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# Physical modeling of desiccation cracking in plastic soils

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## Abstract

Desiccation cracking is a common phenomenon in clay materials, which may considerably increase the hydraulic conductivity of soil. This issue is one of the main concerns in the design and construction of landfill covers, especially, in arid regions. For some highly plastic soils, permeability increases during cyclic drying and wetting are not significant, even though cracking may clearly be noticed in the soil. These cracks may self-heal during subsequent wetting and saturation processes. In the present study, large scale experimental models of various natural clayey soils with various plasticity indices were subjected to cyclic drying and wetting and hydraulic conductivity testing to better understand cracking behaviour and self-healing in fine-grained soils. The soils are candidate clay liner and cover materials. Experimental models in which cracks formed during drying were tested for soil hydraulic conductivity. The results indicated that cracking and hydraulic conductivity of clays are controlled by soil properties, especially plasticity and swelling. Cracking of the specimens resulted in an increase in hydraulic conductivity, sometimes as large as five to ten orders of magnitude. The hydraulic conductivity of highly plastic clays decreased with an increase in permeation time because of self-healing.


*Keywords:* Desiccation; Self-healing; Cracking; Permeability; Physical model; Clay cover

## 1. Introduction

Desiccation cracking is a common phenomenon in clay materials, which may considerably increase soil hydraulic conductivity. This issue is one of the main concerns in the design and construction of landfill covers, especially, in arid regions. As the plasticity of the clay increases, cracks tend to develop during cycles of long dry spells. During periods of rainfall that follow the dry spells, water fills the cracks and fissures. In addition to increasing the hydrostatic forces, the water is slowly absorbed by the clay. The shrink/swell behavior results in deepening of the cracked zone, especially for clays with high plasticity index. Furthermore, the seasonal shrinking and swelling behavior of the cracked clay zone results in a progressive reduction of the bulk shear strength of the clay to the point where it may approach its residual strength. Such changes in engineering properties during cyclic drying and wetting are important in the design and construction of landfill covers and liners and barriers in arid regions.

The effect of cyclic drying and wetting on permeability of clayey soils has been investigated and discussed extensively in recent years. Fine grained soils experienced changes in hydraulic conductivity during cyclic drying and wetting (e.g. Eigenbrod, 1996; Rayhani et al., 2007). Chertkov (2002) investigated the characteristic of crack dimension in saturated drying soils and demonstrated the relationship between the minimum dimension of a shrinkage-induced, quasi-brittle crack and other characteristic dimensions of a crack network in a swelling clay soil. The existence of such a relationship suggests the need for a better understanding of cracking and hydraulic processes in clay soils. Ayad et al. (1997) modeled the entire process of crack propagation in clays, from the initiation of cracking to the prediction of subsequent primary crack spacing. Their method utilizes one-dimensional flow theory, fracture

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mechanics, and finite element analysis, to develop the framework for the analysis of this type of behaviour.

For most clayey soils, changes in hydraulic conductivity during cyclic drying and wetting appear to increase with increasing plasticity of the soil (Othman et al., 1994). However, increases in hydraulic conductivity during cyclic drying and wetting were not significant for highly plastic soils such as sodium-bentonite clays, even though cracking clearly could be noticed in the soil (Rayhani et al., 2007). This could be due to self-healing in highly plastic soils, which resulted in close up of cracks and fractures during wetting. On the other hand, such changes in hydraulic conductivity were found to be small for non-plastic or very low plastic soils, which could be because of either the presence of only a few cracks and/or cracks with tight opening. The closure of cracks in non- or low-plasticity soils could also be due to clogging of fractures by particles eroded from the fracture surfaces during permeation (Eigenbrod, 2003).

Brian and Benson (2001) evaluated the effects of plastic index and soil compaction on volumetric shrinkage strain in natural clays. The results indicated an increase in shrinkage strain with increasing plastic index and decrease of cracking with compactive effort. They also concluded that cracking could increase the hydraulic conductivity by, sometimes, as large as three orders of magnitude.

Desiccation cracking of bentonite–sand mixtures with various moisture contents of 8–32% upon air-drying was investigated by Tay et al. (2000). Mixtures containing 10 and 20% bentonite exhibited desiccation cracking only for volumetric shrinkage greater than 4%.

Yessiler et al. (2000) investigated suction and surficial dimensions of cracks using the crack intensity factor, i.e., the ratio of cracks surface area to the total surface area of the soil, in three compacted liner samples during wet–dry cycles. High suctions and large amounts of cracking were observed in samples with high fines content, and less cracking in soil with low fines content. Yessiler et al. (2000) also found that the change in the number of cracks was not significant after the second dry–wet cycle.

The main objective of the present paper is to present and discuss the results of hydraulic conductivity tests on selected soils from landfill sites. The tests were performed to examine the effect of desiccation cracking on large scale specimens (300 mm diameter by 150 mm height). The study supplements the previous publication (Rayhani et al., 2007) in which the authors investigated desiccation cracking in small scale (Proctor size) specimens. In the present paper, the effects of swelling and self-healing in a wide range of plastic soils and specimen scale on changes in hydraulic conductivity are investigated and discussed.

## 2. Properties of study soils

Three candidate natural soils for landfill liner and cover construction were tested (Karaj, Kahrizak and Gorgan). In addition, one of the natural soils was amended with bentonite to modify plasticity. The properties of the test soils are described elsewhere (Rayhani et al., 2007) and are only briefly summarized here. The plasticity index (PI) of the soils ranged from 11 to 21%, while the amount of clay varied between 15 and 45%. In addition, soil samples with a PI of approximately 37% were prepared by mixing 70% Karaj natural soil with 30% sodium bentonite by weight. This material choice spans the spectrum from low plasticity clays (No.1) to high plasticity clays (No.4), which is believed to be realistic for clays encountered in the field. The soils were identified as CL to CH clay from the Unified Soil Classification System (USCS).

A series of Atterberg limits and compaction tests were carried out to determine the plasticity indices, maximum dry densities, and optimum moisture contents for each soil, in accordance with the relevant ASTM procedures. Table 1 presents the properties of the different soils.

## 3. Physical model tests

### 3.1. Model container

Physical modeling of soil deposits requires a container to support the model soil, and the container/model contact imposes boundary conditions that do not exist in the prototype condition. The effect of model container size and type on the model response is an important concern in physical model tests. An appropriate and successful container design allows the model the freedom to behave in the same manner as the prototype field condition, and minimizes the influence of boundary conditions.

Specimen size is one of the most important parameters influencing soil hydraulic conductivity. Since cracks and pores of soil affect hydraulic conductivity, the model specimen size is very important when simulating permeability. Therefore, in this research, an attempt was made to design a large scale model that took into account the effect of crack size and sample scale effect. Soil porosity can be divided into three types: small pores (0.0001–0.0003 mm), large pores (greater than 0.0003 mm), and porosity due to soil layer discontinuities and desiccation shrinkage cracks, which are much larger than the last two types. Generally, the movement of water in soil is controlled by large pores and cracks, so the physical model sample should be large enough to simulate the large cracks and, as much as possible, represent real-life situation of the model soil.

The depth and spacing of desiccation cracks in different types of soil are about 5–50 mm and 10–100 mm, respectively.

Table 1
Physical properties of soil samples

| Soil Properties | No.1 (Karaj) | No.2 (Kahrizak) | No.3 (Gorgan) | No.4 (Karaj + bentonite) |
|---|---|---|---|---|
| USCS Classification | CL | CL | CL | CH |
| LL (%) | 32.2 | 36 | 42.8 | 62.2 |
| PL (%) | 20.8 | 21.3 | 21.6 | 24.9 |
| PI (%) | 11.4 | 14.7 | 21.2 | 37.3 |
| SL (%) | 14.3 | 15.3 | 16.8 | 19.9 |
| Swelling potential | 0.2 | 1.2 | 2.6 | 8.7 |
| Clay size (% < 2 μm) | 18 | 43 | 50 | 68 |
| Activity | 0.63 | 0.34 | 0.42 | 0.55 |
| $\gamma_d$ (max), gr/cm$^3$ | 1.74 | 1.71 | 1.66 | 1.63 |
| w (opt), % | 17.0 | 18.0 | 20.5 | 22.0 |

The diameter of sample, considering the crack lengths and soil texture should be ≥200 mm. Similarly, the height of sample should be ≥150 mm to consider the soil layer discontinuities. The ratio of model height to diameter ($H/D$) is another important concern in model container design. Reduction of this ratio ($H/D$) in model specimen would decrease the permeability time. Benson and Boutwell (2000) investigated the effect of $H/D$ between 0.5–1.0 on the hydraulic conductivity. The average hydraulic conductivities were almost the same for both $H/D=0.5$ and $H/D=1.0$. Therefore, the model container diameter and depth selected for this research were 300 mm and 150 mm, respectively.

The large scale model container was designed and constructed using cylindrical boxes of composite plastic, after trying many different materials and configurations. In order to prevent leakage of water from the container walls, the flexible wall permeameter incorporating plastic membranes were used. Fig. 1 shows the model properties and sample membrane.

### 3.2. Sample preparation

An appropriate quantity of soil was pulverized and sieved through the No.10 sieve (2 mm opening). Using a mechanical mixer, the soil was mixed with distilled water to bring the water content to approximately 2% above the optimum water content. Following mixing, the mixture was covered with a plastic wrap and allowed to cure for 24 h to improve the distribution of moisture. This curing process produced an even distribution of moisture throughout the soil. A rubber membrane stretched inside the container was used to prevent side wall leakage during the hydraulic conductivity tests, and vacuum was applied to the container. The soil was then deposited in the model container. The test models were prepared by tamping the soil in layers to obtain the desired density (95% of maximum dry density).

### 3.3. Hydraulic conductivity tests

Falling head permeability tests were carried out to assess the effects of drying on the hydraulic conductivity of the soils (ASTM D5084, 1999). For landfill cover design, Wang and Huang (1984) recommend that test samples be prepared at a density equal to 95% of the maximum dry density obtained from the standard Proctor compaction test. Specimens were therefore formed by compacting soil into the large scale model container at 95% of maximum dry density ($\gamma_{d\ max}$). After compaction, the specimens were subjected to a series of drying/wetting and permeability test cycles to assess the effects of cracking on soil hydraulic conductivity. For each of the three candidate soils three specimens were tested in this manner and the average hydraulic conductivity was reported (Fig. 2).

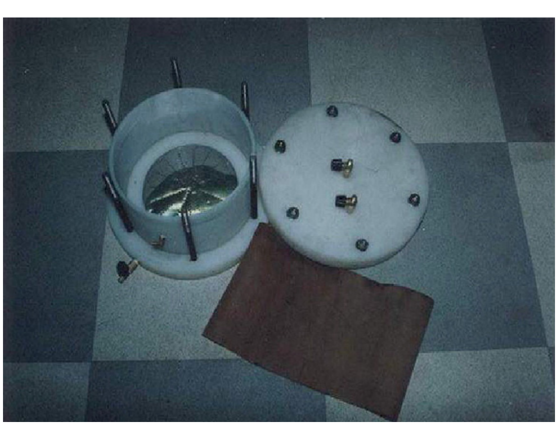

Fig. 1. Model container and rubber membrane.

Fig. 2. Permeability test in large-scale model.

Following compaction, the specimens were tested for their initial, baseline or primary saturated hydraulic conductivity. Model specimens were saturated by allowing a steady state flow of water from the bottom of each specimen to the top at a hydraulic gradient of 20. The hydraulic conductivity tests were continued until three similar continuous readings (less than 25% difference between readings) were obtained, at which point the model specimen was assumed to be close to saturation.

The permeability tests were conducted using ASTM D5084 (ASTM, 2002) falling head hydraulic conductivity test and a hydraulic gradient of 20. After measuring the primary hydraulic conductivity of the models ($K_0$), the specimens were extruded from the container and dried in an oven at 50 °C for 24 h. At the end of 24 h, the models were removed from the oven, placed in the container and connected to distilled water, and tested for the second hydraulic conductivity following 24 h of saturating and saturation ($K_1$). Then the models were placed in the oven for a second drying cycle. After 24 h, they were again removed from the oven and hydraulic conductivity measurements were made after the saturation of the specimens for the third time ($K_2$). The process of drying, wetting and measuring hydraulic conductivity was repeated in three cycles for all models.

Fig. 3. Crack distribution in soil model No. 3 (Gorgan).

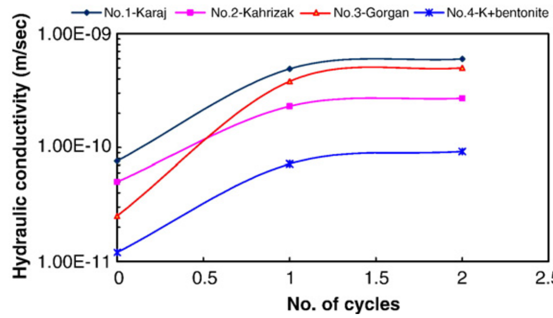


Fig. 4. The hydraulic conductivity records for different cycles of drying and wetting.

### 3.4. Crack measurements

A series of crack measurements were performed to assess the effects of drying on the development of cracks. Prior to the beginning of the final hydraulic conductivity test, the models were removed from the oven and measured for crack dimensions. Surface cracking that had occurred by the end of the last drying cycle was recorded using a digital caliper. The lengths and widths of the cracks on the cylindrical face of the model specimen were measured. The maximum crack width and the average crack depth were also recorded. Fig. 3 shows the crack distribution in model specimen No. 4 (Gorgan) at the end of the last drying cycle.

## 4. Model test results

### 4.1. Crack dimensions

Table 2 presents the average recorded crack dimensions in model specimens. The length of surface cracks varied 92–121 mm for different model soils, while the width and depth of cracks varied 3.2–6.2 mm and 15–63 mm respectively. These crack dimensions are similar to those of naturally formed cracks. It can be noted that the crack dimensions increased with increasing plasticity index. Model specimens No. 3 and No.4 had the highest number of cracks with the largest dimensions. As it can be seen on Fig. 3, the cracks formed predominantly in the vertical direction, suggesting that most of the drying occurred vertically.

Table 2
The average surface crack records in specimens

| Surface cracks records | Surface cracks | | |
|---|---|---|---|
| | Length (mm) | Wide (mm) | Depth (mm) |
| No.1 (Karaj) | 95 | 3.5 | 15 |
| No.2 (Kahrizak) | 92 | 3.2 | 18 |
| No.3 (Gorgan) | 115 | 5.5 | 57 |
| No.4 (Karaj + bentonite) | 121 | 6.2 | 63 |

### 4.2. Hydraulic conductivity

The hydraulic conductivity results for the specimens are presented in Fig. 4. As indicated, the baseline or primary hydraulic conductivity (before cracking) was the highest ($7.6\times10^{-11}$ m/s) for model No.1 and the least value ($1.2\times10^{-11}$ m/s) for model No.4. The observed minimum hydraulic conductivity ratio for the first cycle ($K_1/K_0$) was about 4.6 for model No.2, while the maximum ratio was on the order of 15 for model No. 3. At the end of the drying and wetting process (Cycle 2), the hydraulic conductivity of model No.1 was also the highest amount. The $K_2/K_1$ ratio varied from 1.17 to 1.31 for all model specimens.

The test results indicated that the hydraulic conductivity of all soils (model specimens) increased with drying and wetting cycles. Fig. 4 demonstrates the changes in hydraulic conductivity during cyclic drying and wetting for all models. As it can be seen, most hydraulic conductivity changes occurred during the first cycle of drying and wetting. The change in hydraulic conductivity for the second cycle was very small compared to the first cycle.

## 5. Analysis and discussion

### 5.1. Effect of plasticity index on cracking and permeability

Previous research (e.g. Chamberlain and Gow, 1979) has indicated that most medium to high plasticity clays of normal activity experience increases in hydraulic conductivity with increasing plasticity, often by two to three orders of magnitude. In order to investigate this behaviour, the hydraulic conductivity ratio, $Kr$ ($K_1/K_0$ and $K_2/K_0$), obtained at different cycles were plotted against the respective plasticity index values, as shown in Fig. 5. This ratio shows the hydraulic conductivity changing in different cycles of drying and wetting. The factor, $Kr$, of unity indicates no change in hydraulic conductivity during the drying and wetting cycles.

As it can be noted from Fig. 5, the hydraulic conductivity changed only slightly for low plasticity soils, while in most soils with plasticity index values between 15 and 35%, the ratios increased by a factor of 10 to 20 for both cycles. The slight change in hydraulic conductivity for low plasticity soil is similar

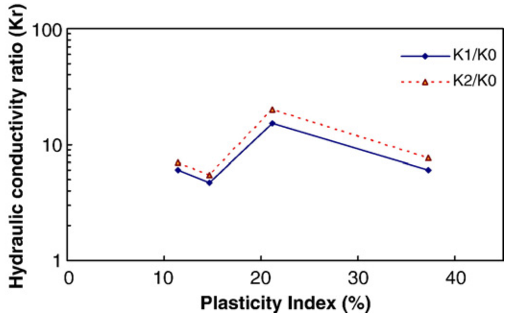


Fig. 5. Effect of soil plasticity indices on post desiccation hydraulic conductivity ratio.

to the findings of Yessiler et al. (2000) for soil with low fines content. The hydraulic conductivity ratio for soils with high plasticity index (>35%) was estimated to be 5–7. In general, these increases in hydraulic conductivity are significantly greater than those reported by Brian and Benson (2001) for natural clays. The ratio decreased with an increase in plasticity index for highly plastic soils, which was likely due to self-healing of cracks and fractures in the soil texture. The maximum values of *Kr* (15 and 20), were measured for model No. 3 with a plasticity index of 21%. These results are similar to those of Eigenbrod (2003) on the freezing and thawing behavior of fine-grained soils.

### 5.2. Effect of shrinkage index on cracking and hydraulic conductivity

Desiccation cracks develop in clayey soils when the moisture content decreases to the value of the shrinkage limit. Therefore, the moisture content difference between the liquid limit and shrinkage limit (LL–SL) has an important role in soil cracking and hydraulic conductivity changes. Fig. 6 shows the variation of this factor with the hydraulic conductivity ratio. The data show that the LL–SL moisture content of the model specimens varied from 17.9 to 42.3%. The *Kr* ratio increased with an increase in LL–SL up to 26%, and then decreased along with decreasing soil hydraulic conductivity, due likely to closure of cracks. Hence, soils with LL–SL<25% experienced only small changes in hydraulic conductivity during cyclic drying and wetting.

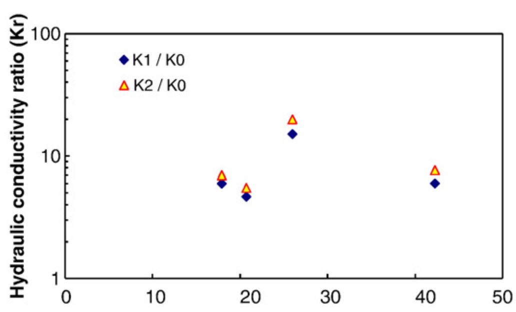


Fig. 6. Variation of hydraulic conductivity ratio versus LL–SL moisture content.

### 5.3. Effect of self healing on cracking and hydraulic conductivity

The results presented in this study show that the hydraulic conductivity of clayey soils changes during drying and wetting. During long dry periods, cracks tend to develop. During periods of rainfall that follow the dry spells, water fills the cracks and fissures. In addition to increasing the hydrostatic forces, the water is slowly absorbed by the clay. The effect of the absorbed water is to increase the unit weight of the clay as well as to decrease its shear strength. These mechanisms result in a simultaneous increase in the driving (sliding) forces and decrease in the resisting (shear strength) forces. This shrink/swell behavior also results in the deepening of the cracked clay zone. During the permeation of the soil with water, cracks tend to disappear and the hydraulic conductivity decreases. In clays with high plasticity index, the process can occur at a fast rate. This phenomenon is generally referred to as 'self-healing'. Soils with high plasticity index tend to a have high self-healing potential.

The phenomenon of "self-healing", which occurs in some types of clays, has been observed in a number of geotechnical engineering studies. While self-healing of clay can be a benefit in waste containment systems, because of decrease in hydraulic conductivity, it can also be a problem in some geotechnical applications. Self-healing in surface soils can cause shrinkage and reduction of crack dimensions during the wetting process (Mallwitz, 1998). The closure of pre-existing tension cracks can lead to the trapping of excess water which, in turn, can result in increased pressures, triggering additional ground movement that may pose a risk to utility pipelines.

In order to investigate the effect of self-healing on the hydraulic conductivity of the model specimens, the hydraulic conductivity of the models were measured again after 2 days ($K'_1$) and 4 days ($K'_2$) of saturation following measurement of the final hydraulic conductivity in the cyclic drying and wetting. The observed results are presented in Fig. 7. As indicated by the data, the post-desiccation hydraulic conductivity of models No.1 and No.2 did not change much after 4 days of saturation and permeation. However, in the two other soil models, the post drying and wetting saturated hydraulic conductivity decreased slightly after 2 days of saturation and remained essentially

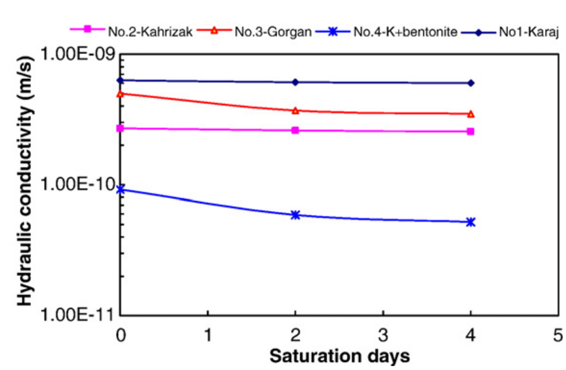


Fig. 7. Hydraulic conductivity of desiccated test soils following 2 and 4 days of saturation.

steady during 4 days of saturation. As discussed earlier, this decrease in hydraulic conductivity following desiccation and saturation varies for different clay materials and depends on soil plasticity and swelling potential. The maximum decrease in the hydraulic conductivity with increase in saturation was recorded for soil model No.4 and was approximately one half an order of magnitude (0.57). As indicated in Table 1, soil model No.4 (Karaj+bentonite) had the highest PI (37.3%), SL (19.9%), swelling potential (8.7) and amount of clay (68%). It can be inferred that the cracks in the high plasticity soils closed, during the permeation, likely because of the swelling of the clay particles in the crack surfaces. These results are in a good agreement with those of Eigenbrod (2003) on freezing and thawing behavior of fine-grained soils.

### 5.4. Effect of swelling on cracking and hydraulic conductivity

It has been demonstrated that self-healing of a fractured, high-plasticity fine-grained soil is governed largely by its swelling potential (Eigenbrod, 2003). In particular, the high swelling Na-bentonite typically does not experience increases in permeability following cyclic drying and wetting (Day, 1996), unlike fine-grained soils of lower plasticity and activity, which generally are characterized by considerable permeability increases. This difference in behavior could be explained by examining the swelling characteristics of these soils and their relationship with changes in hydraulic conductivity. Therefore, variations of soil swelling potential with hydraulic conductivity were compared, as in Fig. 8. The data show that the swelling potential of the model specimens varied from 0.2 to 8.7%. Considering the relationship between plasticity index and swelling of the specimens, it can be noted that the swelling of soil increases with an increase in plasticity index. Therefore, the *Kr* ratio increases with an increase in swelling potential up to 2.6%. Despite the increase in soil swelling potential from 2.6% for model No.3 to 8.75% for model No.4, the hydraulic conductivity ratio decreased by approximately 60%. It can be inferred that self-healing occurred due to swelling of highly plastic soils and the closure of open cracks, which resulted in a reduction in hydraulic conductivity ratios. Therefore, the hydraulic conductivity of high plasticity clays would no longer be controlled by cracks that developed during the drying processes.

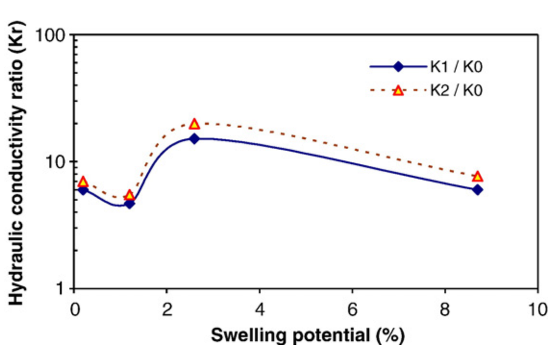


Fig. 8. Hydraulic conductivity ratio versus swelling potential of test soils.

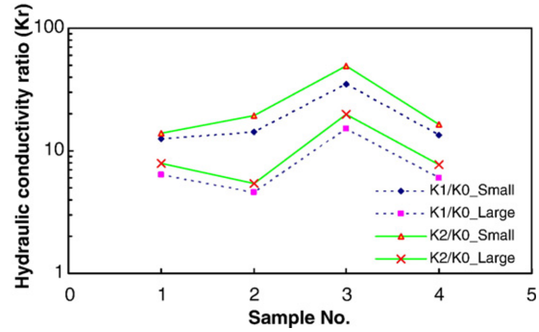


Fig. 9. Hydraulic conductivity ratio of specimens with different sizes.

### 5.5. Effect of specimen size on cracking and hydraulic conductivity

In order to investigate specimen scale on the change in hydraulic conductivity of the study soils, the hydraulic conductivity ratio for the first and second cycles were compared with those reported for Proctor size samples (Rayhani et al., 2007). Fig. 9 shows a comparison of *Kr* for the large scale specimens (300 mm diameter by 150 mm height) used in the present study and the Proctor or small scale samples (100 mm diameter by 116 mm height). As it can be seen, the trend of changes in hydraulic conductivity is similar for both specimens. However, the Kr values in the large specimens are significantly less than those for Proctor specimens. The initial hydraulic conductivities for large specimens are also lower than those of small specimens for all soils. This could be due to greater homogeneity of the large specimens, which is close to the field conditions. The large scale and Proctor size samples were compacted to the same density and optimum water content and hence void ratio. Thus the difference in initial hydraulic conductivity between the large scale and Proctor size samples cannot be attributed to difference in void ratio.

## 6. Conclusions

A series of large scale experimental models were designed to study desiccation induced cracking and hydraulic conductivity in various fine-grained soils. Physical models prepared from four natural and artificial clayey soils, used for clay liners and covers, were subjected to cycles of wetting and drying and hydraulic conductivity testing. Results were discussed with reference to the soil properties such as plasticity, swelling potential and liquidity index.

For low plasticity soils, the change in hydraulic conductivity during cyclic drying and wetting stages, was very small. However, the hydraulic conductivity ratio increased by a factor of 10 to 20 for soils with plasticity between 15 and 35%. This could be because of the presence of a fewer number of cracks and tight openings in low-plasticity soils. The closure of cracks in low-plasticity soils could also be due to clogging of fractures by particles eroded from the crack surfaces during permeation.

The change in hydraulic conductivity during cyclic drying and wetting appear not to be significant for highly plastic soils. The hydraulic conductivity ratio decreased with an increase in plasticity index for highly plastic soils. This behaviour could be due to self-healing of cracks and fractures in the soil following wetting. It can be inferred that cracks in highly plastic soils closed, during the permeation, due to the swelling of the clay particles in the crack surfaces.

Results from variation of the soil swelling potential and the hydraulic conductivity ratio demonstrated that self-healing occurred in highly plastic soils due to large swelling potential of the soils, which closed the open crack, resulting in a reduction in hydraulic conductivity ratios. Therefore, the hydraulic conductivity of high plasticity clays would no longer be controlled by the cracks which developed during the drying processes.

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## References

ASTM D5084, 1999. Standard test method for measurement of hydraulic conductivity of saturated materials using a flexible wall permeameter. Book of Standards Volume: 04.08.

ASTM D698-00ae1, 2000. Standard test methods for laboratory compaction characteristics of soil using standard effort. Book of Standards Volume: 04.08.

Ayad, R., Konrad, J.M., Soulie, M., 1997. Desiccation of a sensitive day: application of the model CRACK. Canadian Geotechnical Journal 34 (6), 943–951.

Benson, C., Boutwell, G., 2000. Compaction condition and scale depended hydraulic conductivity of compacted clay liners, constructing and controlling compaction of earth fills. University of Wisconsin, Madison.

Brian, A.A., Benson, C.H., 2001. Effect of desiccation on compacted natural clays. Journal of Geotechnical and Geoenvironmental Engineering 127, 67–75.

Chamberlain, E.J., Gow, A.J., 1979. Effect of freezing and thawing on the permeability and structure of soils. Engineering Geology 13, 73–92.

Chertkov, V.Y., 2002. Characteristic crack dimension of saturated drying soils. Journal of scientific Research and development, vol. IV. Israel.

Day, R.W., 1996. Winter effects on hydraulic conductivity of compacted clay: discussion. Journal of Geotechnical Engineering 122 (1), 85–86 ASCE.

Eigenbrod, K.D., 1996. Effects of cyclic freezing and thawing on volume changes and the permeabilities of soft fine-grained soils. Canadian Geotechnical Journal 33, 529–537.

Eigenbrod, K.D., 2003. Self-healing in fractured fine-grained soils. Canadian Geotechnical Journal 40, 435–449.

Mallwitz, K., 1998. Crack-healing in damaged compacted clay liners in waste deposits. Proceedings of the 3rd International Congress on Environmental Geotechnics, Lisboa, Portugal, vol. 1, pp. 347–352. 7-11 September.

Othman, M.A., Benson, C.H., Chamberlain, E.J., Zimmie, T.F., 1994. Laboratory testing to evaluate changes in hydraulic conductivity in compacted clays caused by freeze–thaw. In: Daniel, D.E., Trautwein, S.J. (Eds.), Hydraulic Conductivity and Waste Contaminant Transport in Soil. ASTM STP 1142. Philadelphia, pp. 227–253.

Rayhani, M.H.T., Yanful, E.K., Fakher, A., 2007. Desiccation induced cracking and its effect on hydraulic conductivity of clayey soils from Iran. Canadian Geotechnical Journal 44, 276–283.

Tay, Y.Y., Stewart, D.I., Cousens, T.W., 2000. Shrinkage and desiccation cracking in bentonite–sand landfill liners. Journal of Engineering Geology 60, 263–274.

Wang, M.C., Huang, C.C., 1984. Soil compaction and permeability prediction models. Journal of Environmental Engineering. ASCE 110 (6), 1063–1083.

Yessiler, N., Miller, C.J., Inci, G., Yaldo, K., 2000. Desiccation and cracking behavior of three compacted landfill liner soils. Journal of Engineering Geology 57, 105–121.