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Variation of the Hydraulic Conductivity of Clayey Soils in Exposure to Organic Permeants

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Abstract

Clayey soils are the most common material used in waterproofing and play an essential role in waste and contamination control. Permeability is a key parameter in such problems and its determination is needed in ensuring the satisfactory performance of the soil. Research has shown that a permeant fluid with a low dielectric constant can shrink the double layer around the clay particles which will, in turn, increase the permeability of the soil. In this paper, the permeability of two types of clay with different plasticity, exposed to the flow of water and methanol as polar and miscible solvents and gasoline and car oil as non-polar and immiscible solvents is investigated. In addition, the effect of soil properties such as plasticity and compaction water content on permeability of the samples is examined. To this end, soil samples are prepared and compacted at various water contents. Then, permeability tests are conducted according to the modified constant head method and the effects of parameters such as the fluid dielectric constant, water content of the samples and soil plasticity are examined. The results demonstrate that the lower dielectric constant of the organic fluid decreases the thickness of the double layer, providing more space for the flow of the permeant and as a result, the permeability of the clay increases. The reduction of the permeant dielectric constant from 80.4 to 2.28 led to a remarkable increase in soil permeability.

Keywords: Clay; Dielectric Constant; Organic Fluid; Permeability; Water Content.

1. Introduction

In many hydrological and geotechnical problems, soil permeability is considered a key parameter. In recent years, environmental concerns have led researchers to focus their attention on the hydraulic conductivity of clays, due to their important role in waste containment. Clay liners in waste disposal sites are examples where the hydraulic conductivity of clay, plays a critical role. Thanks to the accessibility of clay and lower expenses associated with its use, compacted clay layers are chosen as liners to inhibit the infiltration of contaminants present in solid and liquid wastes into the environment [1]. Following the standards imposed by the regulatory agency in Brazil, the compacted liner's water permeability should be lower than 1×10^{-9} m/s to minimize the potential infiltration [2].

The permeability of clayey soils exposed to the flow of water can be strongly affected by factors such as the grain size distribution (or specific surface), particle arrangements, degree of saturation, porosity, chemistry and concentration of electrolytes. In the case of Non-Aqueous Phase Liquid (NAPL) flow, the relationship between permeability and the physical and chemical properties of the fluid is even more complex [3].

Changes in clay hydraulic conductivity due to its exposure to chemicals have prompted research into the permeability of clay with permeants other than water. In soil with a high clay content, the interactions between the soil surface and the fluid are significant and influence the hydraulic conductivity [4]. In the case of NAPL flow, the highly variable

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dielectric nature of the fluids, further complicates the relationship between permeability and the properties of the fluid. In clayey soils permeated with organic liquids, the properties of the permeating fluids are important factors in permeability [5].

The hydraulic conductivity of a material, represented by the symbol k, also called the coefficient of permeability, is the characteristic used to describe flow through a porous media. The concept of intrinsic permeability (K) has been defined to describe the conductive properties of a medium independent of the fluid flowing through it. It is normally used to convert water permeability values in the expected value of permeability for another fluid in the same soil. The hydraulic conductivity and the intrinsic permeability are related through the following equation [6]:

$$k = K\frac{\gamma_w}{\mu} \tag{1}$$

Where γ_w is the unit weight of water and μ is fluid dynamic viscosity. This equation produces good results in the case of coarse soils. However, when the clay content of the soil increases, the intensity of the interactions between the soil surface and the fluid also increases and this begins to play an important role in the values of k [7].

The diffuse double layer model developed by Helmholtz-Smoluchowski (1879-1914) and improved by Quincke (1861) and Gouy-Chapman (1910-1913) is the most widely accepted conceptual model used to describe the interactions between the fluid and the clay surface. The diffuse double layer consists of clay particles, negatively charged at the surface, absorbed cations plus water molecules and counterions [6-12].

The following equation can be used to predict thickness of the double layer, t, based on the Gouy-Chapman theory.

$$t = \sqrt{\frac{\varepsilon K_b T}{8\pi n_e e^2 v^2}} \tag{2}$$

Where ε is the dielectric constant, K_b is the Boltzmann constant, T is the temperature, n_e is the electrolyte concentration, e is the elementary charge and v is the ionic valence. Eq. 2 shows that a decrease in dielectric constant or an increase in the electrolyte concentration reduces the double layer thickness. The Gouy-Chapman double layer theory can't fully describe the behaviour change caused by the presence of organic fluids in clay soils, but provides a good interpretation of these changes in clay behaviour [11, 12].

A reduction in the thickness of the double layer will allow more space in the voids between the soil particles for the flow of the fluid which will then lead to higher permeability. Moreover, according to Anandarajah (2003), due to the shrinkage of clusters, localized cracks may be formed in the soil through which flow is transferred which can result in wide variations in the measured permeability values. Therefore, a decrease in the dielectric constant of the fluid induces shrinkage in the double layer which will in turn, increase permeability. Due to the low dielectric constant of organic liquids in comparison to water, clay will present higher values of permeability for such liquids. Therefore, these liquids pose a more critical condition with respect to satisfying the required limits on permeability, which may not be properly addressed by regulatory standards that use water as the base permeability value for the evaluation of soil permeability [13, 14].

Some equations found in the technical literature to model K as a function of the fluid dielectric constant are presented below.

Eq. 3 as proposed Budhu et al. (1991) was compiled using one-dimensional compression test data obtained for samples of Kaolinite, Montmorilonite and a natural clayey soil saturated with different organic liquids in addition to experimental data reported by Mesri and Olson (1971) and Kinsky et al. (1971). This equation allows the calculation of the permeability of pure organic fluids based on the permeability of the soil with water as the permeant [15].

$$\frac{K_f}{K_w} = e^{\lambda\left(1-\frac{\varepsilon_f}{\varepsilon_w}\right)} \tag{3}$$

Where K_f is the soil intrinsic permeability for the used fluid and K_w is the soil intrinsic permeability for water. ε, is the relative dielectric constant of the medium. The subscripts "f" and "w" refer to fluid and water, respectively. λ varies with soil type but there is no indication as to which soil properties affect the value of λ.

Equation 4 was proposed by Oliveira (2001) in order to predict soil permeability k for different soils and fluids [16].

$$k = \rho\frac{g}{\mu}\left(\frac{1}{5}\right)\left[\frac{n^3}{(n-1)^2}\right]\frac{B}{\varepsilon^N} \tag{4}$$

Where n is soil porosity, g is gravity acceleration, ρ is the fluid density, the variable B which was not physically related to any measurable parameter of soil, seems to reflect the superficial activity of the soil and N seems to be dependent on the clay content of the soil.

Green et al. (1981) concluded that organic chemical materials tend to shrink the double layer around the clay particles which leads to the shrinkage of soil structure and cracks. Hence, it leads to an increase in the soil hydraulic conductivity. When permeating fluids other than water flow through the samples, a great increase in permeability is observed which is due to the difference between the polarity of water and other fluids [17]. Mersi and Oslen asserted that the contact between the soil particles and the passing fluids changes the soil structure which smooths the way for the fluid to pass through [18].

Fernandez and Quigley (1985), investigated the permeability of clays at optimum water content and estimated the permeability of alcohol to be 10 times and the permeability of oil products to be 1000 times that of water [19].

Foreman and Daniel (1986) used two permeameters to measure the hydraulic conductivity of clays, a rigid-wall and a flexible-wall permeameter. They reported that the type of permeameter had little effect on the hydraulic conductivity of clays permeated with water. However, for samples permeated with organic compounds the rigid-wall permeameter measured a higher hydraulic conductivity in comparison with the flexible-wall device. The difference is due to the confinement along the side-walls and effective stresses [20].

Mosavat and Zalihe Nalbantoglu (2012) investigated changes in the geotechnical properties of clay soil permeated with different hazardous liquids. They reported that changing the pore fluid of soil from water to ethylene glycol, toluene and the sea water caused considerable changes in the engineering properties of the clay soil. Flocculation and aggregation of the soil particles occurred due to a decrease in the dielectric constant of the pore fluid resulting in faster sedimentation of the soil particles. The change in the concentration of the pore fluid resulted in a non-plastic granular texture of the soil. Test results indicated an increase in the permeability of the soil contaminated with different pore fluids. Toluene with a lower dielectric constant (2.4) caused more increase in the permeability of the soil [21].

Machado et.al (2016) used experimental soil permeability data obtained for different fluids (water, gasoline, commercial gasoline with 24% ethanol by volume, ethanol, diesel and carbon tetrachloride) in a variety of soils, from non-cohesive sediments without the presence of fines to swelling soils to derive a model to predict soil permeability of organic fluids based on soil and fluid properties. They calculated permeability by Eq. 1, using water as the base fluid. Result show that values of $K_{exp}/K_{nutting}$ as high as 100,000 can be obtained for high plasticity soils [13].

Goodarzi et al. (2016) investigated the impacts of varying concentrations of different organic chemicals including methanol, acetone, acetic acid, and citric acid on the macro and microstructure responses of Na+-Bent. They reported that pollutants, produce microstructural units and macrostructures that may be noticeably different from the natural soil. This is ascribed to the collapse of the diffuse double layer and (or) reduction in the surface charge density of the particles. In addition, clustering and development of aggregated structure in the presence of the organic chemicals was reported. Such fabric alteration led to the decrease of plasticity index and swelling potential of soil as well as an increase in the permeability of Na+-Bent [22].

In this paper, the permeability of clays exposed to the flow of water and methanol as polar miscible solvents and gasoline and car oil as non-polar and immiscible solvents is investigated and the effect of parameters such as the fluid dielectric constant, fluid viscosity and water content of the samples is examined.

2. Material and Methods

Data from several permeability tests performed at the geo-environmental laboratory of the Guilan university of Iran were analyzed in order to investigate the variation of soil permeability with various parameters associated with both the soil and the permeant including soil plasticity and water content and the fluid dielectric constant and its viscosity.

2.1. Soils

In this experiment, two kinds of soil with different plasticity have been used. Liquid limit and plastic limit of the soils were determined by Atterberg limits test. Figure 1 presents the soil samples position in the plasticity chart. In the plasticity chart two lines, A and U, can be observed. The A-line is used to separate clay-like materials (above line A) from silty materials (below line A), and organic (below line A) from inorganic soils (above line A). The U-line indicates the upper boundary for valid experimental results. High plasticity soils usually present results which are closer to the A line in the plasticity chart. Soil 1 is classified as CL or clay of low plasticity while soil 2 is classified as CH or clay of high plasticity.

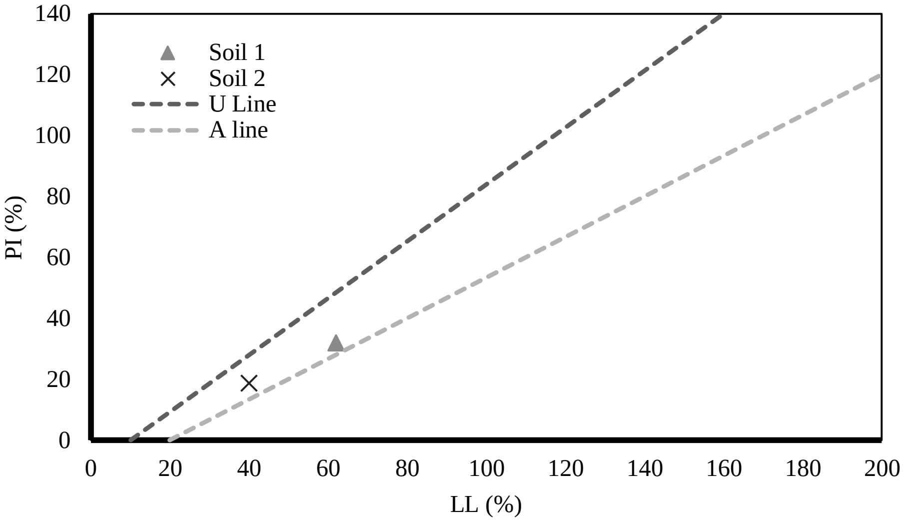

Figure 1. Soil Atterberg limits in the Casagrande plasticity chart

Grading curve and other properties of soils type 1 and 2 are presented in figures 2 and 3 and table 1.

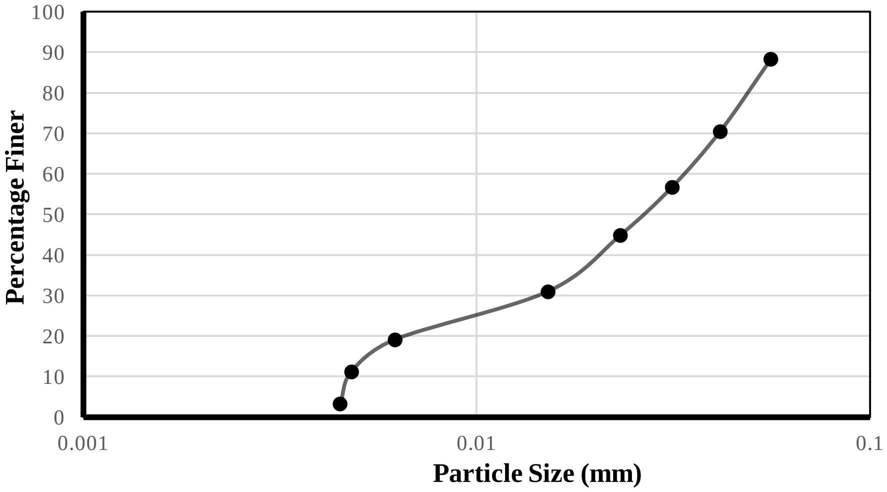

Figure 2. Grading curve of soil 1

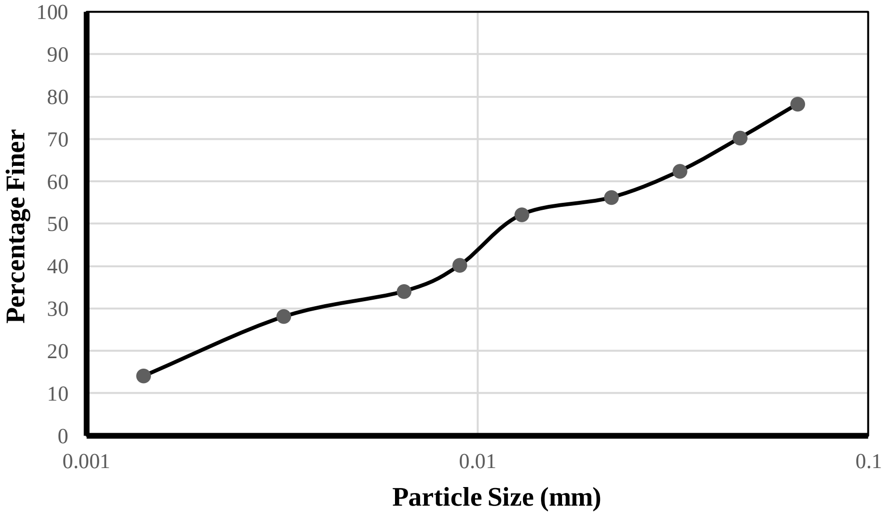

Figure 3. Grading curve of soil 2

Table 1. Soils properties

Property	Soil 1	Soil 2
Optimum water content (%)	25.6	19.609
Maximum dry unit weight (gr/cm^3)	1.708	1.648
Specific gravity	2.74	2.69
Clay percentage (%)	60	45
Liquid limit (%)	62	40
Plastic limit (%)	30.1	21.3
Plasticity index (%)	31.9	18.7

2.2. Liquids

The permeating liquids used in this study include methanol, car oil and gasoline. Methanol is considered as a relatively-polar and miscible solvent while gasoline and car oil are considered non-polar and immiscible. Finally, water was used as the permeant and hydraulic conductivity was measured. Physical and chemical properties of the liquids are listed in Table 2.

Table 2. Fluid properties at a temperature of 20 °C

	Water solubility (g/L)	Density (g/cc)	Viscosity (mPa.s)	Dielectric constant
Water	∞	0.998	1	80.4
Methanol	∞	0.796	0.61	32.6
Car oil	Insoluble	0.812	0.86	2.3
Gasoline	0.7	0.879	0.73	2.28

All three organic liquids caused the soil particles in suspension to flocculate. The low dielectric constant of the organic liquids presumably caused a contraction of the diffuse double layer that surrounded the soil particles, which in turn caused the flocculation of particles.

The saturation cells used in this experiment are cylindrical molds made of aluminium which are 10 cm in diameter and 17 cm in length. In all the performed tests, no water was detected in the collected effluent. This is particularly important in case of using rigid wall permeameters, because the replacement of water as a liquid with a high dielectric constant with a non-polar fluid will cause soil shrinkage and create preferential flow paths. Moreover, the walls of these molds are considered to be rigid in order to prevent the application of any compressive force to the samples or any deformations. There are holes on top and on the bottom of the cells. The bottom hole is used to saturate the samples and in the same way the upper hole is used for the fluid to exit through. The fluid, under constant pressure, enters the sample from the bottom hole and leaves the sample from the upper hole after saturation (Figure 4).

Figure 4. The test mold and inlet and outlet pipes

Soil samples with different water contents as presented in table 3 were prepared and compacted according to the standard compaction test with the same compactive energy (ASTM D 698) [23]. In order to provide drainage for the samples, coarse-grained soil was used at the two ends of the samples. To prevent the particles of the coarse-grained soil from entering the holes on each side, geotextile filters were provided. To accelerate the saturation of the samples, testing was performed according to the constant head method. To this end, the fluid tank was placed in a defined height in proportion to the samples and the applied pressure on the fluid was adjusted by an air compressor. Thus, due to the applied pressure and the length of samples being constant during the experiments, the hydraulic gradient remained constant. The coefficient of permeability of clay samples in modified constant head tests is calculated using the equation below [24].

$$k = \frac{q}{iA} \tag{5}$$

where q is equal to the output fluid discharge (cm^3/s), i is the hydraulic gradient, A is the sample cross section (cm^2) and k is permeability of the fluid (cm/s).

Table 3. Water content of samples

	Water content (%)			
Soil 1	28	25.6	23	18
Soil 2	23	19.6	15	12

First, permeability of samples of different water contents against the flow of water is measured. In the next steps, permeability of similar samples with similar water contents against the flow of other fluids into the sample is measured.

3. Analysis

In this paper, soil samples are prepared and compacted into specific molds. Permeability tests are conducted for samples of two different soils compacted at various water contents, exposed to the flow of different liquids. Water and methanol as polar solvents and car oil and gasoline as non-polar solvents were passed though the samples and the permeability of samples against their flow was measured. Figures 5 and 6 show the hydraulic conductivity of samples against the water content at compaction for the two soils against the flow of four fluids.

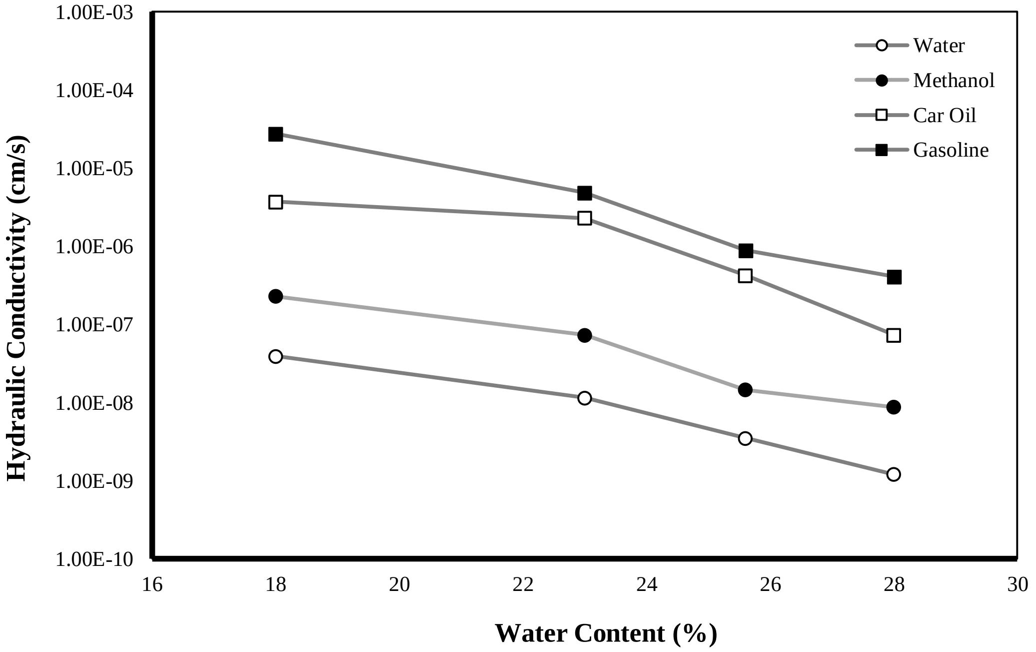

Figure 5. Permeability against water content for different permeants in soil 1

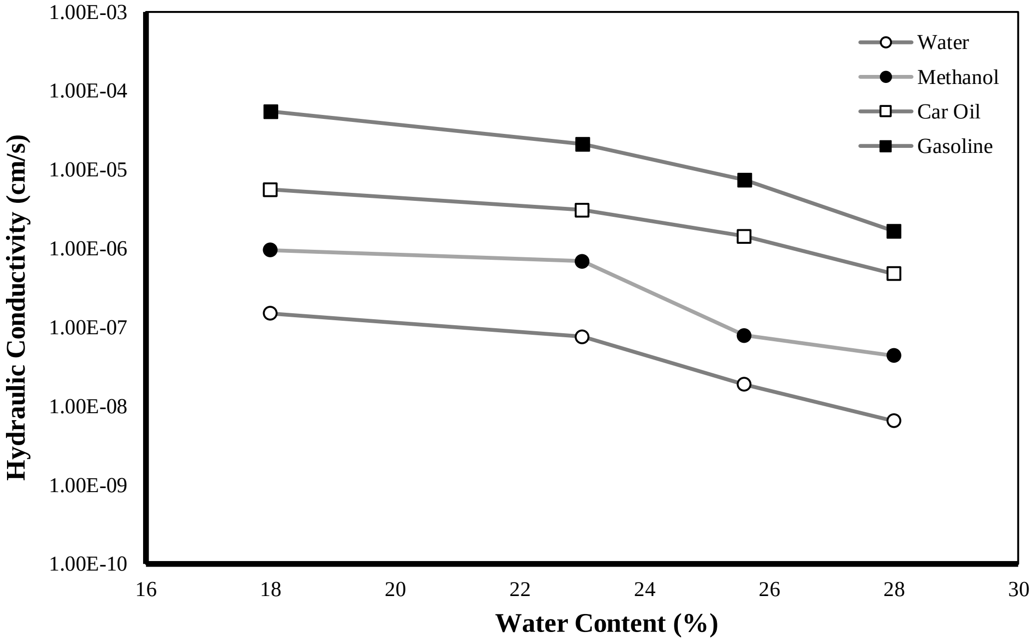

Figure 6. Permeability against water content for different permeants in soil 2

It can be seen from these figures that the permeability of the samples of both soils decreases with water content for all the liquids used. Generally, soil samples compacted wet of the optimum water content have a dispersed structure while in samples compacted dry of the optimum water content, the soil particles have a more random arrangement due to their flocculent structure. This is due to the not yet fully developed absorbed water layer surrounding the particles in samples on the dry side which is the reason why attractive forces are predominant in such samples. Therefore, these samples have a flocculated structure which is comprised of randomly oriented particles with voids between them which result in higher soil permeability. However, in samples compacted wet of the optimum water content, due to the well-developed water layers absorbed by the particles, repulsive forces increase leading to the particles arranged in a dispersed structure. Such a soil will have lower porosity and lower permeability.

In dry condition, soil particles have a large absorbing potential which leads to the absorption of the liquid molecules. Therefore, the liquid molecules are retained by the soil particles. As a result, a thin layer of liquid molecules is created on the soil particles where the intensity of absorption in the first liquid molecular layer is very high. Hence, the permeability of fluids for samples in the dry part is higher and as water content increases, permeability reduces.

Moreover, it is observed that with an increase in water content from dry to wet, permeability decreases as a result of the pores filling up which results in the reduction of porosity and a reduction in the flowrate of fluid through the sample. By increasing the water content of the sample, the space between the soil particles are filled with water. Therefore, the molecules of the permeating water are absorbed by the electrostatic forces of the pore water contained in the samples. Hence, it facilitates the saturation of the samples and reduces the duration of the saturation process which leads to lower difference between the permeability of samples in the dry and wet zones while passing water through.

On the other hand, the lower the polarity of the infiltrating flow, the easier and faster the flow of the permeant in the samples within the dry zone will be, while more time is needed for the saturation of the samples in the wet zone due to the decrease in the existing electrostatic forces between the passing fluid and the water molecules of the sample. Nevertheless, the delayed saturation doesn’t equate with a decrease in permeability, but the lower dielectric constant of the non-polar fluids and its impact on soil structure along with the fluid’s viscosity will increase soil permeability. In the aforementioned case, the difference in the permeability of two zones of dry and wet will increase.

Therefore, gasoline with a dielectric constant of 2.28, as a non-polar and immiscible fluid has the least absorption with the water molecules present in the sample. Therefore, in comparison to other non-polar fluids such as car oil and relatively-polar fluids such as methanol, gasoline requires the least amount of time to pass through the samples in the dry zone and the longest amount of time for passage in the wet zone. Accordingly, the difference between the permeability of the two zones of dry and wet for the flow of gasoline through the samples become more prominent.

Figure 7 presents the variation of soil permeability at optimum water content for the two types of soil samples exposed to the flow of different fluids. Based on this figure and by comparing figure 5 and 6 together, it is observed that soil 1 with a higher clay content and plasticity has a lower hydraulic conductivity in comparison to soil 2 for all the liquids investigated in this study. Higher values of PI result in more interaction between the soil particles with the fluid flowing through the soil, resulting in changes in the soil's structure and a more influential double layer. The double layer inhibits the flow of the liquid in the sample and decreases permeability. For polar fluids with high values of dielectric constant namely methanol and water, there is a significant fall in permeability with the increase in soil plasticity while for non-polar fluids such as car oil and gasoline there is a minor decrease in permeability. This is due to the fact that the plastic properties of clay are induced by the polarity of the pore fluid. Therefore, for the non-polar fluids mentioned above, the clay will not exhibit the same plastic properties as it does for water.

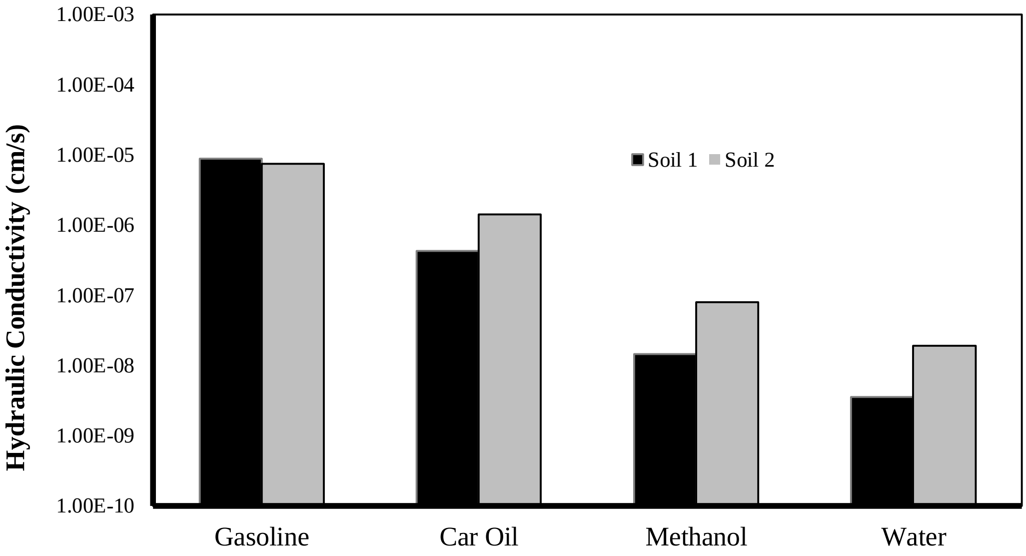

Figure 7. Soil permeability at optimum water content for two types of soil for different permeants

In the following section, the impact of the fluid properties including the dielectric constant on the permeability of soil samples is investigated. Table 4 and 5 present the soil permeability values obtained for different permeants with different values of dielectric constant for soil 1 and 2 respectively. Similar trends were observed for other water contents. To avoid repetition, the results for samples compacted at optimum water content are presented. Results show that the soil permeability for methanol as a relatively-polar fluid is the lowest permeability after water and permeability for gasoline as a non-polar fluid is the highest.

Table 4. Permeability of soil 1 at optimum water content, for fluids with different dielectric constants

Fluid	Dielectric constant	Hydraulic conductivity (cm/s)
Water	80.4	3.5×10^{-9}
Methanol	32.6	1.45×10^{-8}
Car oil	2.3	4.22×10^{-7}
Gasoline	2.28	8.8×10^{-6}

Table 5. Permeability of soil 2 at optimum water content, for fluids with different dielectric constants

Fluid	Dielectric constant	Hydraulic conductivity (cm/s)
Water	80.4	1.89×10^{-8}
Methanol	32.6	7.86×10^{-8}
Car oil	2.3	1.42×10^{-6}
Gasoline	2.28	7.44×10^{-6}

As it was already mentioned, the difference in the polar properties between water and organic liquids is the reason why permeability is increased for such liquids. The water molecule, with a large dipole moment, forms strong hydrogen bonds to the surface of the minerals in the soil. Clays have small pores and often contain high surface area minerals. Most of the pore fluid in clayey soils exists in a film adsorbed by the particles and held in place by intermolecular attractions of various kinds. The existence of such an adsorbed layer of water retained by the surface of the particles effectively reduces the size of the pore channels and inhibits the flow of the fluid through the soil. Fluids with low polarities compared to water, as is the case for many organic liquids (e.g., gasoline, car oil), are less strongly bonded to the soil minerals and they have a lower level of interaction with the particles which allows the fluid to flow more easily through the pore network.

Many organic chemicals tend to shrink the diffuse double layer that surrounds the clay particles, causing the clay particles to flocculate, the soil skeleton to shrink, and cracks to form. Organic fluids can also dehydrate the interlayer zones of the clay. The combination of particle flocculation, cracks, reduction in the thickness of the double-layer and desiccation leads to an increase in hydraulic conductivity.

As it was discussed, the dependency of the thickness of the double-layer on dielectric constant is clear. The higher the dielectric constant is, the higher the double layer thickness will be.

Figure 8 presents the permeability of soil 1 exposed to the flow of fluids with different dielectric constants at optimum water content. Based on the figure, the effect of changes in dielectric constant and viscosity of the fluid on soil permeability is clear. Fluids with lower dielectric constant lead to the contraction of the double layer absorbed by the clay particles and bring about a reduction in its thickness. This will in turn change the soil structure by decreasing the repulsive forces among the soil particles which will then cause the particles to flocculate. In addition, cracks can be formed in the sample.

Moreover, when the dielectric constant of the liquid decreases, the influence of the fluid on soil particle increases. Therefore, vertical cracks appeared across the surface of sample, and flow through the samples decreased. As the cracks slowly increase in length towards the base of the pereameter, the flow continued to decrease. Then, as the leading front of the cracks reached the base of the clay, flow started to increase rapidly.

Water with the highest value of dielectric constant (80.4) and on the second place Methanol with a dielectric constant value of 32.6 had the least permeability. But for the two non-polar fluids of gasoline and car oil, with similar values of dielectric constant, viscosity played an important role on their permeability. Fluids with higher viscosity lead to lower values of permeability. High viscosity hinders the flow of the fluid through the soil while low viscosity facilitates it. Therefore, the low dielectric constant of gasoline causes shrinkage of the double layer surrounding the soils' particles and consequently volumetric drawdown of the sample. Accordingly, gasoline with the lowest value of the dielectric constant and viscosity has a greater value of permeability than car oil and all the other liquids in this study.

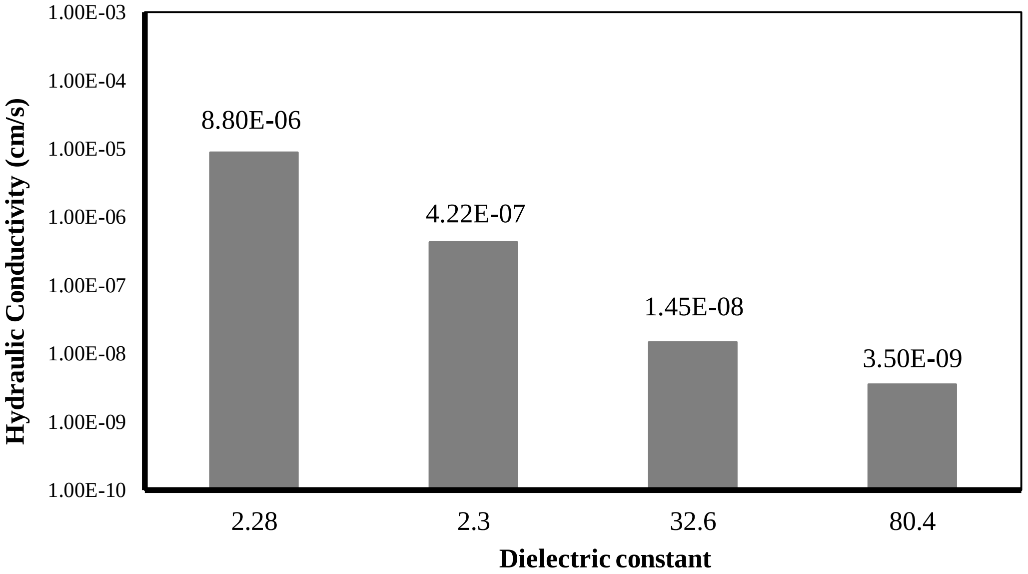

Figure 8. Permeability of soil 1 exposed to the flow of fluids with different dielectric constant at optimum water content

Figure 9, demonstrates the permeability of the samples of soil 2 compacted at optimum water content exposed to the flow of different liquids with different values of dielectric constant.

In soil 2, water with the highest value of dielectric constant and polarity, and methanol with a dielectric constant of 32.6, have the lowest permeability in order. The more the polarity of the permeant liquid decreases, the more prominent the effect of viscosity will become. While the two non-polar fluids investigated in this study have similar values of dielectric constant, gasoline is the one with the lower viscosity between the two. Therefore, penetration through the soil will be easier, resulting in a higher value of permeability in comparison to car oil. In effect, gasoline is more permeable than car oil because of its lower viscosity and dielectric constant.

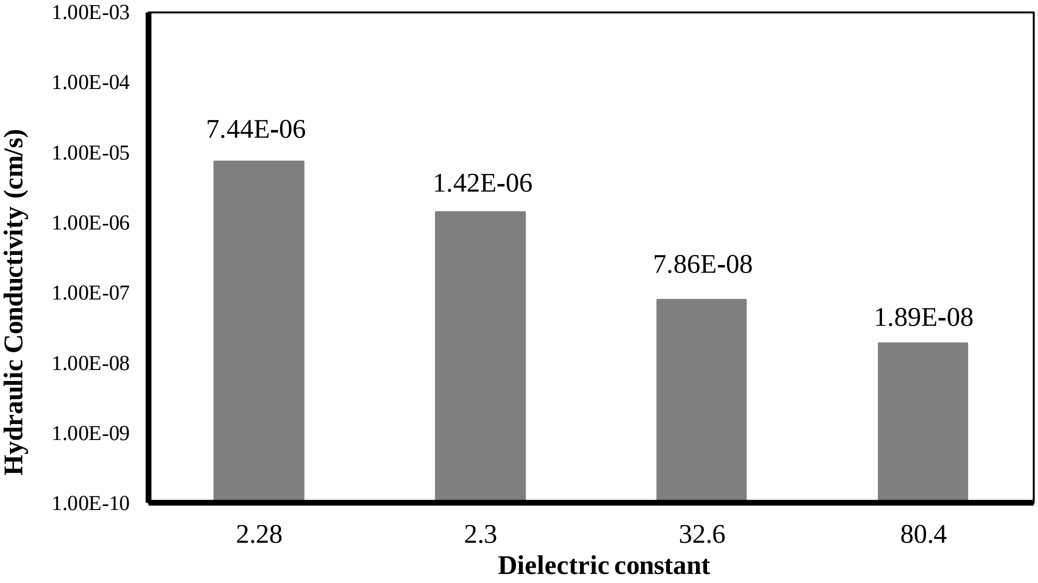

Figure 9. Permeability of soil 2 exposed to the flow of fluids with different dielectric constant at optimum water content

Based on observations from the above figures, it can be concluded that in soil type 1, the permeability will be increased up to 5, 120 and 2500 times that of water for methanol, car oil, and gasoline, respectively. This increase for soil type 2 is 5, 75, and 400 respectively.

Figure 10 presents a comparison of the results of the current study and those presented by Fernandez and Quigley (1985) and Machado et al. (2016). Fernandez and Quigley (1985) investigated the hydraulic conductivity of a clayey soil permeated by 9 different fluids. They distinguished three regions on the hydraulic conductivity versus dielectric constant chart: a low *k* region for polar water of dielectric constant 80; an intermediate region for relatively polar alcohols (ε = 20 – 35); and a high *k* region for the nonpolar aromatics (ε = 2 – 2.5). Machado et al. (2016) presented the results of permeability tests conducted for different fluids (water, gasoline, commercial gasoline with 24% ethanol by volume, ethanol, diesel and carbon tetrachloride) in a variety of soils [13, 19].

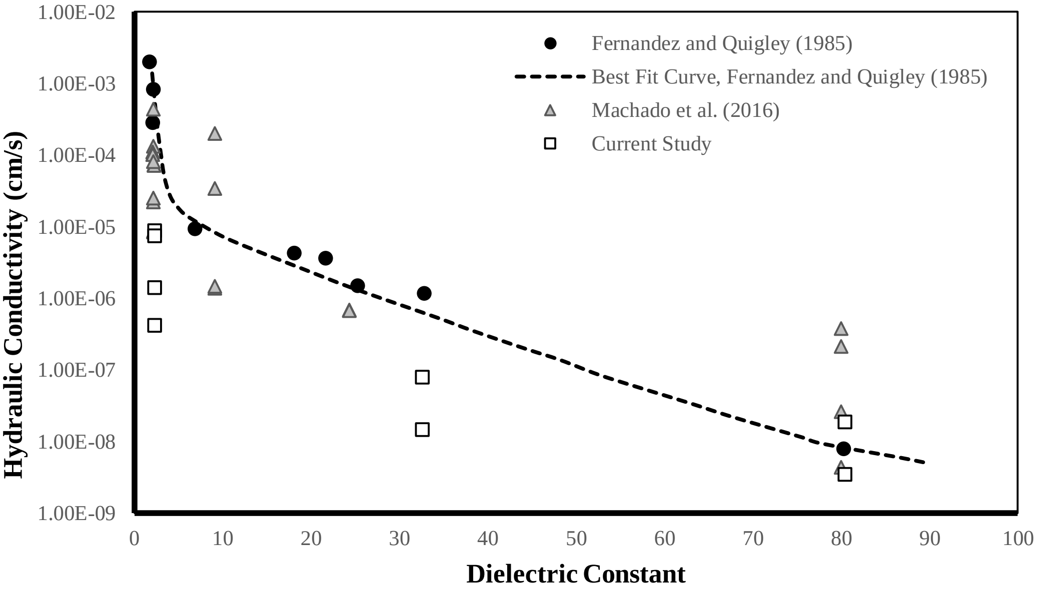

Figure 10. Comparison of results of with Fernandez and Quigley (1985) [13, 19]

It can be seen from figure 10 that the results of the current study conform to the trend of results presented by Fernandez and Quigley (1985) and Machado et al. (2016) but are generally lower in comparison. This difference can be explained by the presence of coarser grains in the soil samples of Machado et al. (2016) and Fernandez and Quigley (1985). These soil samples contained sand content in the range of 4 to 40 %.

4. Conclusion

Three types of organic fluids as permeants are used for the evaluation of hydraulic conductivity of two types of clayey soils with different plasticity. Methanol with a dielectric constant of 80.4 is a relatively polar and miscible fluid, and car oil and gasoline are non-polar and immiscible fluids with dielectric constants of 2.3 and 2.28 respectively.

Studies showed that when clay soils are saturated with an organic fluid like gasoline, permeability is generally greater than if the soil was saturated with water and water was the permeant.

Passage of organic fluids through clayey soils initiates a change in the soil structure which consequently increases soil permeability. For fluids with low values of dielectric constant, the permeability of clay increases due to the direct relationship between the thickness of the double layer absorbed by the clay particles and the dielectric constant. Fluids with a low dielectric constant, cause the double layer to contract and as a consequence reduce its thickness. Finally, clay particles flocculate and the soil structure shrinks which increases the pores and voids in the soil structure, reduces tortuosity by providing a more straightforward path for the flow of the liquids and can cause cracking in the samples. All this provides the fluid with more passage to flow through. Therefore, permeability increases.

The dielectric constant of methanol is large enough. Therefore, there is not a significant difference between the permeability of water and methanol. Lower values of dielectric constant in fluids leave a much more prominent increasing effect on the soil permeability. Therefore, car oil with a dielectric constant of 2.3 and gasoline with 2.28 have the highest values of permeability compared to water.

In addition, the rigid walls of the experiment molds raise the likelihood of the seepage of fluid through the space between the walls and the samples. This is possible in soils which have a tendency towards shrinkage and can cause an increase in permeability.

As the clay content and the liquid limit and the plasticity index of soil increase, permeability of soil against polar fluids like methanol will experience a prominent decrease while this reduction is minor for non-polar fluids like gasoline and car oil.

As a general rule, the higher the fluid dielectric constant is, the lower the soil permeability will be. At a constant compactive energy, the permeability of two soil types was at its highest when exposed to the flow of gasoline as the liquid with the lowest dielectric constant in comparison to the other fluids. The results indicate gasoline to be the most critical permeating fluid among the fluids investigated in this study. This means that if the permeability of soil for gasoline satisfies the required criteria, it will also be appropriate for the other three fluids.

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