

# TEMPERATURE EFFECTS ON GEOTECHNICAL AND HYDRAULIC PROPERTIES OF BENTONITE HYDRATED WITH INORGANIC SALT SOLUTIONS

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**ABSTRACT:** This study investigated the combined effect of temperature and single-species salt solutions on geotechnical properties (swell index and liquid limit) and hydraulic conductivity of bentonite applying different cation types, concentrations, and temperatures. Results showed that both the swell index and the liquid limit decreased with an increase in salt concentration irrespective of the type of cation. Monovalent cations showed higher values of the swell index and the liquid limit compared to divalent cations. In general, the swell index of bentonite increased whereas the liquid limit decreased with increasing temperature for all cation types and concentrations. Significant and high correlations were found between swell index and liquid limit of bentonite at all three temperatures. Hydraulic conductivity of bentonite was found to increase with increasing temperature. No significant change in hydraulic conductivity with time was observed for all concentrations and cation types, and, overall, concentration and valance of cations had little effect on the hydraulic conductivity of bentonite.

*Keywords: Bentonite, Hydraulic conductivity, Liquid limit, Swell index, Temperature effects*

## 1. INTRODUCTION

Geosynthetic clay liners (GCLs) are widely used as an essential component of bottom liner system of landfills for solid waste disposal. GCLs offer a final defense against the migration of landfill leachate into the underlying environment [1]. The main component of GCL responsible for its barrier performance is sodium bentonite, which is primarily composed of clay mineral sodium montmorillonite while the minor constituents include quartz, feldspars, carbonates and micas [2]. Sodium montmorillonite is characterized by its large specific area, high cation exchange capacity and high swelling potential which are responsible for the desirable physical and chemical properties of bentonite [3].

The biodegradation of organic waste inside landfill produces chemicals that are dissolved in the infiltrating water, generating landfill leachate. In addition to the generation of leachate, the biodegradation of organic substances produces heat, which can result in an increase of temperature inside the landfill up to 60 °C [4] - [7]. Chemicals in the landfill leachate, coupled with a rise in temperature, can affect the geotechnical and hydraulic performance of bentonite and its performance as barrier material in the GCL. A number of studies have investigated the effects of chemicals on the properties of bentonite [2], [8] - [15]. However, very few studies have investigated the combined effect of temperature and liquid chemistry on geotechnical properties and hydraulic performance of bentonite. Ishimori and Katsumi [1] investigated the effects of

temperatures (20 °C and 60 °C) on the swelling capacity and barrier performance of bentonite using deionized water (DI water) and three different concentrations (0.1 – 0.4 M) of NaCl solutions and found that swell and intrinsic permeability increased with an increase in temperature. Other studies were focused on hydraulic conductivity [16] - [17] and hydro-mechanical behavior [18] using only water for specific applications in high level nuclear waste repositories. Therefore, the combined effect of temperature and liquid chemistry on bentonite geotechnical and hydraulic properties are needed to better understand the behavior of GCL liners during the required long term performance under landfills.

This study investigated the effects of single-species salt solutions on geotechnical properties (swell index and liquid limit) and hydraulic conductivity of bentonite applying different cations, concentrations, and temperature. Thirteen solutions, (DI water and twelve salt solutions of four major exchangeable cations (Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>), each at three different concentrations (0.01M, 0.1 M, 1M)) were used as hydrating liquids. The swell index and liquid limit tests were carried out using all the thirteen solutions at three different temperatures (20 °C, 40 °C and 60 °C). The hydraulic conductivity was evaluated using DI water, NaCl 0.01M and intermediate concentrations (0.1M) of all the four cation solutions at 20 °C and 40 °C. The hydraulic conductivity tests were followed by pore size distribution analysis to better understand solute transport behavior and chemical effects on bentonite material structure.

## 2. MATERIAL AND METHODS

The bentonite used in this study was sodium bentonite extracted in powdered form from a commercially available typical GCL (Bentofix®). Bentonite passed through US sieve no. 200 (75 μm) was oven dried at 105 °C for subsequent testing. The particle density of bentonite for this typical GCL was 2.61 g/cm<sup>3</sup> [19]. The natural water content, liquid limit, plastic limit and swell index were measured using ASTM Standards. The results are given in Table 1.

Table 1 Physical Properties of Bentonite

Property	Unit	Value
Natural water content	%	11.78
Liquid Limit	%	559
Plastic Limit	%	51
Plasticity Index	%	508
Swell Index	mL/2g	30
Particle density	g/cm <sup>3</sup>	2.61

The permeant solutions used in swell index and liquid limit tests were DI water and the salt solutions of NaCl, KCl, CaCl<sub>2</sub> and MgCl<sub>2</sub>. Concentrations of solutions varied from 0.01 to 1 M and the tests were carried out at three different temperatures (20 °C, 40 °C and 60 °C). Hydraulic conductivity tests were carried out using DI water, 0.01M NaCl and intermediate concentrations (0.1M) of all the four cation solutions, in all cases at two different temperatures (20 °C and 40 °C). The cations Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup> were selected because they are major exchangeable cations in bentonite [20]. Chemicals used for making solutions were purchased in powdered form and their formula weights were mixed with DI water to prepare the desired chemical solutions.

### 2.1 Swell Index Tests

The swell index tests were carried out in accordance with ASTM D5890. Initially, 2 g of oven dried bentonite was dusted into a 100 mL graduated cylinder filled with 90 mL of hydrating solution. After the dusting of bentonite was completed, the cylinder was filled up to the 100 mL mark with the same solution washing the particles adhering to the walls of the cylinder. The cylinder was then covered with plastic wrap to prevent evaporation and carefully placed in a climate control room with a temperature maintained at 20 °C or placed in an oven for elevated temperatures (40 °C or 60 °C). The cylinders were kept undisturbed for 24 h prior to take the readings. The measurements were repeated in triplicates and the averages were used for subsequent data analysis.

### 2.2 Liquid Limit Tests

The liquid limit tests were carried out using the multipoint test method in accordance with ASTM 4318-10. The bentonite samples were prepared by thoroughly mixing the oven dried bentonite with each hydrating liquid at different moisture contents. The samples were then allowed to hydrate for at least 24 hours in double wrapped sealed plastic bags at specified temperatures (20 °C, 40 °C and 60 °C). To avoid evaporation during the hydration process, wet tissue papers were kept between the both wrappings. The samples were remixed before starting the experiment. A minimum of five trials were performed for each test and the liquid limit was determined using equation of the flow curve.

### 2.3 Hydraulic Conductivity Tests

Constant head hydraulic conductivity tests were conducted using a rigid wall permeameter as shown in Fig. 1. The apparatus consisted of a lower ring, a middle ring and an upper ring placed between an upper and lower cap all made of acrylic. First, the bentonite samples were prepared with the permeating solution with a moisture content equal to its liquid limit for that particular solution, and allowed to hydrate for at least 24 h in sealed plastic bags. After 24 h, the prehydrated bentonite samples were placed in the circular middle ring with a porous filter at the bottom placed on the top of lower ring. Typically the inner diameter of the middle ring was 6 cm with a height of 1 cm, which represents the dimensions of the sample.

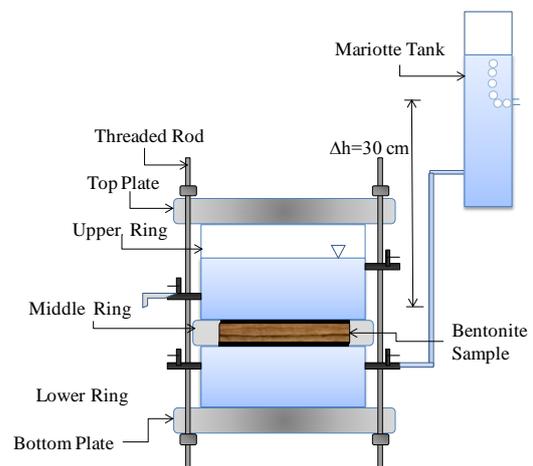


Fig. 1 Schematic of hydraulic conductivity test apparatus

The lower ring was first filled with permeating solution, then sample was placed in the middle ring by slight tamping, making due care to prevent entrapment of air bubbles inside the sample. A porous filter was then placed on top of the sample in such a way that the sample was sandwiched between

the lower and upper porous filters to avoid washing off of the soil particles during the tests. After placing the sample and porous filters, the upper ring was placed on top of the middle ring and the cell was clamped after placing the top cap. To avoid leakage of water at the contact points, silicon grease was used.

The permeant solution was then supplied from a Mariotte tank to the sample through an inlet valve of the lower cell allowing the escape of air bubbles. Once the permeating solution started coming out of the sample ensuring that all air bubbles have escaped, the upper ring was then filled with the permeating solution up to a height equal to that of the lower ring and whole cell was made airtight. After that, the whole setup was placed in the climate controlled room with the temperature maintained at 20 °C or in an incubator with a pre-set temperature of 40 °C. Permeant solution was then supplied to the sample from the Mariotte tank through an inlet valve of the lower ring while maintaining a constant head of 30 cm across the sample which correspond the hydraulic gradient. The effluent was collected from an outlet valve of the upper ring in a collecting jar at specified intervals of time. To measure the evaporation, a reference jar with an opening equal to the collecting jar was placed near the apparatus in the same environment and the evaporated volume was added to the measured volume to minimize the effect of evaporation during the test. The tests were continued for several days and hydraulic conductivity was calculated using Darcy's law [21].

The tests were conducted up to 100 days and electric conductivity (EC) and pH of the effluent was measured during the test period in addition to the hydraulic conductivity. After terminating the tests, the weight of the each sample was measured and one part of it was taken to measure the moisture content ( $w$ ), porosity ( $\phi$ ), and void ratio ( $e$ ) while the rest was freeze-dried to measure the pore size distribution using Mercury Intrusion Porisometry (MIP).

### 3. RESULTS

#### 3.1 Swell Index Tests

The swelling of bentonite can be explained as a two phase process [3]. First phase known as "crystalline swelling" occurs at small scale and a maximum of three to four layers of water molecules can be adsorbed in the interlayer around the interlayer cations which corresponds to less than 25% by mass. This phase is then followed by "osmotic swelling" where numerous layers of water molecules enter the interlayer. The later phase can occur only when the exchange sites are occupied by monovalent cations [22] - [23] having  $\Delta$ radius (hydrated radius - ionic radius) to valance ratio of

greater than 300 and more than three hydration shells (limited to  $\text{Na}^+$  and  $\text{Li}^+$ ) [3].

The swell index seems to be highly controlled by concentration of the solution in bulk pore water as shown in Fig. 2. It was observed that the swell index decreased with increase in concentration irrespective of the type of cation. This finding is consistent with the studies by Jo et al. [11] who explained the phenomenon as a result of the release of interlayer water due to a gradient in free energy caused by the elevated concentrations in the bulk pore water.

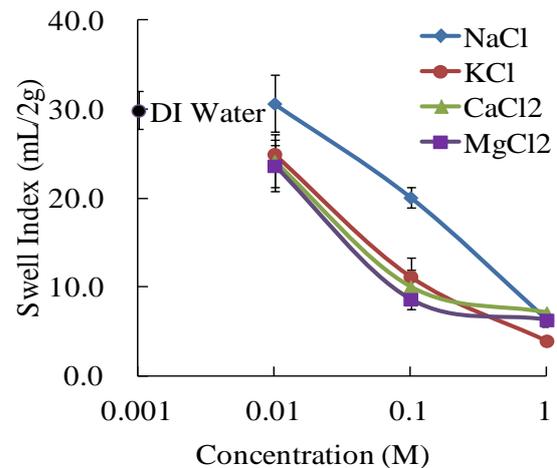


Fig. 2 Effect of liquid chemistry on swell index of bentonite

The highest value of the swell index was observed for the bentonite samples hydrated with NaCl solution at low concentration (0.01M) followed by the samples hydrated with DI water. As the bentonite is hydrated with NaCl solution, all exchange site are occupied by  $\text{Na}^+$  cation which take part in osmotic swelling phase resulting an increase in swell volume. All other cations were found to give similar values of swell index at all concentrations with the lowest value of the swell volume obtained for the bentonite samples hydrated with high concentration (1M) of KCl solution.

Temperature of the hydrating liquid was found to have significant effect at lower concentrations of monovalent cations as shown in Fig. 3 (a) and Fig 3 (b). At intermediate and high concentrations, however, the effect was insignificant. It was observed that for bentonite samples hydrated with DI water and low concentrations of monovalent cations, the swell index increased with an increase in temperature. Contrary to this, there was a tendency of a decrease in the swell index with an increase in temperature at all concentrations for divalent cations as shown in Fig. 3 (c) and Fig. 3 (d).

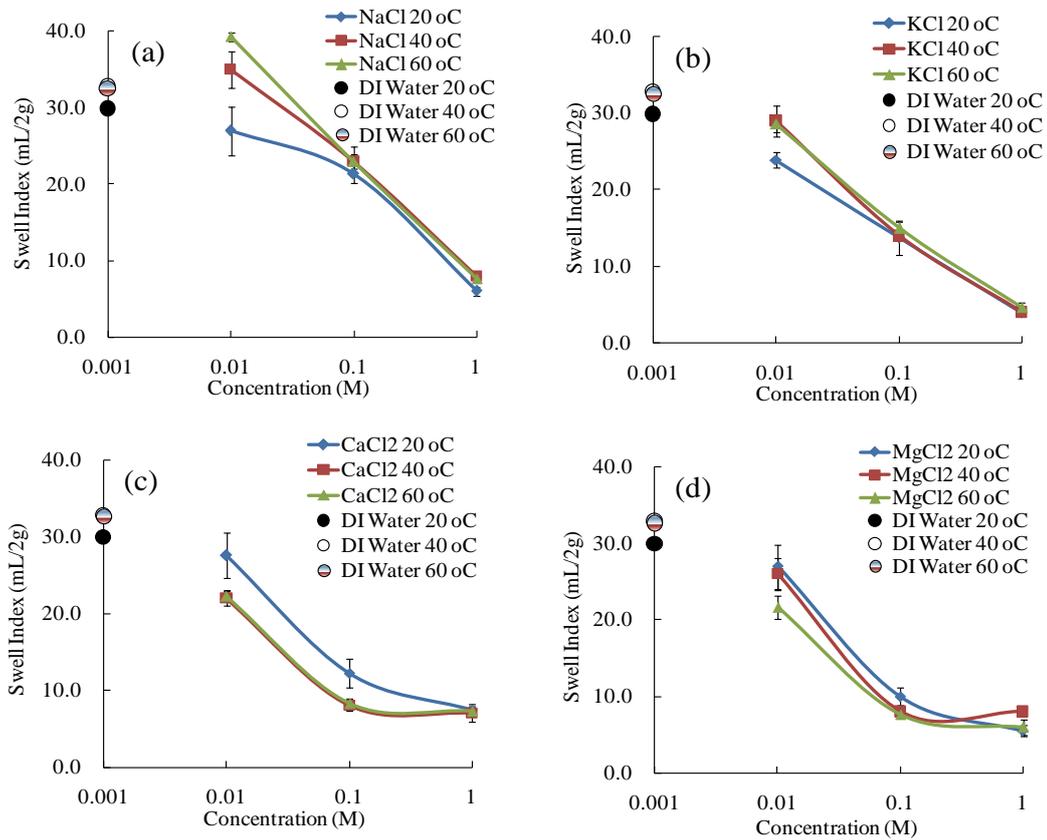


Fig.3 Effect of temperature on swell index of bentonite

### 3.2 Liquid Limit Tests

#### Effect of liquid chemistry

Figure 4 shows the effect of liquid chemistry on the liquid limit of bentonite. It was observed that liquid limit decreased with an increase in salt concentration irrespectively of the type of cation. The liquid limit was highest (559 %) with DI water. The liquid limit was found to be similar at very low

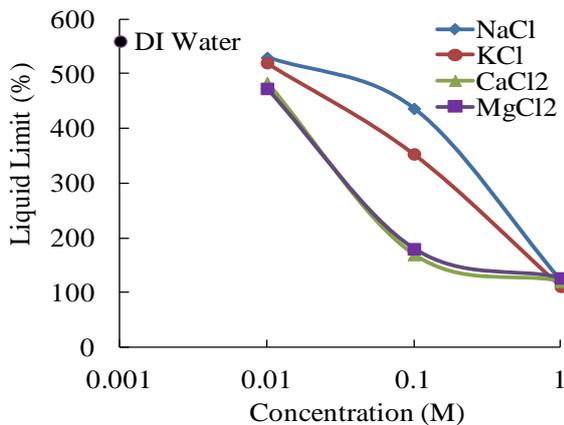


Fig. 4 Effect of liquid chemistry on liquid limit of bentonite

(0.01M) and very high (1M) concentrations irrespectively of the hydrating liquid. However, at intermediate concentration (0.1M), both monovalent cations show higher values of the liquid limit than divalent cations, with highest value of the liquid limit obtained for bentonite hydrated with NaCl solution. Both divalent cations showed similar values of the liquid limit at all concentrations.

#### 3.2.1 Effect of temperature

The effect of temperature on the liquid limit of bentonite is shown in Fig. 5. In general, the liquid limit was found to decrease slightly with an increase in temperature. DI water showed the highest value of liquid limit (559%) when hydrated at 20 °C. The liquid limit was lowest at 60 °C (524%). A similar trend of decrease in liquid limit with increase in temperature was found with bentonite hydrated with NaCl solution at low concentrations. However, at high concentrations the effect of temperature was not significant. Temperature was found to have insignificant effect on the liquid limit of bentonite hydrated with KCl and divalent cation solutions (CaCl<sub>2</sub> and MgCl<sub>2</sub>).

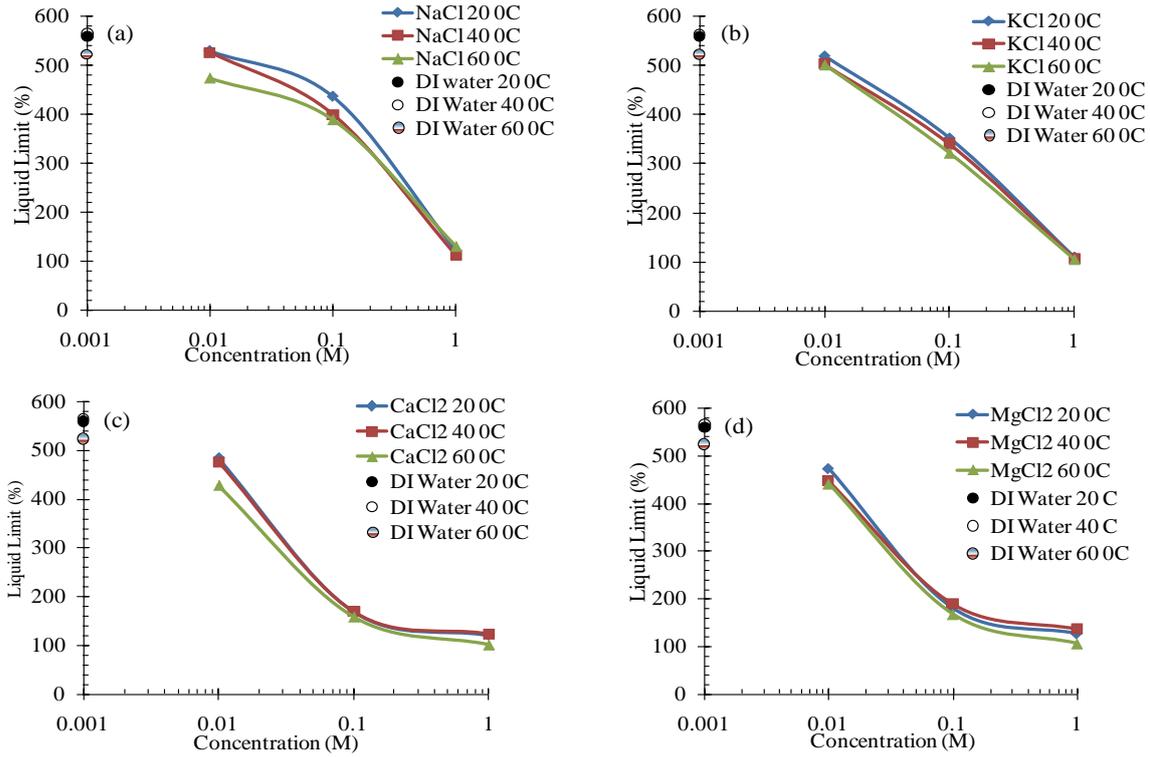


Fig. 5 Effect of temperature on liquid limit of bentonite

### 3.3 Correlation between Swell Index and Liquid Limit

A comparison between the swell index and the liquid limit of bentonite is shown in Fig. 6. It was found that significant and high correlations exist between the both geotechnical properties at all

temperature (Fig. 6 (a) – Fig. 6 (c)).

Figure 6 (d) shows the relationship between slopes of the regression lines with temperature. It is seen that the slope decreases with increase in temperature which confirms a temperature dependence on both the geotechnical properties.

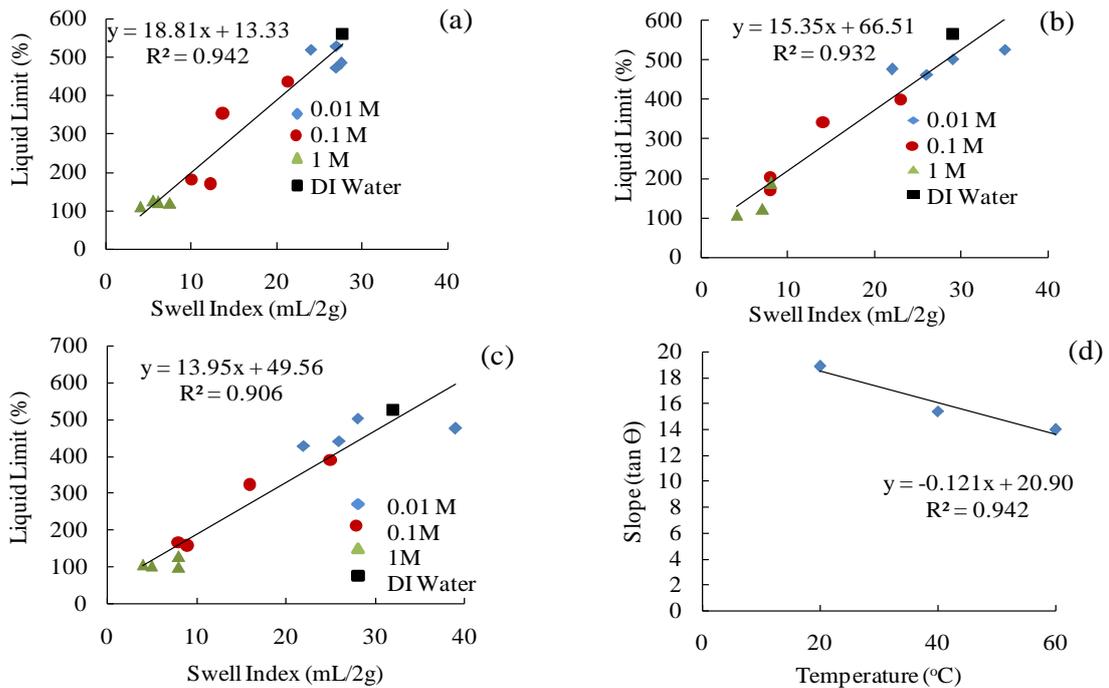


Fig. 6 Correlation between swell index and liquid limit

### 3.4 Hydraulic Conductivity

Hydraulic conductivity of bentonite was measured using all the thirteen permeant liquids. It was observed that for all cation types and concentrations, hydraulic conductivity do not change significantly with time.

Table 2 Summary of hydraulic conductivity tests

Permeant Liquid	Conc. (M)	t (days)	PVF	$\phi$	e
NaCl	0.01	20	2.4	0.94	17.4
	0.1	109	8.9	0.91	10.17
	1	35	5	0.69	2.27
KCl	0.01	123	11	0.91	10.43
	0.1	78	41	0.90	9.93
	1	76	189	0.69	2.32
CaCl <sub>2</sub>	0.01	95	112	0.92	12.01
	0.1	111	71.8	0.81	4.42
	1	106	84.8	0.73	2.73
MgCl <sub>2</sub>	0.01	79	124	0.91	10.51
	0.1	89	29	0.82	4.79
	1	97	51	0.71	2.45
DI water	-	108	4.8	0.94	15.44

The duration of permeation (t), total pore volumes of flow (PVF), total porosity ( $\phi$ ) and void ratio (e) of each permeated sample is shown in Table 2.

Figure 7 shows the effect of concentration on average hydraulic conductivity of bentonite. Hydraulic conductivity was found to increase with

increase in concentration for the samples hydrated with KCl solutions. For other cations, however, concentration was found to have little effect on bentonite samples even though the void ratio (e) increased and total porosity ( $\Phi$ ) decreased with increasing salt concentration.

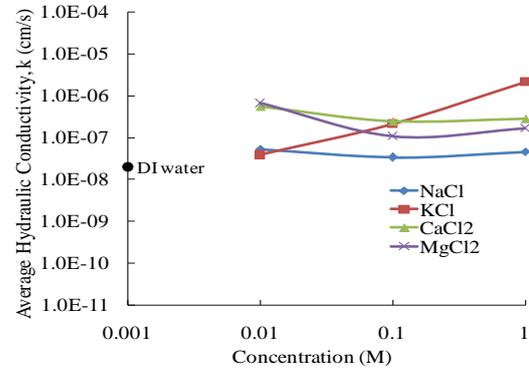


Fig. 7 Effect of cation concentration on hydraulic conductivity of bentonite.

This suggests that the water bound in the interlayer pores in effect, does not take part in the hydraulic conductivity of bentonite. In Support of this, the available pore space for the flow (the effective porosity of bentonite) did not change significantly with change in salt concentrations, see Fig 8.

Hydraulic conductivity test conducted at 20 °C and 40 °C showed that hydraulic conductivity as expected increased slightly with temperature; see Fig. 9.

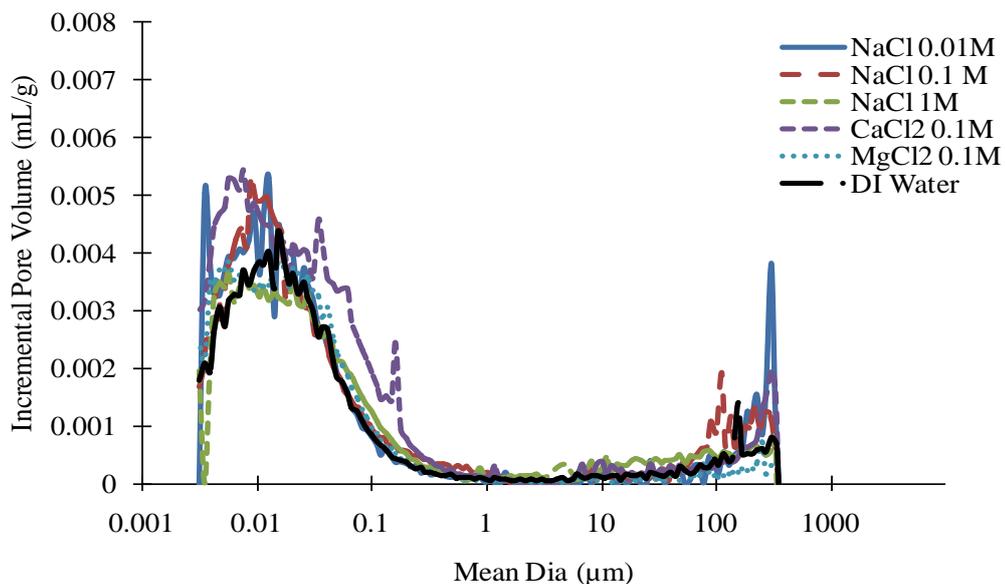


Fig. 8 Pore size distribution of bentonite samples permeated with DI water and salt solutions

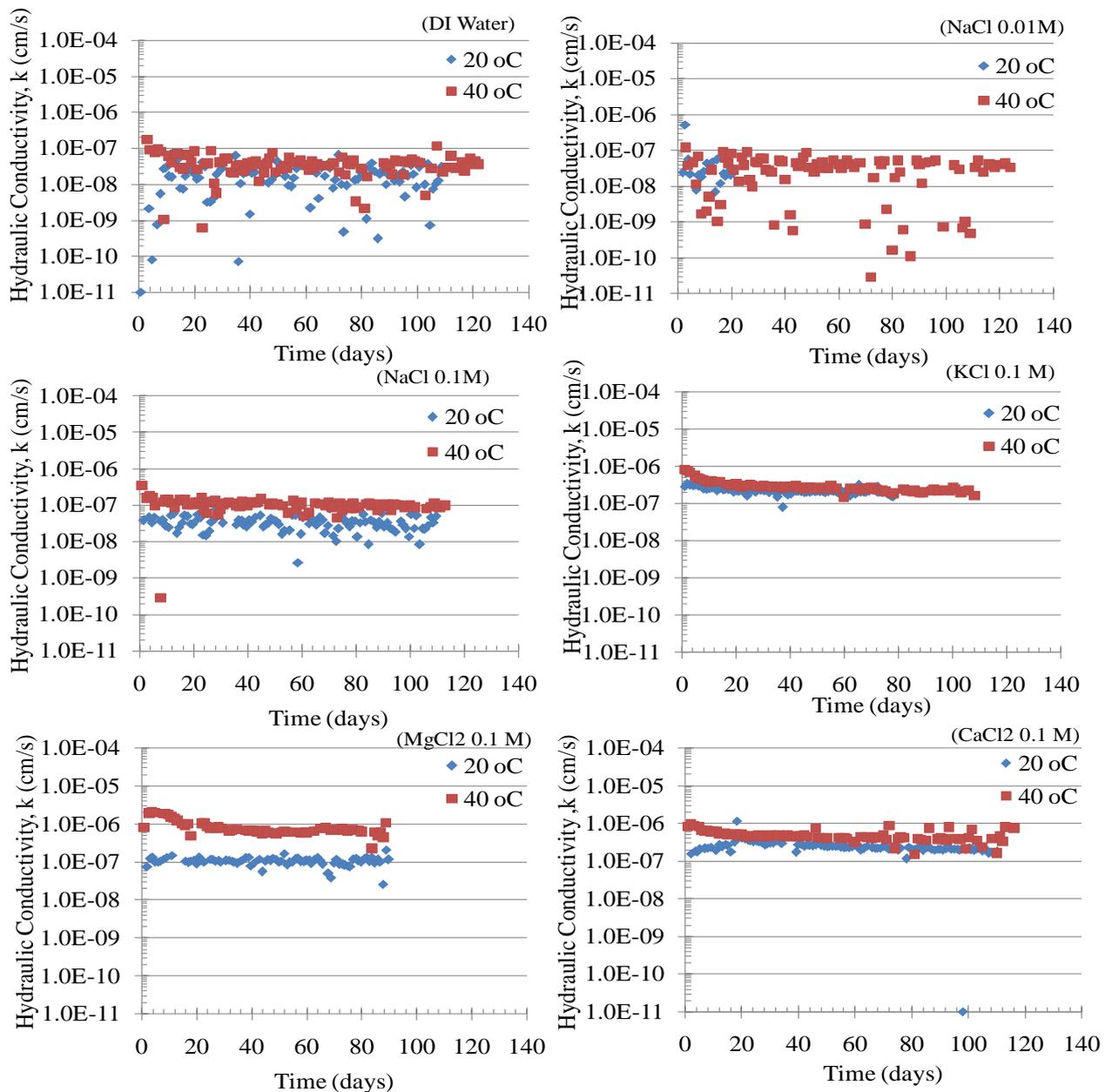


Fig. 9 Effect of temperature on hydraulic conductivity of bentonite.

#### 4. CONCLUSIONS

This study investigated the effect of temperature and liquid chemistry on swell index, liquid limit and hydraulic conductivity of bentonite. Concentration and type of cation were found to have significant effect on swell index and liquid limit of bentonite. However, the effect was small for hydraulic conductivity. It was found that the hydraulic conductivity is mainly controlled by the effective porosity rather than the total porosity. Liquid limit was found to decrease whereas swell index and hydraulic conductivity were found to increase with increasing temperature.

#### 5. ACKNOWLEDGEMENTS

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