Desiccation-induced cracking and its effect on the hydraulic conductivity of clayey soils from Iran

M.H.T. Rayhani, E.K. Yanful, and A. Fakher

Abstract: Clay materials have many environmental applications, especially in situations where a hydraulic barrier is desired. However, as the plasticity of clay increases, cracks tend to develop during cycles of long dry spells. This is particularly a concern in the construction of covers or installation of landfill liners prior to waste filling. In the present study, specimens prepared from three natural clayey soils from Iran used for clay barrier construction, and one artificial clayey soil, were subjected to cycles of wetting and drying. Surface cracks of different dimensions formed as a result of drying. Specimens with the largest volumetric shrinkage strains typically contained the highest number of cracks. Specimens that developed cracks were subjected to hydraulic conductivity testing. The results showed that the dimension of cracks increased with increasing plasticity index and clay content and, so, the initial hydraulic conductivity increased with increasing plasticity index and cycles of drying and wetting. Cracking increased the hydraulic conductivity by 12–34 times, depending on the plasticity of the soil. After a long saturation time, the hydraulic conductivity of the soils decreased with an increase in saturation time, which could be associated with a self-healing process that affects the soils by different degrees.

Key words: desiccation, cracking, plasticity, hydraulic conductivity, clay barriers, self-healing, volumetric shrinkage.

Résumé : Les matériaux argileux ont plusieurs applications environnementales, spécialement dans des situations où l'on désire une membrane étanche. Cependant, à mesure que la plasticité de l'argile augmente, des fissures ont tendance à se développer durant les cycles de longues périodes de sécheresse. Ceci présente une inquiétude particulièrement pour la construction de couvertures ou de mise en place de membranes étanches avant le dépôt des déchets sur les sites d'enfouissement sanitaire. Dans la présente étude, des spécimens préparés à partir de trois sols argileux naturels d'Iran utilisés pour la construction de membranes argileuses, et un sol argileux artificiel ont été soumis à des cycles de mouillage et séchage. Des fissures de différentes dimensions se sont formées à la surface par suite du séchage. Les spécimens avec les retraits volumétriques les plus importants contenaient typiquement le nombre le plus élevé de fissures. Les spécimens qui ont développé des fissures ont été soumis à des essais de conductivité hydraulique. Les résultats ont montré que la dimension des fissures augmentait avec l'augmentation de l'indice de plasticité et de la teneur en argile, et ainsi, la conductivité hydraulique initiale augmentait avec l'augmentation de l'indice de plasticité et les cycles de séchage et mouillage. La fissuration a augmenté la conductivité de 12 à 34 fois, dépendant de la plasticité du sol. Après une longue période de saturation, la conductivité hydraulique des sols a diminué avec un accroissement de la période de saturation, ce qui pourrait être associé à un processus de cicatrisation qui se produit dans les sols à différents degrés.

Mots-clés : desse dynamiqueesiccation, fissuration, plasticité, conductivité, membrane argileuse, cicatrisation, retrait volumétrique.

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Introduction

Clay materials have many environmental applications, especially in situations where a hydraulic barrier is desired. 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 and 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 sliding (driving) forces and decrease in the resisting (shear strength) forces. This shrink–swell behavior also results in deepening of the cracked clay zone, especially for clays with a high plasticity index. Furthermore, the seasonal shrinking and swelling behavior of the cracked clay zone results in a progressive reduction of the shear strength of the clay to the point where it may approach its residual strength.

Desiccation cracking is a common phenomenon in clay materials and can change the hydraulic conductivity of soil. This issue is a major concern in the design of landfill covers especially in arid regions, such as large parts of Iran.

The phenomenon of “self-healing”, which occurs in some types of clays, has been observed in a number of geotechnical

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Table 1. Physical properties of soil samples.

Soil properties	Soil 1 (Karaj)	Soil 2 (Kahrizak)	Soil 3 (Gorgan)	Soil 4 (Karaj + 30% 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
% Clay	18	43	50	68
Activity	0.63	0.34	0.42	0.55
ρ_d (max.), g/cm^3	1.74	1.71	1.66	1.63
W (opt.)	17.0	18.0	20.5	22.0

engineering studies. While the self-healing property of clay can be a benefit in waste containment because of a decrease in hydraulic conductivity, it can be a problem in some geotechnical applications. Self-healing in surface soils can cause shrinkage and reduce crack dimensions during the wetting process (Mallwitz 1998). The closure of preexisting 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. For example, the Transportation Safety Board of Canada (TSB, 1997) investigated the rupture of the Westcoast Energy Inc. Monias pipeline, Mile Post 20 near Fort St. John, British Columbia on April 30, 1997. Geotechnical observation and analysis following the incident suggested that ground movement due to increased pressures in preexisting slide blocks might have stressed the pipe line beyond its design limits.

Several studies have examined the impact of fractures on hydraulic conductivity and the role of self-healing in bentonitic soils (Dixon et al. 1993; Wong and Haug 1991; Daniel and Wu 1993). Generally, these studies suggest that the use of materials with low shrinkage potential would limit the extent of cracking. Yuen et al. (1998) found that the hydraulic conductivity of the clay increased by approximately one order of magnitude, following freezing and thawing or drying and wetting. Other investigators (Peterson 1998; Chertkov 2002) have reported findings on the characteristics of cracks in saturated soils undergoing drying.

Eigenbrod (2003) studied data from freeze–thaw tests on fine-grained soils to identify possible self-healing mechanisms, and to understand when they can be expected. Three main causes for closure of fractures in fine-grained soils were suggested, (*i*) an increase in effective stress above the level of the undrained shear strength of the intact soil, (*ii*) clogging of fractures by particles eroded from the fracture surfaces during permeation for non- or low-plastic soils, and (*iii*) swelling of the clay particles near the fracture surfaces in highly swelling clay.

In the present study, the effect of desiccation-induced cracking on the hydraulic conductivity of clay soils was investigated. Specimens prepared from three natural clayey soils from Iran typically used for the construction of clay liners and covers, and one bentonite (30%) mixed clay, were subjected to cycles of wetting and drying. Volumetric shrinkage strains and crack dimensions were recorded after drying. Specimens that developed cracks during drying were subjected to hydraulic conductivity testing to investigate the permeability behaviour of the specimens after cycles of drying and wetting. The effect of self-healing on the hydraulic conductivity of different clayey soils was also investigated.

Materials and methods

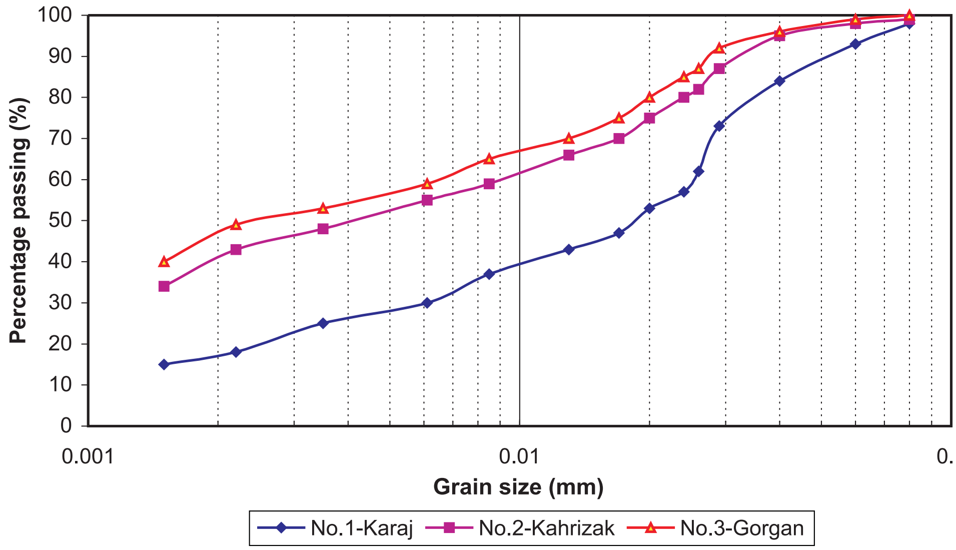
Test soils

Although Iran is situated in the desert belt of the northern hemisphere, it has climatic diversity. The variability of the climate of Iran is the result of extensive geographical latitude, long mountain belts, variable altitude, and the position of the country relative to seas and oceans. Most specifically three types of the climate are

(1) Arid and semi-arid climate in a large part of the interior lands and southern extremities of the country. These regions have long dry periods that can sometimes last up to 7 months of the year. The annual rainfall of some parts of the regions is 25–30 mm.
(2) A mountainous climate that is subdivided into cold mountainous climate and moderate mountainous climate. The cold mountainous climate subregion covers approximately 40 000 km^2 and receives an annual rainfall of more than 500 mm. The moderate mountainous climate subregion covers an area of 300 000 km^2 and receives 250–600 mm. Karaj is located in this region. The Kahrizak landfill is located in the northern part of this region, between the dry climate area and mountainous climate region.
(3) The Caspianic climate in the small and narrow area between the Caspian Sea and Alborz Mountain Belt with an annual rainfall of 600–2000 mm. The city of Gorgan is located in this area.

Samples of three natural clayey soils with a wide range of plasticity, used for the construction of clay liners and covers in Iran, were obtained from Kahrizak, Karaj, and Gorgan. The plasticity index (PI) of the soils ranged from 11% to 21%, while the amount of clay varied between 18% and 50%. 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 value of plasticity indexes was selected because it was believed to be realistic for clays encountered in Iran. The soils were identified as

Fig. 1. Grain-size distributions of natural soils.



CL to CH clay from the Unified Soil Classification System (USCS) (ASTM 1998*a*).

Atterberg limits, maximum dry density, and optimum moisture content (standard Proctor) for each soil were determined in accordance with the relevant ASTM procedures. Table 1 presents the physical and compaction properties of the different soils. The grain-size distributions of soils are shown in Fig. 1.

Sample preparation

An appropriate amount of the soil was pulverized and sieved through a No. 10 sieve. The soil was mixed with distilled water to bring its water content to about 2% above the optimum water content. After mixing was completed, the mixture was covered with a plastic wrap and allowed to cure for 24 h. This curing process produced a more even distribution of moisture throughout the soil.

Specimens were prepared by compacting the soil in a standard Proctor mold (100 mm in diameter × 116 mm in height) to 95% of maximum dry density using the standard Proctor method (ASTM 2000). A rubber membrane stretched inside the mold was used to prevent side-wall leakage during the hydraulic conductivity tests, and vacuum was applied to the mold. Specimens were prepared by tamping of the soil inside the mold to obtain the desired density (95% of maximum dry density). The full height of the specimen was achieved in three layers. Specimens were placed in the hydraulic conductivity device and the upper and bottom caps were assembled.

Hydraulic conductivity testing

Tests were performed to assess the effects of drying on the hydraulic conductivity of the four soils. Test specimens were formed by compacting soil into a standard Proctor mold to 95% of maximum dry density. After compaction, the specimens were subjected to a series of drying and wetting and hydraulic conductivity testing to assess the effects of cracking on soil hydraulic conductivity. Hydraulic conductivity tests were performed on the specimens using the falling head method in accordance with ASTM (1998*b*). A complete cycle of measurement on a specimen consisted of testing for hydraulic conductivity, drying and saturating the specimen, and then repeating the hydraulic conductivity measurement. A hydraulic gradient of 20 was used in the tests (Fig. 2).

Fig. 2. Flexible wall, triaxial hydraulic conductivity equipment.

The saturation of samples was obtained when a steady-state flow of water occurred in the top of the sample. It should be noted that it is difficult to achieve full saturation in clay soils in the falling head test, especially for specimens compacted at the optimum moisture content. In the present study, the hydraulic conductivity tests were continued until three similar continuous readings (less than 25% difference between readings) were obtained, at which point the specimen was assumed to be close to saturation. For each sample (from each site) three specimens were tested in this manner and the average hydraulic conductivity was reported.

Fig. 3. Crack measurements for test specimens.

Table 2. Volume change – cracking records for the soil specimens (dimensions in mm).

	Specimen height			Specimen diameter			Surface cracks		
Volume change – Cracks record	Primary	Cycle 1	Cycle 2	Primary	Cycle 1	Cycle 2	Length	Wide	Depth
Soil 1 (Karaj)	116	114.8	114.3	100	98	97	47	0.5	5.8
Soil 2 (Kahrizak)	116	114.4	114	100	97.5	97	45	0.8	9.7
Soil 3 (Gorgan)	116	113	112	100	96	95	53	1.9	20
Soil 4 (Karaj + bentonite)	116	112	111	100	95	94.5	63	2.1	22

After measuring the initial hydraulic conductivity (K_0), the samples were removed from the permeameter and dried in an oven at 50 °C for 24 h. The 50 °C drying temperature was selected to approximate summer peak temperature in Iran, and to minimize the possible effect of heat on clay minerals present in the soils. At the end of 24 h, the specimens were removed from the oven, measured for crack dimensions, and submerged in distilled water and their hydraulic conductivities were measured again. The mean of the three hydraulic conductivity tests results was presented as cycle 1 (K_1). This completed the first cycle of testing and measurement. The specimens were extruded from the permeameter and placed in the oven again for a second drying cycle. After 24 h, they were removed from the oven, measured for crack dimensions, and then soaked and hydraulic conductivity measurements repeated after the saturation of the specimens. The average hydraulic conductivity in this cycle was presented as cycle 2 (K_2). The process of drying, wetting, and measuring hydraulic conductivity was repeated in two cycles for all specimens, and their mean values were presented along with their initial hydraulic conductivity values.

Cracking test

A volume change – cracking test was used to assess the effects of drying on the development of cracks. The specimens were subjected to a series of drying and wetting cycles to assess the development of cracks. Each series consisted of testing three replicate specimens. As noted in the previous section, the specimens were placed in an oven at 50 °C for 24 h to dry, following initial hydraulic conductivity measurements. At the end of 24 h, the specimens were removed from the oven and cracking and volume-change measurements were made. Similarly, the specimens were subjected to one and two cycles of drying and wetting, as described in the previous section. Prior to the beginning of the hydraulic conductivity tests, cracking and volume-change measurements were obtained for all specimens at the end of each wetting–drying cycle (Fig. 3).

The sample and crack dimensions were recorded with a caliper. Two types of data were collected. Volume-change data (that is, height and diameter after the specimen was extruded) measurements were recorded at the end of each wetting–drying cycle. Surface cracking that had occurred by the end of the last drying cycle was also recorded. The lengths and widths of the cracks on the cylindrical face of the specimen were measured. The maximum crack width, mean crack width, and crack depth were also noted.

Results

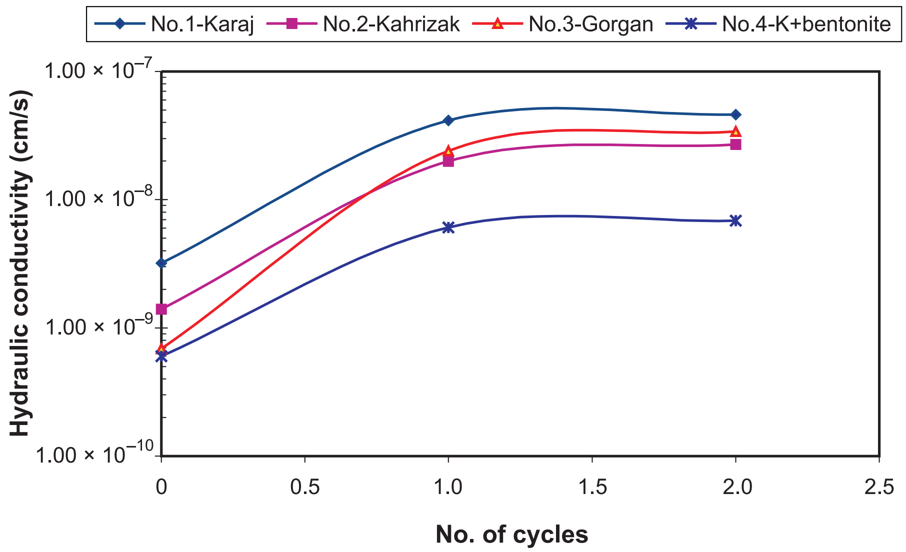
Deformation and cracking of samples

The test results indicated that the volumetric strain was of the order of 11% ± 8% for specimens with plasticity indices greater than 20. Table 2 presents the recorded crack dimensions and the sample deformations. In general, the sample dimensions decreased by 2–5 mm in height and 3–5.5 mm in diameter, following desiccation. Most of these changes happened during the first cycle of drying. The maximum change in height and diameter happened in sample 4, while sample 1 experienced less deformation. The length of surfaces cracks varied between 47 and 63 mm for the different samples, while the width and depth of cracks varied 0.5–2 mm and 5.8–22 mm, respectively. Samples 3 and 4 had the highest number of cracks with the largest dimensions. These measurable cracks occurred in the top and bottom of the

Table 3. Permeability results for soil samples in different cycles of wet–dry.

Sample properties	Primary test, K_0 (cm/s)	Cycle 1		Cycle 2		Cycle effect, K_2/K_1
		K_1 (cm/s)	K_1/K_0	K_2 (cm/s)	K_2/K_0	
Soil 1 (Karaj)	3.29×10^{-9}	4.16×10^{-8}	12.52	4.60×10^{-8}	13.92	1.11
Soil 2 (Kahrizak)	1.40×10^{-9}	1.99×10^{-8}	14.21	2.70×10^{-8}	19.29	1.36
Soil 3 (Gorgan)	6.88×10^{-10}	2.40×10^{-8}	34.88	3.40×10^{-8}	49.42	1.42
Soil 4 (Karaj + 30% bentonite)	6.00×10^{-10}	8.06×10^{-9}	13.43	9.88×10^{-9}	16.47	1.23

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



specimens. There were other visible cracks that were not necessarily measurable because of their extremely small size and shape. Thus, the specimens did not have discernible intact portions arguing. The hydraulic conductivity reported is the bulk value and shows an overall increase compared with the hydraulic conductivity of the initial specimen before subjection to drying and wetting cycles.

Hydraulic conductivity

The average hydraulic conductivity test results for the specimens are shown in Table 3 and Fig. 4. The initial hydraulic conductivity of the soils varied from 3.29×10^{-9} for soil 1 to 6.88×10^{-10} for soil 3. This shows a decrease in primary hydraulic conductivity with an increase in clay content and plasticity index. The results indicate that an increase in hydraulic conductivity of the specimens increased with drying and wetting cycles. The hydraulic conductivity after the drying–wetting cycle was generally greater than the initial value. The change in the hydraulic conductivity was, however, different for the different soils. The permeability ratio, K_1/K_0 (K_r, ratio of hydraulic conductivity at the end of the first cycle to the initial hydraulic conductivity), was of the order of 35 for soil 3 with plasticity indices of about 21 and less than about 14 for other specimens.

Analysis and discussion

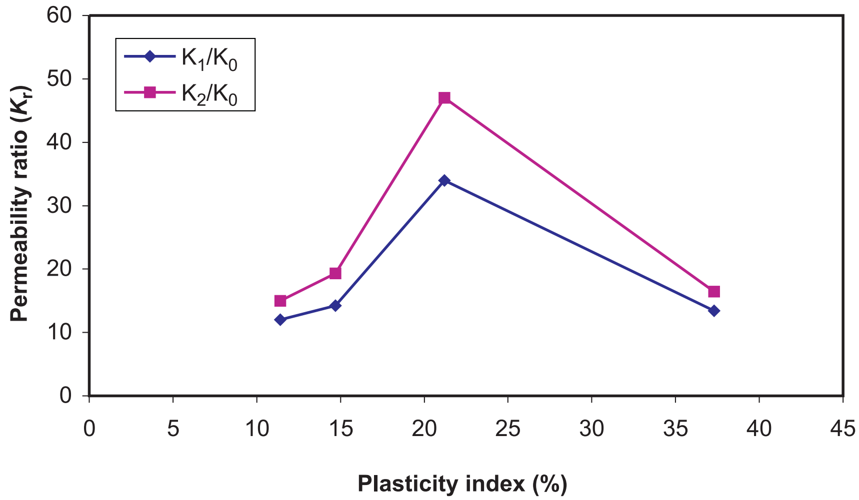
To investigate the effect of soil characteristics on the cracking behavior of the specimens, soil properties such as plasticity index, activity, and self-healing of samples were examined and their effects on the permeability ratio of samples (K_r) were investigated.

Effect of plasticity index on cracking and permeability

Most medium to high plasticity clays experience increases in hydraulic conductivity with increasing plasticity index, often by two or three orders of magnitude (Chamberlain and Gow 1979). However, with very high plasticity soils, such as sodium bentonite, permeability increases during cyclic freezing and thawing were not encountered (e.g., Boardman and Daniel 1996).

The plasticity indices of the test specimens varied from 11.4% to 37.3% (Table 1). The Karaj specimen (No. 1), with 18% clay, had the lowest plasticity index (PI), while specimen 4 (Karaj + bentonite) with a clay content of 68% had the highest plasticity index (37.3%). The permeability ratio was calculated for each specimen and used (see Table 3), along with the plasticity index, to evaluate the effect of plasticity on cracking and permeability behavior of the specimens. This ratio shows the hydraulic conductivity changing in different cycles of drying and wetting. The relation between K_r and the specimen's PI during the different test cycles is presented in Fig. 5. As shown, K_r of the specimens with plasticity indices of 10–15 (samples 1 and 2) is much less than that of sample 3 with a plasticity index of 21.2. The maximum value of K_r (30–35) was observed in sample 3 indicating that the hydraulic conductivity of this sample, after the first cycle of drying and wetting, was approxi-

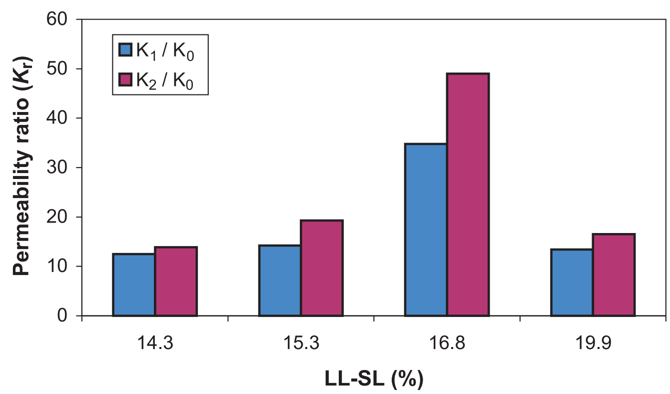
Fig. 5. The ratio of hydraulic conductivity for samples with different PI.



mately 35 times its initial hydraulic conductivity. The permeability ratio shows a decrease to about 13 (K_1/K_0 = 13.4) with an increase in plasticity index of 37.3% for sample 4, which could be due to the effect of self-healing on the permeability behaviour in high plasticity soils. This behavior is similar to the results of other researchers (e.g., Eigenbrod 2003) for fine-grained soils.

The ratio of hydraulic conductivity after the second drying–wetting cycle to the first cycle (K_2/K_1) varied from 1.1 to 1.4 for all specimens, which shows that the effect of the second cycle of drying–wetting on the permeability of the soils was not as significant as the first cycle.

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



Effect of shrinkage index (LL – SL) on cracking and permeability

When the moisture content of a clayey soil decreases below its shrinkage limit, the soil starts to crack. Therefore, the shrinkage index, which is the difference between the liquid limit and shrinkage limit (LL – SL), is an important indicator of soil-cracking behavior and potential changes in permeability. Figure 6 shows the variations of this parameter (LL – SL) with the ratio of hydraulic conductivity. The figure shows that LL – SL varied from 17.9% to 42.3% for all specimens. K_r increased with an increase in LL – SL up to 26%, which could be because of the high void ratio of the soils. As it can be seen from Fig. 6, there is a decrease in the permeability ratio of approximately 18 with an increase in LL – SL moisture content of 42.3% for sample 4, which could be due to the effect of self-healing and swelling of sodium bentonite in the soil. A comparison of Figs. 5 and 6 shows that the shapes of the K_r versus the plasticity index (LL – PL) and K_r versus shrinkage index are similar, suggesting a strong correlation between shrinkage potential and plasticity for the studied soils.

Effect of self-healing on cracking and permeability

The results presented in this study show that the permeability of clayey soils changes during drying and wetting. During long dry cycles, cracks tend to develop. During the wetting and saturation of the soil, cracks tend to disappear and the hydraulic conductivity decreases. In clays with a high plasticity index, the process can occur at a rapid rate. This phenomenon is generally referred to as self-healing. It is believed that the different changes in hydraulic conductivities are associated with self-healing processes that affect the various soil types by different degrees (Eigenbrod 2003). Therefore, one of the goals of the present study was to investigate the behavior of self-healing in different clayey soils.

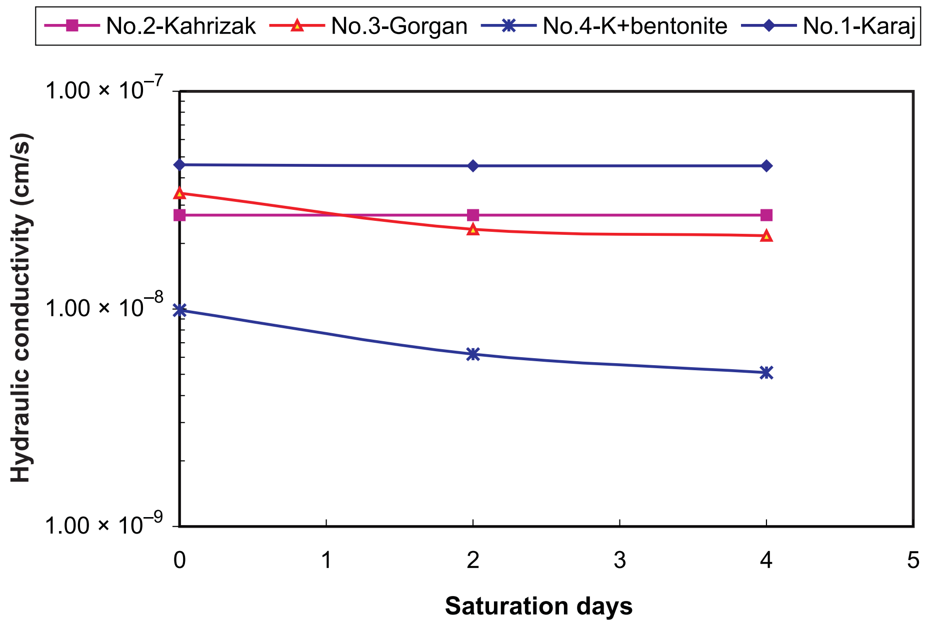
To investigate the effect of self-healing on permeability of the samples, the hydraulic conductivities of some of the samples were measured again during long saturation periods, after 2 days and 4 days of saturation, following the measurement of the last hydraulic conductivity in the drying–wetting cycle. The observed results are presented in Table 4 and Fig. 7. As indicated, the hydraulic conductivity of soils 1 (Karaj) and 2 (Kahrizak) did not change much after 4 days of saturation, but in the other samples, the post-drying and -wetting saturated hydraulic conductivities decreased slightly with an increase in the saturation period. This decrease varies for different clay materials and depends on soil plasticity and swelling potential, which could be due to swelling of the clay particles in high plasticity clays. In the present study, the maximum decrease in the hydraulic conductivity with an increase in saturation time occurred in sample 4 by approximately half an order of magnitude (0.52). These

Table 4. Permeability results for samples from 2 and 4 days after the first test.

Sample	Primary saturated $K'1$ (cm/s)	After 2 days, $K'2$ (cm/s)	$K'2/K'1$	After 4 days, $K'4$ (cm/s)	$K'4/K'1$
Soil 1 (Karaj)	4.60×10^{-8}	4.60×10^{-8}	1	4.60×10^{-8}	1
Soil 2 (Kahrizak)	2.70×10^{-8}	2.70×10^{-8}	1	2.70×10^{-8}	1
Soil 3 (Gorgan)	3.40×10^{-8}	2.42×10^{-8}	0.71	2.17×10^{-8}	0.64
Soil 4 (Karaj + 30% bent.)	9.88×10^{-9}	6.22×10^{-9}	0.63	5.14×10^{-9}	0.52

Note: $K'1$ is the permeability at the end of drying–wetting cycles; $K'2$ is the permeability after 2 days of extra saturation; and $K'4$ is the permeability after 4 days of extra saturation.

Fig. 7. Permeability results for the saturation periods of 2 and 4 days after the first test.



results are in good agreement with those of Eigenbrod (2003) on freezing and thawing behavior of fine-grained soils.

Conclusions

In this research, samples prepared from three natural clayey soils from Iran used for clay liner and cover construction were subjected to cycles of wetting and drying. Volumetric shrinkage strains and crack dimensions were recorded during drying. Specimens that developed cracks during drying were subjected to hydraulic conductivity testing. The results of the study indicated that cracking and permeability of clays are controlled by soil properties. The dimension of cracks increased with increasing plasticity index and clay content, therefore the hydraulic conductivity increased relative to plasticity index and the number of drying and wetting cycles. Specimens with the largest volumetric shrinkage strains typically contained the largest number of cracks. Hydraulic conductivity testing indicated that cracking of the specimens resulted in an increase in hydraulic conductivity, sometimes by as much as several orders of magnitude.

To evaluate the effect of soil properties on the cracking and permeability behaviour, K_r, was used. This parameter can be used to explain the two key criteria for a good barrier: low cracking potential and high self-healing potential. When K_r is close to unity, the soil may be considered suitable for liner or cover application. In the present study, the observed K_r value in the first drying–wetting cycle varied between 12 and 34. The range for the second cycle was 1.11–1.42. Hence, the effects of drying–wetting cycles on the cracking potential and the hydraulic conductivity of the soil in the first cycle were much greater than in the other cycles. Self-healing of the soil likely affected the hydraulic conductivity of the specimens. The hydraulic conductivity decreased with an increase in saturation time, especially in soils with a high plasticity index.

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