# Effect of Thermal Volume Change on the Permeability of Kaolin Clay during a Heating-Cooling Cycle

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## ABSTRACT

Thermal loading changes the hydraulic conductivity of the soil medium. This research aims to study the effect of a heating-cooling cycle on the permeability of Kaolin clay. A temperature-controlled triaxial permeameter cell is used in this study to explore the variations of soil permeability at 20°C, 50°C, and 80°C. The hydraulic conductivity at each temperature is measured after 48 h at each temperature during the heating-cooling cycle to make sure the volume change due to thermal loading is stabilized. Evaluation of void ratio change during heating and cooling has been observed to predict the thermal behavior of Kaolin clay. It is observed that the intrinsic permeability during the cooling cycle is 9%–12% lower than the permeability observed during the heating cycle. The obtained results suggest that Kaolin clay's microstructure can change subject to a heating-cooling process, which creates irrecoverable deformation in the clay and regulates the macro behavior such as permeability of Kaolin clay.

## INTRODUCTION

Permeability is one of the most significant engineering properties of clay that regulates the seepage and water movement in the ground. Hydraulic properties such as permeability emphasize many geotechnical challenges, such as slope stability analysis and landfill designs (Damiano et al., 2017; Dou et al., 2014; Ng and Leung, 2012; Sadeghi and AliPanahi, 2020). The engineering properties of fine-grained soils are subjected to changes in external pressure, wetting and drying cycles, the chemistry of the pore medium, and temperature (Sridharan, 2002). Therefore, previous researchers have investigated the temperature effect on the volumetric strain of Normally Consolidated (NC) clay and over-consolidated (OC) clay under the heating-cooling cycle (Baldi et al. 1988; Samarakoon & McCartney, 2020). It is observed that due to the drained heating and cooling, respectively, plastic volumetric contraction, and elastic contraction may occur in normally consolidated soil (Samarakoon & McCartney, 2020). Moreover, temperature affects the soil structure, inter-particle bond strength, void ratio, water holding capacity of particles, and the corresponding hydraulic properties of soil (Gao and Shao, 2015).

A significant component of the thermomechanical behavior of saturated clay at elevated temperatures is the volume change of components of a clay mineral-water system due to the thermal effect (Baldi et al. 1988). According to Cekerevac and Laloui, (2004), soils with highly over consolidation ratio (OCRs) show reversible thermal expansion followed by irreversible thermal contraction. On the other hand, normally consolidated soils show irreversible volumetric contraction while heated at slow heating rates. This occurs because of the decrease in inter-particle shearing strength during the thermal load causing a collapse of the soil skeleton, eventually reducing the void ratio of the specimen (Campanella and Mitchell, 1968). The aforementioned thermal strains in saturated clays result from the water behavior, thermal expansion of clay minerals, reordering of the clay skeleton structure, as well as drainage conditions (Campanella and Mitchell 1968).

Thermal loading alters soil and fluid properties (Cherati and Ghasemi-Fare, 2019; Monfared et al., 2014; Tamizdoust and Ghasemi Fare, 2020a). Therefore, to properly understand the thermo-hydro-mechanical response of the geotechnical infrastructures, the variations of the soil properties (i.e., permeability) with the temperature change must be studied (Tamizdoust and Ghasemi-Fare, 2020b; Chen et al., 2017; François et al., 2009; Ghasemi-Fare and Basu, 2019). Previous research reported different behaviors for permeability variations of different clays at elevated temperatures. Towhata et al. (1993) and Seiphoori (2015) observed an increase in permeability of clay while some researchers have observed a decrease in intrinsic permeability at elevated temperatures due to the thermal consolidation induced soil densification (Romero et al. 2001; Villar and Lloret, 2004). Alternatively, Delage et al. (2009) conducted temperature-controlled constant head permeability tests on Boom clay and reported no changes in intrinsic permeability in the 20 °C to 90 °C temperature range. Chen et al. (2017) investigated the effect of thermal loading and the corresponding microstructural change on the hydraulic conductivity of Boom clay. They have reported that the microstructure weakening due to the thermal volume change resulted in intrinsic permeability reduction in Boom clay. Similarly, Joshaghani and Ghasemi-Fare (2021) have reported although hydraulic conductivity increases with temperature for Kaolin clay, the intrinsic permeability of Kaolin clay slightly reduces when the temperature rises from 20 °C to 80 °C.

However, in these previous studies, the focus was given to the changes in hydraulic conductivity as well as the intrinsic permeability of soil during the heating/ cooling cycle. It still remains unclear how thermal volume changes and induced soil fabric alteration during a heating-cooling cycle affect clay's hydraulic conductivity at a particular temperature. This study aims to analyze the hydraulic conductivity, intrinsic permeability, as well as thermal volume change of a normally consolidated (NC) Kaolin clay during a heating-cooling cycle. The results help to quantify and compare the thermal volume change (void ratio) during heating and cooling and its effect on hydraulic conductivity and intrinsic permeability during a heating and cooling load

## EXPERIMENTAL PROGRAM

### Sample Preparation

Commercial natural Kaolin clay from Columbus Co. has been selected for this study. To prepare the specimen, the Kaolinite powder was hand mixed with de-ionized water having an initial water content of 30 %. The soil was mixed with water carefully so that no soil lumps exist. Then the soil mixture was compacted into a cylindrical specimen with a height of 25.4 mm, a diameter of 101 mm, and a dry density of 1.4 Mg/m$^3$. Compaction was done in three layers. In order to maintain the same void ratio for the specimens, the height of the specimen was carefully controlled. After compaction, the height of each specimen was determined, and the initial void ratios of all specimens were kept almost constant. Then, the compacted sample was extruded from the cylindrical ring. After that, the specimen was placed between the filter papers and porous stones. Then the membrane was placed around it. The hydraulic conductivity was performed at higher confinement (stress) compared to the initial stress state; thus, all clayey samples were considered normally consolidated clays. A modified triaxial cell capable of controlling the heating-cooling cycle (Joshaghani and Ghasemi-Fare, 2021) was used in this study. The triaxial system was calibrated for thermal deflections (Joshaghani and Ghasemi-Fare, 2020, 2021). The cell was filled with de-aired water, as well as the sample was saturated by allowing the de-aired water to pass through the specimens by applying a pressure gradient between the bottom and the top of the sample. The saturation of the sample was controlled before beginning each test by calculating Skempton's coefficient B value. Cell pressure was adjusted and controlled by one of the digitally controlled flow pumps of the triaxial setup.

The geotechnical and thermal properties of the Kaolin clay used in this research are presented in Table 1. The thermal variations of viscosity and density of "pure water" are adopted from Delage et al. (2009).

**Table 1. Properties of Kaolin clay.**

| Liquid Limit (%) | Plasticity Index | Specific Gravity | Specific Surface area ($m^2/g$) | VCL Slope ($\lambda$) | RCL Slope ($\kappa$) | Thermal conductivity W/(m·K) | Specific heat capacity of Kaolinite; Cp (J/(kg◦C)) |
|---|---|---|---|---|---|---|---|
| 40 | 10 | 2.63 | 12.7373 | 0.228 | 0.08 | 1.798 | 945 (at 20 ◦C) |

**Test procedure**

To perform hydraulic conductivity tests at different temperatures, the adopted test setup was similar to Joshaghani and Ghasemi-Fare, (2021). The detailed description of the modified temperature-controlled triaxial cell can be found in Joshaghani and Ghasemi-Fare, (2021).

After achieving the approximate full saturation of the sample, the pressure gradient has been applied at the bottom and top of the sample. The applied hydraulic gradient was 138". To perform a test, initially, the temperature of the cell was fixed to the desired temperature using a temperature-controlled water bath. The bottom drain valve of the cell has been kept open to allow the generated pore water pressure to dissipate. The volume of dissipated water has been measured by the digital flow pump. Then, the hydraulic conductivity test has been started by employing a pressure gradient between the top and bottom of the sample. The volume of the passed water during the test was measured using a flow pump. After measuring the hydraulic conductivity (H.C) at room temperature (20 ºC), the sample temperature increased to 50 ºC. The hydraulic conductivity and the void ratio changes during a single heating-cooling test are measured after 48 hours of thermal loading. Please note, that 48 hours were selected such that after which no observable volume changes occurred, indicating stabilization of thermal volume change due to thermal loading. At every temperature, H.C is measured three times to ensure the repeatability of the test. To calculate the thermal volume change of the specimen, the equation ($(\Delta V_{dr})\Delta T = \alpha_w V_w \Delta T + \alpha_s V_s \Delta T - (\Delta V_m)\Delta T$), proposed by Campanella and Mitchell, (1968) has been adopted where the thermal volume change of the specimen ($\Delta V_m$) is predicted by measuring the drained or absorbed water ($\Delta V_{dr}$) while taking into account of thermal expansion of water ($\alpha_w V_w \Delta T$) and soil particles ($\alpha_s V_s \Delta T$), respectively. Intrinsic permeability is calculated considering the density and viscosity change of water with temperature ($\kappa = \frac{\gamma_w}{\eta} K$ ,where $\eta$ is dynamic viscosity, $\gamma_w$ is the unit weight of water and $K$ is intrinsic permeability, $\kappa$ is the hydraulic conductivity). Change in the void ratio is also obtained by calculating $V_w$ and $V_s$ after each thermal load.

## RESULTS

Figure 1 illustrates the change of the void ratio of Kaolin clay with a heating-cooling cycle to identify the effect of the thermal volume change of NC Kaolin clay on its hydraulic conductivity as well as intrinsic permeability. It is observed that the void ratio during the heating cycle decreased by 21% while the temperature increased from 20°C to 80°C.

This reflects that increased temperature causes particle rearrangement, resulting in thermal volume contraction of normally consolidated Kaolin clay.

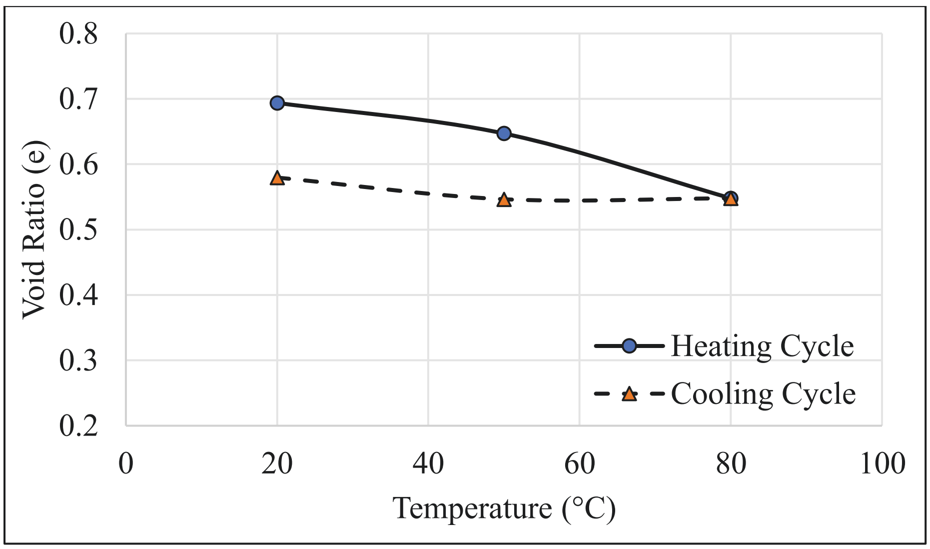


**Figure 1. Changes in the void ratio of Kaolin clay with the heating-cooling cycle under 552 kPa confinement stresses**

It is interesting to report that the void ratio increased during the cooling cycle by 7% while the temperature decreased from 80°C to 20°C. The changes in void ratio during the cooling load also confirm the soil particle rearrangement happens due to the cooling load. The 7% thermal volume expansion confirms that a part of the volume reduction that happens during the heating load was elastic and reversible.

Table 2 represents the differences in the void ratio between the heating and cooling cycle. It is observed that there is an irrecoverable change in the void ratio of Kaolin clay after a complete heating-cooling cycle. Under 552 kPa confining pressure, during heating, the void ratio of the sample is 0.69, 0.64, and 0.54 at 20°C, 50°C, and 80°C, respectively.

But during cooling, the void ratio of the sample is 0.58, and 0.546 at 20°C and 50°C, respectively, showing almost 16% and 15% of irrecoverable volume contraction at 20°C and 50°C, respectively. This result reflects that, during a heating and cooling cycle, there is always a difference in void ratio at a particular temperature, reflecting the irrecoverable volumetric change in the sample due to the thermal load.

**Table 2. Differences in void ratio of Kaolin clay between the heating and cooling cycle under 552 kPa confinement stresses**

| Initial Confining Pressure (kPa) | Temperature (°C) | Void Ratio (e) (after heating) | Void Ratio (e) (after Cooling) | Void Ratio Reduction (after heating and cooling cycle) (%) |
|---|---|---|---|---|
| 552 | 20 | 0.69 | 0.58 | 16 |
| | 50 | 0.64 | 0.546 | 15 |
| | 80 | 0.54 | 0.54 | - |

Figure 2 represents the changes in the hydraulic conductivity of kaolin clay during the thermal heating load. It is evident that hydraulic conductivity increases significantly when the temperature changes from 20 ºC to 50 ºC and then to 80 ºC. Under 552 kPa confining pressure, with the temperature increasing from 20ºC to 80ºC, the hydraulic conductivity increases by 113%. The increase in H.C. at higher temperatures occurs due to the reduction of the dynamic viscosity of water at elevated temperatures, which can facilitate water movements in the flow channels.

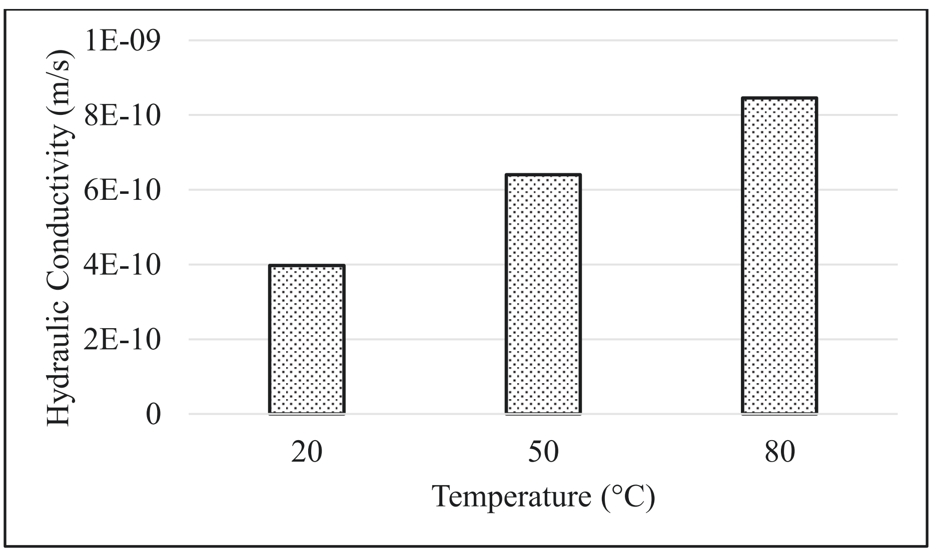


**Figure 2. Variations in hydraulic conductivity of Kaolin clay with the heating cycle under 552 kPa confinement stress**

Figure 3 demonstrates the changes in the hydraulic conductivity of Kaolin clay during the cooling cycle. It is observed that hydraulic conductivity decreases significantly when the temperature reduces from 80 ºC to 50 ºC and then to 20 ºC. Under 552 kPa confining pressure, when the temperature decreases from 80 ºC to 20 ºC, the hydraulic conductivity decreases by 58%.

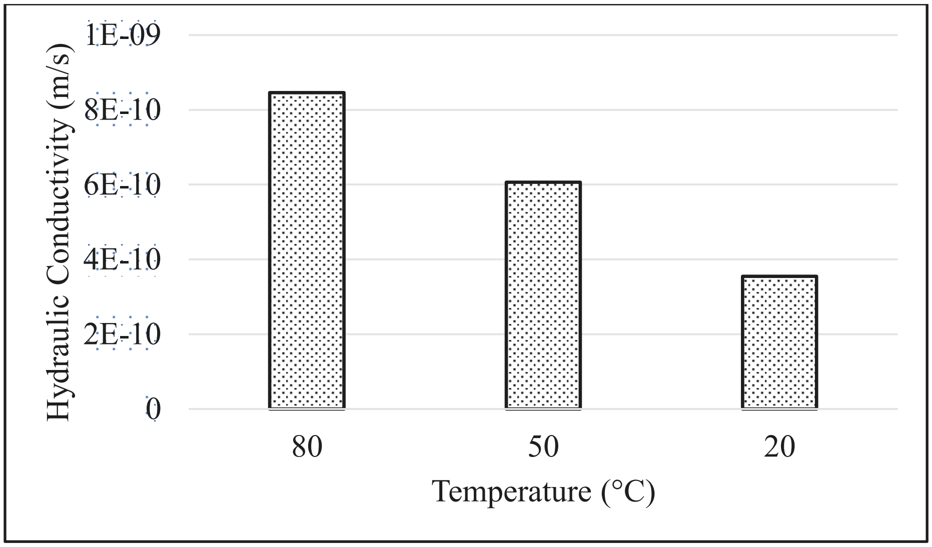


**Figure 3. Variations in hydraulic conductivity of Kaolin clay with the cooling cycle under 552 kPa confinement stress**

Table 3 represents the differences in H.C value observed during the heating and cooling loads. It is observed that there is a permanent change in the H.C of Kaolin clay after a complete heating-cooling cycle. For instance, under 552 kPa confining pressure, during heating, the H.C of the sample is 3.97E-10 m/s, 6.40E-10 m/s, and 8.46E-10 m/s at 20 ºC, 50 ºC, and 80 ºC, respectively. On the other hand, during cooling from 80 ºC to 20 ºC, the H.C of the sample is 3.55E-10 m/s, 6.06E-10 m/s at 20 ºC and 50 ºC, respectively, denoting almost 11% and 5% of lower H.C values, respectively, at 20 ºC and 50 ºC, after the cooling load is applied compared the values observed during the thermal loading.

This result reflects that, during a heating and cooling cycle, at a particular temperature, there is always a difference in H.C values of Kaolin clay, indicating irrecoverable thermal volume change in soil fabric due to the thermal load.

**Table 3. Differences in hydraulic conductivity of Kaolin clay between the heating and cooling cycle under 552 kPa confinement stress**

| Initial Confining Pressure (kPa) | Temperature (°C) | Hydraulic Conductivity, m/s (during heating) | Hydraulic Conductivity, m/s (during Cooling) | Hydraulic Conductivity Differences (%) |
|---|---|---|---|---|
| 552 | 20 | 3.97E-10 | 3.55E-10 | 11 |
| | 50 | 6.40E-10 | 6.06E-10 | 5 |
| | 80 | 8.46E-10 | 8.46E-10 | - |

Figure 4 represents the changes in the intrinsic permeability of Kaolin clay with a heating load. As can be seen in Figure 5, the intrinsic permeability decreases when the temperature increases from 20 ºC to 50 ºC and then to 80 ºC. Under 552 kPa confining pressure, with the temperature increase from 20ºC to 80ºC, the intrinsic permeability decreases by 22%. The decrease in intrinsic permeability occurs due to the thermal volume contraction in higher temperatures.

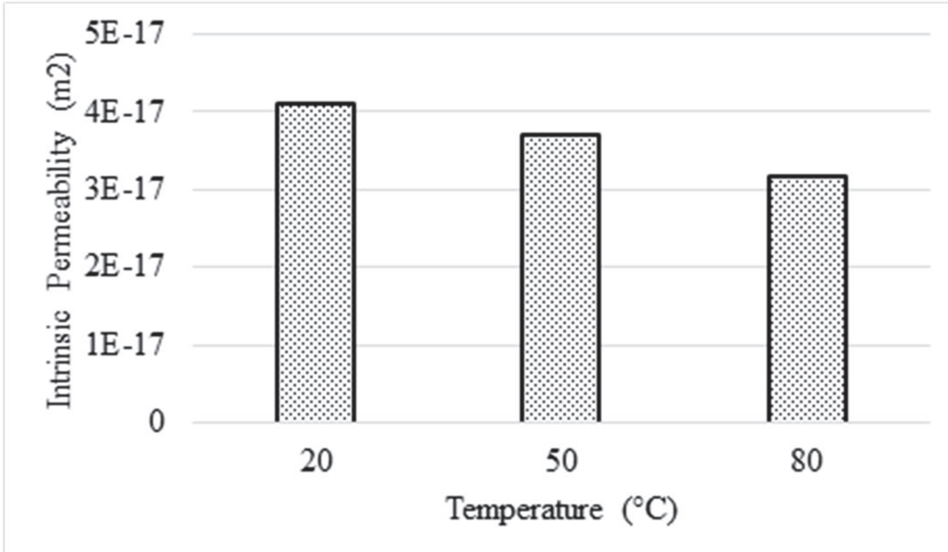


**Figure 4. Changes in Intrinsic Permeability of Kaolin clay with the heating cycle under 552 kPa confinement stress**

Figure 5 demonstrates the changes in the intrinsic permeability of kaolin clay with a cooling cycle. The results determine that intrinsic permeability increases when the temperature reduces from 80 ºC to 50 ºC and then to 20 ºC. Under 552 kPa confining pressure, when the temperature decreases from 80 ºC to 20 ºC, the intrinsic permeability increases by 15%.

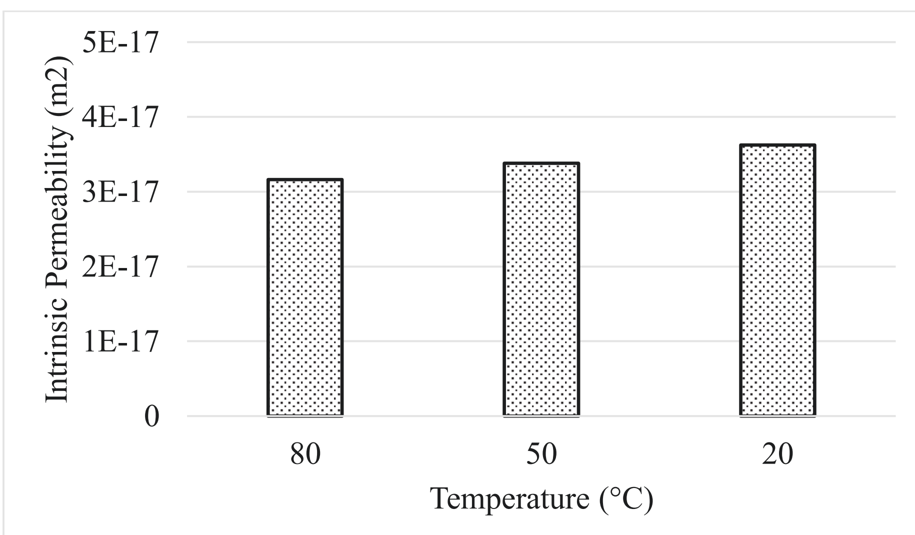


**Figure 5. Changes in Intrinsic Permeability of Kaolin clay with the cooling cycle under 552 kPa confinement stress**

Table 4 represents the differences in intrinsic permeability value between the heating and cooling loads. It is observed that the intrinsic permeability of Kaolin clay measured after a complete heating-cooling cycle is different from its initial value. For instance, at 552 kPa confining pressure, during heating, the intrinsic permeability of the sample is 4.1E-17 $m^2$, 3.71E-17 $m^2$, and 3.16E-17 $m^2$ at 20 ºC, 50 ºC, and 80 ºC, respectively. But during cooling load when soil temperatures are reduced from 80 ºC to 20 ºC, the intrinsic permeability of the sample is 3.62E-17 $m^2$ and 3.38E-17 $m^2$ at 20ºC and 50ºC, respectively, showing almost 12% and 9% of lower intrinsic permeability values during cooling load compared to the values measured at 20ºC and 50ºC, respectively, during the heating load.

**Table 4. Differences in intrinsic permeability of Kaolin clay between the heating and cooling cycle under 552 kPa confinement stress**

| Initial Confining Pressure (kPa) | Temperature (°C) | Intrinsic Permeability, $m^2$ (during heating) | Intrinsic Permeability, $m^2$ (during Cooling) | Intrinsic Permeability Differences (%) |
|---|---|---|---|---|
| 552 | 20 | 4.1E-17 | 3.62E-17 | 12 |
| | 50 | 3.71E-17 | 3.38E-17 | 9 |
| | 80 | 3.16E-17 | 3.16E-17 | - |

This result reflects that, during a heating and cooling cycle, at a particular temperature, there is always a difference in intrinsic permeability values of Kaolin clay, indicating a change in soil fabric due to the thermal load.

## CONCLUSIONS

The hydraulic conductivity of Kaolin clay under 552 kPa confining stresses is measured. Evaluation of void ratio (thermal volume change) during a heating and cooling cycle has been observed to predict the thermal volume change of Kaolin clay. The following conclusions can be illustrated based on the results of this study:

1. After a complete heating-cooling cycle, there is a change in the void ratio compared to the sample's initial void ratio, indicating an irrecoverable volumetric contraction of Kaolin clay due to the thermal load. Hydraulic conductivity measured during a heating model is reduced by 5 to 11% compared to the permeability observed prior to a thermal load. This reduction in hydraulic conductivity is attributed to the irreversible thermal volume change of NC Kaolin clay.
2. Intrinsic permeability during the cooling cycle is 9 to 12% lower compared to the permeability observed during the heating cycle at 20°C temperature.

The obtained results suggest that Kaolin clay's fabric can change when it is subjected to a complete heating-cooling load which creates thermal deformation in the clay and regulates the macro behavior such as the permeability of Kaolin clay.

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