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Hydraulic and Thermal Conductivities of Kaolin–Silica Mixtures under Different Consolidation Stresses

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Stable backfill materials for the heat sensitive structures of buried power cables, hot water pipes, and gas pipelines are suggested to have low permeability and high heat transfer characteristics. The hydraulic and thermal conductivities of backfill materials or clay liners are important parameters in proper design and construction of geotechnical structures involved with heat transfers. In this study, to investigate the optimal natural backfill or liner materials, thermal and hydraulic conductivities of kaolin–silica mixtures examined based on the results from laboratory tests under different consolidation conditions. From the experiment results, the thermal conductivity increases while hydraulic conductivity decreases with increasing density during consolidation process. As a result, back-fill materials with high kaolin content under low consolidation stress were desirable materials for burial of heat sensitive structures.

Keywords: clay liner, consolidation, hydraulic conductivity, kaolin–silica mixture, natural backfill material, thermal conductivity

Introduction

Proper assessment of thermal and hydraulic properties of soils is important in predicting behavior of foundations underneath or encompassing heat sensitive structures. The heat sensitive structures include road pavements, airports pavements, pipelines, energy piles, and clay walls of nuclear waste landfills (Farouki 1981; Gera, Hueckel, and Peano 1996; Tien et al. 2004; Brandl 2006; Laloui, Nuth, and Vulliet 2006; Abuel-Naga, Bergado, and Bouazza 2008). Recently, there has been a growing emphasis on soil thermal properties' assessment due to expanding construction markets of oil pipelines, hot water pipelines, buildings in cold or polar regions, and cold gas transport facilities in unfrozen grounds (Farouki 1981; Kim and Lee 2002; Johnson and Hegdal 2008; Nicolsky, Romanovsky, and Panteleev 2009; Dall'Amico et al. 2011).

Heat transfer indicates a phenomenon that heat at a region with higher temperature flows to another region with lower temperature without any physical movement of heat perceived materials. In physics, measures (such as heat transfer coefficient or thermal conductivity) of heat transfer of a material are inherent characteristics of the material.

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Thermal conductivity of a soil is an important factor in assessing soil behavior in cold regions and is a function of moisture content, particle size distribution, dry density, and frozen susceptibility (Kersten 1949; De Vries 1952; Woodside and Messmer 1961).

When designing the power cables, the buried power transmission efficiency (or capacity) is determined based on the maximum allowable temperature of the cable and also the heat transfer ability of surrounding backfill materials (such as soils). Use of the backfills with high thermal conductivity (a measure of heat transfer ability) is important because the internal heat exerted from the power cables should effectively be transmitted to the surrounding backfill materials to avoid their possible thermal runaway or electric breakdown. Furthermore, the higher susceptibility of moisture change (or moisture movement) of backfill materials due to higher hydraulic conductivity induces significant variation of resistivity against heat of power cable; therefore, for more stable backfill materials, the materials with lower hydraulic conductivity are preferred for the backfill materials (Mitchell and Chan 1982). Transmission voltage and current should be increased to increase the transmission capacity; which induces a significant transmission heat. When significant transmission heat is generated locally, the moisture of the backfill at the significantly heat increased location changes (it generally decreases); therefore, the decrease of moisture of backfill induces an increase of heat resistivity of surrounding backfill material. For this reason, conservative assumptions should be made in heat resistivity determination to secure extra margin of safety.

Widely used backfill materials for buried power cables are compacted frictional soils with high heat resistivity; however, these materials have limitations due to their higher void ratios compared to those of silts and clays (Fukagawa, Imajo, and Ogata 1974). Yun and Santamarina (2008) claimed that greater thermal conductivity is generally expected for larger contact areas among soil particles; therefore, sands have lower thermal conductivity due to smaller soil particle contact areas compared with those of silts and clays. Thalmann (1950) and Becker, Misra, and Fricke (1992) also found that the thermal conductivity of soils increases with increasing contact area between soil particles. The increase of thermal conductivity of soils with increasing soil particle contact area may result from higher thermal conductivities of minerals compared with those of air and water (approximately 0.024 and 0.56 W/mK at temperature of 25°C for atmosphere air and water, respectively). Thalmann (1950) stated that the thermal conductivity in dry soils increases with two important factors, packing density and contact area between soil particles. Under similar particle size and packing density, thermal conductivity of nonspherical particles (which have larger contact areas) was higher than that of spherical particles. Kim and Lee (2002) claimed the necessity of developing new types of backfill materials that have higher thermal resistivity and lower void ratio. Burges et al. (2008) claimed that conservative design of stable backfill of power cables should be done by using backfill materials with lower hydraulic conductivity. In addition, Issa (1996) and Cho, Lee, and Kang (2000) insisted that backfill materials of high-voltage power cables from nuclear power plants should have optimal combination of thermal and hydraulic conductivities.

The properties of backfill or liner materials of clayey soils (mineralogic clays) govern the physical behavior of the clayey soils. Two representative clayey backfill material groups are montmorillonite and kaolin. The properties of these groups were examined in detail in many previous studies (Alawaji 1999; Misra, Sivalingan, and Sharma 1999). The use of these backfill and liner clayey groups is preferred in field applications to those of other man-made materials because these two materials are environmental-friendly natural materials preventing possible destruction of underground environment.

Especially, montmorillonite minerals are widely used as backfill and natural grouting materials, but their significant degree of hydration and adsorption characteristics have induced problems resulting from excessive settlement from shrinkage, heave from swelling, and loss of strength, and stability from shrinkage or swelling. Such problems are a potential threat for hydraulic structures including dams or embankments (Farouki 1981). Kaolin minerals can be considered as the more favorable backfill or grouting material compared to the montmorillonite minerals due to its lower hydration reaction and cation adsorption properties; therefore, the structures backfilled (or grouted) using kaolin minerals would have less shrinkage and heaving problems.

In this study, hydraulic and thermal conductivities of kaolin–silica mixtures were measured from a series of experiments and were analyzed under different consolidation degrees (changes of void ratio or density under different consolidation pressure σ'_c) for their possible uses as backfill materials of heat sensitive structures, such as gas pipelines, hot water pipes, and power cables. The selected backfill materials (kaolin–silica mixtures) should be expected to perform well by obtaining mechanical stability against thermal runaway or electric breakdown of pipelines. In addition, the kaolin–silica mixtures would increase workability in placing backfill materials in fields due to its ease of controlling natural environment friendly kaolin clays and silica silts. From a series of experiments, different amounts of Silica silts are added to kaolin clays to find optimal mixing ratios between silica silts and kaolin clays producing improved hydraulic and thermal conductivities.

Materials

Different test samples were prepared by mixing kaolin clays and silica silts having different mixing ratios by their weights. Silica silts were added to pure kaolin clays by controlling their mixing ratios from 0 to 100% (Table 1). The initially considered kaolin clay mixing ratios by weight were 0, 25, 50, 75, and 100%. However, to examine any possible abrupt changes in hydraulic and thermal conductivities with increasing kaolin clay contents, samples with mixing ratios of 10 and 90% (by weight) of kaolin clays were included in the test program.

Basic laboratory tests were conducted on kaolin clays used in the experiment: The specific gravity (G_s) was 2.63; #200 sieve passing amount was 100%; liquid limit (LL) was 82.1%; and plasticity index (PI) was 48.7%. The kaolin has color of white and platy shape. Molecular formula of the kaolin is $H_2Al_2Si_2O_8 \cdot H_2O$. The particle size of kaolin is typically less than 2 μm.

The G_s and #200 sieve (sieve size of 75 μm) passing amount for silica silts were 2.6 and 100%; however, their LL and PI were not obtainable because they are classified as frictional soils (not clayey soils). To identify the mineral components of specimens, which may be an influential factor on thermal conductivity, X-Ray Diffraction tests (XRD) were conducted on two pure kaolin clay and silica silt specimens. The XRD test results are summarized in Table 2.

Table 1. Mixing ratios of the test samples of pure kaolin, pure silica, and mixtures of kaolin and silica

Sample	Kaolin (weight percent)	Silica (weight percent)
K-100	100	0
K-90	90	10
K-75	75	25
K-50	50	50
K-25	25	75
K-10	10	90
K-0	0	100

Table 2. XRD test results of samples

Soils	Contents of mineral (weight %)			Note
	Quartz	Kaolin	Muscovite	
Kaolin clays	2.6	79.0	18.3	Other minerals with negligible contents are not included
Silica silts	100	–	–	

Experiments

Sample Preparation and Configuration

Thermal conductivity test mold is used to analyze thermal conductivity change with change of void ratio (density or height) of saturated soil specimens during consolidation process. In this study, different consolidation stresses ($\sigma'_c = 5$, 10, 21, 39, 77, 155, 312, and 626 kPa) were imposed to simulate different consolidation scenarios.

Figure 1 shows the test apparatus and set-up for the thermal conductivity measurement. The mold was manufactured using 1 cm-thick transparent acrylic having its radius and height of 10 and 20 cm, respectively. The reason for using transparent acrylic for the mold is to visualize the initial height of specimen and to match the water level in water tank with the upper surface level of the specimen.

Based on the different mixing ratios by weight percentile of kaolin clays and silica silts in Table 1, specimens were prepared into the mold initially at slurry states having water contents of 107%. The slurries were well stirred to obtain relatively homogeneous samples. For full saturation of the samples, the air inside the specimen was extruded under slight vacuum state (approximately less than suction pressure of 2 kPa) and drain board was placed carefully on top of the specimen. Twenty four small holes were perforated on the drain board for easy insertion of thermal conductivity measuring needle probes and for easy drainage. The top drain board was horizontally maintained by installing horizontal guide bar on top of the drain board. After the specimen is placed in the mold, the mold is submerged until the water level reached at the level of specimen top.

During consolidation, the valve of bottom of cell was opened to induce pore water dissipation (water extrusion) in both upward and downward directions. Consolidation tests were performed on the prepared specimens following ASTM D2435 (ASTM 2011), the initial consolidation stress was maintained at relatively low level considering the close-to-slurry states of the specimens.

Hydraulic Conductivity

Coefficients of consolidation and volume change for the test specimens in Table 1 were theoretically evaluated using the following consolidation theory (Terzaghi 1943). The coefficient c_v of consolidation is:

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2} \tag{1}$$

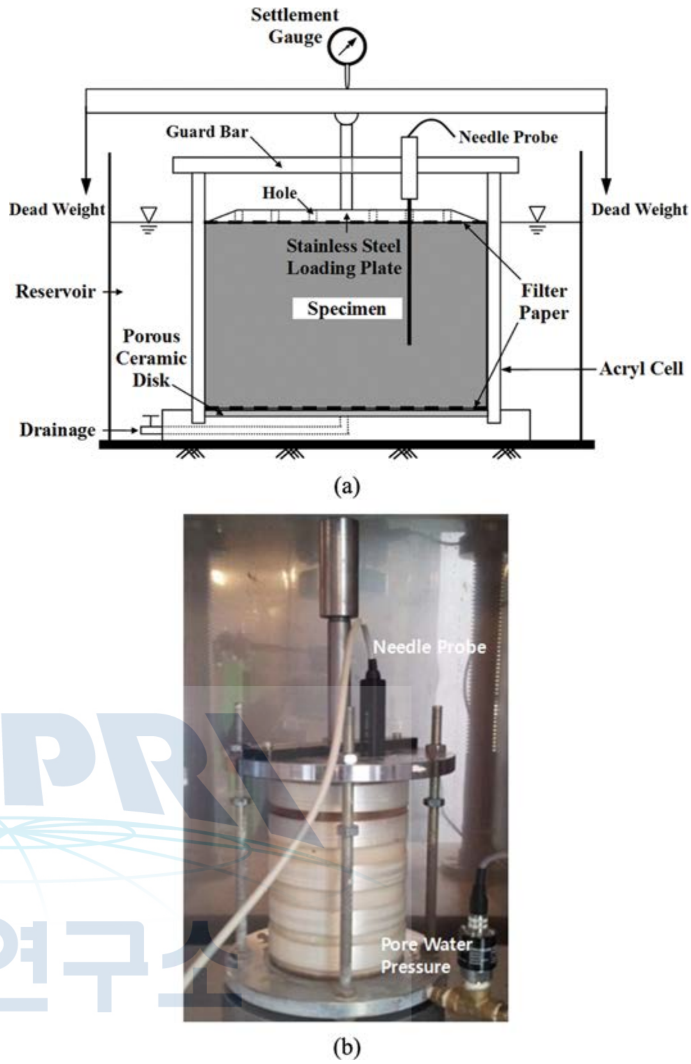

Fig. 1. Experimental apparatus for consolidation tests and thermal conductivity measurement: (a) Diagrammatic sketch and (b) Photo.

where t is the time from the instantaneous application of a total stress increment; u is the excessive pore water pressure; and z is the depth below the top of the soil layer.

Coefficient of compressibility a_v is defined as a minus of the ratio of the void ratio change amount (Δe) to the effective stress change ($\Delta\sigma'_v$):

$$a_v = -\frac{\Delta e}{\Delta\sigma'_v} \tag{2}$$

Coefficient m_v of volume change is a value representing unit volume change with respect to unit incremental effective stress and is mathematically expressed as follows:

$$m_v = \frac{\Delta\varepsilon_v}{\Delta\sigma'_v} = \frac{\Delta d/d}{\Delta\sigma'_v}\left(= \frac{a_v}{1+e_0}\right) \tag{3}$$

where ε_v is the volumetric strain and d is the specimen height.

Finally, from the definition of coefficients c_v of consolidation, hydraulic conductivity k can be calculated as multiplications of coefficients of consolidation and volume change and unit weight γ_w of water:

$$k = c_v \, m_v \, \gamma_w \tag{4}$$

Thermal Conductivity

Thermal conductivity λ was measured using the needle probes (diameter and length of 3 and 129 mm, respectively) following the standard ASTM D 5534 (ASTM 2008) under different consolidation stresses. The needle probes were installed prior to the external loading to minimize the disturbance of samples. The needle probe method used in this study is one of the most generally used methods to assess thermal conductivity (de Vries and Peck 1958). This needle probe method is typically used in laboratories following ASTM D 5534 and D 5930 standards. The needle probe method estimates thermal conductivity of surrounding materials of the needle by measuring temperature change of the needle after increasing needle's temperature to its target value. The needle probe method has an advantage of fast thermal conductivity measurement. Theory supporting the needle probe method assumes homogeneous materials and is derived using Fourier equations for one dimensional heat transfer on cylindrical co-ordinates (Carslaw and Jaeger 1959; Ingersoll, Zobel, and Ingersoll 1954; Hart and Couvillion 1986). From the earlier published reports, the needle probe method is also applicable in the field.

The thermal conductivity measurement equipment is a commercially developed apparatus (Quickline-30, ANTER), in which thermal conductivity response range is from 0.0015 to 6.0 W/mK and its measurement accuracy is reported ±3%. For each consolidation loading step, measurements of density, moisture content, consolidation amount (change of specimen height), and thermal conductivity were carried out after the completion of consolidation. The consolidation is assumed to be completed if the consolidation amount change with respect to time is stabilized.

Results

The experimental results of thermal and hydraulic conductivities of kaolin clay–silica silt mixtures for different consolidation stages ($\sigma'_c = 5$, 10, 21, 39, 77, 155, 312, and 626 kPa) were summarized and analyzed.

Void Ratio and Density Measurement

The specimen height was measured at the interface level between the specimen top and drain board after completion (or stabilization) of settlement at each loading step to examine void ratio (or density) of the specimens. Figure 2a represents consolidation curves (relationship between void ratio e and effective consolidation stress σ'_c) of all the specimens. The virgin consolidation curves exhibit nonlinear relationship between void ratio and logarithm ($\log_{10} \sigma'_c$) of effective consolidation stress. Overall, the decrease of void ratio with increasing consolidation stress is more pronounced with increasing kaolin clay percentage. Figure 2b shows the

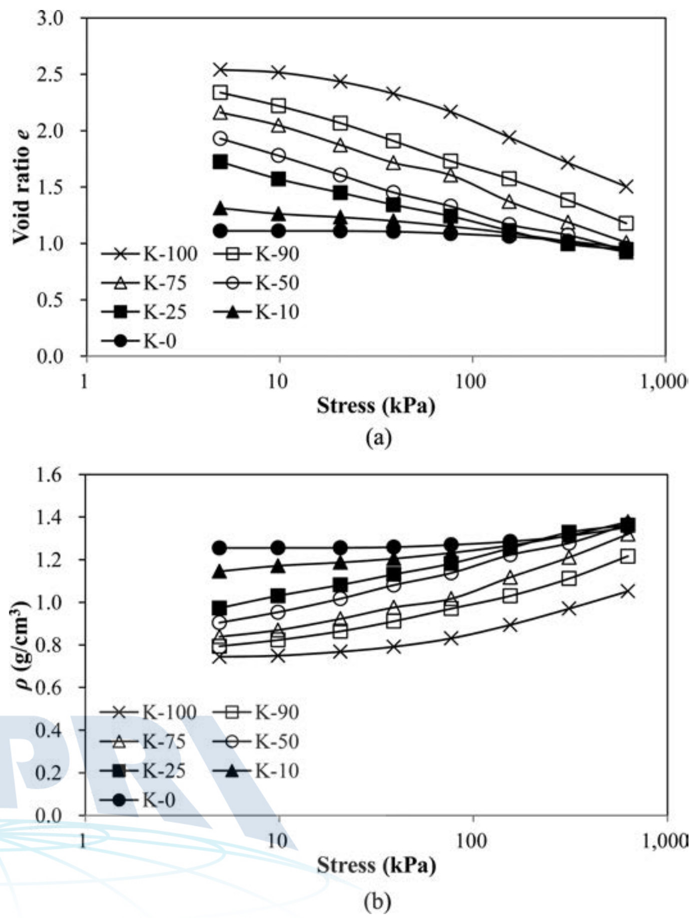

Fig. 2. (a) Consolidation curves and (b) density changes with increasing consolidation pressure.

increase of specimens' densities with increasing consolidation stress. Pure silica silts (K-0) exhibit the minimum increase of density with increasing consolidation stress among the specimens. The least increase in density of the pure silica silt results from the nonfloating fabric characteristics among the contact surface of silica particles (Carraro, Prezzi, and Salgado 2009).

The decrement of void ratio at each loading step increased with increasing percentage of kaolin clays. In addition, the decrease of void ratio was accelerated with increasing logarithm of consolidation stress as the kaolinite clay percentage increased. However, when the kaolinite clay percentage exceeded approximately 25%, the consolidation behavior of the specimens (K-100, K-90, K-75, and K-50) did not show big difference. It can be concluded that kaolin clay governs the consolidation behavior of kaolin–silica silt mixtures if the kaolin clay percentage is approximately higher than 25%. As the fines content increases in the fines-silt mixtures, the fines fill the void among the silt particles and break sand particles chain (detach sand particles from other sand particles); therefore, the engineering properties (including consolidation behavior) of the mixtures change significantly (Kuerbis and Vaid 1988; Vaid 1994; Thevanayagam 1998; Salgado, Bandini, and Karim 2000; Thevanayagam et al. 2002; Carraro, Prezzi, and Salgado 2009).

Hydraulic Conductivity Measurement

Hydraulic conductivity of soils is one of the key parameters in assessing foundation stability. Coefficient k of hydraulic conductivity significantly influences consolidation behavior of geotechnical engineering difficult problems, including seepage in backfill materials, embankment construction on soft ground, and deformation of pavements (Hong 2008). Due to the significant low permeability of clayey soils compared to those of frictional soils, clayey soils are widely used as clay liners (Garcia-Bengochea, Lovell, and Altschaeffl 1979; Sivapullaiah, Sridharan, and Stalin 2000; Carraro, Prezzi, and Salgado 2009); however, the use of pure clays as clay liners worsens constructability (or workability) due to the difficulties in liner installation (Ministry of Environment 2004). Therefore, in this study, Silica silts were added to kaolin clays to improve the workability of pure clays in construction practices, and hydraulic conductivities of their mixtures were evaluated during their consolidation processes. International construction specifications (Folliard et al. 2008) suggest that the recommended hydraulic conductivity of the controlled low-strength materials (CLSMs) is within a range of 10^{-4}–10^{-5} cm/s.

The CLSMs indicate the flowable backfill materials consisted of sand, cement, water, fly ash, and admixture; and are developed for the use of geotechnical applications (ACI 1994). In this study, kaolin–silica mixture properties were evaluated for their uses of backfill or liner materials based on the experimental investigation of hydraulic and thermal conductivities under different consolidation conditions. In addition, the international criteria defining backfill or liner materials' properties were examined and compared.

Figure 3 demonstrates hydraulic conductivity changes with increasing consolidation time of the specimens. The calculation of hydraulic conductivity requires coefficients (c_v and m_v) of consolidation and volume change Eq. (4). The coefficients c_v was obtained from the "log t method" given in ASTM D 2435 (ASTM 2011) and m_v was determined from Eq. (3), respectively, based on the measurements of void ratios and sample heights for each loading step after the initial loading.

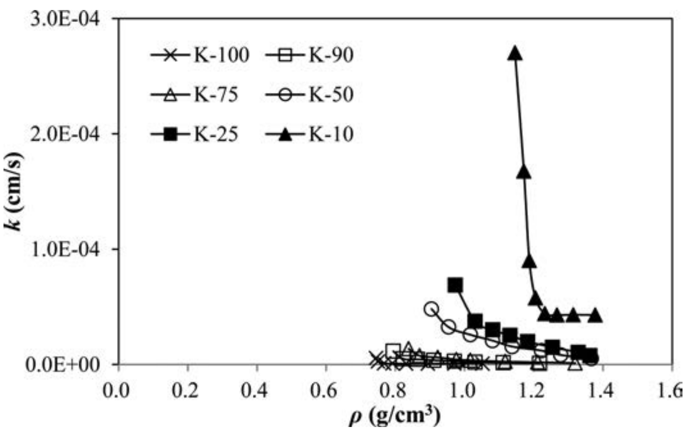

Fig. 4. Relationship between hydraulic conductivity and density of various samples.

Hydraulic conductivities of kaolin–silica mixtures decrease with increasing kaolin clay percentage. The hydraulic conductivity of K-10 specimen dramatically decreases with first four loading steps ($\sigma'_c = 5$, 10, 21, and 39 kPa) and its decrement rate decreases after the 4th loading step. The hydraulic conductivities of K-25, K-50, K-75, and K-100 specimens drop significantly until the second loading step; however, their decrement rates were relatively consistent thereafter.

Figure 4 plots the relationships between hydraulic conductivities of kaolin–silica mixtures and densities of the specimens during consolidation steps, respectively. The hydraulic conductivity of K-10 specimen decreased significantly as the consolidation proceeded with consolidation pressure higher than 100 kPa.

Figure 5 demonstrates the hydraulic conductivity changes with increasing kaolin clay contents for different consolidation stress levels. Under each consolidation stress level, hydraulic conductivity decreases with increasing kaolin clay content and with increasing consolidation stress, respectively. Table 3 summarizes the hydraulic conductivity values for different consolidation stresses and kaolin clay content in weight percentage. The hydraulic conductivities of the

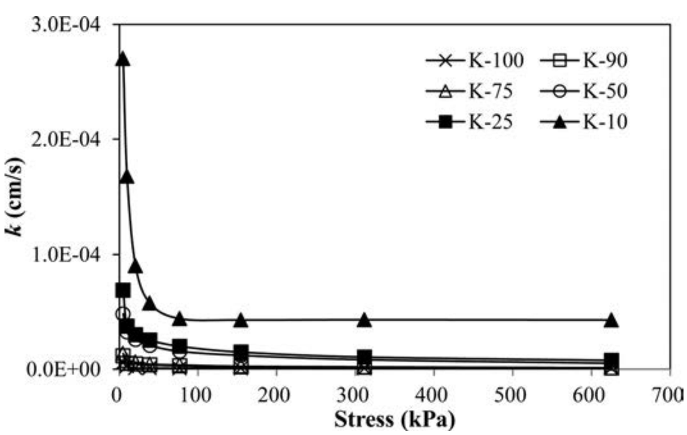

Fig. 3. Hydraulic conductivity changes with increasing consolidation pressure.

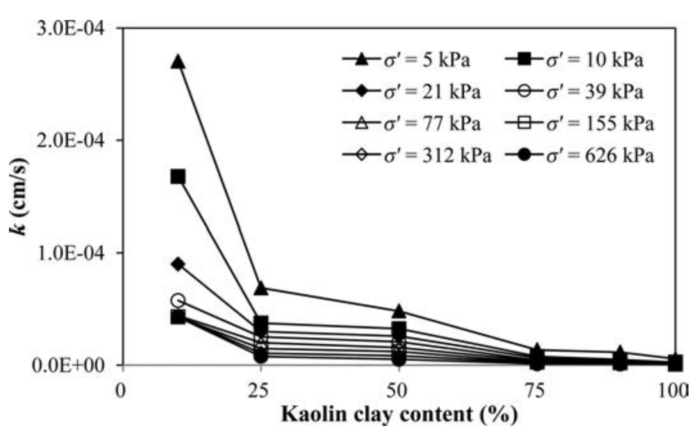

Fig. 5. Hydraulic conductivities of various samples with different kaolin clay content.

Table 3. Hydraulic conductivities of various samples (hydraulic conductivity unit: cm/s)

Sample/Consolidation stress (kPa)	K-100	K-90	K-75	K-50	K-25	K-10
5	5.6×10^{-6}	1.1×10^{-5}	1.4×10^{-5}	4.8×10^{-5}	6.9×10^{-5}	2.7×10^{-4}
10	2.6×10^{-6}	4.9×10^{-6}	7.6×10^{-6}	3.2×10^{-5}	3.7×10^{-5}	1.7×10^{-4}
21	1.0×10^{-6}	4.4×10^{-6}	6.2×10^{-6}	2.6×10^{-5}	3.0×10^{-5}	9.0×10^{-5}
39	9.0×10^{-7}	3.7×10^{-6}	4.4×10^{-6}	2.1×10^{-5}	2.5×10^{-5}	5.8×10^{-5}
77	8.0×10^{-7}	2.9×10^{-6}	3.7×10^{-6}	1.6×10^{-5}	2.0×10^{-5}	4.4×10^{-5}
155	8.6×10^{-7}	2.0×10^{-6}	2.6×10^{-6}	1.2×10^{-5}	1.5×10^{-5}	4.3×10^{-5}
312	7.9×10^{-7}	1.6×10^{-6}	2.0×10^{-6}	8.3×10^{-6}	1.1×10^{-5}	4.3×10^{-5}
626	7.5×10^{-7}	1.0×10^{-6}	1.2×10^{-6}	5.2×10^{-6}	7.7×10^{-6}	4.3×10^{-5}
k5/k626 kPa	749%	1,122%	1,097%	926%	893%	629%

specimens at initial consolidation stress (5 kPa) decreased by 629 to 1,122% when the consolidation stress increased to 626 kPa depending on the kaolin clay content. The specimen having the highest decrease rate of hydraulic conductivity was K-90.

The hydraulic conductivities (Figure 5 and Table 3) of all the specimens tested in the experiments under different consolidation stresses were within the suggested hydraulic conductivity range (from 10^{-4} to 10^{-5} cm/s) of CLSMs. However, to satisfy the hydraulic conductivity criterion ($k \leq 10^{-5}$ cm/s) (Folliard et al. 2008), even under a small consolidation pressure (5 kPa), kaolin–silica mixtures should have kaolin clay content higher than 75%. The K-25 and K-50 specimens can also be used as clay liner when sufficient consolidation takes place to meet the minimum hydraulic conductivities (10^{-5} cm/s) provided by clay liner criteria (Folliard et al. 2008). The other K-0 and K-10 specimens are not suitable for using them as clay liner for the consolidation stress imposed in this study; however, they might be eligible for clay liner if much greater consolidation stress is applied.

Thermal Conductivity Measurement

Thermal conductivity λ (W/mK) is defined as the heat flow amount in one direction per unit cross-sectional area and unit length for a temperature difference of one kelvin. For soils, the thermal conductivity is defined as the heat amount that passes through a unit soil cross-sectional area in unit time, unit length, and unit gradient temperature drop from one end to the other:

$$\lambda = \frac{q}{A(T_2 - T_1)/l} \tag{5}$$

where q is the heat flow amount in unit time; $(T_2 - T_1)$ is the difference in temperature in kelvin ($T_2 - T_1$ for $T_2 > T_1$); A is the cross-sectional area; and l is the length of heat transfer.

Proper quantification of thermal conductivity of soils is a crucial task in assessing many geotechnical engineering problems. The thermal conductivity of soils is an important parameter used for design of roads, airfields, pipelines, buildings in cold regions, underground power cables, hot water pipes, and cold gas pipelines in unfrozen ground. Frost heave and thaw actions of soils induce significant damages or loss of stabilities of structures.

Especially, buried power cables require fast emission of heats to surrounding backfills for efficient electricity transmission. Internal overheat of power cable due to slow heat emission could lead to a failure of the cable. Moisture around power cables also results in a serious problem for power cables, because the thermal conductivity of water ($\lambda_{water} = 0.56$ W/mK at 0°C) induces decrease of thermal conductivities of surrounding foundation or backfill materials. The typical thermal conductivity of normal soil ranges from 0.15 to 1.5 W/mK and those of dry sand and clay are approximately 1.1 and 0.9 W/mK, respectively (Andersland and Ladanyi 1994). Therefore, high thermal conductivity backfill materials should be developed and used.

In this study, the λ of pure Kaolin clay (K-100 specimen) was measured approximately 0.96 W/mK (Figure 6) and is relatively low level of λ for typical soils. The previous studies showed that the λ can be increased when clayey sand frictional soils ratio decreased or admixture is used. Remund and Lund (1993) claimed that λ of clayey soils can be increased by adding sands or artificial Silica sand.

Figure 6 shows the change of λ with increasing consolidation stress. Thermal conductivity of remolded K-0 (pure silica silts) specimen without any confining stress (no consolidation) was measured 1.96 W/mK and was increased to 2.05 W/mK after the final consolidation under consolidation stress of 626 kPa. When kaolin clay is added to silica silts,

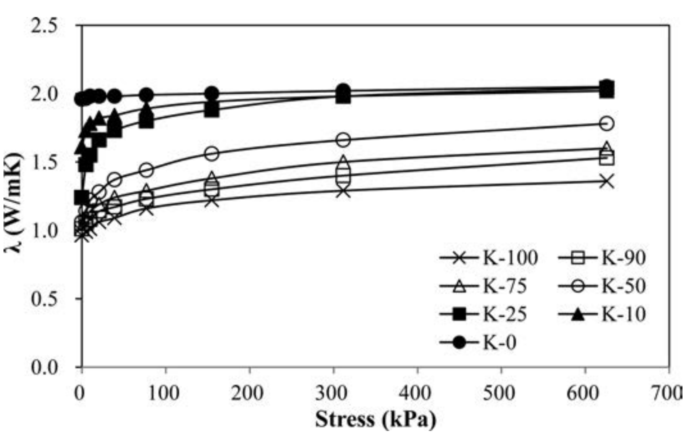

Fig. 6. Thermal conductivity with increasing consolidation stress of various samples.

λ of kaolin–silica mixtures decreased with increasing portion of kaolin clays. The λ values of the specimens contained kaolin clays before consolidation ranged from 1.01 to 1.61 W/mK and increased to a range of 1.26 W/mK through 2.13 W/mK after the completion of final consolidation (under consolidation stress σ'_c of 626 kPa).

When external stress is applied on the specimens, during or after the consolidation (partial or full dissipation of water within the specimens), the soil particles are compressed and their contact areas and pressures are increased. The increased contact areas and stresses among soil particles results in an increase of thermal conductivity. However, the increase of λ with increasing consolidation stress occurs within consolidation stress of approximately 300 kPa and λ somewhat converges even with increasing consolidation stress thereafter.

Figure 7 presents changes of thermal conductivities of saturated kaolin–silica mixtures with respect to the changes of density. Thermal conductivities and densities of the specimens were measured near the end of consolidations of each loading step (nine loading steps: $\sigma'_c = 0$, 5, 10, 21, 39, 77, 155, 312, and 626 kPa). The experiment results reveal that λ increases with or increasing density. The results overall matched with those of the previous studies (De Vries 1952; Woodside and Messmer 1961; Johansen 1975). Because of the different soils used in the experiments by Johansen (1975) from those used in the present study, one-to-one comparison in their relationship of thermal conductivity and density is not possible. However, the results from the paper by Johansen (1975) is added in Figure 7 as a reference.

It is interesting to find distinct separation of relationship between thermal conductivity and density for "K-0, K-10, and K-25" and "K-50, K-75, K-90, and K-100" specimens. The hydraulic conductivities λ of the kaolin clay and silica silt mixtures containing kaolin clay portion less than 25% are similar to λ of pure silica silt (K-0); therefore, kaolin clay does not have a great impact on the λ for these specimens.

When the kaolin clay become dominant (kaolin clay portion higher than or equal to 50%), the relationships between thermal conductivity and density of the specimens are also

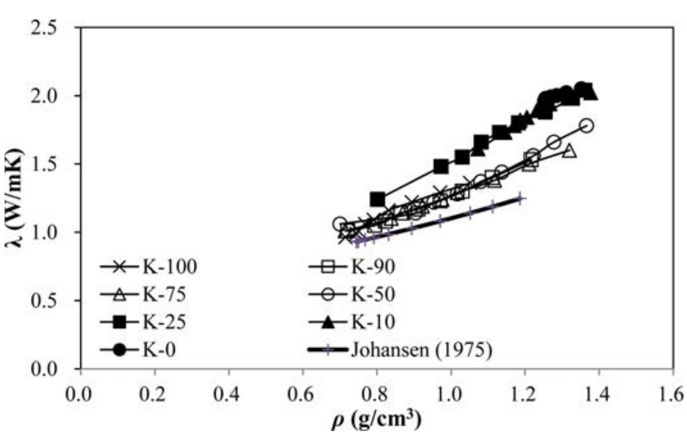

Fig. 7. Relationship between thermal conductivity and density of various samples under different densities.

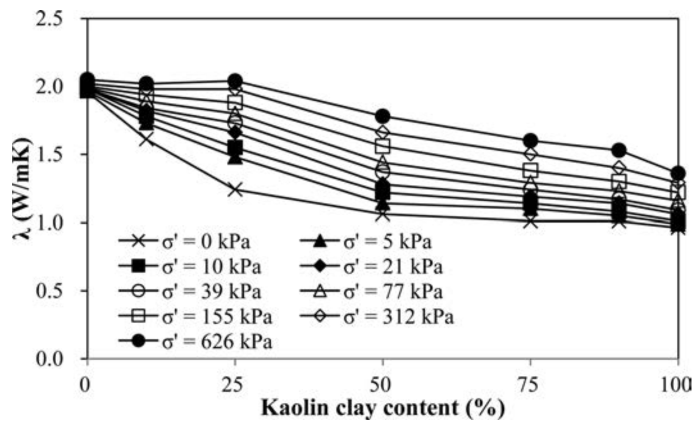

Fig. 8. Thermal conductivity with increasing kaolin clay content of various samples under different consolidation stresses.

similar. It is inferred that the increasing kaolin clay portion among the silica silt particles separate the existing silica silt particle contacts and change the overall thermal properties of kaolin–silica mixtures.

Figure 8 demonstrates the relationship between λ and kaolin clay content under different consolidation stresses. For a given consolidation stress, λ of pure silica silts is higher than that of pure kaolin clays. As a result, under the same consolidation stress, λ tends to decrease with increasing kaolin clay content. The ratio of λ at consolidation stress of 5 kPa to λ at consolidation stress of 626 kPa of kaolin–silica mixtures ranged from 105 to 142% depending on kaolin clay contents (Table 4). The highest λ ratio (168%) was found for the sample (K-50) having equal weights of kaolin clays and silica silts and the pure silica silts (K-0) exhibits the lowest λ ratio.

The λ of kaolin–silica mixtures increased with increasing silica silts content. The kaolin clays (K-100) and silica silts (K-0) have thermal conductivities of 0.96 and 1.61 W/mK (168% of λ of pure kaolin clay), respectively, before the consolidation process ($\sigma'_c = 0$ kPa). Depending on the kaolin–silica mixing ratio, the initial thermal conductivities (λ_{BL} values before consolidation) of the mixtures increased by 146–149% when the consolidation is completed under consolidation pressure of 626 kPa.

As mentioned earlier, Andersland and Ladanyi (1994) found that the thermal conductivity of general soils ranges from 0.15 to 1.5 W/mK. From the comparison of the maximum λ (1.5 W/mK) proposed by Andersland and Ladanyi (1994) and the thermal conductivities from the present study, the thermal conductivities are greater than 1.5 W/mK if silica silts portion is higher and consolidation pressure is greater (the cells satisfying $\lambda \geq 1.5$ W/mK are marked in gray color in Table 4).

Comparison of Thermal Conductivity and Hydraulic Conductivity

Relationships between thermal and hydraulic conductivities (λ and k) of saturated kaolin–silica mixtures were examined during the consolidation process (Figure 9). When silica silts

Table 4. Thermal conductivities of various samples (thermal conductivity unit: W/mK)

Sample#/Consolidation stress σ' (kPa)	K-100	K-90	K-75	K-50	K-25	K-10	K-0	λK-100/λK-10 (%)
Before loading	0.96	1.01	1.01	1.06	1.24	1.61	1.96	168
5	0.99	1.05	1.10	1.14	1.48	1.73	1.96	175
10	1.01	1.08	1.14	1.22	1.55	1.78	1.98	176
21	1.06	1.14	1.19	1.28	1.66	1.82	1.98	172
39	1.09	1.17	1.24	1.37	1.73	1.84	1.98	169
77	1.16	1.23	1.29	1.44	1.8	1.89	1.99	163
155	1.22	1.3	1.38	1.56	1.88	1.94	2.00	159
312	1.29	1.4	1.50	1.66	1.98	1.98	2.02	153
626	1.36	1.53	1.60	1.78	2.04	2.02	2.05	149
$\lambda_{BL}/\lambda 626$ kPa (%)	142	151	158	168	165	125	105	–

*Notations of λ_{BL}, λ_{626} kPa, $\lambda_{K\text{-}100}$, and $\lambda_{K\text{-}10}$ are the thermal conductivities before loading, under consolidation stress of 626 kPa, of K-100 and K-10 specimens.

are dominant over kaolin clays in kaolin–silica mixtures, such as K-10 specimen, thermal conductivity λ does not change significantly while hydraulic conductivity k decreases considerably with increasing consolidation stress. With increasing consolidation stress, increase of thermal conductivity is more pronounced while decrease of hydraulic conductivity becomes less noticeable. Heat flow within a foundation (or soil continuum) consists of particulate materials mainly results from conduction though the contacts between soil particles; therefore, thermal conductivity of the soil is dependent on number of contact and contact interface characteristics between particles (Yagi and Kunii 1957; Yun and Santamarina 2008). With increasing soil density, the thermal conductivity increases while the hydraulic conductivity decreases.

As shown in Figure 9, the specimens satisfying hydraulic conductivity k equal to or less than 10^{-5} cm/s (maximum criterion for liner material) and thermal conductivity λ equal to or greater than 1.5 W/mK were the K-50 and K-75 specimens when the consolidation stresses exceed certain levels. These K-50 and K-75 specimens under certain levels of consolidation stresses can be used as backfill materials for buried power cables due to their low hydraulic conductivities restricting movement of water (or moisture) and high thermal conductivity allowing prompt heat emission to prevent the power cable from overheating.

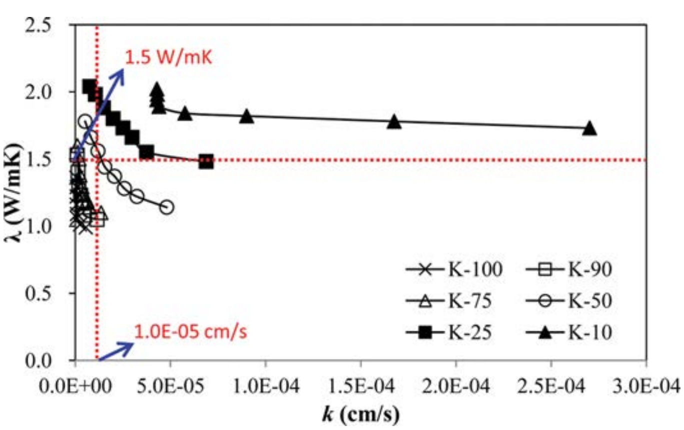

Fig. 9. Thermal and hydraulic conductivities of various samples.

Kaolin clays dominantly found in locations of the Laptev sea and the Eastern Arctic ocean (Naidu et al. 1975; Clark et al. 1980; Dalrymple and Maass 1987; Darby et al. 1989; Berner 1991; Stein, Grobe, and Wahsner 1994; Nürnberg et al. 1995) or Mesozoic and Cenozoic Strata along the north coast of Alaska and Canada (Darby 1975; Naidu and Mowatt 1983; Dalrymple and Maass 1987) are the potential regions to use kaolin-based backfill materials because of the low expected transportation cost.

Conclusions

Thermal and hydraulic conductivities of kaolin–silica mixtures were examined based on the results from XRD tests, consolidation test, and thermal conductivity tests. From the determined thermal and hydraulic conductivities, the following results were concluded.

1. Hydraulic conductivities of kaolin–silica mixtures with small portions of kaolin clays were not significantly different from that of pure silica silts because the structure formed by the silt particles is still maintained after kaolin clays fill the voids between silt particles. The hydraulic conductivity significantly decreases when the kaolin clay portion by weight exceeds 25% of the specimen weight.
2. The hydraulic conductivities of kaolin–silica mixtures and pure kaolin ranged from 2.7×10^{-6} to 7.5×10^{-9} cm/s, where the range falls within the recommended hydraulic conductivity range (10^{-4}–10^{-5} cm/s) of the CLSMs. For the use of kaolin–silica mixture to form barrier walls (or cutoff walls) regardless of consolidation stress level, the kaolin–silica mixtures with kaolin clays portion higher than 75% can be used, as the minimum recommended hydraulic conductivity is 10^{-5} cm/s. However, if the consolidation of kaolin–silica mixtures of K-25 or K-50 is completed under a certain level of consolidation stress, their hydraulic conductivities could satisfy the minimum criterion of materials used for barrier wall construction.

3. The thermal conductivity (0.96 W/mK) of pure kaolin clays before its consolidation can be increased by adding silica silts or by increasing the consolidation stress. The thermal conductivities of kaolin–silica mixtures increased up to 1.01–1.61 W/mK under the lowest consolidation stress of 5 kPa and 1.53–2.13 W/mK under the highest consolidation stress of 626 kPa depending on silica silt contents (silica silt portion from 10 to 90%). The thermal conductivity of kaolin–silica mixture was highly influenced by the consolidation stress and kaolin clay (or silica silt) portion. Thermal conductivity of kaolin–silica mixtures can be increased by increasing silica silts portion or by increasing consolidation stress for their use as backfill materials requiring good heat emission.
4. From the comparison of the hydraulic and thermal conductivities of test specimens, heat flow (or conduction) of foundations consisting of particulate material occurs mainly through contact area among soil particles. Particularly, the thermal conductivity is determined by the contact number and area of soil particles while the hydraulic conductivity is dependent on voids among soil particles. Stable backfill materials for buried power cables, hot water pipes, and gas pipelines should have low hydraulic conductivity and at the same time high thermal conductivity. As kaolin clays are dominantly found in North Arctic area, the use of kaolin clays mixed with other silts or sands as backfill materials, and the transportation cost of backfill materials could be saved.

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References

Abuel-Naga, H. M., D. T. Bergado, and A. Bouazza. 2008. Thermal conductivity evolution of saturated clay under consolidation process. *International Journal of Geomechanics* 8(2): 114–22. doi: 10.1061/(asce)1532-3641(2008)8:2(114)

ACI. 1994. Controlled low strength materials, ACI Committee 229. ACI 229 R-94.

Alawaji, H. 1999. Swell and compressibility characteristics of sand–bentonite mixtures inundated with liquids. *Applied Clay Science* 15(3–4): 411–30. doi:10.1016/s0169-1317(99)00033-2

Andersland, O. B. and B. Ladanyi. 1994. *Physical and thermal properties, an introduction to frozen ground engineering*, 1–62. New York, NY: Chapman and Hall.

ASTM. 2008. ASTM Standard D 5334–08: Standard test method for determination of thermal conductivity of soil and soft rock by thermal needle probe procedure.

ASTM. 2011. ASTM Standard D 2435/D2435 M-11: Standard test method for one-dimensional consolidation properties of soils using incremental loading.

Becker, B. R., A. Misra, and B. A. Fricke. 1992. Development of correlations for soil thermal conductivity. *International Communications in Heat Mass Transfer* 19(1): 59–68. doi: 10.1016/0735-1933(92)90064-o

Berner, H. 1991. Mechanismen der Sedimentbildung in der Fram-strasse, im Arktischen Ozean und in der Norwegischen See. Berichte Fachbereich Geowissenschaften Universität Bremen. 20.

Brandl, H. 2006. Energy foundations and other thermo-active ground structures. *Géotechnique* 56(2): 81–122. doi: 10.1680/geot.2006.56.2.81

Burges, K., J. Bömer, C. Nabe, G. Papaefthymiou, H. Brakelmann, M. Maher, C. Mills, and J. Hunt. 2008. Study on the comparative merits of overhead electricity transmission lines versus underground cable. Department of Communications, Energy and Natural Resources, Ireland.

Carraro, J. A., M. Prezzi, and R. Salgado. 2009. Shear strength and stiffness of sands containing plastic or nonplastic fines. *Journal of Geotechnical and Geoenvironmental Engineering* 135: 1167–78. doi: 10.1061/(asce)1090-0241(2009)135: 9(1167)

Carslaw, H. S. and J. C. Jaeger. 1959. *Conduction of Heat in Solids.* 2nd ed. Oxford: Clarendon Press.

Cho, W. J., J. O. Lee, and C. H. Kang. 2000. Hydraulic conductivity of bentonite sand mixture for a potential backfill material for a high level radioactive waste repository. *Journal of the Korea Nuclear Society* 32(5): 495–503.

Clark, D. L., R. R. Whitman, K. A. Morgan, and S. D. Mackay. 1980. Stratigraphy and glacio-marine sediments of the Amerasian Basin, Central Arctic Ocean. *Geological Society of America Special Papers* 181: 1–65. doi: 10.1130/spe181

Dall'Amico, M., S. Endrizzi, S. Gruber, and R. Rigon. 2011. A robust and energy-conserving model of freezing variably-saturated soil. *Cryosphere* 5: 469–84.

Dalrymple, R. W. and O. C. Maass. 1987. Clay mineralogy of late cenozoic sediments in the CESAR cores, Alpha Ridge, Central Arctic Ocean. *Canadian Journal of Earth Sciences* 24: 1562–69. doi: 10.1139/e87-152

Darby, D. A. 1975. Kaolinite and other clay minerals in Arctic Ocean sediments. *Journal of Sedimentary Research* 45: 272–79. doi: 10.1306/212f6d34-2b24-11d7-8648000102c1865d

Darby, D. A., A. S. Naidu, T. C. Mowatt, and G. Jones. 1989. Sediment composition and sedimentary processes in the Arctic Ocean. In: *The Arctic Seas–Climatology, Oceanography, Geology, and Biology*. Herman, Y. (ed.), 657–720. van Nostrand Reinhold, New York.

de Vries, D. A. 1952. The thermal conductivity of soils, Mededelingen van de Landbouwhogeschool te Wageningen, Nederland. 52(1): 1–73, translated by Building Research Station (Library Communication No. 759), England.

de Vries D. A. and A. J. Peck. 1958. On the cylindrical probe method of measuring thermal conductivity with special reference to soils. I. extension of theory and discussion of probe characteristics. *Australian Journal of Physics* 11: 255–71. doi: 10.1071/ph580255

Farouki, O. T. 1981. *Thermal Properties of Soils*. CRREL Monograph 81-1. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Folliard, K. J., L. Du, D. Trejo, and C. Halmen. 2008. Development of a recommended practice for use of controlled low-strength material in highway construction. NCHRP Report 597, Transportation Research Board, Washington, D.C.

Fukagawa, H., T. Imajo, and N. Ogata. 1974. Thermal diffusion and its application to cable ampacity, CRIEPI-73087.

Garcia-Bengochea, I., C. Lovell, and A. Altschaeffl. 1979. Pore distribution and permeability of silty clays. *Journal of the Geotechnical Engineering Division* 105(7): 839–56.

Gera, F., T. Hueckel, and A. Peano. 1996. Critical issues in modelling of the long-term hydro-thermomechanical performance of natural clay barriers. *Engineering Geology* 41: 17–33. doi: 10.1016/0013-7952(95)00047-x

Hart, D. and R. Couvillion. 1986. *Earth Coupled Heat Transfer*. National Water Well Association, Dublin, OH.

Hong, L. 2008. Optimization and management of materials in earthwork construction. PhD Thesis, Iowa State University.

Ingersoll, L., O. Zobel, and A. Ingersoll. 1954. *Heat Conduction with Engineering, Geological, and other Applications*. New York: McGraw-Hill.

Issa, S. 1996. Performance of unsaturated clay based barrier under opposing thermal and hydraulic gradients, PhD Thesis, McGill University.

Johansen, O. 1975. Thermal conductivity of soils. PhD. diss., U.S. Army Cold Regions Research and Engineering Laboratory (CRREL Draft Translation 637, Hanover, N.H., 1977). 248–53.

Johnson, E. R. and L. A. Hegdal. 2008. Permafrost-related performance of the Trans Alaska oil pipeline. *Proceedings of the Ninth International Conference on Permafrost*, Fairbanks, June 29–July 3, ed. D.L. Kane and K.M. Hinkel, 857–64. Fairbanks, AK: Institute of Northern Engineering.

Kersten, M. S. 1949. Laboratory research for the determination of the thermal properties of soils. ACFEL technical report 23. AD712516, 153–82. University of Minnesota, Minneapolis, MN.

Kim, D. and D. Lee. 2002. Thermal resistivity of backfill materials for underground power cables. *Journal of the Korean Geotechnical Society* 18(5): 209–20.

Kuerbis, R. and Y. P. Vaid. 1988. Sand sample preparation: the slurry deposition method. *Soils and Foundations* 28(4): 107–18. doi: 10.3208/sandf1972.28.4_107

Laloui, L., M. Nuth, and L. Vulliet. 2006. Experimental and numerical investigations of the behaviour of a heat exchanger pile. *International Journal for Numerical and Analytical Methods in Geomechanics* 30: 763–81. doi: 10.1002/nag.499

Ministry of Environment. 2004. Development of technology to transform Ca-bentonite and multi-functional media used at landfill liner and its structure.

Misra, A., S. Sivalingan, and M. C. Sharma. 1999. "Properties of known kaolinite–montmorillonite mixtures". In: *Environmental Geotechnology*. Fang, H. Y. and Inyang, H. I. (eds.), 219–28. New York: John Wiley & Sons Inc.

Mitchell, J. K. and C. K. Chan. 1982. Backfill materials for underground power cables, Phase 1–3, EPRI EL-506, EL-1894, El-4150, Electric Power Research Institute, Palo Alto, CA.

Naidu, A. S. and T. C. Mowatt. 1983. Sources and dispersal patterns of clay minerals in surface sediments from the continental-shelf areas off Alaska. *Geological Society of America Bulletin* 94: 841–54. doi: 10.1130/0016-7606(1983)94<841: sadpoc >2.0.co;2

Naidu, A. S., T. C. Mowatt, D. B. Hawkins, and D. W. Hood. 1975. Clay minerals and geochemistry of some Arctic Ocean sediments: Significance of paleoclimate interpretation. In: *Climate of the Arctic*. Weller, G. and Bowling, S. A. (eds.), 59–67. Fairbanks: Geophys. Inst., University of Alaska.

Nicolsky, D. J., V. E. Romanovsky, and G. G. Panteleev. 2009. Estimation of soil thermal properties using in-situ temperature measurements in the active layer and permafrost. *Cold Regions Science and Technology* 55: 120–29. doi: 10.1016/j.coldregions.2008.03.003

Nürnberg, D., M. A. Levitan, J. A. Pavlidis, and E. S. Shelekhova. 1995. Distribution of clay minerals in surface sediments from the Eastern Barents and Southwestern Kara seas. *Geologische Rundschau* 84: 665–682. doi: 10.1007/s005310050032

Remund, C. P. and J. T. Lund. 1993. Thermal enhancement bentonite grouts for vertical G SHP system. *ASME, Heat Pump and Refrigeration System-Design, Analysis, and Applications* 29: 95–106.

Salgado, R., P. Bandini, and A. Karim. 2000. Shear strength and stiffness of silty sand. *Journal of Geotechnical and Geoenvironmental Engineering.* 126(5): 451–62. doi: 10.1061/(asce)1090-0241(2000)126: 5(451)

Sivapullaiah, P., A. Sridharan, and V. K. Stalin. 2000. Hydraulic conductivity of bentonite-sand mixtures. *Canadian geotechnical journal* 37(2): 406–13. doi: 10.1139/t99-120

Stein, R., H. Grobe, and M. Wahsner. 1994. Organic carbon, carbonate, and clay mineral distributions in eastern central Arctic Ocean surface sediments. *Marine Geology* 119: 269–85. doi: 10.1016/0025-3227(94)90185-6

Terzaghi, K. 1943. *Theoretical Soil Mechanics*. John Wiley & Sons, New York, 286–89.

Thalmann, R. E. 1950. Thermal conductivity of dry soils. M.S. Thesis diss., University of Kansas.

Thevanayagam, S. 1998. Effect of fines and confining stress on undrained shear strength of silty sands. *Journal of Geotechnical and Geoenvironmental Engineering* 124(6): 479–91. doi: 10.1061/(asce)1090-0241(1998)124: 6(479)

Thevanayagam, S., T. Shenthan, S. Mohan, and J. Liang. 2002. Undrained fragility of clean sands, silty sands, and sandy silts. *Journal of Geotechnical and Geoenvironmental Engineering* 128(10): 849–59. doi: 10.1061/(asce)1090-0241(2002)128: 10(849)

Tien, Y. M., P. L. Wu, W. S. Chuang, and L. H. Wu. 2004. Micromechanical model for compaction characteristics of bentonite-sand mixtures. *Applied Clay Science* 26: 489–98. doi: 10.1016/j.clay.2003.12.020

Vaid, Y. 1994. Liquefaction of silty soils, ground failures under seismic conditions. *ASCE Geotechnical Special Publication* 44: 1–16.

Woodside, W. and J. M. Messmer. 1961. Thermal conductivity of porous media. *Journal of Applied Physics* 32(9): 1688–706.

Yagi, S. and D. Kunii. 1957. Studies on effective thermal conductivities in packed beds. *AIChE Journal* 3(3): 373–81. doi: 10.1002/aic.690030317

Yun, T. S. and J. C. Santamarina. 2008. Fundamental study of thermal conduction in dry soils. *Granular matter* 10(3): 197–207. doi: 10.1007/s10035-007-0051-5