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ORIGINAL PAPER

# The effect of soil mineralogy and pore fluid chemistry on the suction and swelling behavior of soils

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**Abstract** Soil suction is one of the most important parameters for describing the moisture condition and engineering behavior of unsaturated soils. Therefore, changes in suction behavior of soils in the presence of saline waters are important for engineered barriers. The aim of this study was to determine the change in suction and swelling behavior of soils, which were exposed to salt solutions (NaCl, $CaCl_2$, natural seawater) with respect to distilled water. The three soil samples were gathered with different mineralogy and plasticity characteristics and tested for determining matric and total suction values and for obtaining free swelling characteristics in the presence of salt solutions. The bentonitic soil sample had the highest total suction value in the presence of seawater. Kaolinitic and zeolitic soil samples had the highest total suction values in the presence of NaCl solution. The highest modified free swell index value of the samples was obtained in the presence of NaCl solution for all the soil samples. No relationship was found between the total suction, matric suction and the modified free swell index value of the tested soils.

**Keywords** Pore fluid chemistry · Total suction · Matric suction · Swell index

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## Introduction

Soil pore water chemistry is one of the most important parameters affecting the engineering behavior of clay soils. When clay soils with especially high swelling potential are exposed to salt solutions in engineered barriers, high settlement occurs or permeability conditions change. For this reason, the effect of salt solutions on the engineering behavior of soils is an interesting subject and deserves further study.

The natural engineered barriers of landfill liners are expected to retard any possible flow of substances during the operating life of the barrier. In the field, natural soils in landfill liners will undergo complex and coupled thermo-hydro-chemo-mechanical processes. In geoenvironmental problems, the effect of negative pore water pressures (suction) becomes important especially on the hydraulic conductivity and volume change behavior of the compacted specimens (Fredlund et al. 1995). Furthermore, the extent and rate of cracking is dependent on various factors, including, negative pore water pressures (suction) which develop in a soil during drying and elastic properties of the drying soil (Morris et al. 1992; Fredlund and Rahardjo 1993). Fine-grained soils are more susceptible to the development of cracks than coarse-grained soils due to the presence of smaller pore spaces, which allow for the development of higher suctions (Mitchell 1993). When unsaturated, compacted natural fine-grained soils are used as landfill liners, it is very important to understand their engineering properties (e.g., permeability, volume change) and suction behavior in the presence of different solutions. Thus, in many instances involving unsaturated soils, knowledge of the pore water pressures or hydraulic heads is of primary interest. In order to model the flow of water in an unsaturated soil, it is necessary to define the relationship between the coefficient of permeability and soil suction. The coefficient of permeability is related to the water content of soil during desorption process and a subsequent sorption process. For that reason, permeability is related to the matric suction of soil (Fredlund et al. 1994). It has shown that the coefficient of permeability of unsaturated soils can be estimated by matric suction value, accurately.

Soil suction is an important parameter for describing the moisture condition affecting the engineering behavior of unsaturated soils. Soil suction is expressed as a pressure term that is a measure of the pulling force (tension) exerted on the water (Snethen 1980). The simplest definition of total suction is that it is the sum of matric suction and osmotic suction. Matric suction is related to permeability and is caused by the surface tension of the pore water. Therefore, matric suction is closely related to capilarity, mineral structure and adsorptive surface forces. Osmotic suction is related to the dissolved salt content in pore water (Bulut et al. 2001; Rao and Shivananda 2005). For this reason, osmotic suction is independent from the water content having the same ion concentration. Many methods were developed in order to measure soil suction. Thermocouple, tensiometer and filter paper are the most common methods (Pan et al. 2010). The filter paper method is the simplest and widely used technique for measuring both total and matric suctions (Deka et al. 1995; Bulut et al. 2001).

Many previous studies which investigated the relationship between the geotechnical engineering properties (swelling potential, shear strength) and suction behavior of a clay soil can be obtained from the literature (Rao and Shivananda 2005; Fredlund and Rahardjo 1993; Cokca and Tilgen 2010). Soil suction is an important parameter, not only for determining water-holding capacity but also for determining the engineering behavior of unsaturated soils. For example, the coefficient of permeability of soils decreases several orders of magnitude as suction increases (Agus et al. 2003). Furthermore, an increase in soil suction increases the shear strength of soils (Cokca and Tilgen 2010). Therefore, factors affecting changes in soil suction are important and should be determined.

The effect of pore water salinity on the engineering behavior of soils is well documented (Moore 1991; Rao et al. 1993; Di Maio 1996; Jo et al. 2001; Di Maio et al. 2004). These studies have shown that soils undergo changes in the particulate levels when soils are exposed to inorganic salt solutions. An increase in pore water salinity decreases the double layer thickness and consequently reduces the compressibility and swell potential of clay soils (Yukselen-Aksoy et al. 2008). Osmotic suction is determined by pore water salinity and increases with the ionic concentration of the pore fluid. In the literature, the effect of different salt solutions on the osmotic suction behavior of soils is not well examined. Furthermore, the effect of osmotic suction on the swelling behavior of soils is not well understood. In this study, the effect of pore fluid chemistry and mineralogy on total and matric suction values were investigated. In order to determine the effect of pore water chemistry on soil suction, the soil samples were prepared in different solutions (distilled water, seawater, NaCl, $CaCl_2$). Then, matric and total suction values were measured for all the soil samples. Modified free swell index (MFSI) parameters were determined for clay soils, then, the relationship between soil suction and swell index parameters was determined.

## Materials and methods

In this study, natural bentonitic (BN), kaolinitic (KL) and zeolitic (ZL) soil samples were used. The grain size distribution (ASTM D 422 1999), liquid limit, plastic limit (ASTM D 4318-10 1999) and specific gravity (ASTM D 854-10 1999) values of the soil samples were determined in accordance with the American Society of Testing Materials standards. In addition, cation exchange capacity was determined by using the Na method (Chapman 1965). The minerological content of the clay soil samples was determined with X-ray analyses using a Shimadzu XRD-6000 device. The physico-chemical properties of the soil samples are summarized in Table 1.

The total and matric suction values of the samples were determined using different fluids namely, distilled water, natural seawater, 0.5 M NaCl and 0.5 M $CaCl_2$ solutions. The natural seawater was obtained from the Mediterranean Sea. The ionic composition of natural seawater was identified using ion chromatography analysis with a GP50 Dionex IC instrument (Table 2).

**Table 1** Physicochemical properties of the soil samples

| Property | KL | BN | ZL |
|---|---|---|---|
| Specific gravity | 2.69 | 2.63 | 2.31 |
| Liquid limit (%) | 33.9 | 421.4 | 60.3 |
| Plastic limit (%) | 27.4 | 58.0 | – |
| Clay fraction (<0.002 mm) (%) | 18.0 | 88.0 | 23.7 |
| Cation exchange capacity (meq/100 g) | 4.0 | 32.5 | 60.9 |
| Mineralogy | Kaolinite<br>Quartz<br>Alunite | Montmorillonite<br>Cristobalite<br>Quartz<br>Illite | Clinoptilolite<br>Quartz |

**Table 2** Ion chromatography analysis results of the seawater

| | Ca (ppm) | Na (ppm) | K (ppm) | Mg (ppm) | Cl (ppm) | $Br^-$ (ppm) | $SO_4^{2-}$ (ppm) | $Sr^-$ (ppm) |
|---|---|---|---|---|---|---|---|---|
| Seawater | 486.6 | 12301.5 | 487.7 | 1481.4 | 23852.0 | 70.3 | 3115.2 | 15.5 |

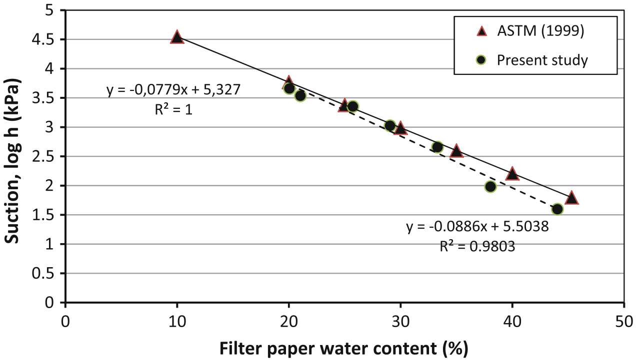

**Fig. 1** Calibration curve for Whatman No. 42 filter paper

Soil samples were prepared at water contents corresponding to 50 % of their liquid limit values. It should be noted that the liquid limit of the BN sample significantly decreased in the presence of $CaCl_2$ solution, from 421.4 to 110 %. Hence, the bentonitic sample was prepared at 110 % liquid limit value with $CaCl_2$ solution. There was no significant difference in the liquid limit values of the KL and ZL samples in the presence of distilled water or seawater. The samples were compacted mechanically, at 17 and 21 kN/$m^3$ unit weights in plexiglass tubes. The diameter of the soil samples was 3.5 cm and the height of the samples was 5 cm. In the filter paper method, the filter papers were placed in contact with the soil samples for matric suction measurements, and the non-contact filter papers were placed on top of a plastic O-ring above the soil samples for total suction measurements. The samples were placed in airproof glass jars and in an incubator at 20 °C for 7 days. After equilibrium was established between the filter paper and the soil, the water content of the filter paper disc was measured. Then, using a filter paper water content versus suction calibration curve, the corresponding suction value was found.

The calibration curve was obtained for the Whatman No. 42 filter papers. However, instead of using soil, the calibration curve was constituted by making use of specified concentrations of NaCl solution. Figure 1 shows the comparison of the obtained calibration curve with the ASTM D5298-03 standard calibration curve. Figure 1 also shows the obtained calibration curve compares well with the ASTM curve. Separate calibration curves were used because the total and matric suction calibration curves are not compatible (Houston et al. 1994; Bulut 1996). For that reason, the calibration curve obtained in this study was used for total suction determinations. The matric suction values were obtained from the matric suction calibration curve of Deka et al. (1995) for the Whatman No. 42 filter paper.

In order to investigate the effect of minerology on soil suction, soil mixtures of 50 % ZL–50 % BN, 50 % KL–50 % BN and 50 % ZL–50 % KL were prepared and tested with distilled water.

In this study, modified free swell indices (MFSI) of the soil samples were determined with the method recommended by Sivapullaiah et al. (1987). In this method, 10 g of oven-dried KL and ZL soil samples and 2 g of oven-dried BN soil sample (swelling type) passing a No. 40 sieve were used. Ninety milliliters of distilled water was transferred to a 100-ml graduated cylinder. In approximately 0.1 g increments, the soil samples were dusted over the water surface in the cylinder, over a period of 20 s (approx.). Sample hydration and settlement was allowed for a minimum period of 5 min. After the final increment had settled, the water volume was raised to 100 ml, rinsing the adhering particles from the sides of the cylinder. After the 24-h hydration period, the volume was recorded at the top of the settled sample. Modified free swell index parameters were determined using Eq. 1.

$$\mathrm{MFSI} = \frac{V - V_s}{V_s} \tag{1}$$

where: $V$ = Volume of the swollen particles, $V_S$ = Volume of the solid particles.

## Results and discussions

The soil minerology and pore liquid chemistry effects on the matric and total suction values were determined on the KL, BN and ZL soil samples. The total and matric suction values of the samples and their mixtures were determined using the filter paper method in the presence of different pore fluids. Figure 2a, b show total and matric suction measurements of BN, KL and ZL samples in the presence of distilled water and seawater.

The total suction values of the BN, KL and ZL samples were similar in the presence of distilled water. It should be noted that all samples were prepared at 50 % of their liquid limit values. All samples had a greater total suction value in the presence of seawater than in distilled water. The higher ionic concentration of the solution results higher suction value (Delage et al. 1998; Rao and Shivananda

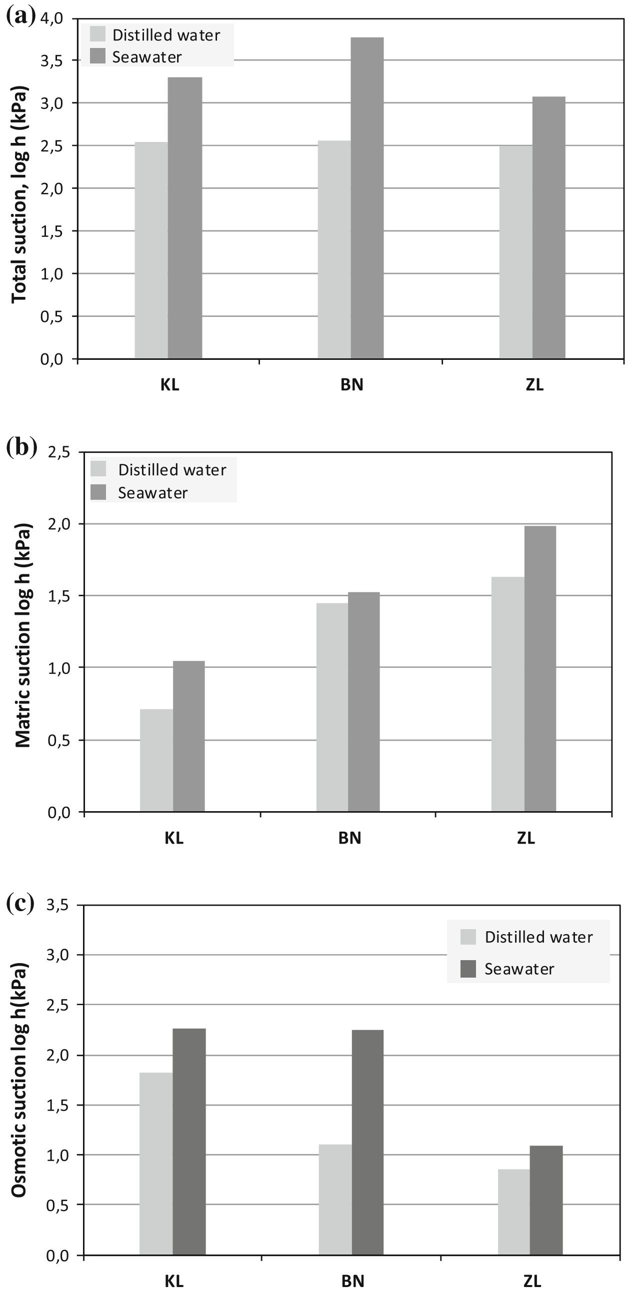

**Fig. 2** Suction behavior of the samples in the presence of distilled water and seawater. **a** Total suction, **b** matric suction, **c** osmotic suction

2005). In the presence of seawater, BN had a higher total suction value than sample KL or ZL. Previous research has shown that there is a direct relationship between specific surface area and liquid limit (Yukselen and Kaya 2006); as the bentonitic sample, BN, has the highest liquid limit value, it has the largest specific surface area. On the other hand, the zeolite sample, ZN, had the highest cation exchange capacity and the lowest total suction value.

Figure 2b shows the matric suction values of the samples in the presence of distilled water and seawater. The matric suction values of the samples were quite different in the presence of distilled water, compared to their similar total suction values. In general, matric suction can be considered to be independent from ionic concentration. There are insignificant differences for each of the samples in the presence of distilled water and seawater, this difference was caused by variations in the initial water content. For example, the BN sample had a liquid limit value of 421.4 and 110 % in the presence of distilled water and seawater, respectively. It can be seen that the ZL sample had higher matric suction values than BN and KL samples in distilled water or seawater (Fig. 2b).

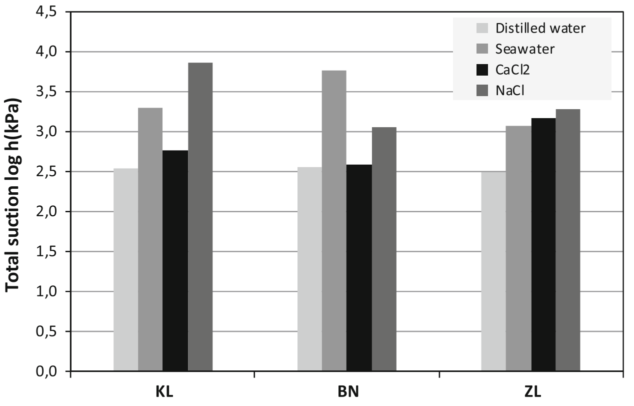

**Fig. 3** Total suction values of soil samples in the presence of different solutions

When the osmotic suction values of samples were compared in the presence of seawater and distilled water (Fig. 2c), the osmotic suction values were higher in the seawater than those in distilled water. The difference is more significant for the BN sample.

Figure 3 shows the effect of pore fluid chemistry on the total suction value. The total suction values of the samples were determined in the presence of distilled water, seawater, NaCl and $CaCl_2$ solutions, and the results were compared. As previously discussed, if the ion concentration increases the suction pressure also increases, (Fredlund and Rahardjo 1993). Since the seawater ionic concentration is higher than the NaCl or $CaCl_2$ solutions, a higher total suction value was obtained with only the BN soil sample. On the other hand, the KL and ZL soil samples had a higher total suction value in the presence of NaCl solution. As the BN soil sample had a large surface area, compared to the other samples, it was able to absorb the cations of the seawater. For this reason, the BN soil sample had a higher value in the presence of seawater (higher salt concentration) than the ZL and KL soil samples (Fig. 3). Similarly, Bayrak (2008) reported that in the experiments conducted using clay-silt samples, divalent $Mg^{+2}$ and $Ca^{+2}$ solutions have higher total suction values than monovalent $Na^{+1}$ and $K^{+1}$ solutions. The results of this study show that this statement is true, but only for the BN soil sample. Whilst the results with the KL and ZL soil samples showed lower total suction values obtained with divalent $Ca^{+2}$ ions, compared to monovalent $Na^{+}$ ions.

In order to determine the effect of soil structure on suction values, the samples were mixed in 50 % proportions. The total suction values of the mixtures were determined using the filter paper method. The measured total suction values were then compared with the calculated ones. The calculated values were obtained by multiplying the proportion of the soil sample with its suction value. Figure 4 shows the total suction values of the sample mixtures. When the calculated and measured total suction values were compared, there is no considerable difference between them. Though there is a slight difference in one mixture, due to a higher total suction value, the new soil structure obtained by mixing different soil samples had no significant effect on the total suction values.

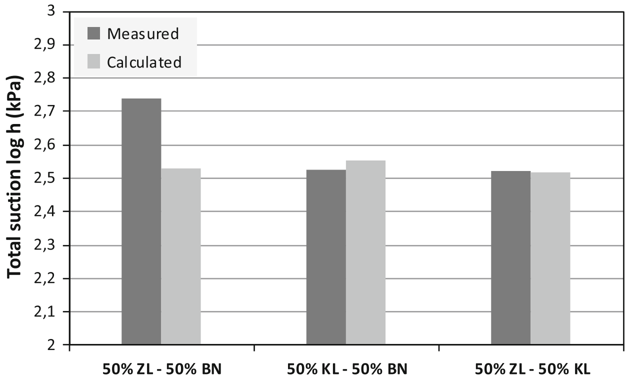

**Fig. 4** Calculated and measured total suction values of the sample mixtures

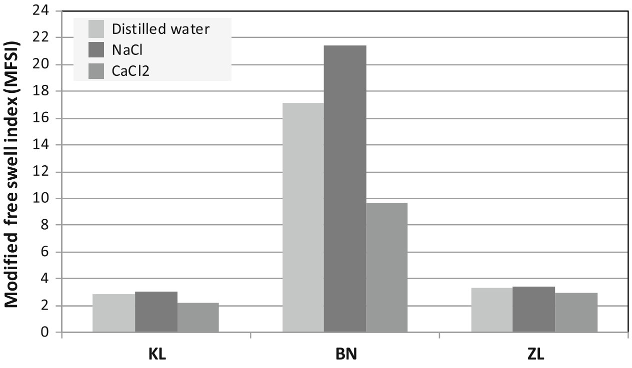

**Fig. 5** Effect of pore water chemistry on MFSI of the samples

In this study, the modified free swell index values of the soil samples in the presence of different solutions, with different pore chemistry characteristics, were also studied. In order to determine MFSI parameters of the soil samples, distilled water, NaCl and $CaCl_2$ solutions were used. Figure 5 shows the MFSI values of samples in the different pore fluids.

The results show that the highest MFSI values were obtained in the presence of NaCl solutions for all the soil samples. Conversely, the lowest MFSI values were obtained in the presence of $CaCl_2$ solutions. The effect was more significant in the BN soil sample which had the highest liquid limit and swelling potential value. The KL and ZL soil samples, with lower liquid limit and swelling potential values, had lower MFSI values than the BN soil sample (Fig. 5).

The relationship between the total and osmotic suctions and MFSI values is shown in Fig. 6. The results show that there is no significant relationship between both suction parameters and MFSI values. Similar results have been reported by Rao and Shivananda (2005), who stated that the swell potential of salt-amended soils is independent of the soil's initial pore fluid osmotic suction. The general equation which predicts swell pressures from suction measurements is not valid for all soils (Cokca 2000). Therefore, it should be noted that it is not possible to predict soil swelling potential from suction parameters.

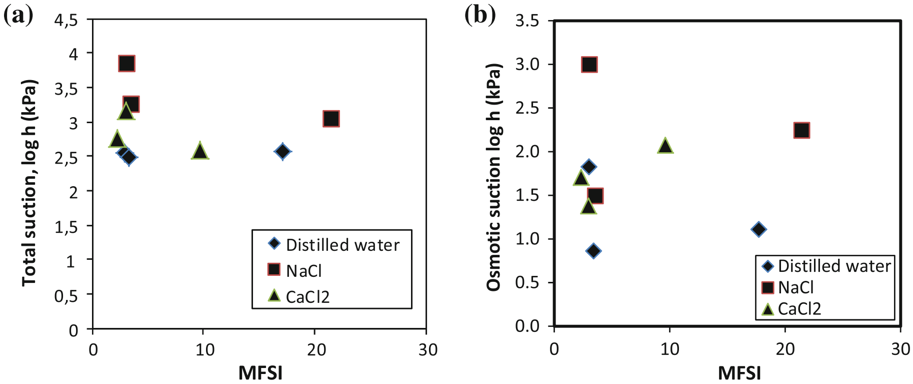

**Fig. 6** Relationship between total and matric suction and MFSI. **a** Total suction, **b** osmotic suction

## Conclusions

The effect of soil mineralogy and pore fluid chemistry on the suction behavior of the kaolinitic, bentonitic and zeolitic soil samples in the presence of distilled water, seawater, $CaCl_2$ and NaCl solutions was investigated. The modified free swell index of the samples were also determined in the presence of different pore fluids and the relationship between soil suction and swelling behavior was investigated.

The results show that the total suction values are similar for three different soil samples in the presence of distilled water. The total suction values increase significantly in the presence of seawater, the effect was more significant for bentonitic, BN, sample. The zeolitic, ZL, sample had higher matric suction values than the BN and KL samples in the presence of distilled water and seawater. When the results of three different salt solutions were compared, the BN sample had the highest total suction value in seawater, however, the KL and ZL samples had the highest total suction values in the presence of NaCl solution. The pore fluid chemistry had no significant effect on the modified free swell index of the kaolinitic, KL; and zeolitic, ZL; soil samples. However, the presence of $CaCl_2$ solution significantly decreased the MFSI of the bentonitic, BN, soil sample. No relationship was observed between the total suction and the MFSI values of the tested samples. The results show that total or matric suction values cannot be used for the estimation of swelling behavior in soils. However, for unsaturated soils, permeability is related to matric suction of soils. For that reason, it is important to know matric suction values in the presence of different pore fluids for landfill liner applications.

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