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Effect of water temperature and soil type on infiltration

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Abstract. Temperature is one of the important factors affecting the permeability of water in the soil. In the present study, the impact of water temperature on hydraulic conductivity (k) with and without coarse aggregations by considering six types of soils was analyzed. Moreover, the effect of sand and gravel presence in the soil was investigated through the infiltration based on constant and inconstant water head experiments. Results indicated that by increasing the water temperature, adding gravel to sandy soil caused the hydraulic conductivity to raise. It is supposed that the gravel decreased the contact surface between the water and the soil aggregates. It is deduced that due to decreasing kinetic energy, k tends to have lower values. Furthermore, adding the sand to sandy silt-clay soil showed that the sand did not have a marginal effect on the variation of k since the added sand cannot increase the contact surface like gravel. Finally, increasing the main diameter of the soil will increase the effect of the water temperature on hydraulic conductivity.

Keywords: coarse aggregates; hydraulic conductivity; porosity; soil properties; water temperature

1. Introduction

Hydraulic conductivity of the soil is dependent on some circumstances like the climate of the area, the condition of the exploitation, the intensity and timing of the rainfall, soil properties, the percentage of the vegetal cover, initial soil moisture content, entrapped air, and depth of the groundwater table (Raghunath 2006, Yang and Zhang 2011, Ma *et al.* 2021, Subramanian *et al.* 2020), and also the water and soil temperatures. Measuring the infiltration rate is of great importance in water management, considering both aspects of intensity and amount of infiltration in the design and implementation of all water structure methods, and it can be employed to predict the amount of runoff via area. Besides, investigating the parameters on which the infiltration rate is dependent on these parameters is an indispensable part of studies on this issue. Many researches have been performed on the infiltration process and its effect on different soil types (Song and Hong 2020, Rasool and Kuwano 2020, Rasool and Aziz 2019, Qi *et al.* 2019, Guerra *et al.* 2019, Zhu *et al.* 2018, Torabi *et al.* 2020, 2022).

Al-Hinti *et al.* (2017) conducted some experimental tests to measure the temperature distribution profile in vertical and horizontal orientations for a year near the city of Zarqa in Jordan. Their results were presented as the daily, monthly, and seasonal profiles by considering the depth parameter and elevation of the underground water. Based on field measurements, they indicated that the variation of the underground temperature profile was diminished by increasing the depth and reaching the constant values throughout the year at around 21ºC starting from a depth of 5 m below the surface; however, the cyclic nature of the daily and seasonal variations of the soil ambient and ground surface temperatures. By employing the non-linear technique, a semi-empirical model was presented to predict the temperature profile. Beier *et al.* (2018) validated the models, which were based on water and soil heat exchangers, versus the multi-flow rate of the benchmark tests. They developed a vertical borehole ground heat exchanger model. Furthermore, in order to measure the average of the field temperature through the soil ambient, a model was presented for short-circuiting by an analytically computed weighting factor. They indicated that the weighting factor portion of the model technique can be simply employed to develop other ground heat exchanger models.

Soil properties like hydraulic conductivity and infiltration, as well as the variation of the ground heat exchanger, are related to the soil temperature profiles, which are supposed to be changeable factors over time and space. Furthermore, the variation of the soil temperature profiles is defined as a dependable function of the heat transfer rate extracted from or transferred to the soil. Kayaci and Demir (2018) studied the contributing parameters in heat exchange between water and soil, experimentally.

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Based on both experimental and numerical information, they indicated that the heat exchange between the soil strata with different water contents is directly related to the temperature of the induced discharge rate. Ouzzane *et al.* (2014) indicated that the energy balance between water and soil can be considered as boundary conditions to propose a new model for simulating the heat exchange in two multiphases of water and soil. They presented a one-dimensional numerical model based on the equation for the transient heat.

In hydrology, runoff flows result from exceeding the surface flow over the infiltration rate. In order to predict the runoff by considering the hydrologic modeling perspective, predicting the values of the infiltration and hydraulic conductivity are indispensable steps of the runoff. Some parameters can directly effect on the infiltration rate and hydraulic conductivity such as soil properties, water and soil temperature, percentage of moisture, and also compaction rate. Generally, the most commonly presented equations and models employed parts of the contributed parameters to predict the hydraulic conductivity and infiltration rate, such as temperature, soil compaction, and soil main diameter size. To attain the defined purpose, Sajjadi *et al.* (2016) proposed the relationship between infiltration rate and soil texture, moisture, and compaction. The effect of soil properties and their relations to infiltration rate were calculated from experimental data, and finally, an equation was presented to calculate the cumulative infiltration depth by employing non-linear regression.

The effect of the temperature can be considered an important discussion through the soil mechanic subjects. There are a number of distinguished studies that were mainly carried out on this parameter. Janyns (1990) investigated experimentally the effect of temperature variation on hydraulic conductivity. Hydraulic conductivity and infiltration rate, as well as soil temperature, were calculated daily through the borehole. Based on the observed information, he developed a new model to calculate the infiltration rate by considering the variation in temperature. By employing the observed data as the defined boundary conditions, a newly developed numerical model was also constructed and employed to demonstrate the field model. The vertical and horizontal temperature profiles were extracted from the numerical model and were compared with the observed information.

Braga *et al.* (2007) developed a methodology to simulate varying infiltration rates. The effect of the soil content and its effects were discussed by making a comparison between the sizes of the soil particles. They mentioned that the thermal regions, like frozen conditions and warm water situations, affect the infiltration rate and hydraulic conductivity due to different particle sizes. Tokoro *et al.* (2010) proposed an approach that allowed the use of water as a penetrating fluid by keeping the bottom and top of the soil at normal temperature and the center at negative temperature eliminating the influence of the ice lens on the continuous water flow by applying axial stress to the soil sample. Furthermore, their investigations on the warm water condition indicate that increasing the temperature of the water can increase the infiltration rate significantly due to proper porosity.

Watanabe and Osada (2016) carried out some experimental tests to investigate the effect of the water temperature in warm and frozen conditions. They developed a new experimental method for measuring the hydraulic conductivity of warm and frozen soil with pure water. Their results indicate that due to the frozen soil condition, hydraulic conductivity was controlled by the temperature. It is supposed that the hydraulic conductivity is dependent on the temperature, and the intensity of this effect is changed by the percentage of the porosity.

Chen and Zhang (2020) developed a new model to estimate the values of hydraulic conductivity within frozen soil. To evaluate the accuracy of the presented model, the predicted values based on the developed numerical model and hydraulic conductivity values calculated based on constant load tests soil were compared in eight experimental tests. Their results demonstrated that the hydraulic conductivity of warm water through frozen soil is mainly determined by the unfrozen water content, which is controlled by the temperature and soil particle size distribution.

Other researchers have also verified that k increases with increasing temperature (Villar and Lloret 2004, Abuel-Naga *et al.* 2006, Delage *et al.* 2011). In fact, the influence of temperature on water movement in porous media is more significant than expected (Gao and Shao 2015). In general, changing water viscosity may be the main factor of infiltration in temperature effects (Jim and Fred 1991, Cho *et al.* 1999, Delage *et al.* 2000). To do so, in this study, the results of an experimental and numerical study to investigate the effect of different water temperatures on hydraulic conductivity through different soil types are presented and discussed.

2. Materials and methods

In this section, the employed materials and method of this study are presented. Experiments with the constant and inconstant water head methods are discussed in the hydraulic conductivity section. The properties of the used soils are presented based on the sieve standard and hydrometry experiments. Soil samples with different properties, and moistures (six soil classified samples) were prepared and settled into the experimental setup.

2.1 Hydraulic conductivity

In order to calculate the soil hydraulic conductivity, two methods were employed based on the types of soil. The constant water head was used for coarse soils, which are mainly classified into the SM and CL-ML soils (Stevens, 1982), (e.g., Tests No. 1, 2 ,3, and 4). Fig. 1(a) shows the components of the constant water head test. Also, Equation (1) is employed to calculate the hydraulic conductivity from an unsaturated to a saturated soil status. To measure the hydraulic conductivity of the fine soils, which are mainly classified into the ML and CL-ML (e.g., Tests No. 5 and No. 6) (Stevens 1982), inconstant experiments were employed, as demonstrated in Fig. 1(b). Also, Fig. 2 shows

Table 1 The employed soils properties in this study (G_s is the specific gravity of the soil particles, C_c is the coefficient of gradation, C_u is the uniformity coefficient)

Test No.	Soils	Percentages				G_s	d_{50}	d_{10}	d_{30}	d_{60}	C_c	C_u
		Gravel	Sand	Silt	Clay							
1	SM, Silty Sand	0	84	11.8	4.2	2.76	1.36	0.05	0.55	1.67	3.8	35.77
2	SM, Silty Sand with Gravel	23.3	41.5	25.8	9.4	2.8	0.27	0.02	0.6	0.76	0.25	35.6
3	CL-ML, Sandy Silty Clay	0	19	45	36	2.54	0.72	0.01	0.04	0.09	1.26	6
4	CL-ML, Silty Clay with Sand	0	42	35	23	2.7	1.67	0.01	0.03	0.06	1.5	35.77
5	ML, Sandy Silt	0	62	19.1	18.9	2.78	0.82	0.04	0.58	1.82	4.78	46.53
6	CL-ML, Sandy Silty Clay	0	42	41.3	16.7	2.54	0.72	0.01	0.04	0.09	1.26	7.14

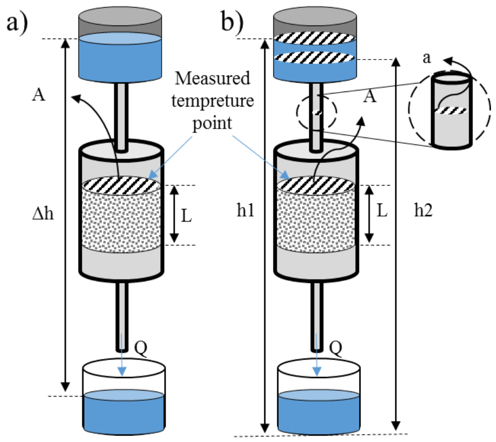

Fig. 1 Constant and inconstant water head experiments; (a) constant water head and (b) inconstant water he

Fig. 2 Experimental equipment, (a) SG calculating process, (b) constant and inconstant water head experiments and (c) hydrometry experiment

the experimental equipment for experiments. Eq. (2) is used to calculate the hydraulic conductivity for the inconstant water head test.

$$k = \frac{QL}{A\Delta h}, \tag{1}$$

$$k = 2.3\frac{aL}{tA}Log\frac{h_1}{h} \tag{2}$$

The parameters of Eqs. (1) and (2) were presented in Fig. 1. k values were measured based on experimental results by considering three temperatures to show the effect of water temperature on the infiltration rate. Moreover, some comparisons were carried out due to the change in the percentages of gravel, sand, and silt in the soil groups. It was supposed that the samples (e.g., No. 1 and No. 2) were considered to investigate the effect of the gravel aggregates (the difference between their gravel percentages), and the second group was involved with the samples (No. 3) and No. 4), which have variation in their sand percentage (see Table 1). Furthermore, to investigate the silt effects, two soil groups were considered, and these groups were involved in the soils with different silt percentages (e.g., No. 5 and No. 6).

2.2 Main soil diameter sizes

To calculate the amount of clay, sand, silt, and gravel percentage in the used soil samples, two approaches were employed experimentally. The soil passed from Sieve #200 was used to perform the hydrometry test; however, for soil above Sieve#200, the standard sieves were employed to calculate the percentage of soil diameter into their dominations. As a result, Fig. 3 was presented based on experiments conducted, which shows the dominance of diameter for soil samples. Also, based on the Unified Soil Classification System (USCS), and the soil details, the class of soils was presented and employed through the figure.

The first four soils (see Table 1) were considered to make a comparison for showing the effect of sand and gravel on the variation of temperature through the infiltration process. Regarding the hydrometry test, for the soils with a diameter smaller than 0.075 mm, a sample of

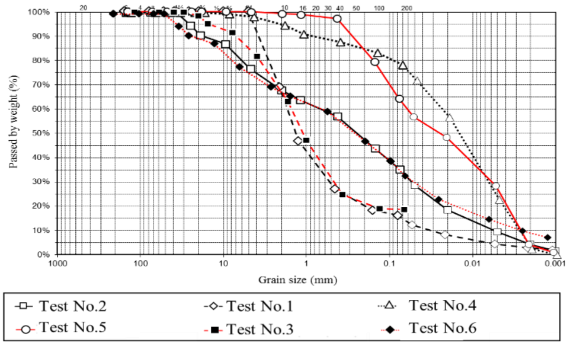

Fig. 3 Particle size distribution of the used soils

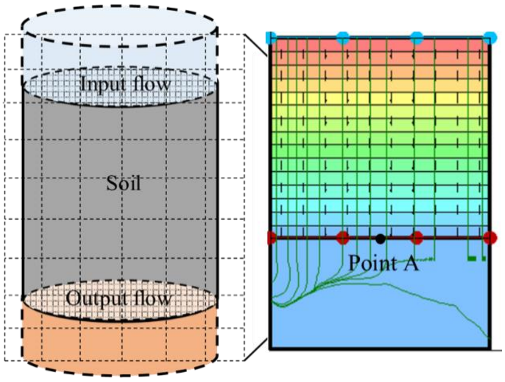

Fig. 4 Numerical simulation due to different temperatures

the soil was mixed into the vertical cylinder, and after making a fine mixture of soil and water, the density of the made liquid was calculated over time. Finally, based on the hydrometer test process, the diameter of the soil was counted step by step, and their results were presented in Fig. 3.

2.3 Numerical model

In order to investigate the hydraulic conductivity due to a wide range of temperatures and soil properties, the Seep/W and Temperature models of Geo-Studio which were validated by experimental data, were employed. *k* values were extracted through the numerical model due to the various hydraulic conditions and different soil diameter sizes, which were considered based on d_{10} and d_{60} of the experimental samples. It should be noted that the values of *k* were extracted from the numerical model in Point A (see Fig. 4).

Darcy's law and its modification (Richards 1931) are commonly solved by the two-dimensional (2D) Finite Element Method (FEM). The governing equation used in the software SEEP/W (GeoStudio Ltd., 2018) for transient 2D seepage analysis is given by

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right)+Q=m_w \gamma_w \frac{\partial H}{\partial t}, \tag{3}$$

where H is the total head; k_x and k_y are hydraulic conductivity in the x and y directions; Q is the applied boundary flux; γ_w is the unit weight of water; t is the time; and m_w is the slope of the soil-water characteristic curve.

2.4 Contributed forces in infiltration

The infiltration process is a physical occurrence that is affected by some physical forces that are involved, including gravity forces, kinetic energy, and capillary forces. The gravity forces can have a constant effect on the infiltration process due to the specific value of the water head at the soil surface; however, it is supposed that the kinetic energy effects depend on increasing and decreasing water temperature. Also, the capillary forces are directly affected by the size of the porosity. Therefore, it is assumed that, due to stabilizing the porosity, the effect of the capillarity would be equal. The kinetic energy is directly related to the water temperature, and by increasing the temperature, it is predicted that the infiltration values will reach a higher rate. By increasing the surface area of the soil that is contacted by water, the equilibrium temperature increase. In order to investigate the effect of the soil surface on the infiltration process, Eqs. (4) and (5) were employed as coefficients to calculate the effective contact surface of soil particles with water and used surface of soil particles in numerical modeling, respectively, due to its variations in the experimental and numerical models.

$$S=\frac{1}{4\pi\left(\frac{d_{10}}{2}\right)^2+4\pi\left(\frac{d_{30}}{2}\right)^2+4\pi\left(\frac{d_{50}}{2}\right)^2+4\pi\left(\frac{d_{60}}{2}\right)^2} \tag{4}$$

$$S'=\frac{1}{8\pi\left[\left(\frac{d_{10}}{2}\right)^2+\left(\frac{d_{60}}{2}\right)^2\right]} \tag{5}$$

The soil with large porosity was affected by lower capillary forces. Increasing the contact surface, reduce the temperature and caused the kinetic energy to decrease as a result the kinetic energy was removed at the lower position and water just infiltrate by gravity and capillarity forces. Furthermore, the lake of sand and gravel aggregate through the soil profile increases the contact surface and causes the kinetic energy to decrease through the porosity holes. Consequently, the kinetic energy was diminished dramatically at the lower position, and water was just infiltrated by gravity and lower capillarity forces. In order to investigate the effect of the mentioned forces, the hydraulic conductivity of the six samples of soil with different gravel, sand, and silt percentages was measured experimentally and numerically. Finally, based on the experimental information, *k* was predicted.

3. Results and discussions

In this section, the effect of the coarse aggregates (sand and gravel) on the hydraulic conductivity of soils with different water temperatures was presented.

3.1 Gravel effect on k in water temperature variation

Two soil classifications were considered to investigate the effect of gravel percentage on *k* with water temperature variations. Two soils (Tests No. 1 and No. 2) with different

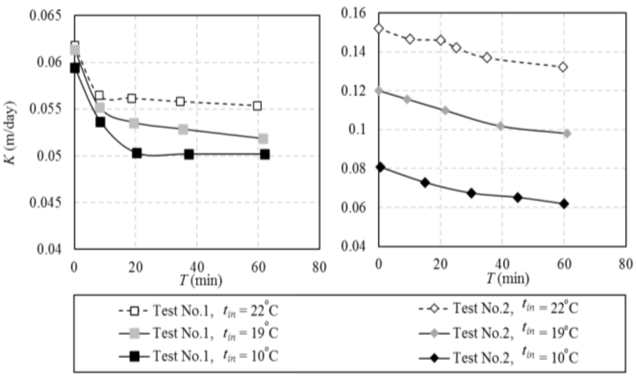

Fig. 5 Variation of *k* for soils with and without gravel with the same soil properties condition due to the different water temperature

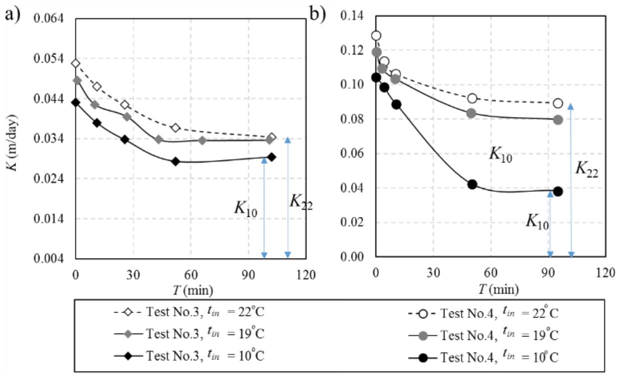

Fig. 6 Variation of *k* for soils with and without percentage of sand with same soil properties condition due to the different water temperatures

percentages of gravel (i.e., increasing the gravel percentage from zero to 23.2%, Table 1) and almost the same hydraulic condition were tested by employing the constant water head test. During the experiments, the used water in the infiltration process was heated constantly, and the water temperature was measured consequently at the entrance of the soil cylinder (see Fig. 1). Comparisons showed that by adding the gravel into the tested soil, the effect of the raising water temperature is meaningful and it is caused that *k* be increased due to increase the water temperature from 10ºC to 22ºC (see Fig. 5). In equal temperatures for Test No. 1 and No. 2, it can be deduced that due to the lower temperatures (up to 10ºc) the effect of temperature is negligible and *k* is related to the soil properties; however, due to the increase in the water temperature (e.g., T_{in}=22ºc), the effect of the gravel through the soil is significant. It is supposed that due to the increase in water temperature, the narrow tunnels and porosities through the soil have been filled by warm water, which generally has much kinetic energy. As a result, the temperature raising can increase the kinetic energy so the movement of the water molecules is increased. On the other hand, due to the tests with lower temperatures, it can be concluded that the low temperature generates lower kinetic energy, so the water flows through the porous media with a lower velocity, which causes the hydraulic conductivity to decrease.

3.2 Sand Effect on k in water temperature variations

In order to investigate the effect of the main diameter size of soil on the variation of *k*, another group of soils was considered as a sample with different percentages of sand (Tests No. 3 and No. 4), which almost have a near mechanical property with different percentages of the sand content (e.g., Test No. 3 with 19% of sand and Test No. 4 with 42% of the sand). Fig. 6 illustrates the hydraulic conductivity for both considered soils. It seems that, although the sand presence increased *k* values (compare Figs. 6(a) and 6(b)), it is assumed that the sand effect is significant once the water temperature is raised. If both curves and soil types were compared together due to the same temperature, it could be concluded that the percentage of sand in the soil aggregates can have a significant effect on *k* once the water temperature is raised at the entrance of the soil cylinder of the constant water head test.

By considering the fraction of $(K_{22}- K_{10})/K_{10}$ due to different percentages of the sand, it can be deduced that due to 19% of the sand, the variation of the temperate raises the infinite hydraulic conductivity almost 41.6%; however, due to 42% of sand, the fraction of $(K_{22}- K_{10})/K_{10}$ is almost 143.5%. As a result, contributing to the sand can increase the temperature effect on *k*. Also, this fraction can be counted for gravel tests (e.g., Tests No. 1 and No. 2), which were counted as 10% and 128.8% for zero and 23.3% for gravel, respectively.

An important result is deduced by comparing the sand and gravel presence due to the water temperature variation: by decreasing the porous media and main diameter size of soil, the effect of water temperature variation is related to the soil properties; however, increasing the main diameter size of soil causes *k* to increase where the water temperature is raised. It means, *k* in the lower water temperature depends on the soil properties; however, this factor can be affected by the water temperature raising. Based on the results, it seems that kinetic energy plays the main role in the infiltration process.

3.3 Silt effect on k in water temperature variation

In order to investigate the effect of the percentage of silt on the variation of *k*. Two soils were tested by changing the water temperature between 10ºC and 20ºC. *k* was measured by conducting the inconstant water head (see Fig. 1). Due to the increase in the water temperature, variations of *k* were measured over time. Comparison between finite hydraulic conductivity indicates that due to counting the fraction of $(K_{22}- K_{10})/K_{10}$, due to different silt content, (e.g., silt content for Tests No. 5 and No. 6 are 19.1 and 41.3, respectively), the variation of *k* is negligible compared by sand and gravel tests. As can be seen in Fig. 7, by raising the temperature, the values of *k* due to infinite status are the same, and variation of silt content is negligible.

3.4 Porosity and water temperature effects

Based on the results, two parameters were presented to

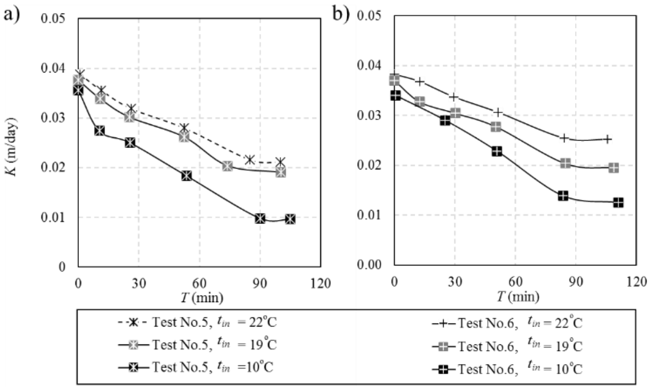

Fig. 7 Variation of *k* for soils with and without percentage of silt with same soil properties condition due to the different water temperatures

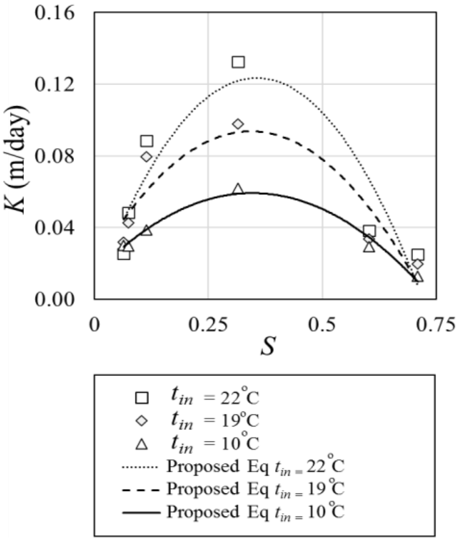

Fig. 8 Effect of the specific surface area on *k* due to different temperatures

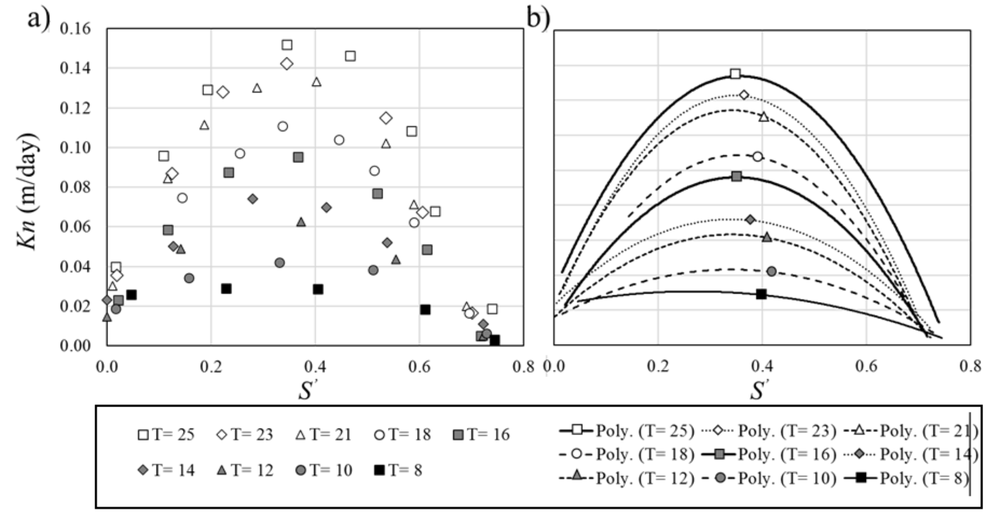

Fig. 9 Effect of variation of the specific surface area on *k* due to different temperatures based on the numerical simulations

increase *k* through the soil. It seems that accompanying these two parameters causes *k* to be raised. The gravel presence through the tested soil verified this matter that variation of *k* is directly related to the porosity and water temperature; however, tests with different percentages of the silt indicated that raising the water temperature with no appropriate porosity is not an effective parameter. Otherwise, the variation of temperature with no proper porosity is the ineffective parameter to raise *k*.

As can be seen from Fig. 8, by increasing the contact surface, *k* reaches a peak and then falls to lower values. Increasing the contact surface can be defined as finer soils, and decreasing this parameter is related to coarse soils. Due to the same experimental condition, the gravity force was equalized for experimental tests. Generally, by increasing the soil porosity (e.g., Tests No. 1 to No. 2 and Tests No. 3 to No. 4), it is predicted that the kinetic energy will be raised; however, the capillarity will be decreased because the capillarity has a reverse relation to the diameter of the porosity, which can be considered as the average value of the holes. So, it is sensible that the surface contact attains an optimum value which are around 0.34 (see Fig. 8) that due to this value both kinetic energy and capillarity reach their maximum effect to increase *k*.

The effect of the variation of a specific surface area on *k* due to different temperatures based on the numerical simulations was presented in Fig. 9. As it can be seen, due to S^*=0.37 the optimum values for *k* were obtained. It can be deduced that in soils with S = 0.34-0.37, the effect of the capillarity and kinetic energy enhances its maximum, and due to increasing the water temperature, *k* is raised.

4. Conclusions

Water infiltration in the soil is a challenging and important subject in soil studies. Much research have been done due to recent years to make clearer this process and show the effect of different parameters on it. In the present research, the effect of water temperature on the hydraulic conductivity of different soils was investigated, both experimentally and numerically. The effect of two parameters was investigated through this study as the size of the soils and water temperature on the hydraulic conductivity. Results verified this matter that variation of *k* is directly related to the porosity and water temperature; however, tests with different percentages of the silt, indicated that the raising water temperature with no appropriate porosity is not an effectible parameter. The gravity force is considered the same value for all tests. It is supposed that by increasing the water temperature, the impacts among water and soil molecules are raised, so the water molecules penetrate through the soil easier. By increasing the soil porosity (e.g., Tests No. 1 to No. 2 and Tests No. 3 to No. 4), it is predicted that the kinetic energy will be raised; however, the capillarity will be decreased because the capillarity has a reverse relative to the diameter of the porosity. So, it is sensible that the surface contact attains an optimum value, which is around 0.34, and that due to this value, both kinetic energy and capillarity reach their maximum effects to increase the hydraulic conductivity. Also, due to S^*= 0.37, the optimum values for *k* were obtained. It can be deduced that in soils with S = 0.34-0.37, the effect of the capillarity and kinetic energy enhances its maximum, and due to increasing the water temperature, *k* is raised.

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