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IMPACT OF EFFECTIVE STRESS AND TEMPERATURE ON THE HYDRAULIC PERMEABILITY OF SOILS

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ABSTRACT

Aim of the study

Heavily compacted soils are often used as engineering barriers for the disposal of high-level industrial waste subjected to thermo-hydro-mechanical actions, such as heat dissipation. This study examines the impact of stress and temperature on the hydraulic permeability (*k*) of three different soil types: two types of glacial till soils from northern Germany and a loess soil from Azerbaijan.

Material and methods

A heating chamber containing a constant head permeameter measuring apparatus was used in the laboratory. The effects of four isotropic cell pressures (100, 200, 250, 300 kPa) on effective stress were tested, as were the effects of four temperatures (20, 30, 40, 50°C) on permeability.

Results and conclusions

Hydraulic permeability (*k*) is proportional to temperature due to the reduced viscosity of pore water upon heating. Conversely, (*k*) decreases with increasing cell pressure (effective stress), which is caused by a reduction in soil voids under extra confinement.

Keywords: soil, hydraulic permeability (*k*), effective stress, temperature

INTRODUCTION

Heavily compacted soils are commonly used as engineering barriers for the disposal of high-level industrial waste. Initially unsaturated, these soils undergo combined thermo-hydro-mechanical effects, including heat dissipation from nuclear waste packages, water infiltration from surrounding geological barriers, and mechanical stresses due to swelling within confined environments. The impact of temperature on the engineering properties of soils must be thoroughly studied before designing and implementing related systems. Moreover, it is necessary to understand how soils behave when subjected to thermal, hydraulic, and mechanical events to ensure a reliable and effective conception of these systems. Therefore, the impact of temperature on these systems should be carefully studied in advance to optimize design, minimize the cost, and ensure the safety of the system.

The significant impact that changes in temperature have on the hydraulic characteristics of soils have been discussed extensively in the literature. Based on

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equation (1), it can be noted that the permeability is inversely related to the fluid viscosity, which in turn is inversely related to temperature. Thus, there is a direct relationship between permeability and temperature.

$$k \propto \frac{1}{\mu} \alpha \text{ temperature} \tag{1}$$

Romero et al. (2001) also examined the permeability of clay at different temperatures with constant saturation and void ratio. Their results indicated that the temperature change in permeability is not as pronounced as it would have been predicted by the temperature variation in the viscosity of water alone. This variation points to the fact that further mechanisms, including redistribution of porosity in the clay matrix, and thermo-chemical interactions that act on the clay structure, as well as on the properties of the pore fluids, add to the overall permeability behavior.

Levy et al. (1989) conducted a study on the problem of soil hydraulic conductivity (HC) through the simulation of soil columns and rainfall(s) (25 mm · h^{-1} and 45 mm · h^{-1}). Rates of infiltration and crust formation at different water temperatures (0°C, 21°C, and 45°C) were also examined. The findings showed that elevated water temperatures significantly affected the hydraulic conductivity of soils due to the reduced viscosity of warmer water.

Ren et al. (2013) investigated the permeability behavior of silty clay by determining the joint effect of the dry bulk density and water temperature on the hydraulic conductivity. They found that, as the dry bulk density was further increased to 1.6 g/cm, the hydraulic conductivity decreased exponentially, from 10^{-4} to 10^{-5} cm/s at temperatures between 10 and 25°C. Additionally, the hydraulic conductivity was approximately three times higher at a constant temperature of 25°C than at a constant temperature of 10°C for all densities (1.4, 1.5, and 1.6 g/cm^3). This indicates that permeability in silty clay was highly dependent on temperature.

The environmental conditions and the type of particle determine the permeability of soil. In soils rich in clay, the primary increases in permeability can be caused by vertical shrinkage fissures, whereas in coarser soils with angular silt or sand grains, the permeability can be increased by reducing the solid volume in the pore spaces. Additionally, temperature significantly affects the hydraulic properties of clays, which is crucial for designing barriers in underground repositories for the disposal of high-level radioactive waste (Gens et al., 1998; Kanno et al., 1999).

This study examines the influence of stress and temperature variations on the permeability characteristics of three distinct soil types. The research presented here is based on previous work performed under Project Angus II (Germany), as well as ongoing work in Europe and Iraq, where there are significant environmental and social problems with regard to urban heat / cooling solutions for residential, public and industrial buildings.

EXPERIMENTAL PROGRAM

Soils

This study uses three types of glacial till soil from northern Germany, referred to here as S1, S2 (Hailemariam and Wuttke, 2023), and S3, and a collapsible loess soil from Azerbaijan, referred to here as S4 (Hailemariam et al., 2017). The physical properties of the soils are presented in Table 1. These soils were selected, because glacial tills are very prominent in northern Germany due to historical ice cover. The fourth soil, the collapsible soil from Baku, was selected to provide a variety and a different perspective in order to study the soils' hydraulic behavior under varying temperature and stress conditions.

Equipment

The hydraulic permeabilities (conductivities) of the soils that are dependent on stress and temperature were measured using a newly developed climate box and permeameter set-up in the Geomechanics and Geotechnics laboratories at Kiel University (Fig. 1). This set-up allows the hydraulic conductivity of medium- to fine-grained soils to be measured using the high-pressure constant head method, which complies with the ASTM D. 2000 and DIN 1998 standards. It includes a permeameter cell placed inside a climate box for heating of the cell and therefore the sample, a burette system for the application and control of the cell and back pressures applied to the sample, a heat pump for heating the climate box via a circulating fluid, and a PC control and data logger units for data recording.

Table 1. Physical properties of the soils used

Physical properties	Values			
	S1	S2	S3	S4
Location	Northern / Germany	Northern / Germany	Northern / Germany	Baku / Azerbaijan
Specific gravity (g/cm^3)	2.650	2.696	2.556	2.7–2.72
Initial water content wc (%)	14.68	9.52	13.37	5–10
Liquid limit (%)	NA	NA	NA	36.3
Plastic limit (%)	NA	NA	NA	17.8
Plastic index (%)	NP[(a)]	NP[(a)]	NA	18.5
Gravel % (> 2 mm)	2.85	4.72	5	3–6
Sand % (0.063–2 mm)	50.98	57.08	48	20–21
Silt % (0.002–0.063 mm)	43.20	37.39	33	41–42
Clay % (< 0.002 mm)	2.97	0.81	14	33–34

[(a)] non-plastic

The climate box is heated by a fluid circulated by the heat pump through coiled loops of copper pipes inside the climate box (Figs. 1c, d, e). The inner lining of the climate box is insulated to improve the system's heating efficiency, and a radiator inside the climate box distributes the heat evenly to maintain a even distribution of temperature throughout the heating box (Fig. 1c). The water for applying cell pressure, back pressure and the fluid flowing inside the sample for measuring the hydraulic permeability is provided by the burette water pressure system, which is connected to and placed next to the heating box. This water pressure system has a total of three burettes (Fig. 1b): one for applying cell pressure, and one each for applying the bottom and top back pressures to the two faces of the specimen. Upon entering the chamber box, the water from the burette system is allowed to equilibrate with the temperature of the climate box by flowing through several looped pipes before entering the sample. B-values were not determined directly in this study. But saturation was ensured, firstly, by guaranteeing that sufficient amount of water flowed out of the top face of the samples after entering via the bottom side during the saturation phase. Secondly, the magnitude of the applied stresses during saturation was comparable to that in other triaxial test studies on the same soils, where the B-value was studied and sufficient values were achieved.

The actual soil temperature inside the permeameter is checked using a K-type thermocouple placed at the bottom base of the permeameter, in contact with the bottom face of the soil sample. An additional K-type thermocouple is also placed inside the cell in contact with the cell water to check the temperature of the cell water in the permeameter. A third K-type thermocouple is suspended inside the climate box to monitor the air temperature inside the box (Fig. 1c). The target temperature of the soil is achieved by heating the climate box, and therefore the permeameter cell, until the set temperature of sample is reached, as verified by the temperature recorded by the thermocouple in contact with the specimen.

Experimental procedure

The soil samples were prepared at natural or field densities and water contents at remolded conditions with a diameter of around 95 mm and a height in the range of 113 to 126 mm. After compaction to the desired density, each sample was enclosed within a standard rubber membrane. To ensure proper pressure separation during testing, filter paper and porous stone assemblies were placed on both faces of the samples, along with O-rings that secured the membranes to the

Fig. 1. Stress and temperature dependent hydraulic permeability measurement set-up: a) climate chamber or box for controlling temperature, b) burette water pressure system for the application and control of the cell and back pressures applied to the sample, c) bottom base of permeameter cell inside the climate chamber, d) soil sample inside permeameter and covered with membrane, e) soil sample inside permeameter filled with cell water (Source: own elaboration)

bottom pedestal and top cap. This setup maintained the separation of cell and back pressures during the experimental procedures.

After preparing the samples and filling the permeameter cell with water, the samples were allowed to saturate by flowing water from the bottom face (drainage) of the samples to the top, while applying a set cell pressure under isotropic or hydrostatic conditions and a back pressure from the bottom face of the samples. At the same time the drainage on the top face of the samples was opened (i.e. with no back pressure), allowing water to enter to the samples and replace the entrapped pore-air in the samples. Once a sufficient amount of water had flown out of the top drainage (cap), the desired confining cell pressure was applied, along with the set back pressures on both faces of the specimens for several days. This process involved pressurization and dissolution of the gaseous phase inside the samples, and ensured that a maximum B-value could be attained. The samples were heated to the desired temperature by heating the climate box, and by allowing the temperatures recorded by the thermocouples to stabilize and reach steady-state conditions before proceeding with the hydraulic conductivity tests.

To perform the hydraulic conductivity tests, the target cell pressure was applied, and flow of water from the bottom face of the sample to the top side was induced by using a higher bottom back pressure, compared to the top back pressure. For all samples, a constant head of around 0.7 m of water pressure was used to measure the stress and temperature dependent hydraulic conductivities. To study the stress dependency of the hydraulic permeabilities of till soils, cell pressures of 100, 200, 250 and 300 kPa were used under isotropic or hydrostatic conditions. The temperature dependency of the hydraulic permeabilities of till soils was measured at temperatures T of 20, 30, 40 and 50°C. The hydraulic conductivity of each sample was calculated at least five times for each applied stress and temperature state, and the data were plotted for comparison. Error data were also plotted alongside the computed the standard deviation.

In order to examine the temperature dependency of the hydraulic permeabilities of till soils, temperatures *T* was measured at 20, 30, 40 and 50°C. For each applied stress and temperature state, the hydraulic conductivity of each sample was reported at least five times, and this data was used to plot the measurement data including the calculation of standard deviation for error plots. The hydraulic permeability of the samples corresponding to a particular stress and temperature state, was finally calculated based on the time taken to achieve the desired volume of water flow through the sample. A detailed explanation of the various experimental methods used to determine the hydraulic conductivity of soils can be found in (Diminescu et al., 2019).

RESULTS AND DISCUSSIONS

Soil temperature and stress, such as net normal stress and suction, affect the hydraulic permeability of soils depending on the extent to which water is carried through their pores. Hydraulic permeability, or the speed at which water flows through connected pores in the soil, is an important parameter in soil mechanics and environmental engineering (Das, 2008). To have a better understanding of these effects, this study involved the measurement of permeability at various temperatures and pressure conditions.

Effect of temperature on hydraulic permeability

As shown in Figures 2 and 3, The permeability properties of the soils that were evaluated at different temperatures and stress conditions reflected high variability throughout the study. Generally, the results suggest that the soil permeability increases together with an increase in soil temperature. This can be attributed to the reduction in water viscosity and the increase in pore size as the temperature rises. The viscosity of liquids diminishes with increasing temperature, as the kinetic energy of molecular movement escalates alongside a reduction in surface tension. This facilitates the infiltration of water into the soil particles more effectively, in turn enhancing hydraulic permeability. These findings corroborate the previous investigations conducted by (Romero et al., 2001 and Zhang et al., 2013).

The hydraulic permeability (*k*) of soil S3, and to a lower extent of soil S4, at the range of the adopted temperatures were lower than those of soils S1 and S2, possibly due to their comparatively higher clay fraction. Interestingly, when high confining stresses were applied, the permeabilities of all soils decreased or remained more or less constant when heated, mainly due to the continued compaction of the soils caused by compaction at the high stress level. Gao and Shao (2015) stated that the hydraulic permeability in in general a decreasing function of water content, though over some compaction ranges, permeability may increase as a function of matric potential. Soils S1 and S2 generally exhibited a more pronounced increase in permeability with an increase in temperature, mainly due to their comparatively lower clay content.

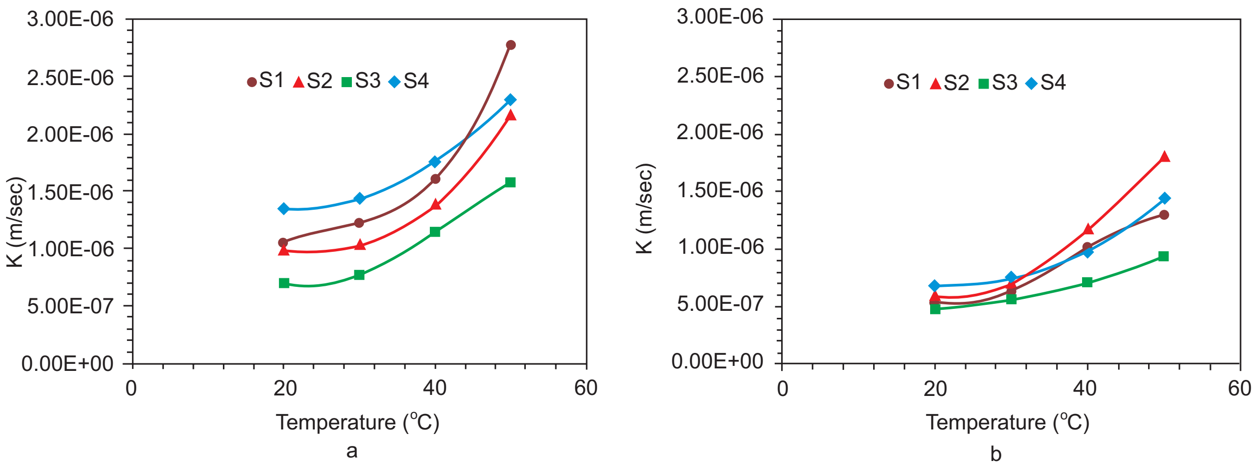

Fig. 2. Effect of temperature T on the hydraulic permeability (k) at: a) stress 100 kPa and b) stress 200 kPa (Source: own elaboration)

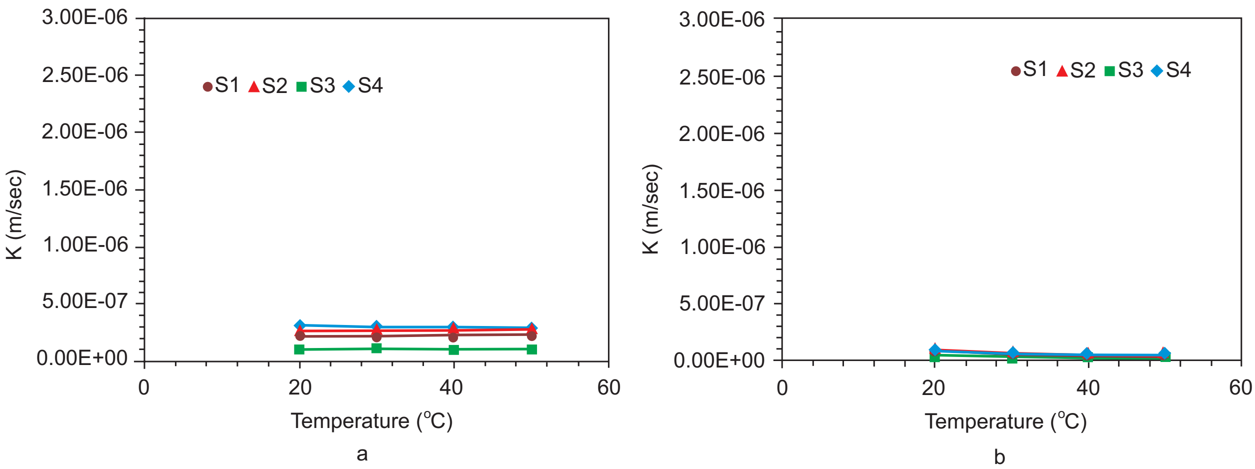

Fig. 3. Effect of temperature T on the hydraulic permeability (k) at: a) stress 250 kPa and b) stress 300 kPa (Source: own elaboration)

Structural changes in collapsible soils only occur at unsaturated and dry states, when the soils are suddenly inundated with water. However, since the soils were fully saturated first prior to the permeability tests in our study, the collapse effects were not applicable or studied.

Effect of confining stress on hydraulic permeability

Applying stress to soil has a significant influence on its hydraulic permeability. The implications of confining stress (cell pressure) on the permeability of the soils examined in this study, together with the aforementioned temperature effects, are illustrated in Figures 4 and 5. In summary, it is evident that an increase in applied confining pressure corresponds to a decrease in soil permeability. The decrease in soil permeability due to compaction observed could largely be linked to the decrease in cross-sectional area and tightening of pore voids with increased confinement (Fredlund and Rahardjo, 2012). The transfer of water is regulated by the pore network, and with escalating pressure and/or compaction, these pores progressively diminish in size, resulting in a reduced hydraulic permeability (Ye et al., 2009; Zhongle Cheng et al., 2026; Hongbei Gao et al., 2015).

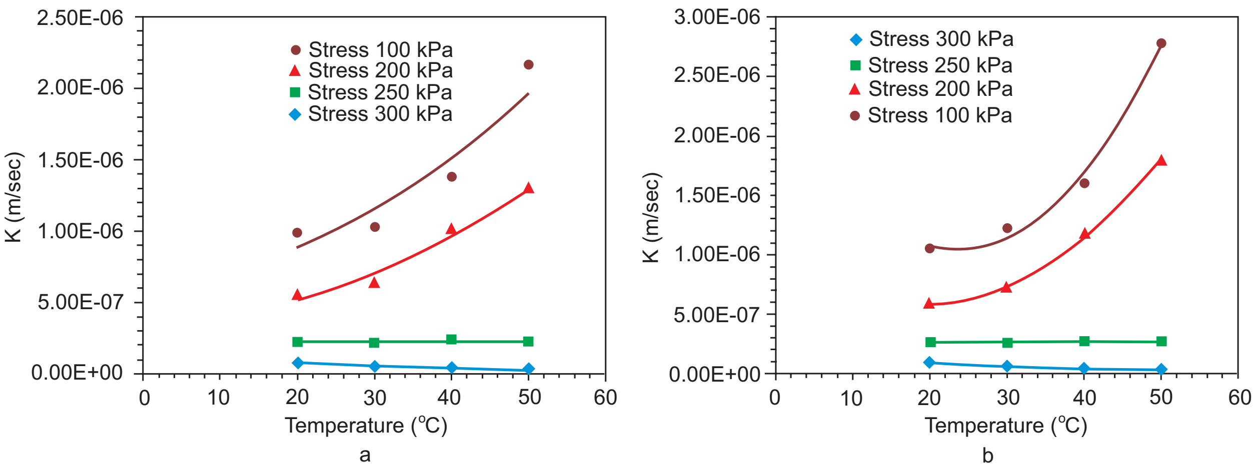

Fig. 4. Effect of stress on the hydraulic permeability (k) of: a) soil S1 and b) soil S2 (Source: own elaboration)

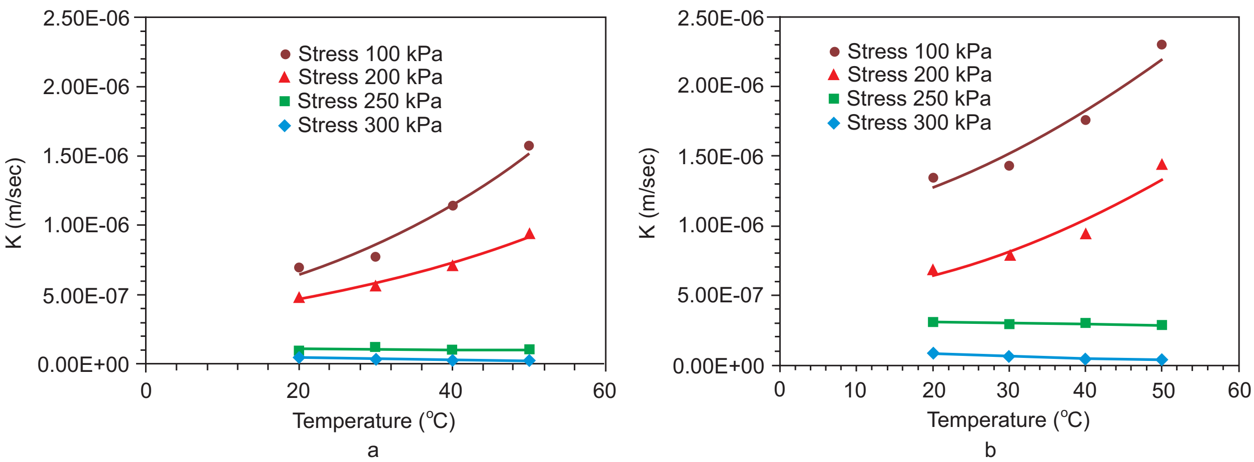

Fig. 5. Effect of stress on the hydraulic permeability (k) of: a) soil S3 and b) soil S4 (Source: own elaboration)

CONCLUSIONS

The experimental results of the hydraulic permeability (k) of the studied soils indicate that the hydraulic conduction decreased with confining stress, but increased with higher medium temperature, in corroboration with previous literature. The increase in permeability of the soils when heated is due to the inverse relationship between permeability and water viscosity. When heated, the increase in liquid energy which leads to a reduction in surface tension, allowing water to penetrate soil particles more easily. With regards to the effects of confinement on permeability, compaction reduces the soil pore-void volume, thus restricting the movement of water and hence hydraulic conductivity. Moreover, the rate at which hydraulic permeability of soils increase with heating was the highest when the confining cell pressure was the lowest, and vice versa.

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WPŁYW NAPRĘŻENIA EFEKTYWNEGO ORAZ TEMPERATURY NA PRZEPUSZCZALNOŚĆ HYDRAULICZNĄ GLEB

ABSTRAKT

Cel badania
Gleby silnie zagęszczone są często wykorzystywane jako bariery inżynieryjne do składowania odpadów przemysłowych o wysokim poziomie zanieczyszczenia, poddawanych działaniu czynników termicznych, hydraulicznych i mechanicznych, takich jak rozpraszanie ciepła. Niniejsze badanie analizuje wpływ obciążeń i temperatury na przepuszczalność hydrauliczną (k) trzech różnych rodzajów gleb: dwóch rodzajów gleb morenowych z północnych Niemiec oraz gleby lessowej z Azerbejdżanu.

Materiały i metody

W laboratorium zastosowano komorę grzewczą wyposażoną w urządzenie pomiarowe typu przepuszczalnościomierz stałego ciśnienia. Zbadano wpływ czterech izotropowych ciśnień komórkowych (100, 200, 250, 300 kPa) na naprężenie efektywne, a także oddziaływanie czterech temperatur (20, 30, 40, 50°C) na przepuszczalność.

Wyniki i wnioski

Przepuszczalność hydrauliczna (*k*) jest proporcjonalna do temperatury ze względu na zmniejszoną lepkość wody porowej po podgrzaniu. Natomiast *k* maleje wraz ze wzrostem ciśnienia komórki (naprężenia efektywnego) spowodowanego zmniejszeniem pustych przestrzeni w glebie pod wpływem dodatkowego ściskania.

Słowa kluczowe: gleba, przepuszczalność hydrauliczna (*k*), naprężenie efektywne, temperatura