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FACTORS IMPACTING THE ELECTRO CONDUCTIVITY VARIATIONS OF CLAYEY SOILS[*]

V. R. OUHADI[**] AND A. R. GOODARZI

Dept. of Geotechnical Eng., Bu-Ali Sina University, Hamedan, I. R. of Iran
Email: vahidouhadi@yahoo.ca

Abstract– The variation of pore fluid properties in soil has a major effect on soil behaviour. This effect is a function of pore fluid properties and soil mineralogy. Such variation usually happens in the reservoirs of dams or in some geotechnical projects. The electro conductivity (EC) measurement is a simple method to monitor any variation in the pore fluid of soils. EC is the ability of a material to transmit (conduct) an electrical current. This paper focuses attention on the effect of soil-pore fluid interaction on the EC of clayey soils. A set of physico-chemical experiments are performed and the role of different factors including soil pH, soil mineralogy, soil: water ratio, cation and anion effects are investigated. The results of this study indicate that for soil that has a relatively low CEC, the anion type is an important factor, while the cation type does not noticeably affect the EC of the soil-solution. However, for such soil, an electrolyte property, i.e. its solubility, is much more effective than the CEC of the soil. In addition, it was observed that in the presence of neutral salts such as pore fluid, the pH of the soil-solution decreases causing an increase in the EC of the soil sample.

Keywords– Electro conductivity (EC), soil behaviour, pore fluid, pH of soil, salt

1. INTRODUCTION

In the majority of the world, soluble salts are found to be one of the main factors affecting soil behaviour. This is common in arid and semi-arid areas. Salts can be found in soils in soluble and exchangeable forms. Soil performance is affected by different types of cations and anions [1, 2]. In this process the soil mineralogy and its quantities play a significant role. Consequently, any variation in pore fluid properties and types may affect the soil performance. Such variation usually happen in the reservoir of dams or in some geotechnical, and geo-environmental projects. Electro conductivity (EC) may be used as a practical tool for monitoring any change in the pore fluid. The primary purpose of the conductivity measurement logging system is to determine variation in soil conditions with depth. This data can then be used to aid in the interpretation of subsurface geology and groundwater or contaminant movement. Agricultural scientists can also use it for the purpose of determining optimum soil salinity.

One important aspect of soil-solute interaction is the seepage of fresh water, which can dissolve the soluble salt of soil. A decrease in the concentration of soluble salt not only provides several micro and macro pores in the soil, but also affects the geotechnical and geo-environmental performance of soils. Soil settlements, consolidation settlements, piping and dispersivity are some of the side effects of salt removal in soils by fresh water [3, 4]. In terms of geotechnical aspects, it is known that if the quantity of soluble salts exceeds one percent of the dry weight of soil, some treatment is required before any foundation can be built on it. In addition, if the salt content of soils exceeds 6 percent, it may need to be replaced in some

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[**] Corresponding author

specific projects [5, 6, 7]. A measurement of EC is a practical tool for finding out about the quantity of the soluble salts of the pore fluid of soil [8]. For this purpose, it is recommended to assume the whole salt fraction of soils has the possibility of being removed during the seepage of fresh water. During such a process, a significant change in soil performance may occur. Based on this fact, in experimental studies it is essential to take into consideration the soil:water ratio, making sure that all soluble salts come to the pore fluid.

Several kinds of instruments for measuring water content and EC in soil have been reviewed [9]. Theories behind measuring water content and salinity of soil using TDR (time domain reflectometry) are introduced by Noborio [9]. An experimental investigation by Utset and Castellanos [10] shows that drainage not only reduces EC values, but also notably changed EC. The effects of EC and the sodium adsorption ratio (SAR) on soils possessing various amounts of organic matter were addressed under laboratory conditions [11]. A multi-needle probe was presented which could yield the measurement of soil thermal diffusivity, volumetric heat capacity and soil EC [12]. In terms of the soil pore fluid effect on the EC variation, it is reported that the variations of the EC of soil samples are a pH dependent phenomenon [8]. It is also shown that a sodium chloride solution with a concentration of 0.05 mol/l raises the reactivity of the EC probe [13]. It is also indicated by Blewett *et al*. [14] that conductivity measurements could be used to track ionic movement through clay during a diffusion process. In such a case, from the measurements of conductivity of the pore fluid, one can quantify the pore tortuosity and the effective diffusion coefficient of saturated clay.

It is known that the conductivity of soils can be influenced by many factors. Usually, high conductivities are associated with clay-rich soils, and low conductivities are associated with sandy and gravelly soils. This can be attributed to the shape and fabric of these soils. Clay particles tend to be pancake-shaped and lie flat against each other, giving them a high degree of surface-to-surface contact and thus allowing electricity to pass easier from grain to grain. Sand grains tend to be more spherical and thus they have a lower degree of grain-to-grain contact. In general, the specific conductance or EC of a solution is a function of the total amount of dissolved ions, the type of ions, and their potential to form charged or non charged pairs or complexes.

Generally, while more attention has been paid to the different methods for the EC measurement of soil pore fluid, less attention has been paid to the effect of soil pH, soil mineralogy, soil: water ratio, and cation and anion effects on the EC variation of soil. The objective of this study is to conduct an investigation of the impact of soil-pore fluid on the EC of clayey soils. An attempt is made to relate and to investigate the impact of pore fluid properties of soils, soil: water ratio, clay mineralogy, pH, and anion and cation type on the EC variation of soils.

2. MATERIALS AND METHODS

This study was performed using natural un-weathered marly soil, representing the marly soils of the north–west area of Iran (Azarbayjan province, Tabriz). The marly soil of this region will be slaked immediately in contact with water and needs treatment before being used in any geotechnical project. A pure illitic soil is also used in this research. Illite (Domtar sealbond) was obtained from Domtar Construction Materials, Ltd., and comes from pulverizing Canadian old marine shale and is known as a major material of the Champlain Sea Clay [15].

Various experiments were performed based on the methods given by different investigators [16-18] as follows. EC was measured by the method given by Tanji [16]. CEC was determined by the $BaCl_2$ replacement method [17]. Physical and chemical properties including specific gravity, particle size distribution, atterberg limits, and pH measurement were determined according to ASTM standards [18].

Pore fluid chemistry analysis was performed to focus attention on the chemical aspects of soil samples. An Atomic Absorption Spectrophotometer (AAS-GBC 932, AB Plus) was used to analyze the soil pore fluid of the samples.

To measure the EC of pore fluid, a conductivity-meter model WTW-LF538 was used. The sensor of the conductivity-meter simply consists of two metal electrodes that are exactly 1 centimeter apart and protrude into the water. A constant voltage (V) is applied across the electrodes. The voltage difference is then measured between the electrodes. The greater the voltage difference, the lower the EC of the soil that is in contact with the probe. An electrical current (I) flows through the water due to this voltage. This current is proportional to the concentration of dissolved ions in the water.

Soils that have more ions in their pore fluid will be more conductive. Distilled water or de-ionized water has very low dissolved ions; therefore, there is almost no current flow across the gap of the probe, showing a low electrical conductivity. EC can be expressed by two units of micro-mhos per centimeter (μmhos/cm) and micro-Siemens/cm (1 μmhos/cm=1μS/cm).

Tables 1 and 2 present some physico-chemical characteristics of the marl and illitic samples used in this study, respectively.

Table 1. Characteristics of marly soil of Tabriz

Characteristic	**Quantity Measured**
Liquid Limit (LL%)	68.2
Plasticity Index (P.I. %)	40.8
Total Dissolved Salt (TDS, (Cmol/Kg soil))	5.02
CEC (Cmol/Kg soil)	14.8
EC (dS/m) (1:10, soil:water ratio)	0.66
pH (1:10, soil:water ratio)	8.9
G_s	2.59
Clay Fraction	58%
Soil Classification	CH (Clays of High Plasticity)

Table 2. Characteristics of illitic soil

Characteristic	**Quantity Measured**
Liquid Limit (LL%)	27.5
Plasticity Index (P.I. %)	8.4
Total Dissolved Salt, (TDS, (Cmol/Kg))	2.11
CEC (Cmol/Kg soil)	46.4
EC (dS/m) (1:10, soil:water ratio)	0.2
pH (1:10, soil:water ratio)	8.6
G_s	2.67
Clay Fraction	28%
Soil Classification	CL (Clays of Low Plasticity)

3. SAMPLE PREPARATION

The quantity of added salt is calculated based on the weight of the dry sample according to the following equation:

$$PS=[Ws/(Wd+Ws)] \times 100 \qquad (1)$$

In Eq. (1):

PS: Percent of salt

Wd: Dry weight of soil

Ws: Salt weight in soil

After the addition of the required salt to the dry marl and illite, respectively, distilled water was added to the samples. The addition of water was enough to prevent the salt-saturated condition of the soil samples. To achieve this, different soil:water ratios were chosen as follows: 1:0.5, 1:1, 1:2.5, 1:5, 1:10, 1:50, 1:100, and 1:200. In each experiment, 4 grams of soil was used. Based on the above soil:water ratio, the term "soil content of mixture", which is used in the rest of this paper, is defined as the amount of the soil over the weight of the soil:water mixture. Therefore, for the above soil: water ratios, the corresponding percentage of "soil content of mixture" will be 66.67, 50.00, 28.57, 16.67, 9.09, 1.96, 0.99, and 0.50%, respectively. After the samples were prepared they were shaken for 2 hours on a horizontal flat shaker. Samples were then kept for 24 hours to achieve equilibration without any shaking. After this process, the samples were shaken again for a short period and centrifuged for 15 minutes at 3000 rpm. The supernatant from each sample was analyzed for EC. This is in accordance with the method proposed by several authors (APHA/AWWA/W PCF, [16, 19]). For the same samples, pH was measured using a pH meter model HANNA Hi-9321. For instrument calibration, a 0.01 molar solution of KCl with a known EC=1.413 dS/m was used for EC measurement. Solutions with pH 4.1, 7, and 9.2 were used for calibrating the pH meter.

For a precise evaluation of the experimental results of the EC measurements, a series of experiments were allocated for the error analysis of the results. 10 samples of illitic soil were mixed with 1% sodium sulfate and diluted to a 1:10 soil: water ratio. The aforementioned procedure of sample preparation for the EC measurement was performed on these samples. Then, the EC rates of the samples were measured, taking into consideration the error caused by the preparation process. The same procedure was repeated for a sample of the same soil with 10% sodium sulfate as an additive. The results indicate that both the variance and the coefficient of variation (COV) of the experiment are affected by solution concentration. For instance, while the COV of a sample with 1% additive concentration is 0.32%, the COV of a sample having a 10% concentration of sodium sulfate is 0.1%. In other words, the COV decreases with increasing additive concentration, showing an increase in the precision of the experiment with the increase of the electrolyte concentration. In addition to this, it was observed that the measured EC was not affected by taking readings at different time intervals.

4. RESULTS AND DISCUSSION

One of the problems associated with marly soils is their slaking behaviour in contact with water. Since natural marl needs to be ground before the application of any geotechnical and geo-environmental test, it is necessary to investigate the effect of grain size distribution of marly soil upon its EC. Furthermore, the evaluation of the cation effect, the anion effect, and pH variation on the EC measurement of soils are the other objectives of this study.

a) Size effect on EC measurement of marl

Figure 1 compares the variation of the EC of marly samples in different soil content mixtures. The variation of the EC of the soil in two cases, soil-passing sieve #10, and soil passing sieve # 200 are compared. Grain size analysis of the marly sample shows that after grinding, more than 95% of the sample passes through sieve #200. During the grinding process, it was observed that grinding counteracts the weak bonding of particles that are formed by the consolidation process. Considering this piece of information, one may come to the conclusion that the grinding process of a marl sample will not noticeably affect the EC characteristics of soil. The same conclusion can be drawn from Fig. 2, in which the pH measurements of the same two samples are presented. An error analysis on a series of controlled samples shows that the coefficient of variation of the EC measurement is 0.32%, which means that the difference of the EC of the samples in Fig. 1 is less than the error caused by sample preparation. These conclusions confirm the accuracy of the method for the marl sample preparation for experimental studies proposed by Ouhadi and Yong [21].

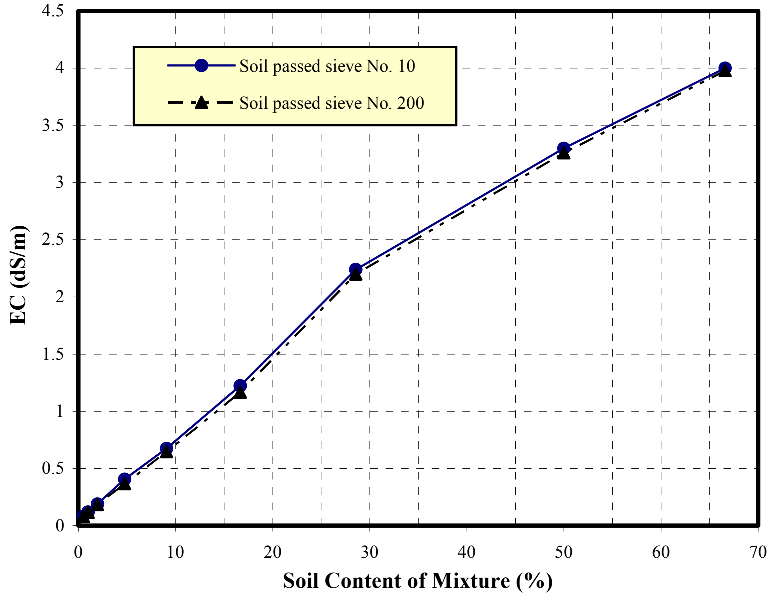

Fig. 1. Soil content and particle size effect on EC

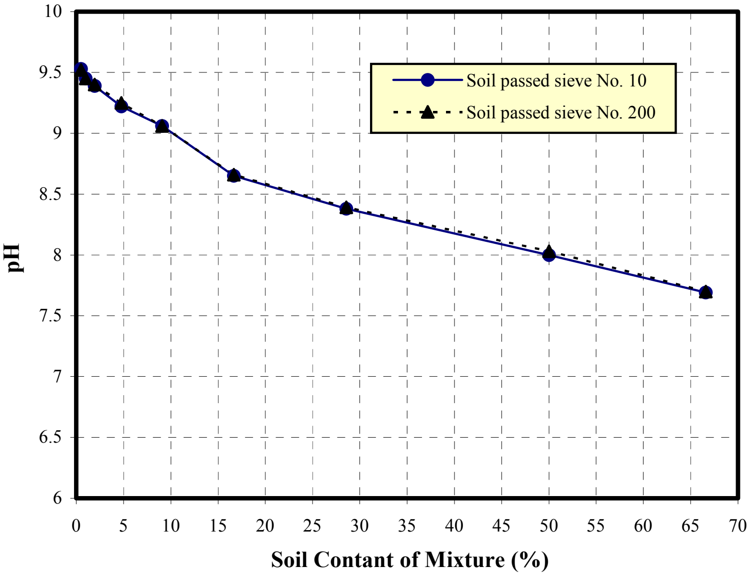

Fig. 2. Effect of particle size on pH

b) Cation effect on EC measurement

The most common cations of soils include Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}. Among them, Ca^{2+} and Na^{+} are the most common cations found in the pore fluid analysis of soils [1]. One of the applications of the EC measurement could be the achievement of the impact of cation type and/or cation concentration of pore fluid on the EC response of soils. In particular, calcium and sodium ions are known to affect soil behavior and performance differently. For example, while the presence of calcium ion in the pore fluid leads to a more flocculated structure, providing higher porosity, increasing short-term settlement and decreasing consolidation (long-term) settlement, the presence of sodium in the pore fluid of soil may cause different behaviours in different concentrations present in soils [1, 2].

To investigate the effect of cation type and concentration on the EC response of soils, several experiments were performed as follows. For this purpose, the role of sodium chloride and calcium chloride, in different concentrations, on the EC of an illitic sample and a marly sample were investigated. Figures 3 and 4 show the results. It can be seen in Fig. 3 that, as expected, by increasing salt concentration, the EC of the sample was increased in all experiments. An important conclusion, which may be drawn from the results presented in Fig. 3, is that regardless of cation type, sodium and calcium in like proportion presented in the pore fluid provide similar EC. The same conclusion can be drawn from data presented in Fig. 4. In other words, in the case of illitic and marly samples, with similar salt concentrations of $CaCl_2$ and NaCl, a similar EC is achieved. Specifically, the difference between the EC of samples having a similar percentage of salt is less than the standard deviation of experiments already addressed. Based on these results, one may come to the conclusion that since the concentration of salt is a major factor causing EC, the cation type of pore fluid does not noticeably affect the EC of soils having a relatively low CEC.

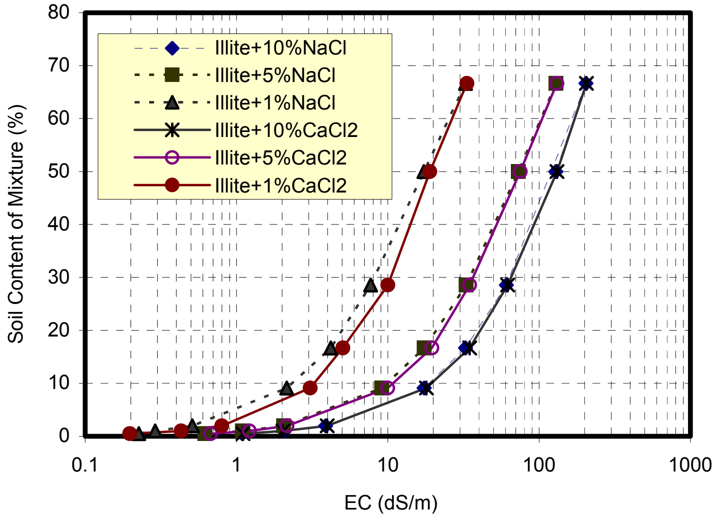

Fig. 3. Effect of cation type on EC of illitic soil

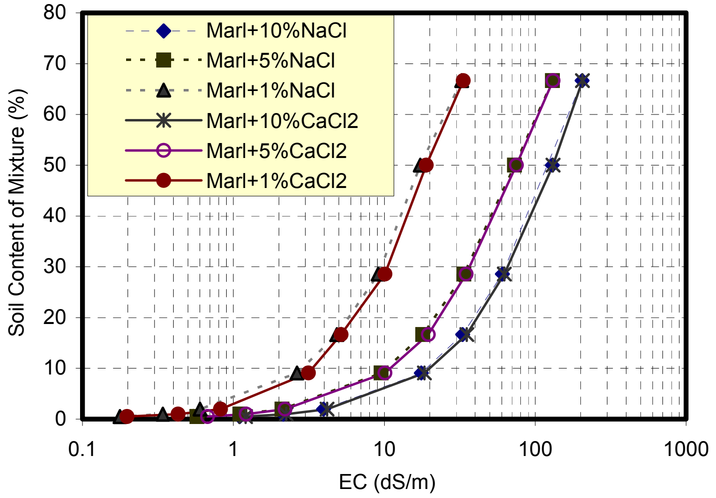

Fig. 4. Effect of cation type on EC of marly soil

c) Anion effect on EC measurement

The type of anion present in the pore fluid of soil may affect soil behaviour in different ways. Specifically, the presence of potential determining ions (PDI) such as HCO_3^- are known to increase the negative charge of particles, causing a more dispersed structure [17].

To investigate the role of different anions on the EC response of soil, several samples were prepared by mixing the soil samples and four different solutions including calcium chloride ($CaCl_2$), sodium chloride (NaCl), sodium sulfate (Na_2SO_4) and sodium bicarbonate ($NaHCO_3$). The achieved results are presented in Fig. 5. As can be seen in this Figure, the marly and illitic samples have the same EC pattern. This may be attributed to the relatively low CEC and pore fluid concentration of the marl and illitic samples. In contrast with the data presented in Figs. 3 and 4, it can be observed that solutions having similar percentages of cations with different anion species have different levels of EC. In fact, one may conclude that the achievement of similar EC in experiments presented in Figs. 3 and 4 is not only based on a similar concentration of cations, but is also based on similar anion types in pore fluid. A decrease in the EC of the samples with a PDI as their anion, in comparison with that of samples having sulfate or chloride as their anion, can be attributed either to the role of potential determining ions or to the difference of the solubility of additives. A series of experiments were performed to investigate which one of the aforementioned phenomena governs soil-electrolyte interaction. For this purpose the EC of soil-additives and other additives were measured separately. The results presented in Fig. 6 indicate that the second phenomenon governs soil-additive interaction. This behaviour may also be attributed to the relatively low CEC of the soil samples studied in this research.

d) The Role of pH variation on the EC of soils

It is known that pH variation may significantly affect the soil behaviour. While low pH may cause a flocculated structure, high pH may result in a dispersive or oriented structure. In addition, variations of pH may affect the suction performance of soil [3]. Even though there are several factors that may provide acidity or alkaline conditions, neutral salt concentration also may affect pH variation [2]. To investigate the role of salt concentration and the soil content of mixtures on the pH measurement of the samples, a series of experiments were performed. The results of these experiments are presented in Fig. 7. There we see the role of salt concentration and the soil content of mixtures on pH variation in pure marl and illitic samples. As can be seen in this figure, with increasing salt concentration, assuming that the soil content of the mixture is constant, i.e. moving down on a vertical line on the figure, we are faced with a decrease of pH in both series of samples. The presence of salts has at least two effects on soil behaviour. First, the presence of salt develops a flocculated structure in the soil sample because of the decrease in repulsive forces due to the neutralization of the negative charge of the soil surface. Second, because of the low pH level of the soil samples with a high concentration of salt, an increase in hydrogen concentration occurs, causing a multiple decrease in the repulsive force known as the pH effect. It is known that a soil: water ratio of 1:10 is a suitable soil content concentration for pH measurement. However, the results presented in this figure indicate that a soil: water ratio between 1:1 and 1:0.5 (i.e. soil content of mixture equals to 0.5 and 0.667, respectively) is much more effective in providing an equilibrium condition.

Part of the purpose of this study is to investigate the relationship between EC variation and pH change. Figure 8 shows the results for marly samples and illitic soil. As can be seen in this figure, a similar pattern can be observed for both soils. While a decrease in the EC in relation to an increase of pH is a normally expected behaviour, this figure shows that the EC of a sample with a specific concentration of salt is very sensitive to the soil: water ratio. For instance, when a soil: water ratio changes from 1:0.5 to 1:200, we are faced with several orders of magnitude of EC variations. The results of these experiments may be affected by the soil-cation interaction of the negatively charged surfaces of clay particles and different cation concentrations as follows: by increasing soil content concentration, two phenomena occur at the same time. First, increasing soil concentration provides much more surface to adsorb the cations of the environment, causing lower EC. Second, a decrease in pH means an increase in the hydrogen ion concentration, which in turn produces a higher EC. The results presented in Fig. 8 indicate that the second phenomenon controls the soil-electrolyte interaction in the soil samples used in this research. More experiments are needed to investigate the effect of the soil surface area, clay mineralogy and adsorption characteristics on this behaviour. Such an investigation will highlight the more effective factors controlling marl and illite behaviour with high and low salt concentrations.

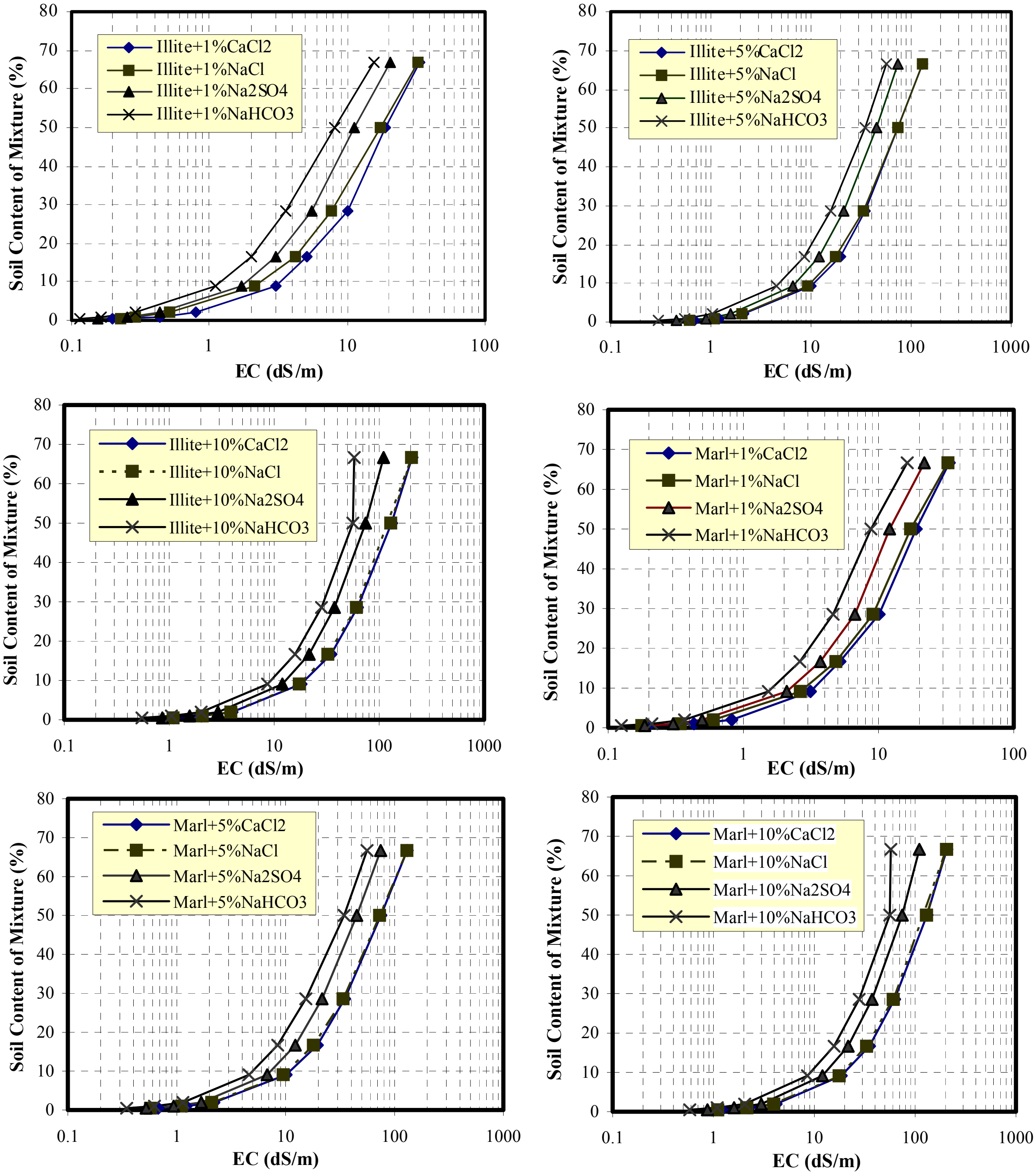

Fig. 5. Anion type effect on EC of marly soil and illite

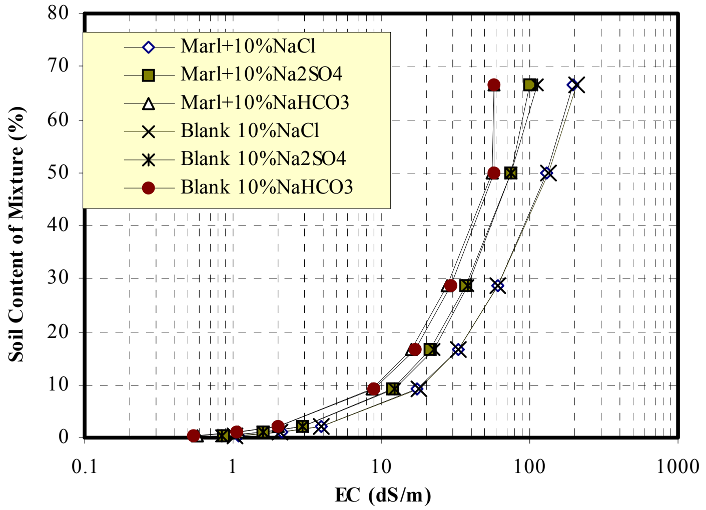

Fig. 6. Effect of solubility of additives on EC

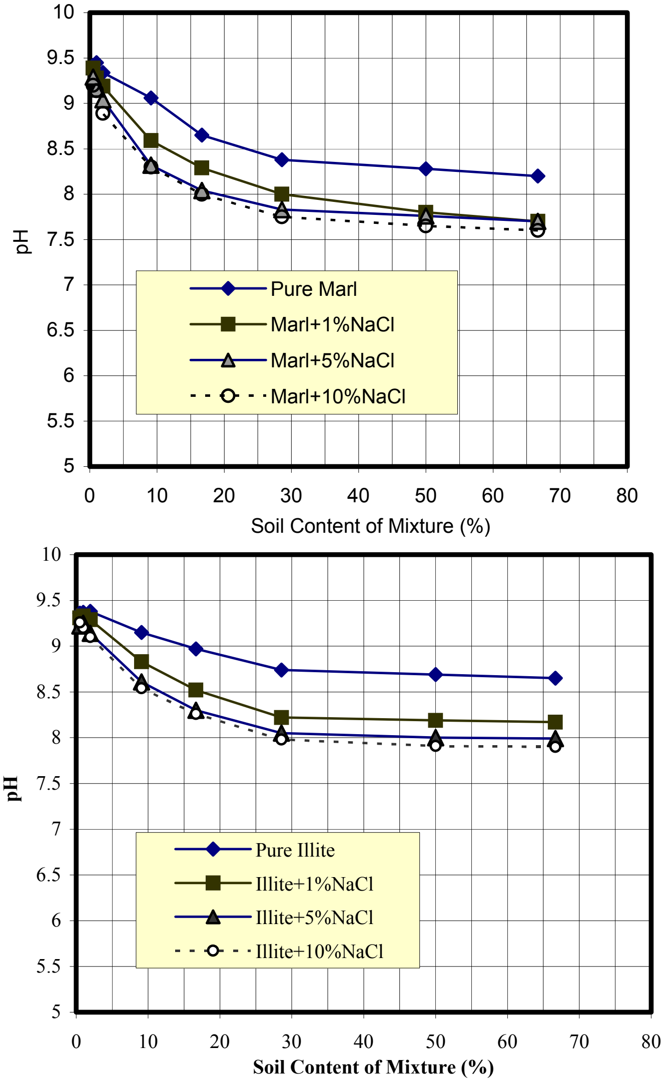

Fig. 7. Effect of salt concentration and soil content of mixtures on pH

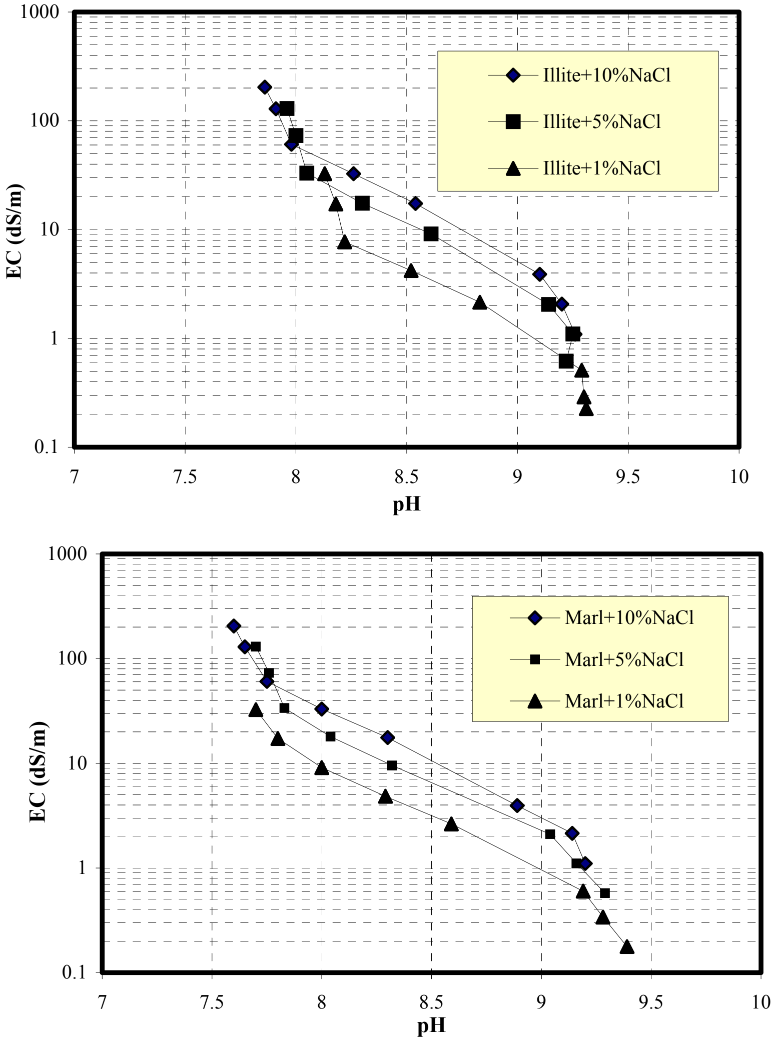

Fig. 8. Effect of pH on EC of marly soil and illite

e) Soluble mineral content estimation of soil

One of the applications of EC measurement is estimating the soluble mineral content (SMC) of soil. For this purpose, the following equations are proposed [20]:

$1\ \text{mmhoscm}^{-1}\ (\text{EC}) \times 10 = 10\ \text{meq L}^{-1} \times 64\ \text{mg (meq)}^{-1}$

$= 640\ \text{ppm (dissolved solids)}$

In other words, we can conclude that:

$$\text{(Dissolved solids) DS} = \text{M} \times \text{EC} \qquad (2)$$

The unit of EC in the above equation will be dS/m and the unit of M is ppm/(dS/m), which is equal to 640. Therefore the dissolved solids will be obtained with ppm. Finally, one may calculate the percent of SMC based on the following equation [4]:

$$\text{SMC (\%)} = \text{A/B} \qquad (3)$$

In Eq. (3);

$\text{A} = \{\text{DS (mg/L)} \times \text{Volume of Water (L)} \times 100\}$ and,

$\text{B} = \text{Specimen mass (g)} \times 1000\ \text{(mg/g)}$

The above-mentioned equation entails the following assumption: increasing the soil:water ratio causes a decrease in SMC. This assumption is an acceptable one since an increase in the soil:water ratio causes more surface interaction with electrolytes. Therefore, due to the higher adsorption of electrolytes by soil particles, a lower SMC will result. On the other hand, the main problem associated with these suggested equations is the fact that they do not take into account the effect of the anion type on EC, or the pH effects on this phenomenon. Figure 9 is a plot of the data achieved in this research based on the equation proposed for SMC estimation by different authors [4, 20]. This figure indicates that for similar cation concentrations with different composition sources, i.e. different anion types, the above-proposed equation estimates different levels of SMC. In general, one expects to have a similar SMC for soil samples prepared with similar concentrations of NaCl and Na_2SO_4. One may conclude that the usefulness of the EC measurements of solutions may be restricted to the estimation of optimum soil: water ratio, which causes a salt saturation condition. Such a condition is understood from the horizontal part of the curves presented in Fig. 9. In all six cases, it seems that a soil: water ratio of around 1:1 to 1:2.5 provides a relatively saturated condition. To confirm this conclusion, the EC measurement versus the soil content of mixtures for a series of marly soils, having different solutions with similar salt concentrations is presented in Fig. 6. This figure shows that at a soil:water ratio between 1:1 and 1:0.5 the trend of the data becomes almost vertical. In other words, with the increasing soil content of the mixture one may conclude that at a soil: water ratio between 1:1 and 1:0.5, a salt saturation condition is achieved.

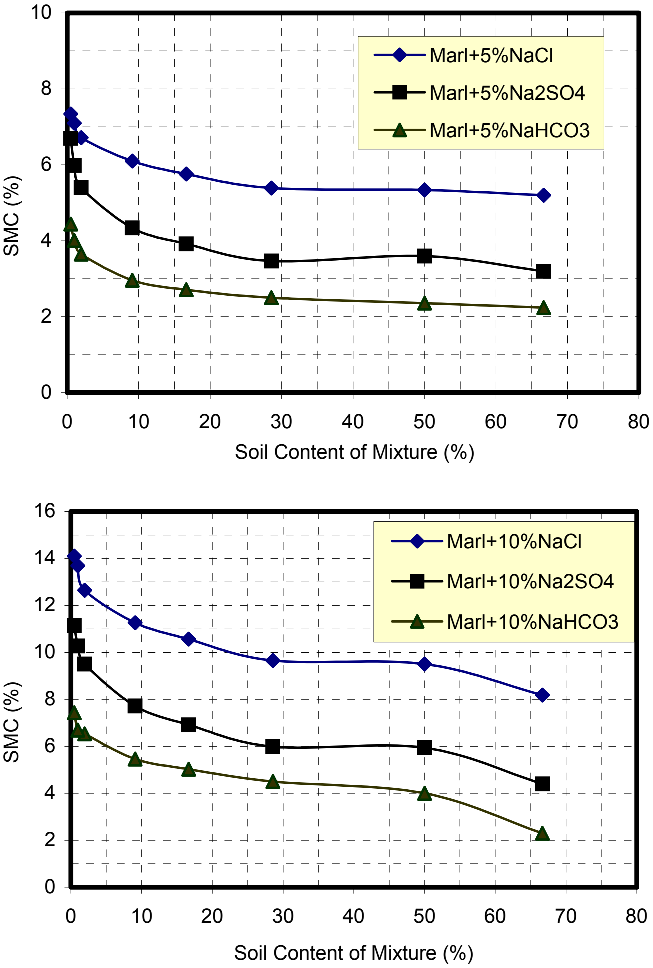

Fig. 9. Estimation of SMC in controlled samples

5. CONCLUDING REMARKS

From the results of this research the following conclusions can be drawn: (1) For soil having a relatively low CEC, while the cation type does not affect the EC of the soil-solution, the anion type is an important factor. However, for such a soil, electrolyte properties such as its solubility are much more effective than the CEC of the soil. (2) It was observed that in the presence of neutral salts such as pore fluid, the pH of the soil-solution decreases, causing an increase in the EC of the soil sample. (3) In the case of soils having a relatively low CEC, in terms of the EC variation of the soil-solution, the degree of solubility of additives used in this research is a more effective factor than the soil-additive interaction. (4) It was observed that a soil: water ratio between 1:1 and 1:0.5 provides the optimum equilibrium condition for the pH measurement, while a soil:water ratio between 1:1 and 1:2.5 provides a better equilibrium condition for SMC measurement. (5) The greatest benefit of the EC measurement of solutions may be restricted to the ability to estimate the optimum soil: water ratio that provides salt saturation conditions mainly in terms of cation monitoring.

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