



Temperature Effects on Volume Change and Hydraulic Properties of Geosynthetic Clay Liners

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ABSTRACT

As geosynthetic clay liners (GCLs) are becoming integral components of modern municipal solid waste landfill lining systems, increased interest is directed at investigating their behaviour under different environmental stresses such as temperature, chemical compatibility, etc. Such stress can be due to biological decomposition of organic matter within municipal solid waste involving exothermic reactions leading to heat generation and consequently, increased temperatures within the waste mass as well as at the landfill base. This paper presents the results of an experimental investigation on temperature effects on the volume change and hydraulic conductivity behaviour of GCL specimens. A Rowe cell modified to handle elevated temperatures up to 60°C was utilized. Series of thermal consolidation and hydraulic conductivity tests were conducted under saturated condition at different elevated temperatures, varying from 20°C to 60°C, and different stress levels.

1. INTRODUCTION

Over the past two decades, design engineers and environmental agencies have shown a growing interest in the use of geosynthetic clay liners (GCLs) as an alternative to compacted clays liners (CCLs) in cover systems or in base lining systems of municipal solid waste landfills because of their very low hydraulic conductivity to water ($k < 10^{-10}$ m/s) and their relatively low cost. As a result, they have been subject of considerable research, dealing especially with their hydraulic and diffusion characteristics, chemical compatibility, mechanical behaviour, durability, and gas migration (Shackelford et al., 2000, Bouazza, 2002, Zornberg et al., 2005, Guyonnet et al., 2005, Touze et al., 2006, Bouazza et al., 2006a). However, it has been identified recently that the high temperatures generated in landfills due to microbial activity over time could also cause desiccation of GCLs (Southen & Rowe, 2005; Rowe, 2005), thereby rendering them potentially ineffective as hydraulic barriers. As elevated temperatures are common in landfills their long term performance comes into question since elevated temperature may have significant implications on their service life.

The aim of this study was to investigate the effects of thermal loading on the volume change and hydraulic conductivity of GCLs. For this purpose, a Rowe cell permeameter was modified so volume change and hydraulic conductivity tests could be performed at temperatures as high as 60°C. In the following sections, the experimental program is described in detail, test results are presented and discussed and conclusions are drawn regarding thermal effects on long term GCL performance.

2. BACKGROUND

The effect of heat generated in landfills, as the result of the biological decomposition of waste, on the performance of GCLs has been flagged recently as a significant research area (Rowe 2005). The available data indicate that landfill liner temperature can be expected to reach 60°C under normal landfill operations (Yesiller et al. 2005; Rowe 2005; Koerner and Koerner 2006, Bouazza et al. 2006b). Even higher temperatures (up to 70°C) may occur at the base of landfills where a significant leachate mound occurs (Yoshida et al. 1996). These results highlight that GCLs may be subjected to temperature variations and thermal gradients outside the range of the conditions typically considered during testing and design of these materials. Therefore, a thorough understanding of the hydraulic transport properties of GCLs under conditions that consider coupled thermo-chemo-hydro-mechanical behaviour is required to ensure an effective and safe design of landfill liner systems. During the last two decades some studies have been directed at investigating the hydraulic transport properties of clay soils under thermo-mechanical conditions (Habibagahi 1977; Morin and Silva 1984; Towhata et al. 1993; Delage et al. 2000; Tang, 2005; Abuel-Naga et al. 2006; Lloret and Villar 2007). In contrast, due to the complex nature of the multi-physics problem, the studies on the clay behaviour under thermo-chemo-hydro-mechanical condition have lagged behind (Cleall et al. 2007). To the authors' knowledge, there are no published studies on the hydraulic transport properties of GCLs under either thermo-mechanical or thermo-hydro-mechanical conditions. Thus, an urgent need exists to advance our understanding of key variables and processes influencing fluid flow through the GCL at elevated temperatures. The present study is directed at coupled thermo-hydro-mechanical behaviour by investigating the temperature effects on volume change behaviour and hydraulic conductivity of GCLs at different stress levels.

3. TESTED MATERIAL

The basic characteristics of the GCLs investigated in this study are presented in Table 1. GCLs consist of air-dry (water content typically < 15%) powder (<200 mesh) bentonite sandwiched between polypropylene geotextile layers. The geotextiles are held together as a composite material by needle-punching. The mass per unit area of air-dried bentonite (M_b) was determined from the difference between mass per unit area of GCL and mass per unit area of geotextiles ($M_b = M_{GCL} - M_g$). M_{GCL} was determined following the procedure outlined in ASTM D5993; whereas the value of the mass per unit area of geotextiles (M_g) was based on the information supplied by the manufacturer. H_{GCL} represents the thickness of the GCL at as received conditions.

Table 1. Characteristics of geosynthetic clay liners used in the present study.

GCL type	Bentonite type	Bonding	Upper geotextile	Lower geotextile	M_{GCL} (kg/m ²)	M_b (kg/m ²)	H_{GCL} (mm)
GCL-1	Sodium/powder	Needle punched ^a	NW	NW+SW	4.75	4.45	7.8 - 8.7
GCL-2			NW ^b		5.5	5.0	10 - 11

Note: GCL=geosynthetic clay liners; W=woven; NW=nonwoven; SW=slit film woven; and NW+SW= nonwoven reinforced by slit film woven. ^a Thermally treated; ^b Impregnated.

4. TEST APPARATUS

A modified Rowe cell has been used in this experimental investigation to study the temperature induced volume change and the thermal evolution of hydraulic conductivity coefficient under different stress conditions (void ratios). The modified Rowe cell, as shown in Fig. 1, consists of a conventional Rowe cell apparatus, a ring heater that is attached to the outer ring, two K-type thermocouples, and a thermo-controller unit with accuracy $\pm 0.1^\circ\text{C}$. The temperature of the consolidated specimen is increased indirectly by heating the outer ring of the Rowe cell. The ring heater optimized the temperature homogeneity around the GCL sample during the test period. A K-type thermocouple (TC1), placed inside the top inlet pipe above the tested sample, enabled GCL sample temperature to be monitored. Another thermocouple (TC2) placed between the outer surface of the Rowe cell ring and the ring heater was used to provide feedback signal for the thermo-controller unit.

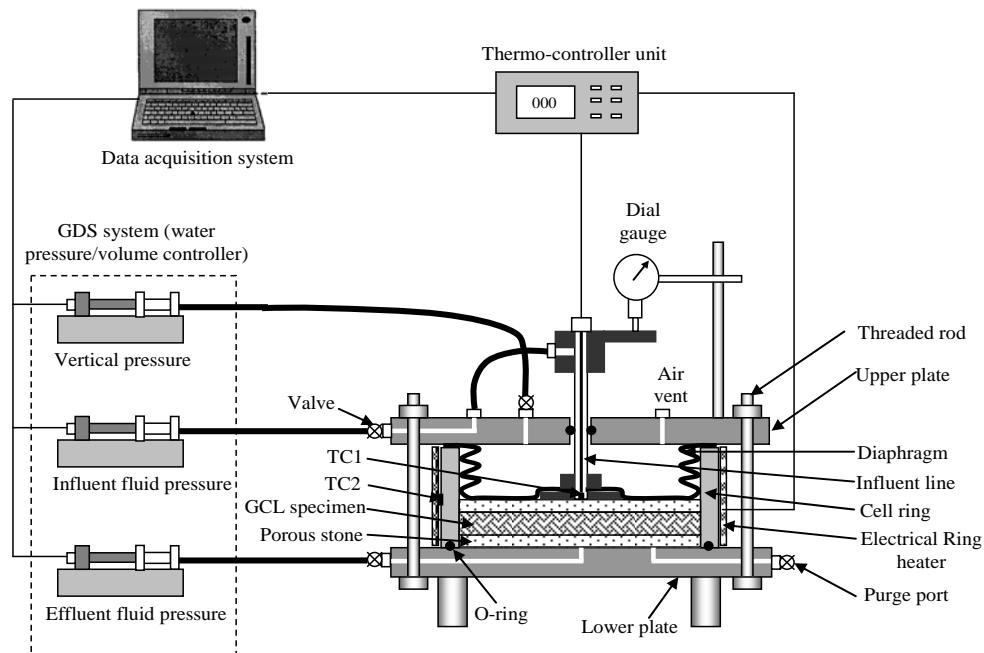


Figure 1: Modified Rowe cell test apparatus.

Calibration tests showed that the time to attain the required temperature at the centre of the sample (using TC1) was about 25 minutes. The thermal gradient between the outer surface of the cell ring and the centre of the cell was about 1°C. The thermal displacement of the oedometer apparatus due to the non-isothermal test conditions thus had to be calibrated. The average thermal vertical dilatation of test apparatus based on three heating/cooling cycles is shown in Fig. 2. A positive sign indicates contractive volume change; whereas a negative sign indicates expansive volume change. Vertical displacement was measured using a displacement dial gauge (0.01 mm resolution) mounted on top of the modified Rowe cell as shown in Fig. 1. These measurements were made where the loading platen was placed directly over the saturated porous stone discs. The results show reversible contraction on heating and expansion on cooling. This unusual behaviour is attributed to the longitudinal thermal expansion of the stainless steel retaining rod, which when under applied vertical pressure, causes upward movement of the upper plate of the modified Rowe cell. As the displacement gauge is mounted on the upper plate, the upward movement is reflected by a contraction reading in the displacement dial gauge. The measured readings under non-isothermal conditions during actual tests on GCL samples were corrected using the results shown in Fig. 2.

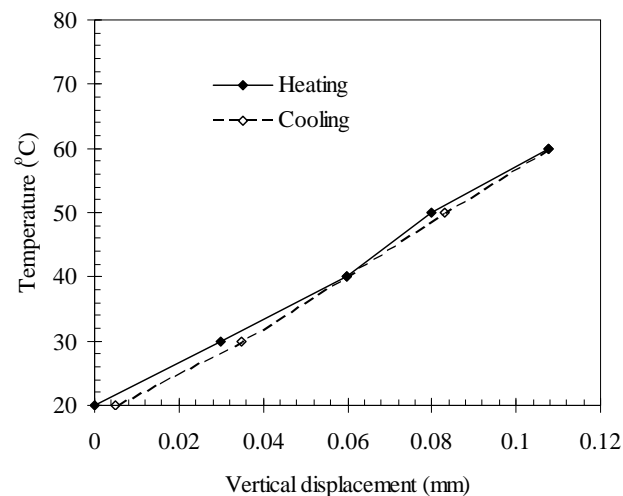


Figure 2: Thermally induced vertical displacement of the modified Rowe cell

The constant head approach was used in the hydraulic conductivity tests. It implies that the influent and effluent ends of the system are open to constant different applied fluid pressure sources to generate the required constant hydraulic gradient. Two pressure controller/volume measurement units (GDS, UK) were used for this purpose. Another pressure controller/volume measurement unit was used to apply the designated vertical stress through the diaphragm.

5. EXPERIMENTAL PROGRAM AND TESTING PROCEDURE

The experimental program involved measuring the thermally induced volume change and hydraulic conductivity of 75 mm diameter GCL specimens at different vertical pressures (up to 150 kPa) and temperature levels (20, 40, 60°C) as shown in Fig. 3. Only distilled de-aired water was used as the permeant in this study. GCL-1 was used for sample 1 whereas GCL-2 was used for samples 2 and 3. All samples were hydrated under a 20 kPa vertical stress by subjecting the sample to back pressure of 5 kPa. At the end of the hydration stage, the sample was subjected to the designated vertical consolidation pressures and temperature and the hydraulic conductivity test was started. It should be mentioned that the heating phase of GCL sample was started after completion of the mechanical consolidation stage. An incremental drained heating/cooling approach was adopted in this study (Towhata et al. 1993; Delage et al. 2000; Abuel-Naga et al. 2006), which involves raising /decreasing the temperature incrementally (10°C) once the volume change was stabilized. The applied hydraulic gradient during the hydraulic conductivity test was in the range of 200 to 250. This gradient was sufficient to create a measurable flow with insignificant effects on the measured hydraulic conductivity value due to the thinness of the GCL sample (Shackelford et al. 2000).

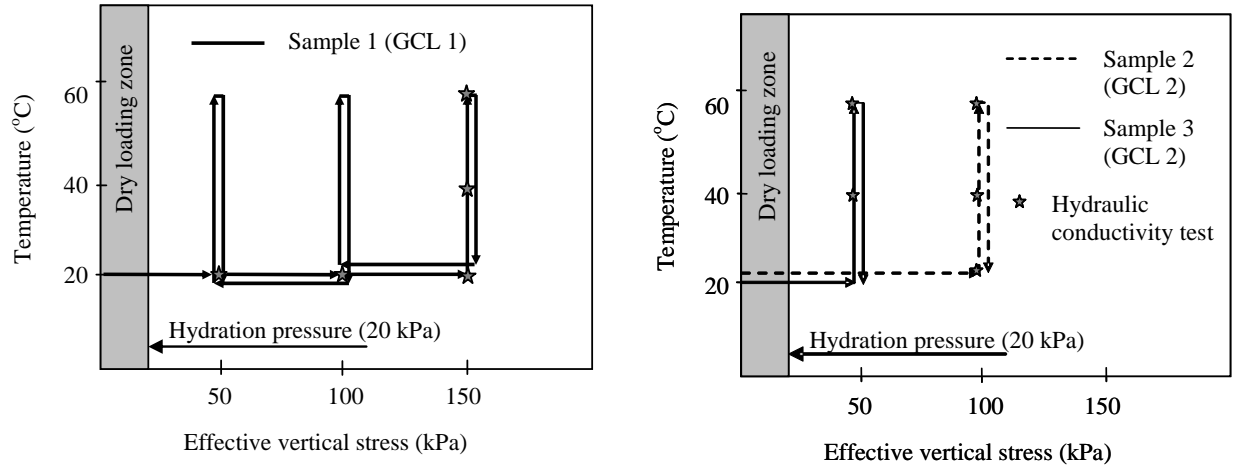


Figure 3: The experimental program

5.1 Trimming of GCL Specimen

GCL specimens were cut from large GCL sheets, using a sharp utility knife, to A4 size (210 X 297mm). A circular stainless steel cutting ring with an inner diameter of 76 mm was used to cut the GCL samples. Each GCL sample was placed between a cutting ring and a plywood plate, which was used as a cutting base. The GCL was then placed on the platen of a compression machine for cutting. To achieve an effective cut, a force of approximately 15 to 20 kN (1.5 to 2.0 tonnes) was applied. The cutting ring containing a GCL sample was weighted to determine the mass per unit area. The initial un-hydrated GCL height was measured under an applied normal stress of approximately 2 kPa using a high gauge vernier. The GCL was then gently pushed from the cutting ring directly into the Rowe cell ring. A plastic disc with a diameter slightly smaller than the inner diameter of the ring was used to support the GCL during extraction from the cutting ring. Care was taken not to lose any bentonite from the outer edge of the GCL sample. The GCL was then confined in the Rowe cell. The initial moisture content was determined from the GCL cuttings.

5.2 Hydraulic Conductivity Test

Standard methods were followed for testing the hydraulic conductivity of GCL specimens. The termination criteria of hydraulic conductivity test were as follows: (1) at least three hydraulic conductivity measurements were determined, (2) the ratio of outflow to inflow fell within ± 0.3 of the average of the last three hydraulic conductivity measurements, (3) no upward or downward trend existed in the last three hydraulic conductivity measurements, and (4) the last three consecutive hydraulic conductivity measurements fell within ± 0.25 of their average. The average of the last three measurements was reported as the hydraulic conductivity. The hydraulic conductivity coefficient k was calculated as follows:

$$k = \frac{q}{i} \quad (1)$$

where q is the flow flux and i is the applied hydraulic gradient to create flow through the GCL.

6. TEST RESULTS AND DISCUSSION

6.1 Thermally Induced Volume Change

The vertical displacement of samples 1 and 2 during hydration and the vertical consolidation process is shown in Fig 4. The results show that GCL-1 (sample 1) had a higher swelling capacity than GCL-2 (sample 2), probably reflecting differences in the manufacturing process. As the bentonite clay mineralogy of GCL-1 and GCL-2 are similar, the difference in their swelling capacity could be attributed to the difference in the density of the needle-punched fibres. Figure 5 shows the thermally induced volume change test results of sample 1 at different vertical stress levels. Under 150 kPa vertical stress; sample 1 shows reversible thermally induced volumetric contraction when subjected to a heating/cooling cycle (20°C to 60°C to 20°C). Under 50 and 100 kPa vertical stresses; lower values of volumetric contraction were observed with heating in comparison to the test results at 150 kPa. However, volumetric expansion was observed upon cooling to room temperature. Moreover, it was observed that the thermally induced volume change is reversible within the temperature range of 40°C to 60°C. Therefore, it can be concluded that the thermally induced volume change is dependent on the level of stress applied.

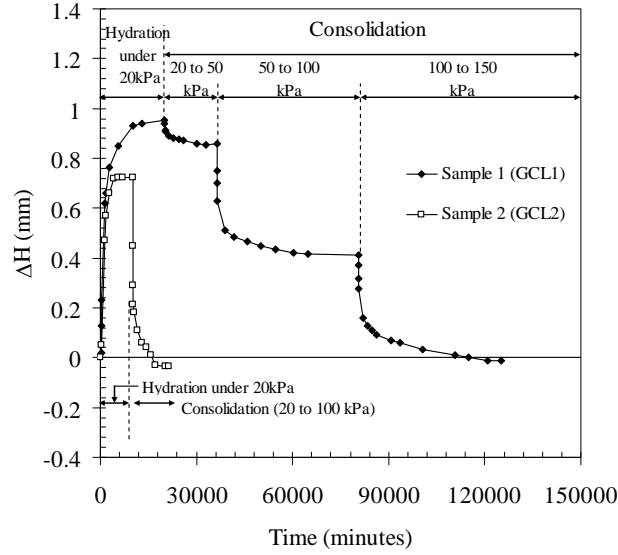


Figure 4: Hydration and mechanical consolidation results of the tested GCLs

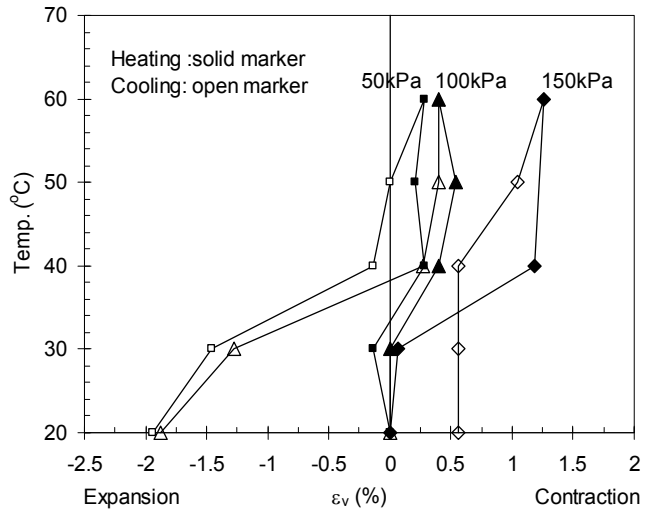


Figure 5: Thermally induced volume change of sample 1 at different vertical stress levels

6.2 Effect of Temperature on Hydraulic Conductivity

Figure 7 shows typical data collected during hydraulic conductivity tests to satisfy the termination criteria. In general it was found that the condition related to the ratio of inflow/outflow (#2 above) required substantially longer time to achieve than the other criteria. Consequently, it can be considered as the dominant test termination criteria. In order to normalize the influence of the different types of tested GCLs on the measured hydraulic conductivity values, the results of hydraulic conductivity tests at different vertical effective stresses and temperature levels will be presented using the bulk GCL void ratio (e) as proposed by Petrov et al. (1997).

$$e = \left[\frac{H_{GCL}}{H_b + H_g} \right] - 1 \quad (5)$$

where H_{GCL} is the GCL thickness, H_b and H_g are the thickness of bentonite and geotextile solids, respectively. The bulk void ratio is related to the thickness of the bentonite and geosynthetic components through

$$H_b = \frac{M_b}{\rho_b (1 + wc)} \quad (6)$$

$$H_g = \frac{M_g}{\rho_g} \quad (7)$$

where M_b and M_g are the mass per unit area of bentonite and the geotextile, respectively. The terms ρ_b and ρ_g are the specific unit weight of bentonite (2.6 g/cm^3) and geotextile (0.9 g/cm^3), respectively. Figure 8a shows the result of the hydraulic conductivity test on GCL samples at different temperatures and void ratios in e -log(k) plot where k is the hydraulic conductivity coefficient. The results indicate that, at constant void ratio, the hydraulic conductivity increases as the GCLs temperature increases.

To better investigate the mechanism that controls the thermal evolution of the hydraulic conductivity coefficient, let's consider the three factors that govern the magnitude of the hydraulic permeability of porous material: (1) the physical properties of the fluid (soil liquid phase) which includes the viscosity and the unit weight of the fluid; (2) the properties of the solid matrix which describe the size of flow channel; and (3) the physico-chemical interactions between the solid particles and the permeant fluid which are a function of mineral characteristics of the solid particles as well as the chemical composition of the pore fluid. The strength of physico-chemical interactions determines the size of the immobile adsorbed liquid layer (diffuse double layer) which can have a significant effect on the size of the flow channel. The thickness of diffuse double layer can be estimated as follows (Mitchell 1993):

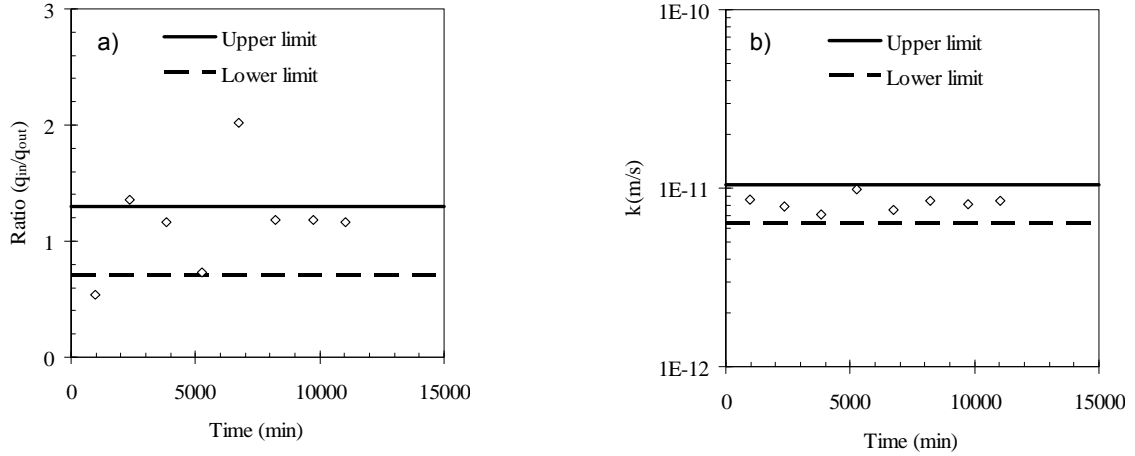


Figure 7: Typical collecting for satisfying termination criteria of hydraulic conductivity test (Sample 1, $\sigma_v=150$ kPa, $T=40^\circ\text{C}$)

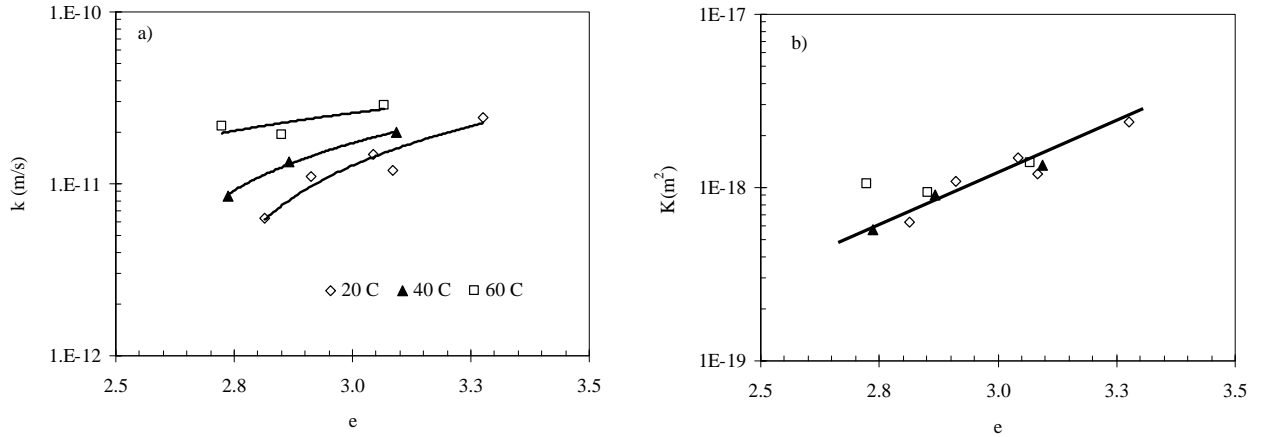


Figure 8: Effect of temperature on (a) hydraulic conductivity; (b) intrinsic permeability of tested GCLs

$$\mathcal{G} = \sqrt{\frac{\varepsilon_o \kappa R T}{2 F^2 c v^2}}$$

(8)

where $\varepsilon_o = 8.86 \times 10^{-12}$ F/m (permittivity of vacuum), κ is relative dielectric permittivity of the pore fluid, $R = 8.314$ J·mol⁻¹·K (gas constant), T is temperature, $F = 9.65 \times 10^4$ C/mol (Faraday's constant), c is pore-fluid concentration, and v is valence of the prevailing counter ion.

Mitchell (1993) found that as the temperature increases the value of the dielectric constant decreases showing little variation in the size of the double diffuse layer with temperature. Thus, we assert that at constant void ratio the increase in the hydraulic conductivity is largely attributed to the thermal evolution of properties of the liquid. To establish this effect, the intrinsic permeability, K , has been calculated from the hydraulic conductivity test results at different elevated temperatures

$$K = \frac{k\mu(T)}{\gamma_w(T)} \quad (9)$$

where, $\mu(T)$ and $\gamma_w(T)$ are the pore water viscosity and unit weight at the tested temperature, respectively. In the range of temperature considered in this study there is insignificant change in the unit weight of water with temperature in

comparison with the change in viscosity. The thermal evolution of free pure water viscosity μ (T) can be estimated according to Hillel (1980) as follows:

$$\mu(T) = -0.00046575 \ln(T) + 0.00239138 \quad (10)$$

Figure 8b shows that the intrinsic permeability can be considered as temperature independent. Thus, the change of hydraulic conductivity with temperature can be attributed mainly to the variation of viscosity of water with temperature. The scatter of the points in Figure 8b shows that a portion of the increased hydraulic conductivity can be attributed to changes in void sizes due to the effect of temperature on the clay fabric. While saturated clay gels exposed to temperatures $<100^\circ\text{C}$ are unlikely to be subjected to extreme conditions which are known to lead to irreversible collapse of interlayers (such as can occur at temperatures $>105^\circ\text{C}$ when clays are initially in an air-dried state, see e.g., Bujdák and Slosiariková, 1994; Komadel et al., 1996), it is possible that some reversible redistribution of intra- and inter-particle pores may occur under the conditions of our study. This result is consistent with the results reported by Abuel-Naga et al. (2006) and Delage et al. (2000) for soft Bangkok clay and Boom clay, respectively. Likewise, Kharaka and Smalley (1976) found similar results for Na-bentonite, Mingarro et al. (1991) and Cho et al. (1999) for a granite/Ca-bentonite mixture and Ca-bentonite, respectively, and Khemissa (1998), for a kaolinite. Therefore, at a constant void ratio, the ratio between the hydraulic conductivity at tested temperature $k(T)$ and at room temperature $k(T_o)$ can be estimated using the following equation:

$$\frac{k(T)}{k(T_o)} = \frac{\mu(T_o) \gamma_w(T)}{\mu(T) \gamma_w(T_o)} \quad (11)$$

where, $\mu(T)$ and $\mu(T_o)$ are the pore water viscosity at tested and room temperature respectively and $\gamma_w(T)$ and $\gamma_w(T_o)$ are the pore water unit weight at tested and room temperature respectively.

7. CONCLUSIONS

According to the experimental results reported here, it can be concluded that the thermally induced volume change of GCLs is stress level dependent. However, more experimental evidences are still required to confirm and explain this behaviour. The results of this study also show that the hydraulic conductivity of GCLs increases as the temperature increases. The increase can be attributed mainly to the evolution of the permeant viscosity with temperature, but also probably due to a redistribution of intra-and inter-particle pores.

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