shrinkage limit (%)	Volume change (%)
Hsin-chu Clay	16.7	15.61
Chung-li Clay	19.6	39.88
Kaolinite	40.5	30.64

Table 4 Results of fixed-wall hydraulic conductivity tests.

Soil	k (m/s)
Hsin-chu Clay	4.6×10^{-9}
Chung-li Clay	1.2×10^{-9}
Kaolinite	2.8×10^{-9}

Note: Hydraulic gradient = 100.

The two GCLs tested in this study were a needle-punched GCL and a stitch-bond GCL, which will be designated as GCL-A and GCL-B, respectively. GCL-A is comprised of a nonwoven needlepunched geotextile that is needle punched again through a layer of bentonite into a woven slit-film geotextile. The bentonite content is 3.6 kg/m^2. The water content of the bentonite in dry GCL-A is about 10 - 12%. In GCL-B, 3.6 kg/m^2 of bentonite is sandwiched between woven geotextile on the top and open weave geotextile at the bottom.

The shrinkage limits of the bentonite in the GCLs are listed in Table 5. It is interesting to note that the shrinkage limits of the bentonite are very low comparing to the high water content of saturated bentonite.

Table 5 Results of shrinkage limit tests on bentonite in the GCLs.

GCL	Shrinkage limit (%)	Volume change (%)
GCL-A	35.2	87.86
GCL-B	29.9	88.15

Water Retention Test

Clay liner specimens were placed under 0.5 m of moist sand and loosely compacted moist clay in two 86-liter plastic buckets separately. The specimens had been allowed to absorb water under dead weights that imposed a vertical stress that is equivalent to 0.5 m of soil before they were put in the buckets. The test was performed over a 90-day period spanning from March to May. The monthly average temperatures were 17.2°C, 21.1°C, and 24.6°C, respectively. The average humidity during the test period was about 85%. The suction in the cover soils was monitored with tensiometers.

The soil water characteristics of the clay liner samples were determined with a 15-bar pressure cell. The main drainage curves (MDC) of the compacted clay specimens are shown in Fig. 2. The specimens were soaked to enhance saturation before the test. On the other hand, the specimens of water retention tests were placed in the surrounding soils immediately after they had been cut from the compacted samples. As a result, the water contents of the retention test specimens were a little less than those indicated by the MDC.

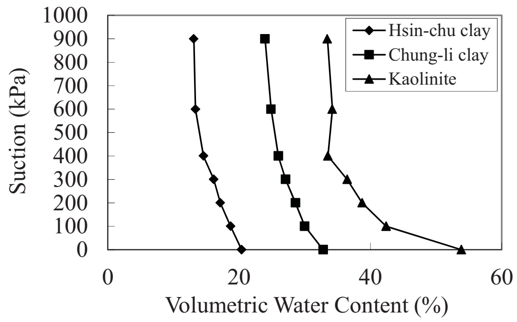


Fig. 2 Soil water characteristic curves of compacted clay samples.

Air Permeability Test

The diameter and the height of the CCL specimens were 101.6 mm and 19.5 mm, respectively. The clays were compacted at a water content 2% wet of optimum with 48% of standard Proctor compaction energy. In order for the cracks to develop more easily, it was decided to use shorter CCL specimens. Therefore, the specimens were compacted in a compaction mold of reduced size. The compacted samples were trimmed and then retrieved from the compaction mold.

The GCL specimens were cut from the rolls supplied by the manufacturer to a diameter of 114.5 mm. The specimen was placed in an acrylic mold with an inner diameter of 114.5 mm. The specimen was then hydrated with tap water for 1 day.

Both CCL and GCL specimens were placed

inside an oven and heated under a temperature of around 35°C for a given period of time. During the desiccation period, a dead load weighing 4 kg was put on top of each specimen to provide a normal stress equivalent to that created by 300 mm of topsoil. In addition, the CCL specimens were put on top of a sheet of sand paper to prevent them from shrinking as a whole so that cracks could develop. This process was repeated for different drying times to obtain specimens with various water contents.

The air permeability tests of CCL specimens were performed with flexible-wall permeameters (Fig. 3). During the tests, a low cell pressure of 3.5 kPa (0.5 psi) was applied to ensure good contact between the membrane and the specimen.

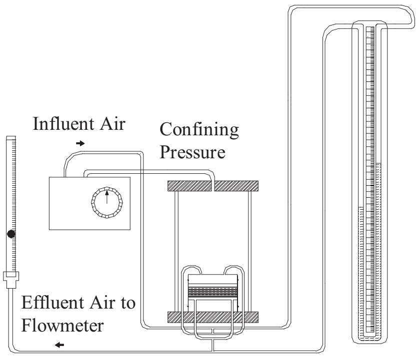


Fig. 3 Schematic diagram of the compacted clay air permeability testing system.

Figure 4 shows the schematic diagram air permeameter for testing the GCL specimens. GCL specimens were clamped between two ring-shape holders. Bentonite paste was placed along the edges of the specimens to prevent air leakage.

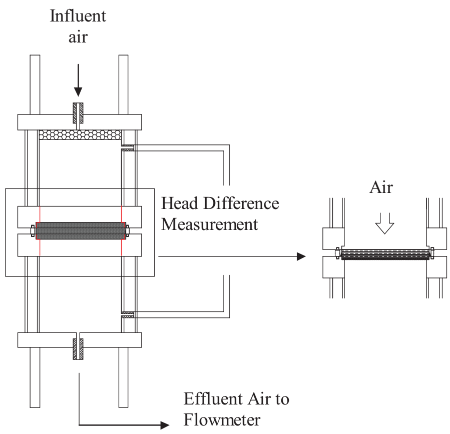


Fig. 4 Schematic diagram of the permeameter for measuring air permeability of GCL (Shan and Yao 2000).

For testing of both types of materials, the flow rate of air was adjusted by regulating influent air pressure with the pressure control panel (Fig. 5). Very low influent air pressure was used for the tests (less than 2 kPa). The range of flow rate was as high as 27 l/min for the more permeable specimens under larger gradients and as low as 0.5 l/min for less permeable specimens under smaller gradients. The head loss across the specimen was measured by U-tube manometer. For each specimen, head differences corresponding to 5 different flow rates were measured. The linear relationship between flow rate and gradient justified that the gas flow was in the laminar range. The test results of one of the compacted Chung-li clay specimen are shown in Fig. 6 as an example. After each test, the water content and the dimensions of specimen were measured.

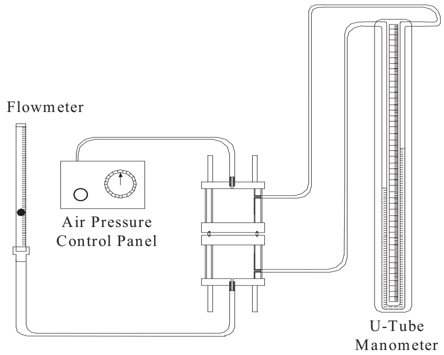


Fig. 5 Schematic diagram of the gcl air permeability testing system (Shan and Yao 2000).

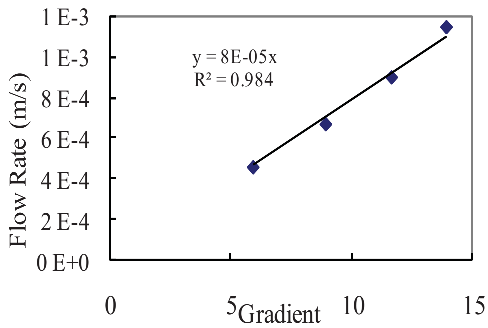


Fig. 6 Relationship between flow rate and gradient of air permeability tests.

The air permeability of the specimens was computed with the following equation:

$$k = \frac{q / A}{\left(\frac{\Delta h_{total} - \Delta h_{equipment}}{t} \right)} \qquad (1)$$

where Δh_{total} is the total head loss measured (mm); $\Delta h_{equipment}$ is the head loss of system without specimen in it (mm); k is the air permeability (mm/s).

The compressibility of air has been taken into account when computing the flow rates that passed through the specimens from the values measured with the flowmeter.

RESULTS AND DISCUSSIONS

Water Retention Tests

Results of the water retention tests show that the hydrated GCLs did not have a strong ability to retain water. The variations of the water content of GCL specimens with time are shown in Fig. 7. The final water content of GCL-A and GCL-B buried in sand are 48% and 53%, respectively. The final water content of GCL-A and GCL-B buried in clay are 27% and 28% which are lower than the shrinkage limit of bentonite. The water contents of the specimens at the end of the tests were much lower than those reported by Geoservice (1989). On the other hand, the final water contents of the specimens are comparable to the results of absorption tests performed by Daniel et al. (1993).

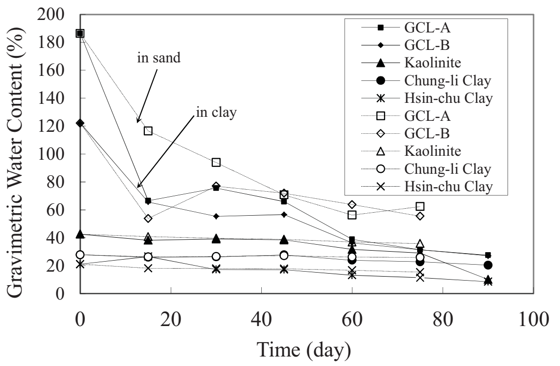
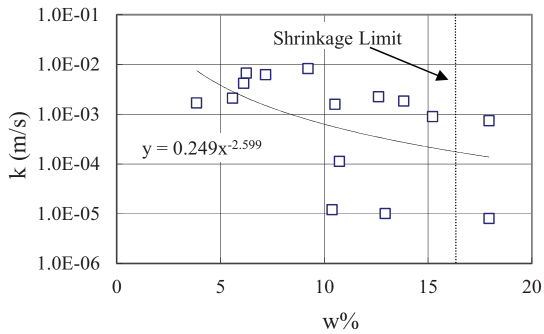


Fig. 7 Variation of water content of CCL and GCL specimens with time.

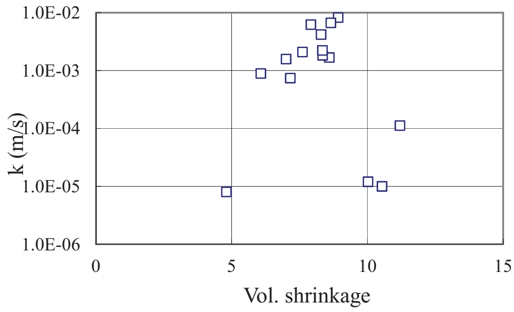
The CCL specimens also lost considerable amount of water during the test period. The difference between final water contents of specimens buried in sand and clay is most significant for kaolinite. On the other hand, only a small difference in water content was measured for Chung-li clay. In addition, the final water contents of kaolinite and Hsin-chu clay were all lower than their shrinkage limits. By comparing the results with the index properties, it can be concluded that clays with higher plastic limit are capable of retaining more water.

Air Permeability Tests on CCLs

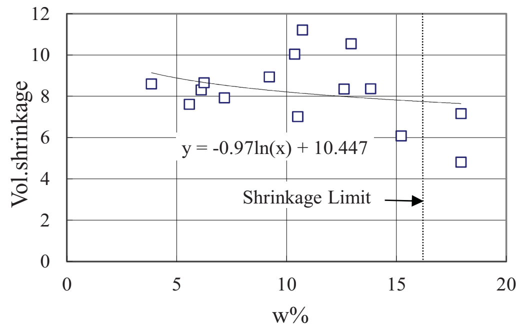
The relationship between air permeability and water content of CCLs are depicted in Fig. 8a, Fig. 9a, and Fig. 10a. The air permeability of the compacted clay specimens shows a slight increase as the water content decreases. The trend is most obvious for kaolinite.



(a) Relationship between air permeability and water content



(b) Relationship between air permeability and volume change

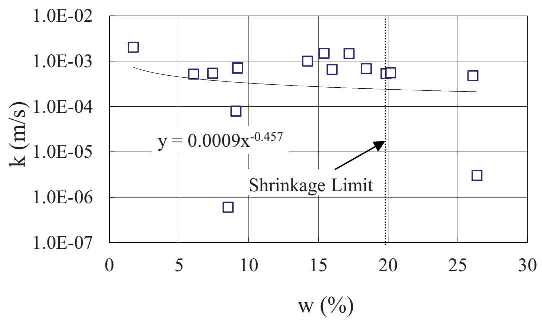


(c) Relationship between volume change and water content

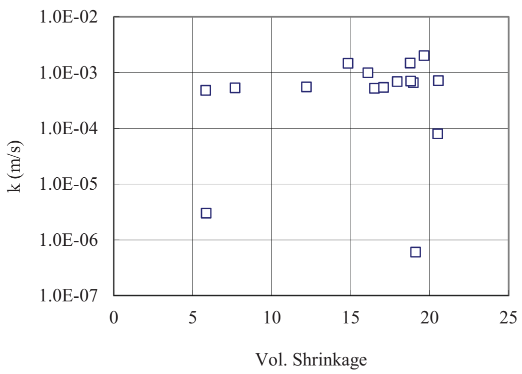
Fig. 8 Relationship between air permeability, water content, and shrinkage of compacted hsin-chu clay.

Among three CCLs, kaolinite has the lowest air permeability while Hsin-chu clay has the highest. It is interesting to note that the hydraulic conductivity of Hsin-chu clay is also the highest among the three clays (Table 4).

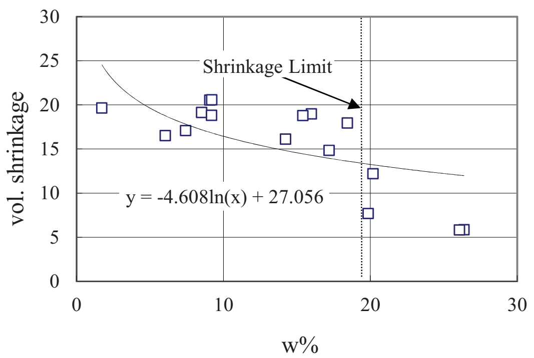
The increase of air permeability with decreasing water content did not seem to be solely related with the increased number of cracks. The cracks developed before the water content of the specimens fell below the shrinkage limit. The loss of water of clay particles along the cracks might actually widen the pathway for air.



(a) Relationship between air permeability and water content

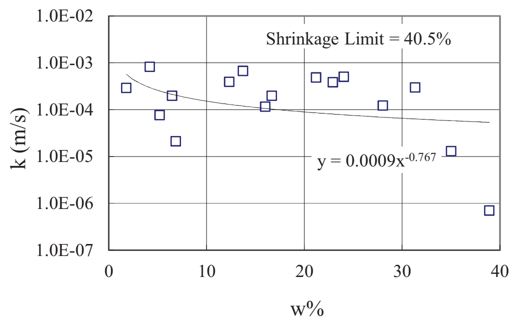


(b) Relationship between air permeability and volume change

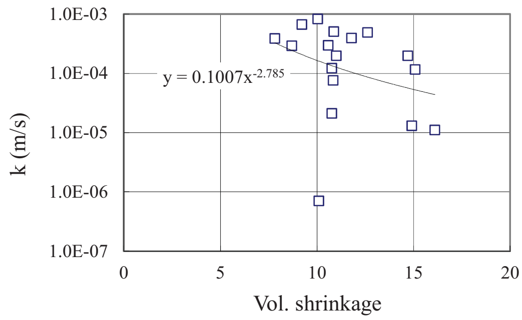


(c) Relationship between volume change and water content

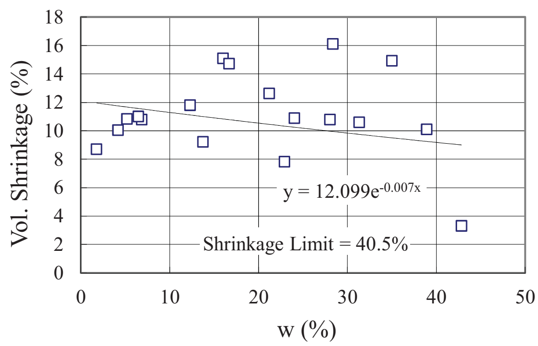
Fig. 9 Relationship between air permeability, water content, and shrinkage of compacted chung-li clay.



(a) Relationship between air permeability and water content



(b) Relationship between air permeability and volume change



(c) Relationship between volume change and water content

Fig. 10 relationship between air permeability, water content, and shrinkage of compacted kaolinite.

The relationship between the air permeability and shrinkage of the clay specimens are shown in Figs. 8 (b), Fig. 9 (b), and Fig. 10 (b). Only the air permeability of compacted kaolinite decreased at the same time when it shrank (Fig. 10(b)). For Hsin-chu clay and Chung-li clay, there did not seem to be any relationship between air permeability and shrinkage (Figs. 8 (b) and 9 (b)). Again, the reason is that the air permeability of the CCLs is related to the widening of the cracks rather than the reduction of the total volume.

It is interesting to note that the optimum water content of Hsin-chu clay and Chung-li clay are higher than the shrinkage limits whereas the optimum water content of kaolinite is lower than the shrinkage limit. As a result, the volume change of kaolinite specimens was only about 1/3 of the volume change determined from shrinkage limit test, while this ratio was about 1/2 for the other two clays. In addition, kaolinite has more fine particles and lowest plastic index value. These factors may contribute to the low air permeability of desiccated kaolinite.

On the other hand, the content of fines of Hsin-chu clay is slightly below 50% such that the sand particles may be in contact with each other. Therefore, as the water content decreases, the clay in between the sand particles shrank and pathways of air formed. As a result, Hsin-chu clay had higher air permeability than the other two types of CCLs.

Theoretically, the volume of the clays does not change after the water content dropped below the shrinkage limit. However, as shown in Figs. 8 (c) and 9 (c), for Hsin-chu clay and Chung-li clay, the specimens still experienced noticeable volume change when dried to a water content below the shrinkage limit. In addition, visual observation showed that as the water content decreased, the number of cracks remained approximately the same. The water left in the desiccated specimens either occupied the smallest pores or adhered to the surface of the clay particles. Further decrease of water content made the pathways become wider and allowed faster flow of air. As a result, the air permeability of Hsin-chu clay and kaolinite increased slightly as the water content decreased below the shrinkage limit (Figs. 8 (a) and 10 (a)).

On the contrary, for Chung-li clay, which has more than 90% of clay-size particles and the highest plastic index value, the air permeability remained almost unchanged when dried beyond the shrinkage limit (Fig. 9 (a)). It is noted that the desiccated Chung-li clay specimens shrank considerably with decreasing water content although the water content is lower than the shrinkage limit (Fig. 9 (c)). However, it is possible that compacted Chung-li clay liner may have much larger cracks than the other two clays in the field such that air will flow through it more easily.

The air permeability of the CCL specimens with water content drier than their shrinkage limits are listed in Table 6. Desiccated Kaolinite has the lowest air permeability, followed by Chung-li clay and then Hsin-chu clay. Daniel and Benson (1990) have concluded that compacted sandy clay (SC) is best suitable for hydraulic barrier because it has low permeability, high shear strength, and low shrinkage potential. However, the Hsin-chu clay (SM-SC), which consists of about 50% of sand has the highest air permeability. The most possible reason is that air not only passed through the cracks but also through the primary pores more easily than the other two clays. Although the structure formed by sand particles in contact with each other made the soil have low shrinkage potential, it also had larger pathways for air to go through when the clay shrank. The pathways were developed as the clay particles between the sand particles shrank such that additional pore space became available for transmitting air. Shrinkage of this scale is difficult to be measured or even be observed by visual inspection.

Table 6 Average air permeability of compacted soils drier than shrinkage limit.

Soil	k_a (m/s)
Hsin-chu Clay	2.8×10^{-3}
Chung-li Clay	8.2×10^{-4}
Kaolinite	2.7×10^{-4}

The ability of CCLs to transmit air can also be expressed as the permittivity to air in order to allow for comparison between barrier materials with different thickness. The permittivity is computed with the following equation:

$$\frac{k}{t} = \Psi = \frac{q}{\Delta h \times A} \tag{2}$$

The relationships between the air permittivity of CCLs and water content are shown in Fig. 11. Although the data are scattered considerably, it is obvious that the air permittivity values of desiccated CCLs are sensitive to the change of water content.

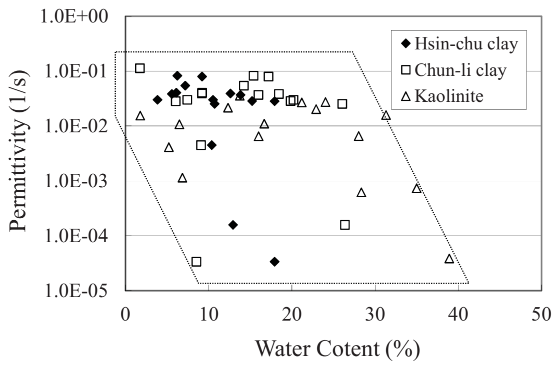


Fig. 11 Air permittivity of compacted clay liners.

Air Permeability Tests on GCLs

Since the results of air permeability tests of GCLs has been described in detail by Shan and Yao (2000), only a summary of the results is presented here. The relationships between air permeability and water content for GCL-A and GCL-B are shown in Fig. 12. For GCL-B specimens with water content higher than 190%, no flow of air was observed. On the other hand, it was unable to detect any flow of air for GCL-A specimens with water content higher than 170%. It can be clearly seen that air permeability increases as the water content decreases. The relationship between air permeability and water content of GCL-B is much clearer than that of GCL-A.

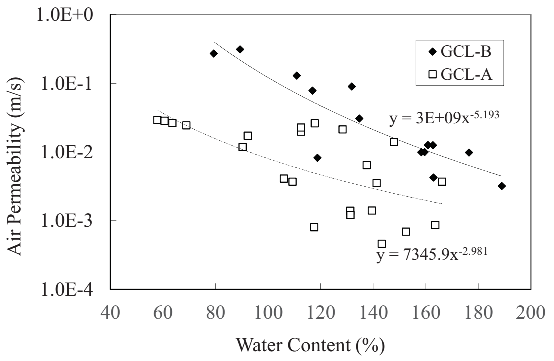


Fig. 12 Relationship between air permeability and water content of GCLs (Shan and Yao, 2000).

Cracks could be observed for GCL-B specimens with water content lower than about 140%. The bentonite in these specimens formed chunks of about 1 cm2 such that the GCL developed a network of wide-open cracks (Fig. 13). For specimens with very low water content, the cracks were as wide as 3 mm. A similar pattern of desiccation cracks of GCL-B specimens have been reported by Shan and Daniel (1991), Boardman (1993) and LaGatta et al. (1997). For GCL-B specimens with water content higher than about 140%, only barely visible hairline cracks in the bentonite was observed.

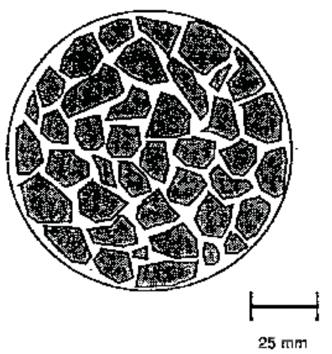


Fig. 13 Crack pattern of GCL-B specimens.

On the other hand, there was no network of large cracks found in the desiccated GCL-A specimens. Instead of forming large chunks, the bentonite in the GCL-A specimens shrank to form small granules as when it was manufactured. The needlepunched fibers seemed to prevent the bentonite from forming chunks during the drying process. As a result, the air permeability of desiccated GCL-A specimens was much lower than that of GCL-B specimens.

The relationships between the air permittivity of GCLs and water content are shown in Fig. 14. The air permittivity values of desiccated GCL-B are much higher than those of desiccated GCL-A for water content ranging from 50 - 150%. Beyond 150%, the air permittivity of both GCLs is very low.

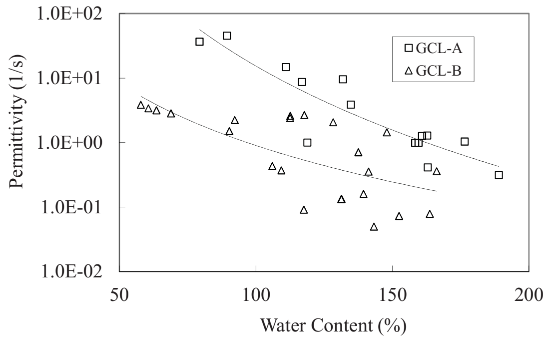


Fig. 14 Air permittivity of GCLs.

The air permittivity of 3 CCLs and 2 GCLs are compared in Fig. 15. The air permittivity of desiccated CCLs is much lower than that of desiccated GCLs. This means that desiccated GCLs will allow air to pass through more easily.

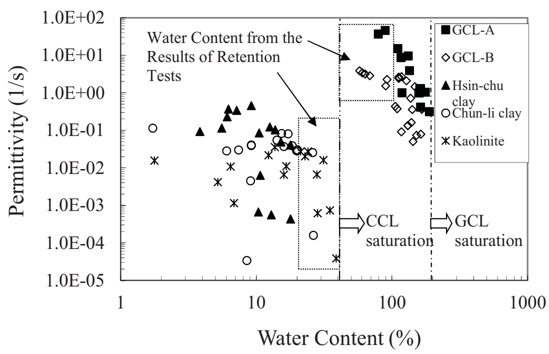


Fig. 15 Air permittivity of clay liners.

PRACTICAL IMPLICATIONS

The emission rate of the landfill gas can be estimated for a landfill under specific conditions. The rate of convective flow of landfill gas through clay liners can be computed with Darcy's law. In order to compare the flux through CCLs and GCLs, the following field condition is assumed. The head difference across the barrier layer is assumed to be

1.0 mm H_2O. The thickness of CCLs and GCLs are assumed to be 600 mm and 6 mm, respectively. The flux was computed with air permeability of CCLs and GCLs corresponding to three different suction levels, which are 30 mb, 60 mb, and 80 mb, respectively.

An appropriate reference suction value is the one that corresponds to the field capacity of the cover soil. Field capacity of a soil is usually defined as the water content of the soil after 24 hours of gravitational drainage. Some soil scientists have proposed to take the water content of a soil under a suction of 30 kPa (0.3 bar or 300 mb) to be the field capacity. Another relevant reference suction value is the wilting point of the plants is 1500 kPa (15 bar), beyond which the plants are not able to absorb water from the soil.

Table 7 is a list of the rate of convective flow through the desiccated clay liners per unit area. These results are also graphed in Fig. 16. It is clear that the gas flux through GCLs is much higher than the flux through CCLs. It is not only resulted from the higher air permeability of GCLs but also because of the fact that CCLs are thicker than GCLs. The thinness of GCLs caused the hydraulic gradient to be approximately 100 times higher than that across CCLs.

Table 7 Convective flux through clay liners ($m^3/m^2/day$).

Suction (mb)	30	60	80
Hsin-chu clay	1.91×10^{-2}	2.02×10^{-2}	3.26×10^{-2}
Chung-li clay	2.91×10^{-2}	2.95×10^{-2}	2.98×10^{-2}
Kaolinite	7.55×10^{-3}	7.83×10^{-3}	8.89×10^{-3}
GCL-A	7.32×10^{1}	3.24×10^{2}	7.88×10^{2}
GCL-B	1.78×10^{3}	9.87×10^{3}	7.79×10^{4}

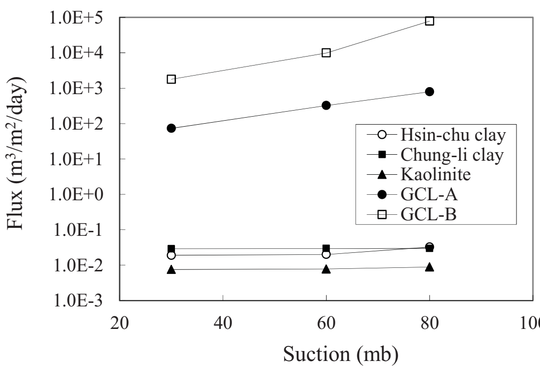


Fig. 16 Gas flux through clay liners.

CONCLUSIONS

The air permeability of both CCLs and GCLs were measured in this study. The compacted clay liners, in spite of being infamous for cracking upon desiccation, have much lower air permeability than GCLs do. In addition, the air permittivity of CCLs is also lower than that of GCLs. Although GCLs have been proved to be effective hydraulic barriers, their air permeability increases rapidly once they start to lose pore water. The results of water absorption tests by Daniel et al. (1993) and water retention tests by Yao (1998) indicate that GCLs will not maintain fully hydrated when they are in contact with soils. Therefore, GCLs are not as reliable in limiting gas emission out from the landfills as they are in preventing water infiltration into the landfills.

Both advection and diffusion should be taken into account when estimating the gas flux through the clay liners in a landfill cover system. For desiccated clay liners with lower water contents, advection dominates the gas transport. For clay liners with high water contents, only a very small amount of gas would diffuse through the material. It is thus important to maintain the clays in a near saturation state in order to limit the gas migration.

With regards to the concern on the emission of landfill gas, the design of final cover system of MSW landfills must take the high air permeability of desiccated clay liners into account. It is suggested that for landfills that are expected to generate large amount of landfill gas, geomembranes may be a better choice than clay liners as the hydraulic barrier for the final covers.

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