Temperature Effects on Geotechnical Properties of Kaolin Clay: Simultaneous Measurements of Consolidation Characteristics, Shear Stiffness, and Permeability Using a Modified Oedometer

Ei Ei Mon, Shoichiro Hamamoto, Ken Kawamoto, Toshiko Komatsu, and Per Møldrup

***Abstract*— The increased worldwide use of shallow geothermal energy systems including ground source heat pumps (GSHPs) have given concerns of possible temperature effects on soil geotechnical properties. In this study, the effects of temperature on mechanical characteristics such as consolidation settlement, shear stiffness, and permeability of kaolin clay were investigated. A modified oedometer apparatus which allows the simultaneous measurements of consolidation settlement, shear wave velocity, and hydraulic conductivity was developed and used. Consolidation tests on preconsolidated kaolin samples (two sample sizes: ϕ 6 cm x H 10 cm and ϕ 6 cm x H 2 cm) were performed under sequentially increasing consolidation pressures at three different temperatures (5 °C, 15 °C, and 40 °C). Larger apparent preconsolidation pressure, P_{ac}, was seen at higher temperature (40 °C) for both sample sizes, but only for samples having relatively high initial void ratios between 1.53 and 1.62. Relatively higher shear modulus as a function of void ratio was observed for samples at higher temperature, suggesting that changes in fabric structure (likely caused by enhanced inter-particle forces between clay particles at higher temperature) resulted in the increased shear stiffness and, thus, higher P_{ac} at 40 °C. Oppositely, temperature effects on the permeability of kaolin clay were not significant within the studied temperature range between 5 °C and 40 °C.**

***Index Terms*— consolidation characteristics, kaolin clay, permeability, shear modulus, temperature**

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I. Introduction

Geothermal structures such as nuclear waste disposal facilities, ground source heat pump (GSHP) systems, groundwater heat pump (GWHP) systems, and aquifer thermal energy storage systems are widely being constructed in the geo-environment [1], [2]. As a consequence, understanding of the engineering behaviors of soils as influenced by temperature is essential in order to minimize undesired effects due to heat disturbances [3], [4], [5]. Most previous studies on temperature effects in the subsurface have focused on the elevated temperature particularly for waste disposal barrier materials [6], [7], [8]. Recently, GSHP/GWHP systems are increasingly being used in public areas (schools, hospitals) with the purpose of reduction in green house gas emissions from energy consumption [9], [10]. The seasonal operation of GSHP/GWHP systems causes local temperature anomalies (cold or heat plumes) in the geo-environment, with elevated or depressed subsurface temperature of maximum ±10 ˚C [9], [2], [11]. However, the detail investigations of temperature effects on geotechnical properties of sediments considered for the elevated or depressed subsurface temperature condition are still limited.

Since elevated temperature can cause a change in hydraulic and mechanical properties of clays, many studies have investigated the elevated temperature effects on hydro-mechanical properties of clays, in particular for swelling clays (i.e. bentonite) [12], [13], [14], [15], [16], [7], [17], [18]. Especially, the references [19] and [20] reported thermal consolidation of Boom clay for a temperature range between 5 °C and 55 °C, and viscous behavior of natural clays for a temperature range between 5 °C and 35 °C, implying a decrease of preconsolidation pressure with increased temperature. An increase of hydraulic conductivity of clays at elevated temperature was observed in most studies due to temperature dependent water properties such as viscosity and, also, fabric or pore structures changes [13], [15], [21].

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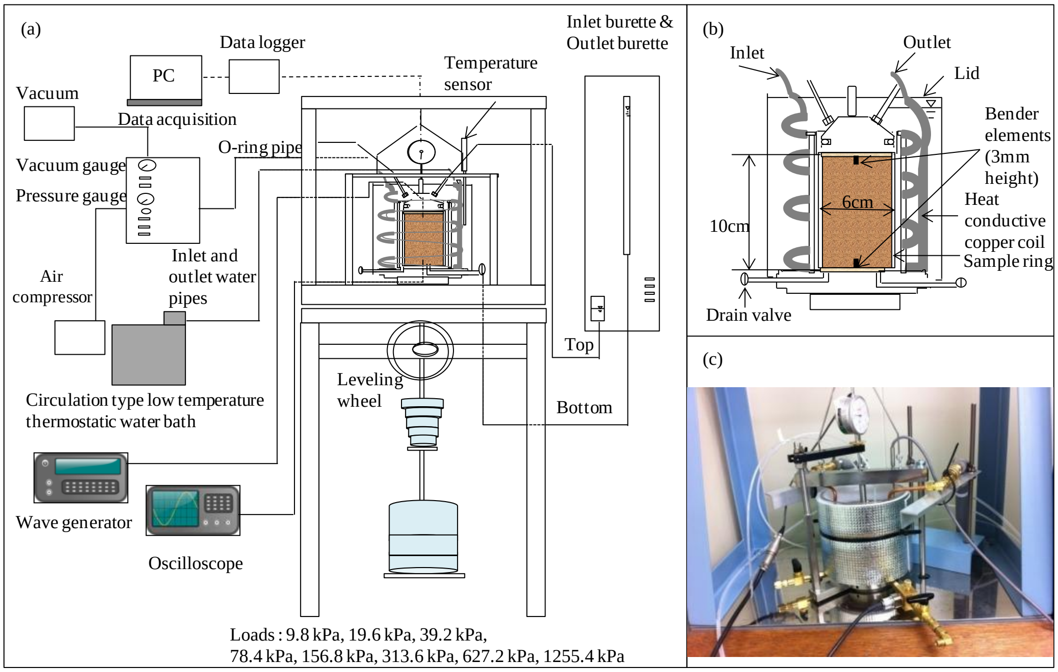

Fig. 1. (a) Overview of a modified oedometer apparatus (b) Detail of sample cell (c) Photo of sample cell

Greater shear strength [7] and shear stiffness [12] of clays at higher temperature under a range of 20 °C to 90 °C was found by performing triaxial compression tests. Although empirical formulas for shear modulus as a function of void ratios and applied pressures were developed [22], [23], the shear modulus as a function of wide range of applied pressures are still lack of measurements especially under temperature control condition. In addition, previous observations related to temperature effects on hydro-mechanical behavior were mostly obtained from conducting the measurements of consolidation, shear stiffness, and hydraulic conductivity on separate clay samples, respectively. Therefore, it is essential to acquire a unified understanding of temperature effect on consolidation characteristics, shear stiffness, hydraulic property of clays measured on the same samples under a wide range of pressures, since these three geo-mechanical properties are closely interrelated with each other.

The main objective of the present study was therefore to investigate the effect of temperature on consolidation characteristics, shear stiffness, and permeability of kaolin clay. Using a newly-developed oedometer apparatus, sequential measurements of consolidation settlement simultaneously with change in shear wave velocity and hydraulic conductivity of the preconsolidated kaolin clay samples under a wide range of pressures were performed at three temperatures (5 °C, 15 °C, and 40 °C). The consolidation characteristics of the clay were evaluated in terms of temperature effects on consolidation parameters such as apparent preconsolidation pressure (P_{ac}), coefficient of consolidation (c_v), and compression index (C_c). Similarly, shear stiffness of the clay was evaluated in terms of temperature effect on the shear modulus (G) as a function of void ratio (e), hereunder comparing measurements with existing empirical formulas for estimating the shear modulus. For permeability of the clay, it was evaluated in terms of temperature effect on the permeability (k) as a function of void ratio. This was coupled with pore structure measurements by mercury intrusion porosimeter (MIP).

II. Materials and Methods

A. Material

Kaolin clay (ASP 100 clays) was used in this study. The liquid limit (69%) and plasticity index (39%) were measured under room temperature (20 °C). The N_2 specific surface area (representing the external surface area of particles) and the particle density were also measured, yielding 16.25 m^2/g and 2.658 g/cm^3.

B. Modified Oedometer Apparatus

The laboratory experiments were conducted by a modified oedometer apparatus as shown in Fig. 1. The standard oedometer apparatus was modified by installing heat conductive copper coils, bender elements, and inlet and outlet burettes to measure consolidation settlement and shear wave velocity simultaneously, as well as hydraulic conductivity. The specified temperature can be maintained throughout the consolidation test under sequential consolidation pressures by circulating cool non-freezing liquid or hot water from the circulation type low temperature thermostatic water bath (Thomas, TRL-11LP) to the heat conductive copper coils [24], [25]. The sample ring inside the water-filled cell was heated indirectly by the surrounding water (heated by the spirally placed copper coils). Water temperature inside the cell was measured by a temperature sensor which provides the feedback signal to the circulation bath. The bender element system has been recently developed for the measurement of soil stiffness at very small strains in the laboratory by means of elastic shear

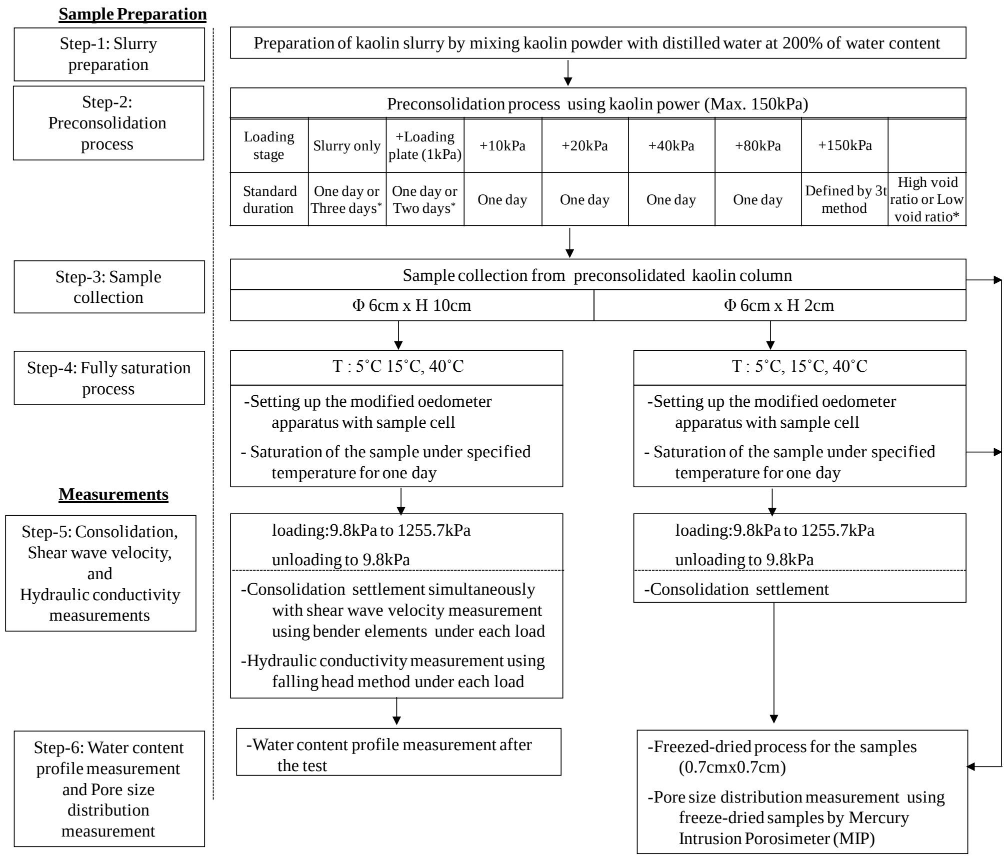

Fig. 2. The experimental procedures performed on the kaolin clay

wave propagation [26], [27]. In the new apparatus (Fig. 1), the 3-mm long bender elements were placed at opposite ends of the kaolin specimen by installing a pair of bender elements in top cap and base of the cell. The travel time between a transmitter (bender element at top cap) and a receiver (bender element at the base) was determined using a wave generator or a multifunction synthesizer (nF, Wavefactory WF 1943A 1CH), and a digital storage oscilloscope (Hitachi, VC-6723A). Since a measurement of hydraulic conductivity by the falling head method was carried out immediately after the consolidation test at each applied pressure, the O-ring was inflated by a air compressor, and the drain valve was closed to seal the system thereby avoiding the continued consolidation process. Then, distilled water was applied from the bottom (from the inlet burette) to the top (to the outlet burette) of the kaolin sample while the hydraulic conductivity measurement was conducted. Water level in the inlet burette was observed as a function of time. After the hydraulic conductivity test, the O-ring was deflated by a vacuum and the consolidation test was continued by loading at a higher pressure. Sequential measurements of consolidation settlement, shear wave velocity, and hydraulic conductivity were performed under the given temperature conditions as described above.

C. *Sample Preparation*

The experimental procedures performed in this study are described in Fig. 2. The kaolin slurry was prepared by mixing kaolin powder (< 0.85 mm) with distilled water at room temperature (20 °C) to adjust water content to 200% (Step-1 in Fig. 2). Air bubbles inside the slurry were removed by vacuum compressor for one hour. The slurry was poured into a column (ϕ 8 cm x H 25 cm) and kept for one day in slurry condition. The slurry was preconsolidated under different loads (pressures) with the maximum applied preconsolidation pressure (P_c) of 150kPa. The initial void ratios of samples, from here on denoted as high void ratio (1.53~1.62) and low void ratio (1.43~1.47) samples, were controlled by varying the standard duration period (see Step-2 in Fig. 2). Once the final load was completed, the total load was released and the sample was allowed to swell for at least one day. From the preconsolidated kaolin columns, two sizes of remolded kaolin samples (ϕ 6 cm x H 10 cm and ϕ 6 cm x H 2 cm) were taken using samples rings. The sides of the sample rings were smeared with silicone grease to reduce side friction.

D. *Measurements*

The temperature range investigated in this study was selected to represent a variation of ±10 °C, taken relative to the typical subsurface ground temperature of 15 °C in Japan [28]. Additionally, a temperature of 40 °C was considered as an extreme, representing a temperature change of 25 °C and better allowing comparison with previous studies. After the preconsolidated sample preparation (Step-3 in Fig. 2), all the measurements were conducted at three different temperatures (5 °C, 15 °C, and 40 °C). The preconsolidated kaolin sample (ϕ 6 cm x H 10 cm or ϕ 6 cm x H 2 cm) was mounted in the modified oedometer apparatus, Fig. 1. Then the sample was brought to the desired temperature which was kept constant throughout the test. Prior to measurements, the sample was saturated to fully water-saturated condition. Using the H 2 cm samples, only consolidation settlement could be measured, since the sample height was not sufficient to transmit shear wave using bender elements (Japan Geotechinical Scoiety, JGS 0544-2011). Under sequentially increasing pressures (from 9.8 kPa to 1255.4 kPa using an approx doubling of applied pressure for each step: 9.8 kPa, 19.6 kPa, 39.2 kPa, etc.), consolidation test was performed for the H 2 cm samples, while both consolidation settlement simultaneously with shear wave velocity measurements and hydraulic conductivity measurements were performed for the H 10 cm sample size. Both loading and unloading processes were considered since after the final loading step, samples were unloaded directly from 1255.4 kPa and back to the 9.8 kPa. Each pressure was maintained for one day to complete primary consolidation. Under each pressure, the settlement displacements were monitored during consolidation processes, via personal computer using a data logger. In the shear wave velocity measurement on the H 10 cm samples, the travel time of the elastic shear wave propagation from top to bottom of the sample was measured at various time intervals during one day. For the H 10 cm samples, the hydraulic conductivity was measured alternatively after each consolidation process under each pressure, using the falling head methods as described above. Finally, the water content profile of the tested sample was measured at the end of the test under each temperature condition to evaluate the sample structure's uniformity along the height of 10 cm. For the H 2 cm samples, pore size distribution measurements were carried out using mercury intrusion porosimeter (MIP) (Micromeitrics, Auto Pore IV). This was done to compare sample fabric structure with the results of the geotechnical properties measurements. For the MIP measurements, samples obtained from three conditions (pure preconsolidated samples, fully saturated samples, and samples obtained after the unloading process) were used. Smaller samples (0.7 cm x 0.7 cm blocks) were trimmed from the original samples and freeze-dried using a vacuum freeze dryer (AS ONE, VFD-03) as pretreatment before the MIP test. All the measurements were duplicated for each temperature condition.

Terzaghi's theory for one-dimensional consolidation [29] was applied to determine the consolidation characteristics. Here, the compression index (C_c) is the linear slope of the normal consolidation line which is the linear portion of the e – log p curve (void ratio versus the logarithm to consolidation pressure) whereas the swelling index (C_s) is the slope of unloading line. The apparent preconsolidation pressure (P_{ac}) was graphically defined by Casagrande's theory using e – log p curve.

The shear modulus at small strain range (around 10^{-6} order) ($G_{b.e}$) by the bender elements is calculated using a propagation velocity of shear wave as follow,

$$G_{b.e} = \rho \times (v_s)^2 \tag{1}$$

where ρ is the density of the sample (g/cm^3), and v_s is the shear wave velocity (m/sec).

The hydraulic conductivity is calculated as follow,

$$K_s = \left\{ -\ln\left(\frac{h_2 + h_0 - L}{h_1 + h_0 - L}\right) \times \frac{La}{A\Delta t} \right\} \tag{2}$$

where K_s is saturated hydraulic conductivity (cm/sec), h_1 is head difference between inlet and outlet at t_1, h_2 is head difference between inlet and outlet at t_2, h_0 is the difference between top of the sample and outlet, L is length of specimen (cm), a is cross sectional area of inlet burette (cm^2), A is cross sectional area of specimen (cm^2), and Δt is time difference between two readings. The calculated saturated hydraulic conductivity (cm/sec) was transformed to intrinsic permeability (cm^2).

III. RESULTS AND DISCUSSION

A. *Performance of the Temperature Control Systems*

Preliminary experiments were conducted in order to check the performance of the installed temperature control system. A thermometer was embedded inside a preconsolidated kaolin sample with void ratio of 1.55, while the cell water temperature was either increasing or decreasing from room temperature of 20 °C to either 40 °C or 5 °C. Based on the results shown in [30], the temperature inside the kaolin sample had reached target temperature (± 0.2 °C) within 3 hours with a 30-minute delay compared to the water temperature in the cell. Therefore, it was assumed that the kaolin sample has reached the desired temperature condition throughout the experiment at times greater than 3 hours.

B. *Effect of Temperature on Consolidation Characteristics*

Table 1. Apparent preconsolidation pressures, compression and swelling indices values at each temperature condition.

Sample size	Temperature (°C)	Initial void ratio, e_0	Apparent preconsolidation pressure, P_{ac} (kPa)	Compression Index, C_c	Swelling Index, C_s
Φ 6 cm x H 10 cm (high e_0)	5±0.2	1.54	57	0.22	0.06
	15±0.2	1.57	67	0.23	0.05
	40±0.2	1.57	81	0.25	0.05
Φ 6 cm x H 2 cm (high e_0)	5±0.2	1.62	56	0.21	0.07
	15±0.2	1.61	62	0.23	0.10
	40±0.2	1.59	117	0.34	0.09
Φ 6 cm x H 2 cm (low e_0)	5±0.2	1.47	114	0.25	0.10
	40±0.2	1.46	108	0.25	0.10

The measured consolidation parameters (apparent preconsolidation pressure (P_{ac}) obtained from e-log p curve, compression index (C_c), and swelling index (C_s)) at each temperature are given in Table 1. For the samples with high initial void ratio, the coefficient of consolidation (c_v) was fairly constant (Fig. 3a) at different consolidation pressures. Values changed within one order of magnitude over a wide

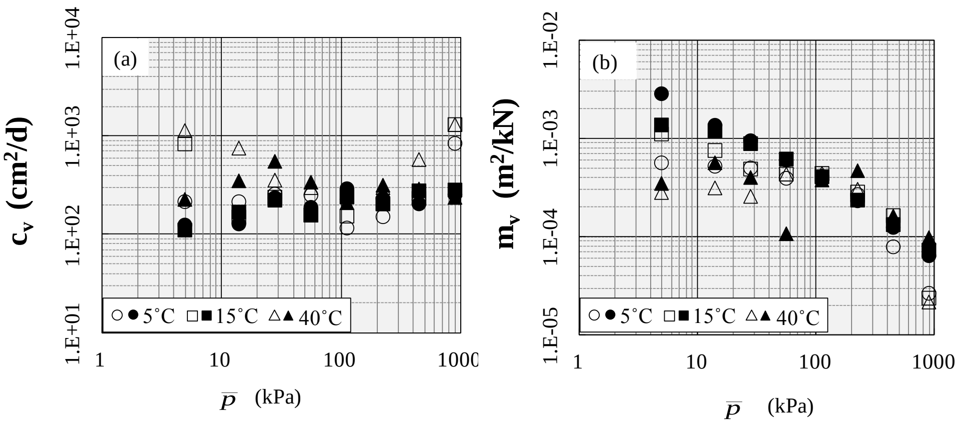

Fig. 3. (a) The coefficient of consolidation (c_v) vs mean pressure ($\bar{p}$) (b) the coefficient of volume compressibility (m_v) vs mean pressure ($\bar{p}$). Open symbols represent the results for ϕ 6m x H 10cm samples and filled symbols represent the results of ϕ 6m x H 2cm samples.

range of applied vertical consolidation pressures at each temperature for both the H 2 cm and H 10 cm samples. Although reference [31] suggested that the coefficient of consolidation decreased with increasing specimen height, the results in this study for both sample sizes indicated only minor scale dependency on the application of Terzaghi's theory to one-dimensional consolidation experiments. Additionally, a maximum variation of only 2% in measured gravimetric water content along the water content profile for all samples (not shown) supported the applicability of the one-dimensional Terzaghi's theory to the H 10 cm samples. For both sample sizes, the coefficients of consolidation (c_v) for both the H 2 cm and H 10 cm samples slightly increased with increasing temperature especially under overconsolidated state, indicating rapid dissipation of water at high temperature as compared to low temperature due to the change in water viscosity with temperature. With increasing consolidation pressure, a decrease in coefficients of volume compressibility (m_v) was obtained (Fig. 3b). Lower coefficients of volume compressibility at higher temperature were observed particularly under overconsolidated state. Higher coefficient of consolidation (c_v) and lower coefficient of volume compressibility (m_v) exhibited under overconsolidated state at higher temperature whereas similar coefficients (c_v and m_v) was observed under normally consolidated state at three temperature conditions. This probably indicates that temperature effects on consolidation coefficients are likely stress state dependent. Previous studies reported that thermally induced volume change behavior is stress history dependent and stress level independent [7], [13].

The obtained apparent preconsolidation pressure (P_{ac}) for H 10cm sample was relatively less as compared to H 2cm sample at each temperature condition. Nevertheless, for both H 10 cm samples and H 2 cm samples with high initial void ratio (1.53 to 1.62), higher apparent preconsolidation pressure (P_{ac}) was found at higher temperature, showing higher yield strength of the kaolin at higher temperature. The compression index (C_c) was slightly larger at higher than at lower temperature. Opposite, for the H 2 cm samples with low initial void ratio (1.43~1.47), the apparent preconsolidation pressure (P_{ac}) decreased with increasing temperature and the same compression index (C_c) value was obtained for both 5 °C and 40 °C conditions. In Fig. 4, the normalized void ratio (e/e_0) was plotted against logarithm of consolidation pressure (log p) for the H 10 cm samples with high initial void ratio (in Fig. 4a) and the H 2 cm samples with both high and low initial void ratios (in Figs. 4b and 4c) to show temperature dependent consolidation behavior. The normalized void ratio was used to eliminate minor differences in initial void ratio of each sample.

For natural undisturbed clays, a negative correlation between the apparent preconsolidation pressure (P_{ac}) and temperature was previously proposed by [32] and [20] in which constant-strain tests were carried out under temperatures ranging between 5 °C and 55 °C. For remolded clays with low initial void ratio (< 1), a decrease of the apparent preconsolidation pressure (P_{ac}) with increased temperature was reported by [33] for a temperature range of 5 °C to 40 °C and by [5] for a temperature range of 20 °C to 90 °C. In addition, they suggested that the compression index (C_c) was probably independent of temperature. The observed decrease in apparent preconsolidation pressure (P_{ac}) at 40 °C for the H 2 cm samples with low initial void ratio were in agreement with previous findings for pure remolded clays. However, a clear and opposite trend for samples with high initial void ratio was observed in this study. Reference [34] suggested that the influence of temperature on the preconsolidation pressure is strongly dependent on the testing technique. Thus, the discrepancies may be caused by different sample properties such as initial void ratio and clay fabric structure due to differences in pretreatment method, heating or cooling periods, applied preconsolidation pressure (P_c), and different experimental procedures or testing techniques. In summary, the consolidation parameters (P_{ac}, C_c, c_v and m_v) which reflect the consolidation characteristics of the kaolin clay were under most conditions dependent on temperature.

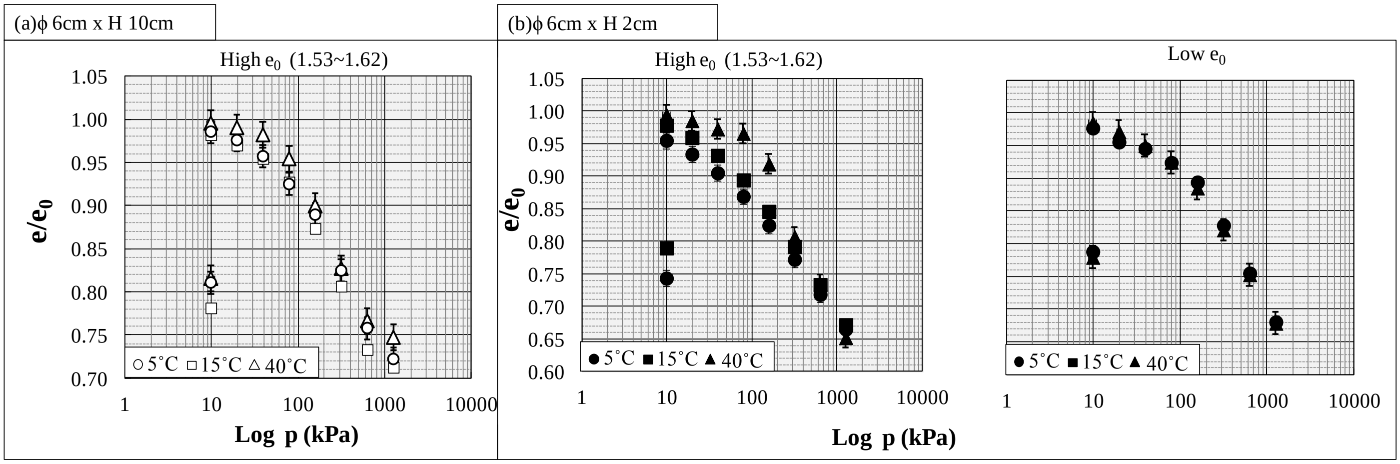

Fig. 4. Normalized e-Log p curves (a) ϕ 6cm x H 10cm samples (b) ϕ 6cm x H 2cm samples.

C. Effect of Temperature on Shear Stiffness

The shear modulus or stiffness ($G_{b.e}$) of the kaolin clay was evaluated using shear wave velocity measurements following Eq. (1). The shear wave velocity was measured under successive consolidation pressures in the consolidation test at each temperature condition (5 °C and 40 °C). The change in shear wave velocity with time of 24 hours was observed at each consolidation pressure. The temporal changes in shear wave velocity at the three consolidation pressures (overconsolidated state, normally consolidated state, and unloading stage) were shown in Figs. 5a, 5b, and 5c. In general, shear wave velocity increased with time under a given consolidation pressure for the loading process (Figs. 5a, and 5b) for both 5 °C and 40 °C. Oppositely, it decreased with time for the unloading process (Fig. 5c). The increase in shear wave velocity with time was observed until the time of 90% completed consolidation (t_{90}) which will correspond to the primary consolidation stage in the loading process (Figs. 5a, and 5b). In addition, the shear wave velocity continuously increased with time even during the secondary compression stage (corresponding to the time after $(10/9)*t_{90}$) where the variation of void ratio with respect to effective pressure was very small. Asimilar time-dependent behavior of clay has been stated by [35] and [36]. They suggested that the strengthening of physico-chemical bonds between particles contributes to the shear wave velocity increase during the secondary compression of clays. Additionally, the observed shear wave velocity at high temperature was greater than that at low temperature showing larger stiffness at high temperature. During the unloading process (Fig. 5c), the shear wave velocity decreased with time at both temperatures. This was probably due to a recovery of the previous clay fabric structure when removing the applied pressures from the consolidated clay.

The shear modulus property of soil is controlled by changes in void ratio and effective pressure [37], [23]. Figure 6a and 6b present the change in shear modulus ($G_{b.e}$) as a function of normalized void ratio (e/e_0) and void ratio (e_0) during successive consolidation processes including initial, overconsolidated and normally consolidated states for loading and unloading processes, respectively. The void ratio at the end of the one-day consolidation process under each pressure was plotted in terms of normalized void ratios in Fig.6a. Under both 5 °C and 40 °C conditions, the shear modulus increased sharply with decreasing void ratio (increasing consolidation pressure) in overconsolidated state while it increased gradually in normally consolidated state. Thus, the shear stiffness property of the kaolin clay with respect to applied consolidation pressure was found to be stress state dependent.

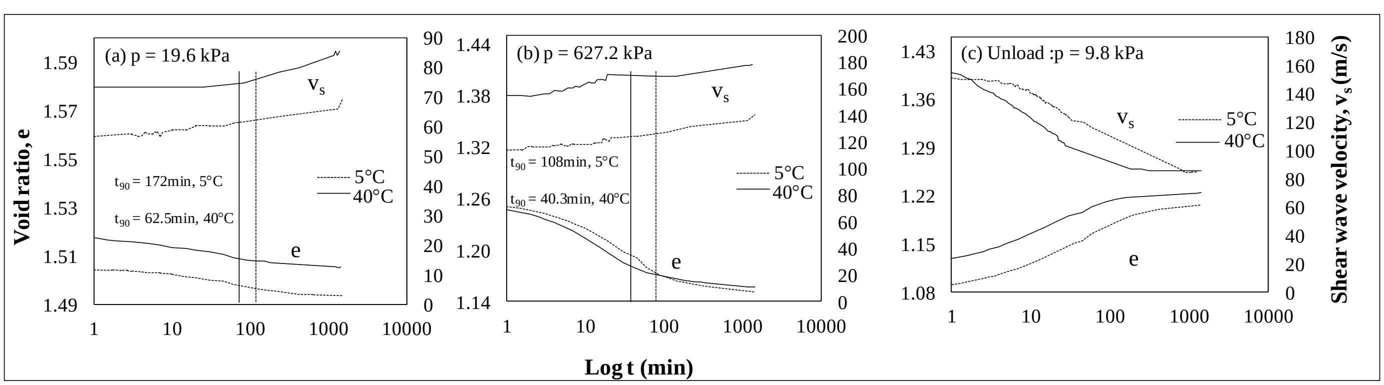

Fig. 5. An example of change of void ratio (e) and shear wave velocity (v_s) with the logarithm of time (log t) at selected pressures (loading) (a, b), and at constant pressure of 9.81kPa (unloading) (c). The dotted lines show the data obtained at 5 °C and solid lines show the data obtained at 40°C. The vertical solid line shows the time for 90% completed consolidation (t_{90}).

Interestingly, a larger shear modulus at higher temperature was found, even at the same void ratio (Fig. 6a). Typically, sample strength properties such as stiffness represent the soil state and structure. Thus, the present result indicates that fabric structure of kaolin clay, which is determined by the arrangements and subsequent adjustments in inter-particle forces between clay particles [36], was possibly influenced by temperature. Reference [38] described that the electrical attractive forces at particle level in clays strongly govern the engineering behavior of soils. The inter-particle forces between clay particles such as Coulombic forces and van der Waals forces vary inversely with the dielectric constant property of the pore medium which is temperature dependent property [39], [40]. The dielectric constant of water, k, decreases with increasing temperature, for instance the dielectric constant at 40 °C is 15% less than at 5 °C. As a result, the strong inter-particle forces between particles at 40°C might enhance microscopic physico-chemical interactions between particles in assemblage, causing that the shear stiffness of kaolin clay increased with temperature. Hence, the increase of shear stiffness at 40 °C may correspond to increase in apparent preconsolidation pressure (P_{ac}) at 40 °C, suggesting highly interrelated mechanical properties under the consolidation process. However, since marked temperature effects on consolidation characteristics were only observed for samples with higher initial void ratio, the assumed heat induced changes in inter-particle forces may be significant only for high porous materials. In perspective, laboratory experiments under temperature control using different clays and a wide range of void ratios should be conducted to further investigate this.

Reference [41] characterized the shear modulus of a cohesive soil by developing functional relations to parameters including effective octahedral normal stress, void ratio, degree of saturation, grain characteristics, soil structures, and temperature. Later, [22] and [23] proposed empirical formulas for shear modulus as a function of void ratio and effective pressure. The empirical formulas are as follows;

$$G = 3300 \times \frac{(2.97-e)^2}{(1+e)} \times p'^{0.5} \quad \text{(Hardin and Black, 1968)} \quad (3)$$

$$G = 4500 \times \frac{(2.97-e)^2}{(1+e)} \times p'^{0.5} \quad \text{(Marcuson and Wahls, 1972)} \quad (4)$$

where G is shear modulus (kPa), e is void ratio, and p´ is effective pressure (kPa).

The measured change in shear modulus as a function of void ratio was compared with the above empirical formulas (Fig. 6b). The trend of the measured shear modulus behavior closely followed the two models, but the models over-estimated the measured data. This is most likely due to the difference in shear modulus measurement techniques, as the torsional vibration method was used by [22], and the resonant-column method by [23]. Also, differences in material properties and experimental procedures may partly explain the deviation between models and measurements. However, similarly to the measured data, the models represented higher $G_{b.e}$ values for the sample at high temperature condition, supporting heat-induced changes in consolidation characteristics (i.e., e – log p relation) influenced shear modulus behavior.

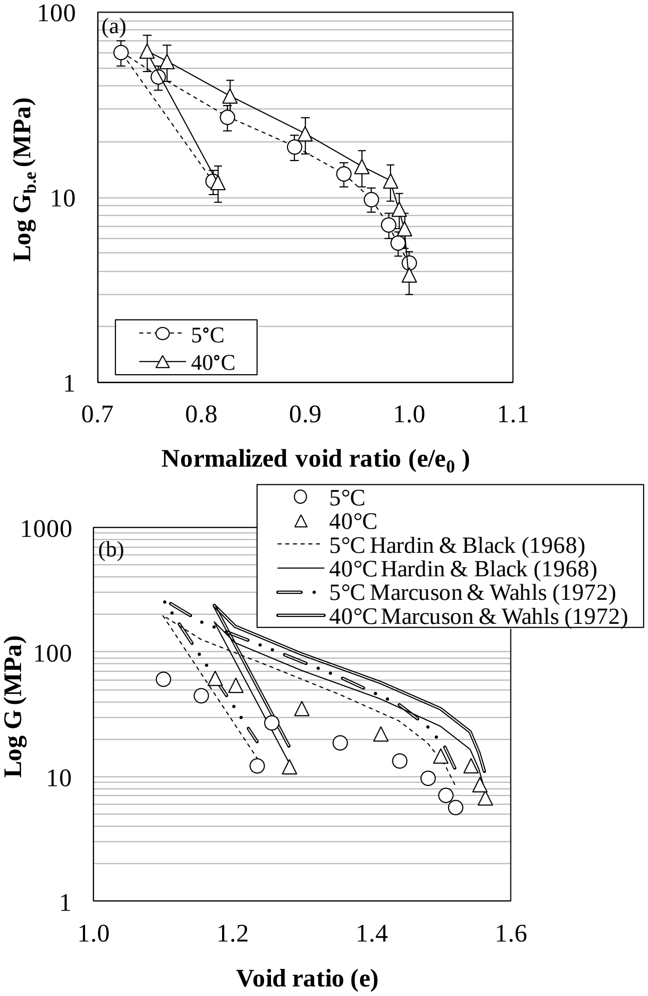

Fig. 6. The relationship between shear modulus ($G_{b.e}$) and normalized void ratio (e/e_0), obtained after 24 hours of each pressure (stress) step, at 5 °C and 40 °C (b) The relationship between measured shear modulus (G) and void ratio (e) as well as the estimated relationships using the Hardin & Black equation (1968) and Marcuson & Wahls equation (1972), at 5 °C and 40 °C.

D. *Effect of Temperature on Permeability*

Using Terzaghi's theory of one dimensional consolidation, permeability values were obtained for both H 10 cm and H 2 cm samples. Based on hydraulic conductivity measurement for H 10 cm samples, the saturated hydraulic conductivity (cm/sec) for kaolin clay was obtained using Eq. (2) and then transformed to intrinsic permeability (cm^2). The relationship between permeability and void ratio was described by the Kozeny-Carman equation [42],

$$k = \frac{n^3}{5A_m^2(1-n)^2} \quad (5)$$

where k is intrinsic permeability (cm^2), A_m is specific surface (volume based specific surface area) (cm^{-1}), and n is porosity, related to void ratio by $n = \frac{e}{1+e}$.

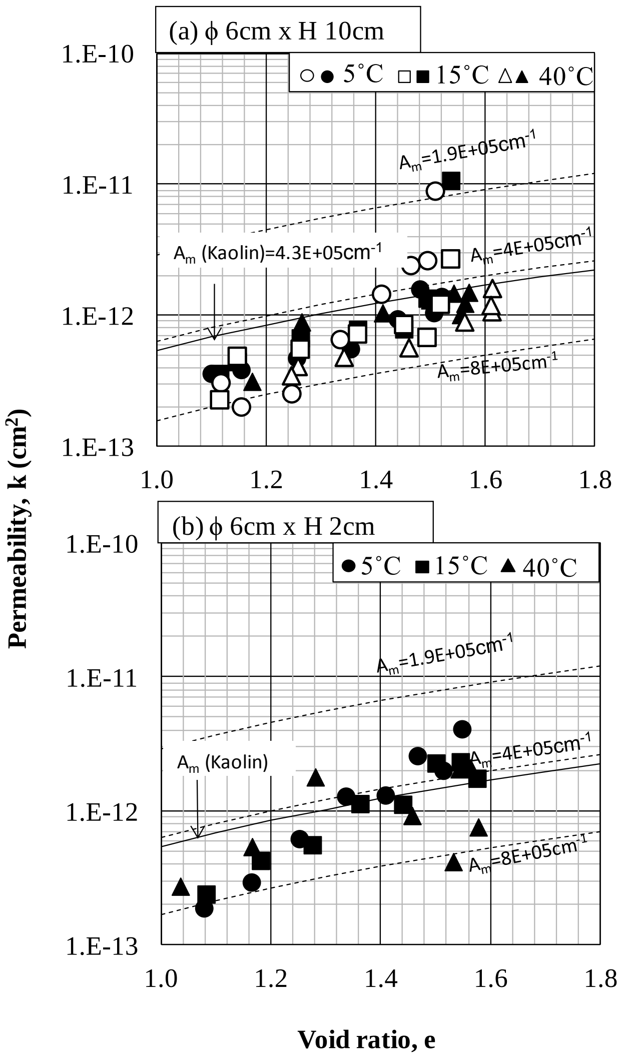

Fig. 7. The correlation between water permeability (k) and void ratio (e). The dotted lines are the predicted lines with respect to specific surface area (A_m) using the modified Kozeny-Carman equation. The solid line shows the predicted line using the measured specific surface area of kaolin clay. Open symbols represent the data obtained from direct measurement and filled symbols represent the data obtained by the modified oedometer using Terzaghi's theory of one-dimensional consolidation.

In Fig. 7, the permeability of the kaolin clay is shown as a function of void ratio. The measurements for H 10 cm samples were done by both direct measurement in the modified oedometer and Terzaghi's theory while the measurements for H 2 cm samples with high initial void ratio were obtained from Terzaghi's theory. Predictive model lines using the Kozeny-Carman equation (with A_m set equal to N_2 measured volume specific surface area) were added in Fig. 7 in order to confirm the likely permeability range of the tested kaolin clay. For both H 10 cm and H 2 cm samples, permeability values ranged from 10^{-13} cm^2 to 10^{-11} cm^2, and agreement with the Kozeny-Carman equation was relatively good for both direct and theory measurements. This implies a good performance of the modified oedometer apparatus for measuring water permeability. For both samples sizes, the coefficient of intrinsic permeability (cm^2) generally decreased with decreased void ratio. The reason for this permeability behavior as a function of void ratio is that particle assemblages become closer with increasing consolidation pressure (decreasing void ratio), and the subsequent reduction in total void space causes a reduction in water permeability [43]. The measurements indicated that permeability of kaolin clay for both H 10 cm samples and H 2 cm samples was less affected by temperature (Figs. 7a and 7b). However, the hydraulic conductivity was slightly influenced by temperature due to temperature dependent pore water properties (viscosity and density). Similar observations were reported by [7] on the hydraulic properties for soft Bankok clay, showing temperature dependent hydraulic conductivity property whereas intrinsic permeability showed no temperature dependency up to 100 °C.

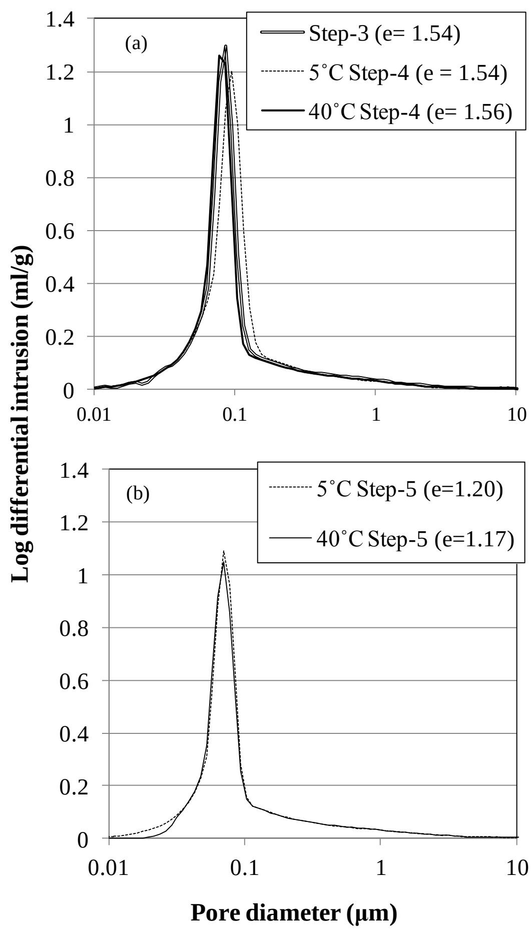

Fig. 8. Pore size distribution curves obtained using samples at experimental procedure Step-3 and Step-4 (Fig. 2), at 5 °C and 40 °C (b) Pore size distribution curves obtained using samples from Step-5, at 5°C and 40 °C.

The pore structure variation in tested samples was investigated by MIP. The initial pore size distributions for a preconsolidated kaolin H 2 cm sample after full water saturation at 5 °C and 40 °C, respectively, are shown in Fig. 8a. The pore size distributions of consolidated samples representing Step-5 in Fig. 2 at 5 °C and 40 °C, respectively, are shown in Fig. 8b. The pore diameters inside preconsolidated kaolin clay ranged from 0.05 μm to 1 μm. There was no detectable temperature effect on the pore structure of the kaolin samples, showing quite identical pore diameter range at 5 °C and 40 °C. This is in agreement with the similar permeabilities measured at the two temperatures. Based on the results, it can be concluded the elevated temperature of kaolin clay may enhance microscopic physico-chemical interactions between particles, causing higher shear stiffness and apparent preconsolidation pressure, but does not significantly affect macroscopic pore structure, causing similar permeability of kaolin clay at different temperature conditions.

IV. Conclusion

A modified oedometer apparatus was developed, allowing for simultaneous measurements of consolidation characteristics, shear wave velocity (shear stiffness), and water permeability on porous media samples at a given, controlled temperature. For the sample with high initial void ratio (1.53 to 1.62), the increase in apparent preconsolidation pressure (P_{ac}) at the higher temperature (40 °C) was observed. In addition, the measurements of shear wave velocity of the samples through for a wide range of applied pressures showed larger shear modulus values at 40 °C, indicating enhanced inter-particle bonds at the high temperature. However, the measurements of permeability and pore-size distribution of samples revealed that temperature effects on macroscopic pore structure governing water permeability are less significant within the studied temperature range (5 °C to 40 °C). Further research on clays across a wide range of initial void ratios coupled with different chemical solutions is needed to verify the temperature effects on consolidation characteristics and shear stiffness of clays which may be partly governed by temperature-dependent physico-chemical particle interactions and hereby derived microscopic changes in clay fabric structure.

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