

Research Article

Effect of Pore-Water Salinity on the Electrical Resistivity of Partially Saturated Compacted Clay Liners

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The aim of this paper is to investigate the effect of pore-water salinity on the electrical resistivity (ER) of different compacted clay liners (CCLs) in terms of its mineralogical composition. For this purpose, an experimental programme was conducted where ERs of different kaolin-dominant CCL specimens, reconstituted using water having different concentrations of NaCl (0 M, 0.5 M, and 1.0 M), were measured. The kaolin-dominant CCL specimens tested in this study include pure kaolin, three different kaolin-bentonite mixtures, and three different kaolin-sand mixtures. The experimental results show that the ERs of CCL specimens decrease as the salt concentrations in pore water, moisture content, and dry density increase. At constant density and moisture content, the test results also indicate that increasing the sand content in kaolin-dominant CCL specimens increases its ER regardless of the water salinity level. This behaviour could be attributed to the lower surface conduction of sand compared to kaolin. However, at constant density and moisture content, increasing the bentonite content in kaolin-dominant CCL specimens decreases its ER in the distilled water environment as surface conduction of bentonite is higher compared to that of kaolin. On the contrary, in saltwater environments, ER increases as the bentonite content increases. This behaviour could be explained in terms of the expected aggregated microstructure of bentonite in the saltwater environment that could reduce the number and area of interparticle contacts, and consequently, increase the ER of CCL specimens.

1. Introduction

Landfill facilities that usually have a cover and liner system are constructed to store the municipal solid wastes (MSWs) to protect the environment [1]. The compacted clay liners (CCLs) in the liner system are constructed as a layer of hydraulic barrier to separate the leachate or toxic pollutants from the MSW into the subsoils or groundwater, to ensure good conditions of the subsoils [2–6]. The CCLs are constructed of the natural soils or by combining them together with some other geosynthetics (e.g., geomembrane, geotextiles, and geosynthetic clay liners) based on different hazardous levels of MSW [7]. The requirement for CCLs is to have a hydraulic conductivity less than 10^{-9} m/s [8]. Among these natural soils to form the CCLs, bentonite is considered as an excellent material to have low hydraulic conductivity ranging 10^{-11} – 10^{-12} m/s [9, 10]. However, due to the

unavailability in some regions and strong volume change after swelling/shrinkage [8, 11, 12], other soils to satisfy the same requirement for the CCLs are also being used [13–16]. One example to replace bentonite is to add a specific percentage of clay (e.g., kaolin) or sand (e.g., silica sand), so the CCLs in the liner system will have less deformation [12]. In fact, the suitability and advantages of some man-made clay liners with kaolin-bentonite (K-B) or kaolin-sand (K-S) mixtures with different compositions have been reported in some research [13, 17]. They have shown that the additions of kaolin and sand will reduce the swelling capacity and improve the mechanical behaviour of the liner system [14, 18–20].

Leachate with different chemical compounds from MSW is a potential issue that will compromise the CCLs, resulting in the subsoils and groundwater significantly contaminated [8]. In fact, monitoring the performance of CCLs and

leachate is important to the environment and community; thus an observation for CCLs maintained in good condition is critical. There are several geophysical methods available to be used such as electrical resistivity imaging (ERI), seismic refraction, ground penetrating radar, and multiple-channel analysis of surface waves. Among those techniques, ERI is recommended to evaluate the homogeneity of CCLs as the technique is an efficient method since it diminishes the time and cost constraints [21, 22]. The ERI technique is used to perceive the continuous changes in the ER of the geo-materials due to the presence of contaminants at a large or small portion. As a result, the relationship between ER of CCLs and other physical properties should be established. Several studies have reported that soil ER can also be controlled by soil mineralogy, pore-water salinity, particle-size distribution, the impact of compaction, the degree of saturation, and porosity [23–28]. However, investigations on the ER of kaolinite-dominant clay liners affected by different salt concentrations in water have been insufficient. The present paper aims at analysing the influence of pore-water salinity on the ER of CCLs at different compositions.

2. Materials and Methods

2.1. Characterisation of Materials. Two types of clay, namely, kaolin (K) and bentonite (B), and one type of sand (S) were used in this study to constitute seven different soil mixtures in this study as listed in Table 1. Table 2 provides the geotechnical properties of clays, obtained from [26, 27], whereas Figure 1 illustrates the particle-size distribution of the clays (laser diffraction method) and sand [29]. The maximum and minimum void ratios of the sand were 0.97 and 0.58 [30, 31]. The liquid and plastic limits of clays are based on [32].

2.2. Sample Preparation and Experimental Setup. For each CCL mixture, a known mass of dry soil mixture was mixed with a specific amount of water to obtain the desired moisture content. Four to five different moisture contents were targeted in this study ranging between 5% and 25%. To investigate the effect of pore-water salinity on ER, three different NaCl-water solutions (0.0 M, 0.5 M, and 1.0 M) were used in this study. An automatic mortar mixer was used to guarantee the proper mixture of soil specimen and water. To ensure uniform distribution of moisture, water was sprayed on each specimen to reach the targeted water content. After the mixing procedures, each soil mixture was carefully placed inside air-tight bags at room temperature for 24 hrs for moisture equilibrium, in compliance with some relevant research [33, 34]. After 24 hrs, the soil mixture was placed into a ring, which has a diameter of 50 mm and a height of 20 mm. Then, the top of the test specimen was properly levelled.

To get different dry densities of the test specimens, static compaction using a displacement-controlled loading method was applied in this study as shown in Figure 2. Under the static compaction, a negligible discrepancy in density along the sample's height can be achieved if the

TABLE 1: Kaolin-dominated mixture (by weight).

Mixture name	Kaolin (K) %	Sand (S) %	Bentonite (B) %
k10	100	0	0
k9s1	90	10	0
k8s2	80	20	0
k7s3	70	30	0
k9b1	90	0	10
k8b2	80	0	20
k7b3	70	0	30

TABLE 2: Properties of testing soils [26, 27].

Properties	Kaolin	Bentonite
Liquid limit (%)	74	504
Plastic limit (%)	32	53
G_s	2.58	2.68
pH in water (28%–40% solid)	7	9.5
Cation exchange capacity (meq/100 g)	0.075	80
Total surface area (m^2/g)	20	750
Surface charge density ($\mu C/m^2$)	0.36	10.24
Optimum moisture content (%)	29	23
<i>Main chemical composition (weight %)</i>		
SiO ₂	45.2	63.8
Al ₂ O ₃	38.8	13.6

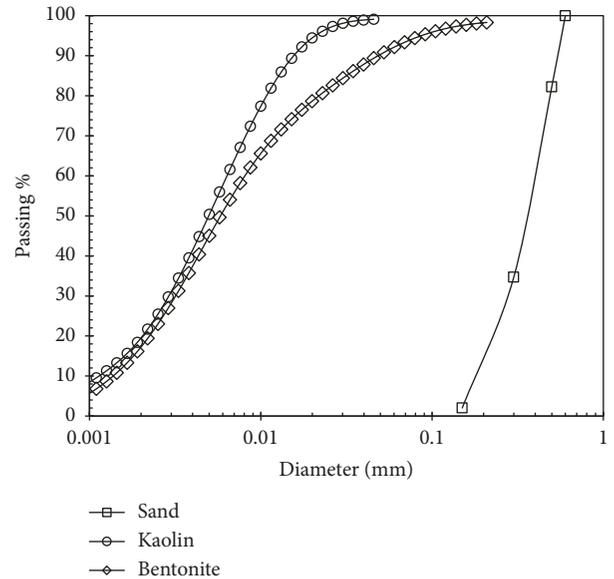


FIGURE 1: Particle-size distribution of tested soils.

specimen's diameter is greater than the doubled height [35]. The ring used in this study satisfies that condition.

The ring, including the test specimen, was placed in a loading frame where the upper surface of the specimen was subjected to a constant displacement rate of 0.2 mm/min via a top loading steel cap as presented in Figure 2. Once the targeted height was achieved, the loading procedure was stopped. The specimen was left under a constant volume

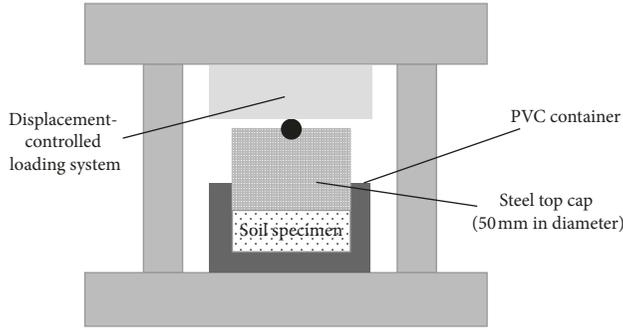


FIGURE 2: Controlling dry density using the displacement-controlled loading system.

condition for around 1.0 hr to ensure the homogeneity and stress relaxation of the specimen and to minimise its elastic rebound during the unloading step. After the unloading, the ring was carefully taken out of the frame. In the next step, the final height, ER, and the total mass of the specimen were measured. The Wenner four-electrode method was applied to measure the ER of test specimens (Figure 3) [36], which has been discussed in the succeeding section. Once the measurements were done, the ring was repositioned into the loading frame to obtain the next targeted height. This process was repeated four times to obtain ER-dry density relationship of the tested soil mixtures at certain moisture content. Since the moisture content was kept constant, the degree of saturation increased as the height decreased under static compaction process. The experimental programme in this study produced over 400 readings of ER for test specimens having different soil mixtures, moisture contents, dry densities, and pore-water salinities. Figures 4 and 5 illustrate the range of dry density, water contents by mass (% W_c), degree of saturation (%Sr) of the different test specimens in this study.

2.3. Measuring Electrical Resistivity. The ER of test specimens was measured using the Wenner four-electrode method [36]. For this purpose, the steel loading cap used for the static compaction purpose was replaced by a modified plastic cap containing four copper electrodes (two outer and two inner electrodes, each 0.8 mm in diameter) as shown in Figure 3. As per the configuration, the electrical current flows through the two outer electrodes and the voltage drop was monitored by the inner electrodes. It has been reported in the literature that four-terminal pair configuration deals with perturbation better than the two-electrode method, as the former is capable of reducing the electrical interference and the electrode polarisation [37].

According to the Wenner four-electrode method, the four electrodes are aligned linearly with equal spacing, a , from each other (approximately 5 mm) and a protrusion of 1 mm into the soil specimen. A voltage was applied between the outer electrodes, and the corresponding current, I , and the voltage drop between the inner electrodes, V , were calculated. The calculated values were computed in the ER measuring equation, which is as follows:

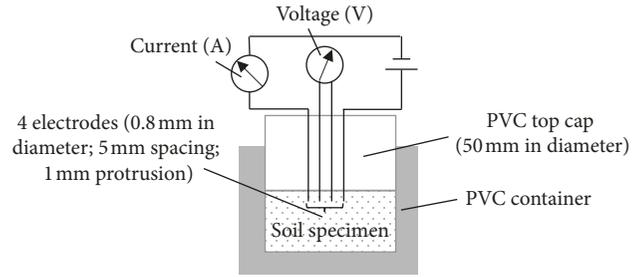


FIGURE 3: Measuring electrical resistivity using the Wenner four-electrode method.

$$ER = 2\pi a \left(\frac{V}{I} \right). \quad (1)$$

The Wenner four-electrode method provides an average ER of a hemisphere of space within the test specimen where the radius of hemisphere space is approximately proportional to the electrode spacing and the term $2\pi a$ is a geometric factor defined based on a semiinfinite boundary condition (half space). The impact of geometric factors is decisive to confirm the precise measurement of ER. To calibrate the experimental setup used in this study, the test cell was filled at different heights with two reference salt concentrated water solutions of known ER. Similar approach was used before by Suits et al. [37]. The calibration results showed that the measured ER is quite identical to that of reference salt solutions, up to 10 mm of height. Therefore, an accurate measurement of ER can be made, using the developed cell in this study, provided the thickness of the test specimen is greater than 10 mm.

3. Results and Discussion

Figure 6 shows the typical test results in the 3D domain of electrical resistivity (ER), water content (W_c), and dry density (ρ_d) for k7s3 and k7b3 where different water in terms of the salinity levels (0.0 M and 0.5 M) were used. The results in Figure 6 indicate that a constitutive electrical resistivity surface (CERS) in the domain of ER- W_c - ρ_d can be determined for each CCL mixture where the range and the geometric configuration of CERS are functions of the CCL composition and the pore-water salinity. In general, the typical results in Figure 6 show that, regardless of CCL composition and pore-water salinity, ER decreased nonlinearly as the water content and dry density increased. Furthermore, as the fine content/plasticity of CCL and/or pore-water salinity level increased, ER decreased as seen in Figure 6.

To understand the effect of pore-water salinity on ER of different soils in terms of its composition, moisture content, and dry density; a parametric sensitivity analysis was conducted using the extensive experimental results of this study. For this purpose, a statistical approach was used to model the different generated CERS in this study where the minimum correlation coefficient (R^2) of the models was >0.98 as presented in Figure 6. In the following sections, a conceptual understanding for the possible effect of changing pore-water salinity on ER of CCL will be discussed. Then, the

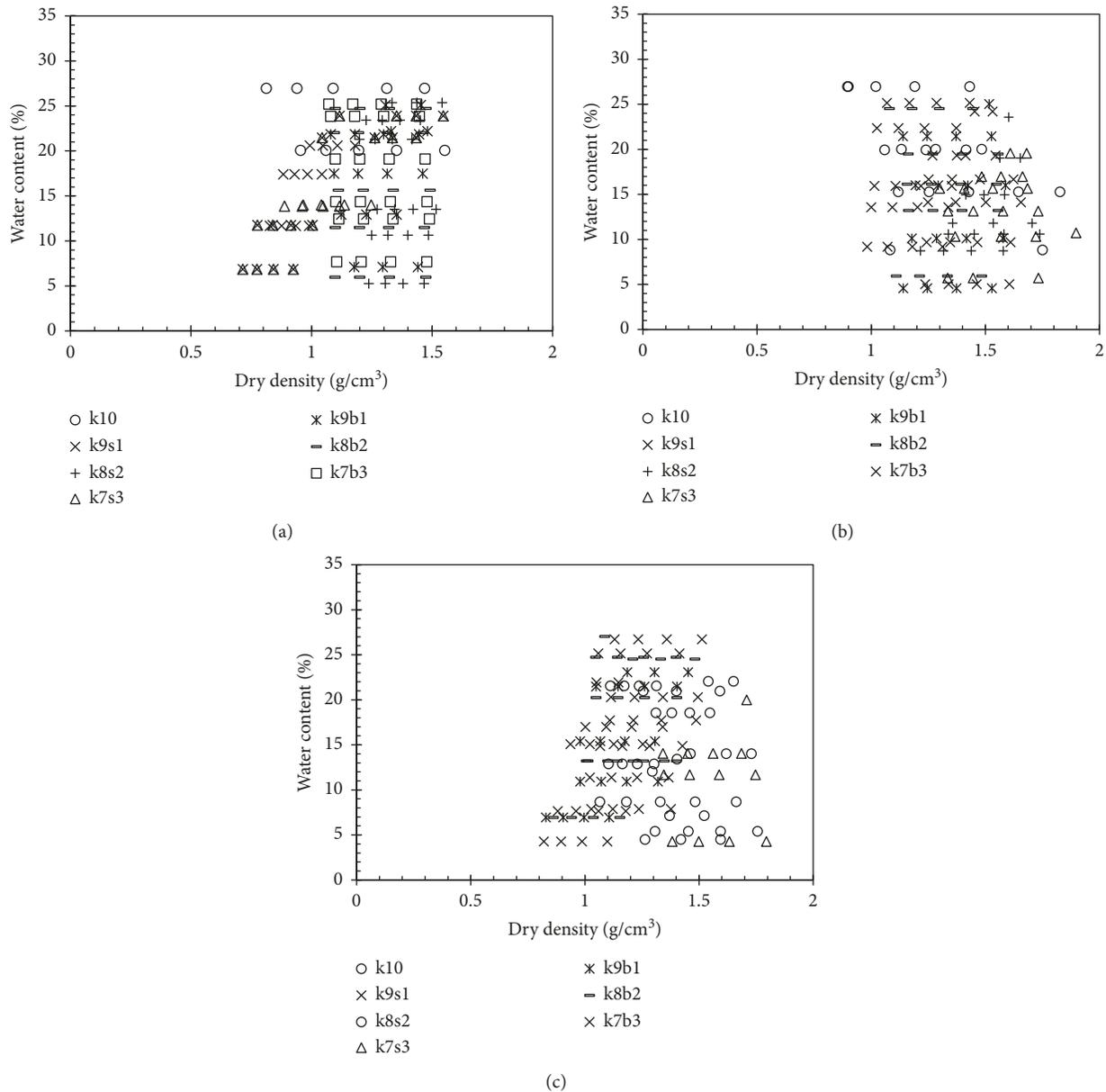


FIGURE 4: Water content (%) against dry density (g/cm^3) of kaolin (K), kaolin-sand (K-S), and kaolin-bentonite (K-B) constituted at different salt concentrations: (a) 0 M, (b) 0.5 M, and (c) 1 M.

experimental evidence on the effect of pore-water salinity on ER results, from this study, will be presented and discussed taking into consideration the possible role of mineralogical composition of CCL.

3.1. Conceptual Understanding for the Effect of Pore-Water Salinity on ER of CCL. ER of clays is a function of water content and salinity, pore-water connectivity, surface conduction of clay particle, number and area of interparticle contacts (microstructure configuration and dry density), and temperature [26, 27]. It is known that as the salinity of pore water increases, its ER decreases and consequently ER of clay should also decrease. However, it is believed that the effect of

pore-water salinity on ER goes beyond this direct effect. Hasan et al. [27] reported that the surface conduction of clay particle is a function of clay plasticity and salinity level of pore water. The surface conduction increases as the clay plasticity and pore-water salinity increase. Therefore, the contribution of surface conduction into ER of clay increases and brings ER further down as the salinity level of pore water increases.

Several studies [5, 38–40] reported that the salinity of the water could affect the microstructure configuration of compacted clay liner. In fact, the microstructure configuration of CCL is controlled by the magnitude of developed interparticle repulsive forces during the hydration process of clay particles [11]. The hydration-induced interparticle

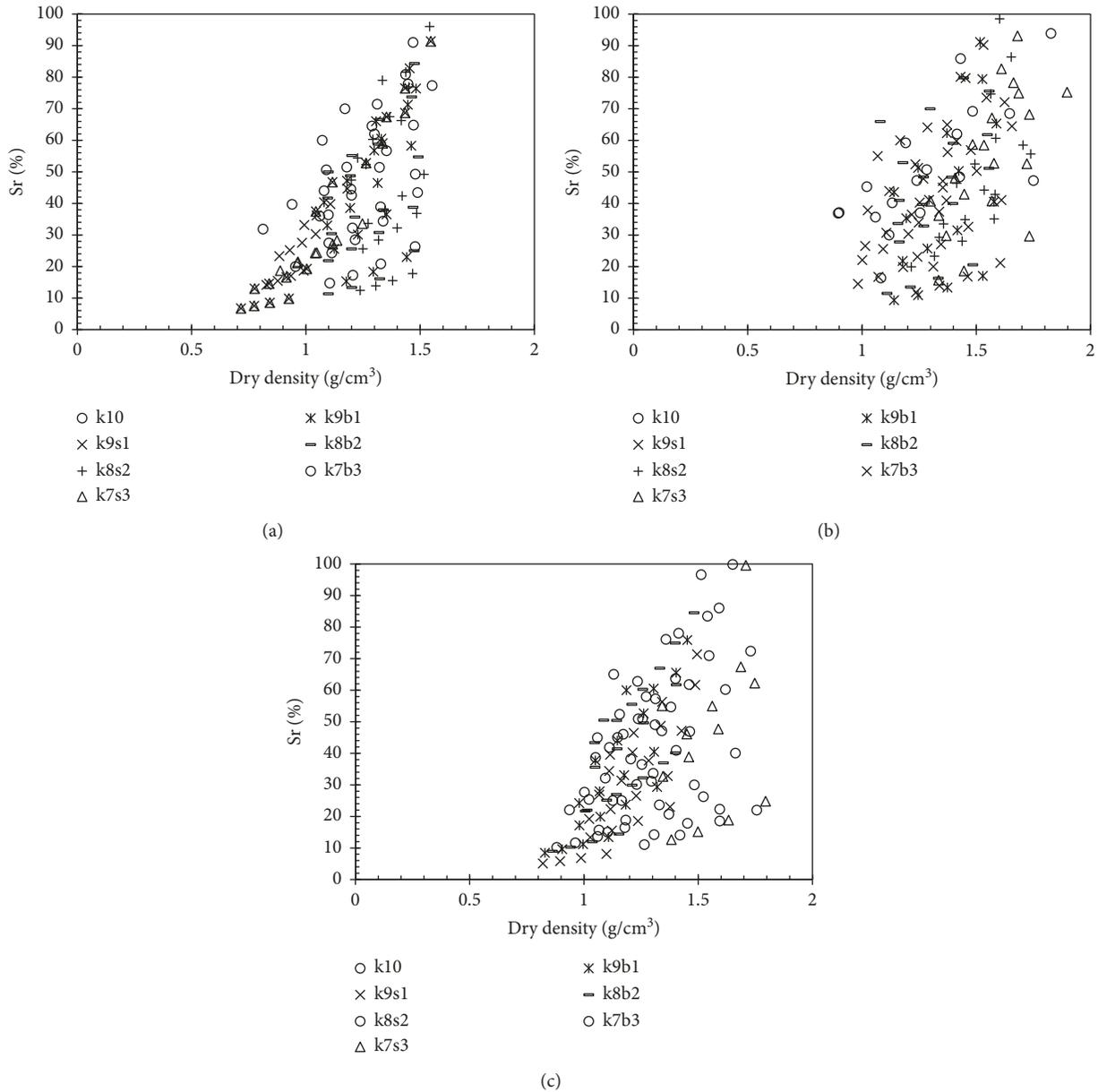


FIGURE 5: Degree of saturation (Sr %) against dry density (g/cm^3) of kaolin (K), kaolin-sand (K-S), and kaolin-bentonite (K-B) prepared at different salt concentrations: (a) 0 M, (b) 0.5 M, and (c) 1 M.

forces depend on the available water content, salinity of water, and mineralogy of clay particles [41, 42]. For partially saturated clays, as the salinity of water decreases and water content and clay plasticity increase, the interparticle repulsive forces increase [43]. Several researchers showed that reconstituting a clay specimen with distilled water could produce a monomodal pore size microstructure (uniform pore size) whereas aggregated microstructure (bimodal pore size) is expected as the salinity of pore water increases [5, 38, 44, 45]. Therefore, for clay specimens reconstituted at constant water content and dry density but using different water in terms of its salinity level, a different number and area of interparticle contacts are expected. Consequently, ER of these specimens will also be affected.

3.2. Effect of Pore-Water Salinity on ER of Pure Kaolin Specimens. The results in Figures 7 and 8 depict the evolution of ER of K10 CCL specimens as pore-water salinity, moisture content, and dry density change. The results indicated that, as the pore-water salinity, dry density, and moisture content increased, ER decreased nonlinearly. These results can be interpreted in terms of the increase in electrical conductivity of pore water as its salinity increased, the expected increase in the number and area of contact between the soil particles as the dry density increased which enhanced the flow of the electrical current through the moist soils, and the increase in pore-water connectivity as the water content increased which offered more conductive channels through the soils.

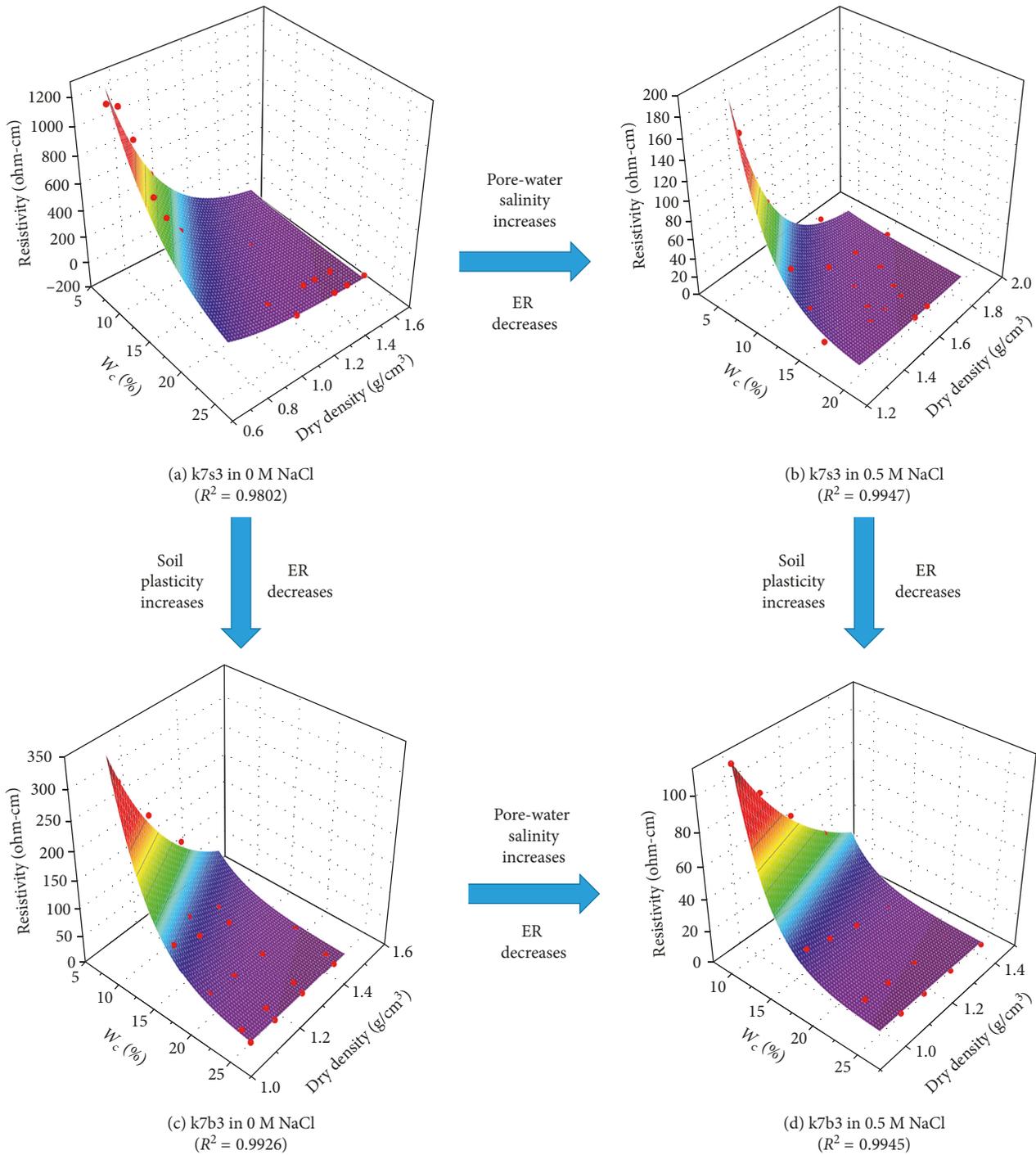


FIGURE 6: Examples of 3D plots for resistivity (Ohm-cm), water content (W_c), and dry density.

Therefore, at constant moisture content and dry density, the differences observed in ER of the specimens could be explained in terms of the change in electrical conductivity of pore water and the microstructure configuration of clay specimen, as water salinity increases.

3.3. Effect of Pore-Water Salinity on ER of K-S Specimens. Under constant water content and dry density conditions, replacing the kaolin in the pure kaolin specimen (K10) with

coarse soil (sand) and/or changing the salinity of pore water should change ER of CCL as shown in Figure 9. In fact, two mechanisms can be proposed to explain the observed ER change in Figure 9. These mechanisms consider the expected change in surface conduction and the availability of water for clay particles as the mineralogical composition of CCL and pore-water salinity change. From the mineralogy perspective, as kaolin has higher surface conduction than sand, increasing the content of sand in CCL will reduce the overall surface conduction contribution of CCL and consequently

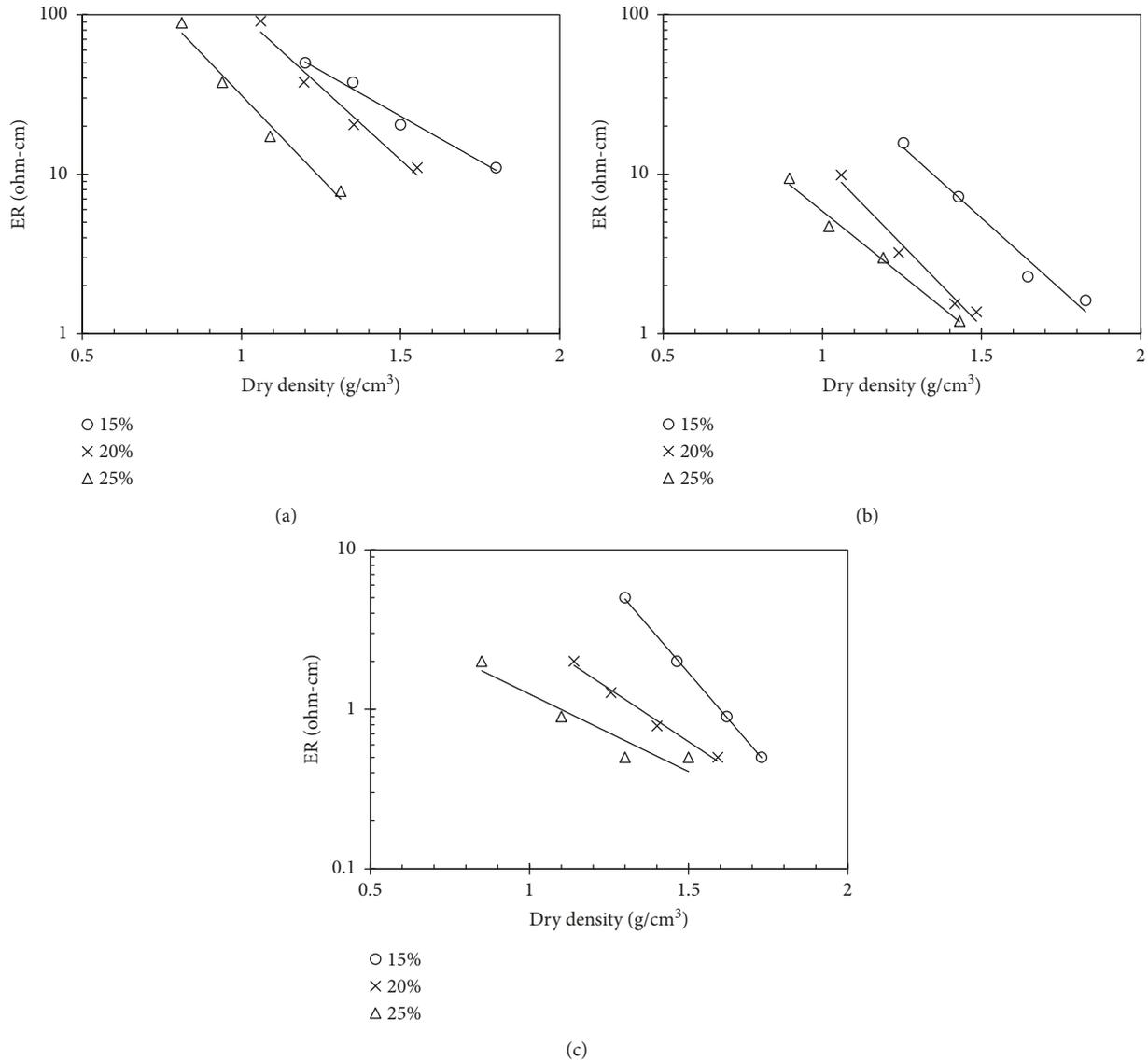


FIGURE 7: ER for k10 in (a) 0 M, (b) 0.5 M, and (c) 1 M NaCl solutions at 15%, 20%, and 25% water content.

increase its ER. On the contrary, as the specific surface area of sand and its electrochemical surface activity is much smaller than kaolin, replacing the kaolin with sand will involve releasing of the adsorbed water of the replaced kaolin in the pore space. This released water will increase the water availability for the remaining kaolin clay particles to enhance its hydration level which should improve its surface conduction level. Furthermore, this released water can also play a role in improving the pore-water connectivity. Consequently, this behaviour could decrease ER as sand content increases.

In conclusion, the overall ER change behaviour as sand content increases is controlled by the relative contribution of the two mechanisms. The result in Figure 9(a) reveals that for low water content (15%) and distilled water (0 M NaCl) cases, as the sand content increases, the contribution of surface conduction change and water availability mechanisms were almost equal. Therefore, ER did not change as the sand content increased. However, for the distilled water case,

as the water content increased (from 20% to 25%), ER increased as sand content increased, as shown in Figures 9(b) and 9(c). This behaviour elucidates the existence of a critical water content which is enough to fully hydrate the clay particles and establish primary water channels through the pores. So, if the soil specimen holds water content greater than this critical value, the released water due to the replacement process will have an insignificant role in enhancing the surface conduction level of the clay particle and will also play a secondary role in improving pore-water connectivity. Consequently, the contribution of the water availability mechanism will be less than the contribution of surface conduction mechanism due to the replacement process and ER increased as the sand content increased.

It should also be mentioned that, for partially saturated clay specimen in saline water environment, the released water due to the sand replacement process could enhance the chemically induced microstructure change that depends

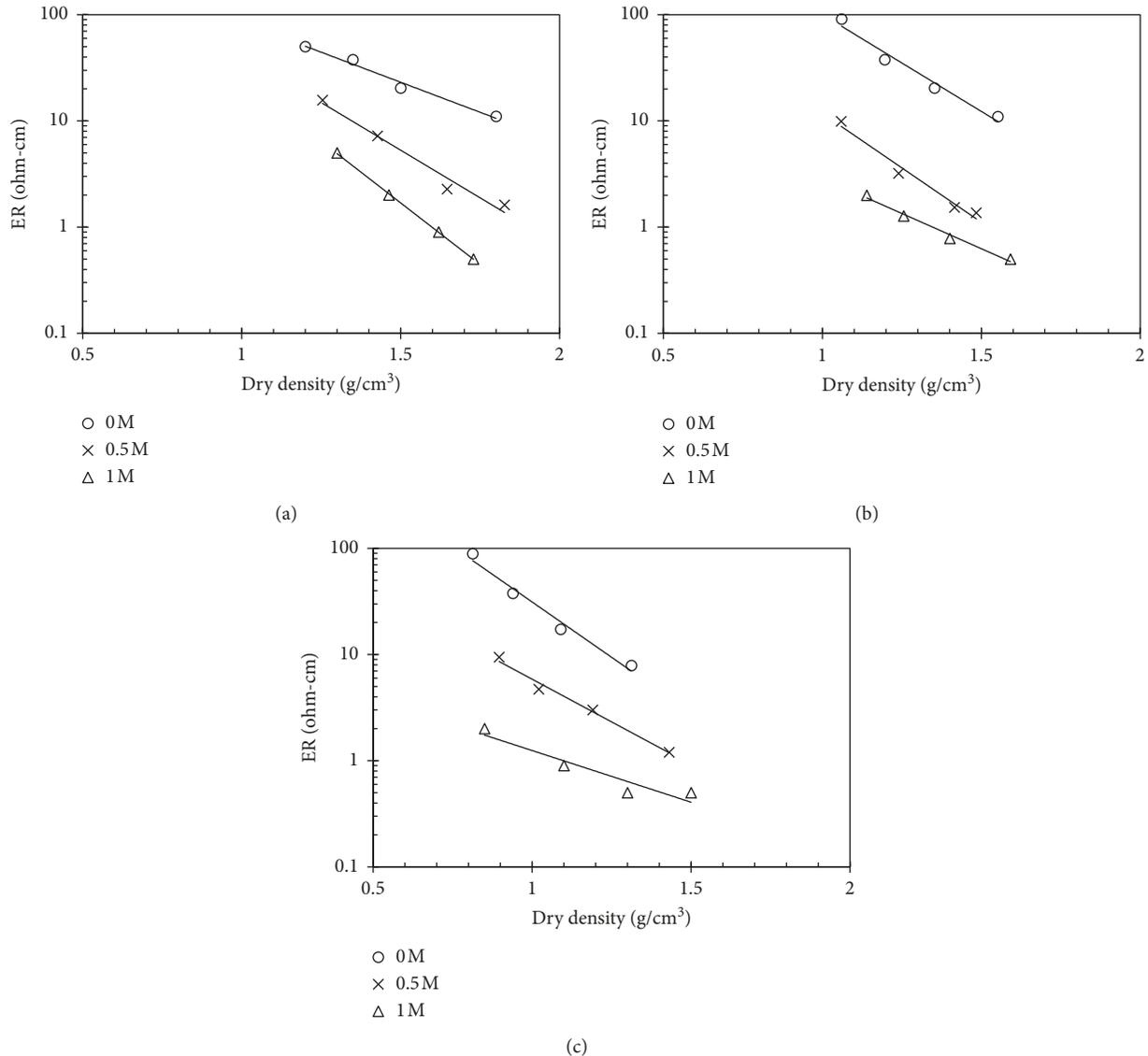


FIGURE 8: ER for k10 at (a) $W_c = 15\%$, (b) $W_c = 20\%$, and (c) $W_c = 25\%$ water content in 0 M, 0.5 M, and 1 M NaCl solutions.

on the hydration level of the clay particle. As mentioned before, the clay particles tend to have an aggregated microstructure when it is hydrated by saline water. Consequently, as the hydration level increases, the aggregation level increases. Since the aggregated microstructure can be characterised as the bimodal pore size system, the existence of large pores could reduce pore-water connectivity and consequently leads to an increase in ER. The results in Figure 9 for saline water cases show that the aggregation and surface conduction mechanism due to the replacement process dominated the ER change behaviour as sand content increased. Therefore, for these cases, ER increased as sand content increased.

Figures 10(a) and 10(b) exhibit the effect of dry density change on ER change behaviour of K-S specimens as the sand content and pore-water salinity change. The results indicated that increasing the dry density would decrease ER. However, the overall ER change behaviour as the sand content and pore-water salinity change stayed the same.

3.4. Effect of Pore-Water Salinity on ER of K-B Specimens.

The results in Figure 11 highlight the effect of different pore-water salinity levels on the evolution of ER of kaolin clay specimens as the bentonite content increased at different water content levels but constant dry density. The results show that, for the case of distilled water, ER decreased as the bentonite content increased regardless of the water content level. However, for the cases of saline pore water, increasing the bentonite content increased ER regardless of the water content level. This behaviour can also be explained in the light of the change in the mineralogy and the availability of water for clay particles as the bentonite content increased.

Compared to kaolin, bentonite clay has a higher specific surface area and electrochemical surface activity. Therefore, compared to kaolin, the bentonite holds a higher surface conduction and requires more water for its hydration process. At constant water content and density, the bentonite's higher surface conduction should lead to a reduction in ER as the bentonite content increases. However, the

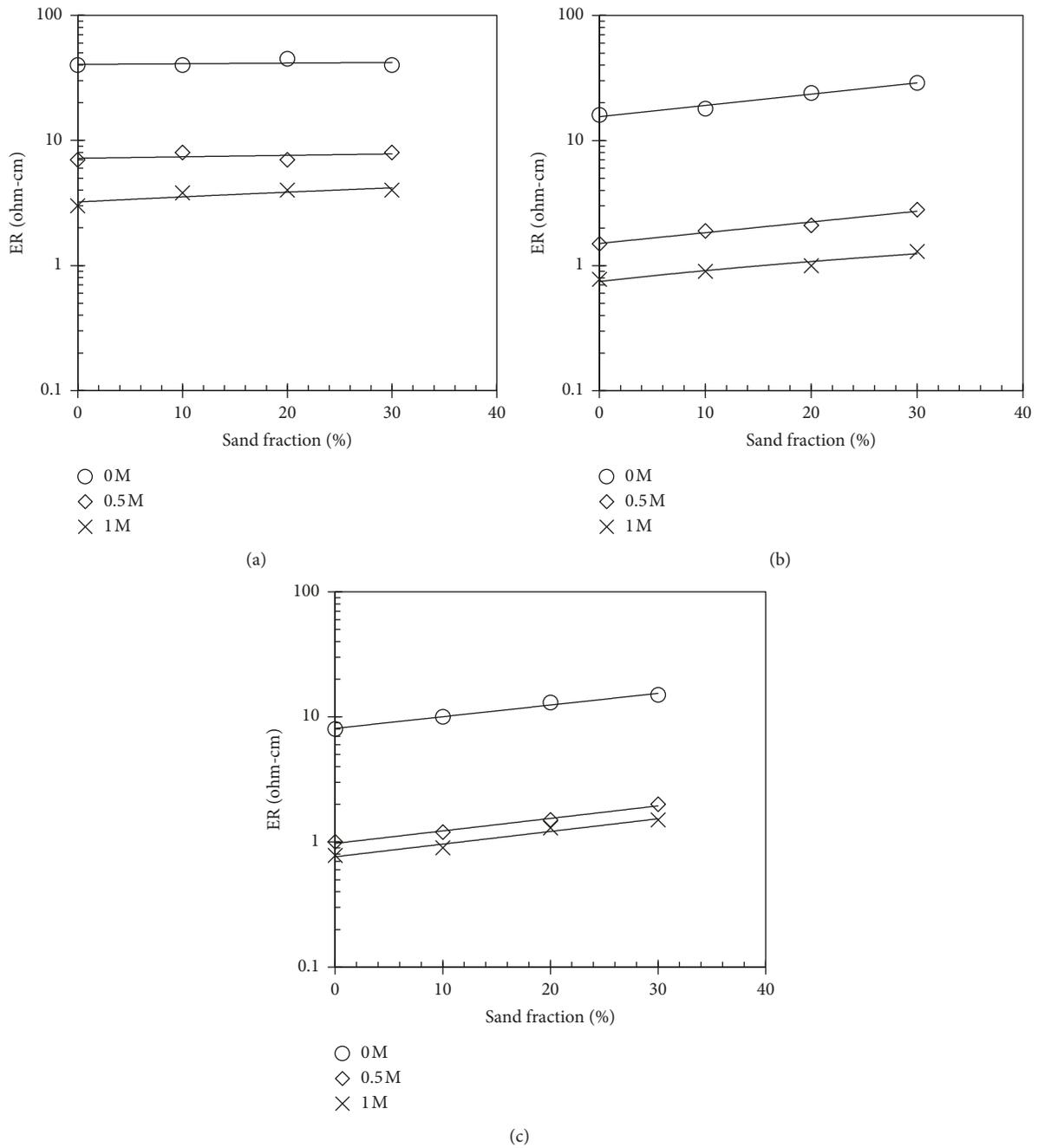


FIGURE 9: ER against sand fraction in NaCl solutions (0 M, 0.5 M, and 1 M) at (a) $W_c = 15\%$, (b) $W_c = 20\%$, and (c) $W_c = 25\%$ water contents.

bentonite needs higher water content for its hydration process, which should lead to an increase in ER due to the shortage in the water available for hydration process as the bentonite content increases. For a clay specimen with high water content, free water can be available in its pores. Nevertheless, when the kaolin is replaced with bentonite, at constant water content, this free water would be used to supply the demand of bentonite hydration process which requires more water content than the kaolin. The use of the free water, in this case, will reduce the pore-water connectivity and should also increase ER.

The results in Figure 11 for distilled water also suggest that the overall increase in the surface conduction as the increase in bentonite content dominates the observed behaviour. Consequently, ER decreased as bentonite content increased. However, the increase in ER as the bentonite content increased for cases of saline pore water can be attributed to the shortage of water available for hydration process of bentonite and the possible aggregation microstructure which decreased connectivity of pore water.

Figures 10(c) and 10(d) show the effect of dry density change on ER change behaviour of K-B specimens as the

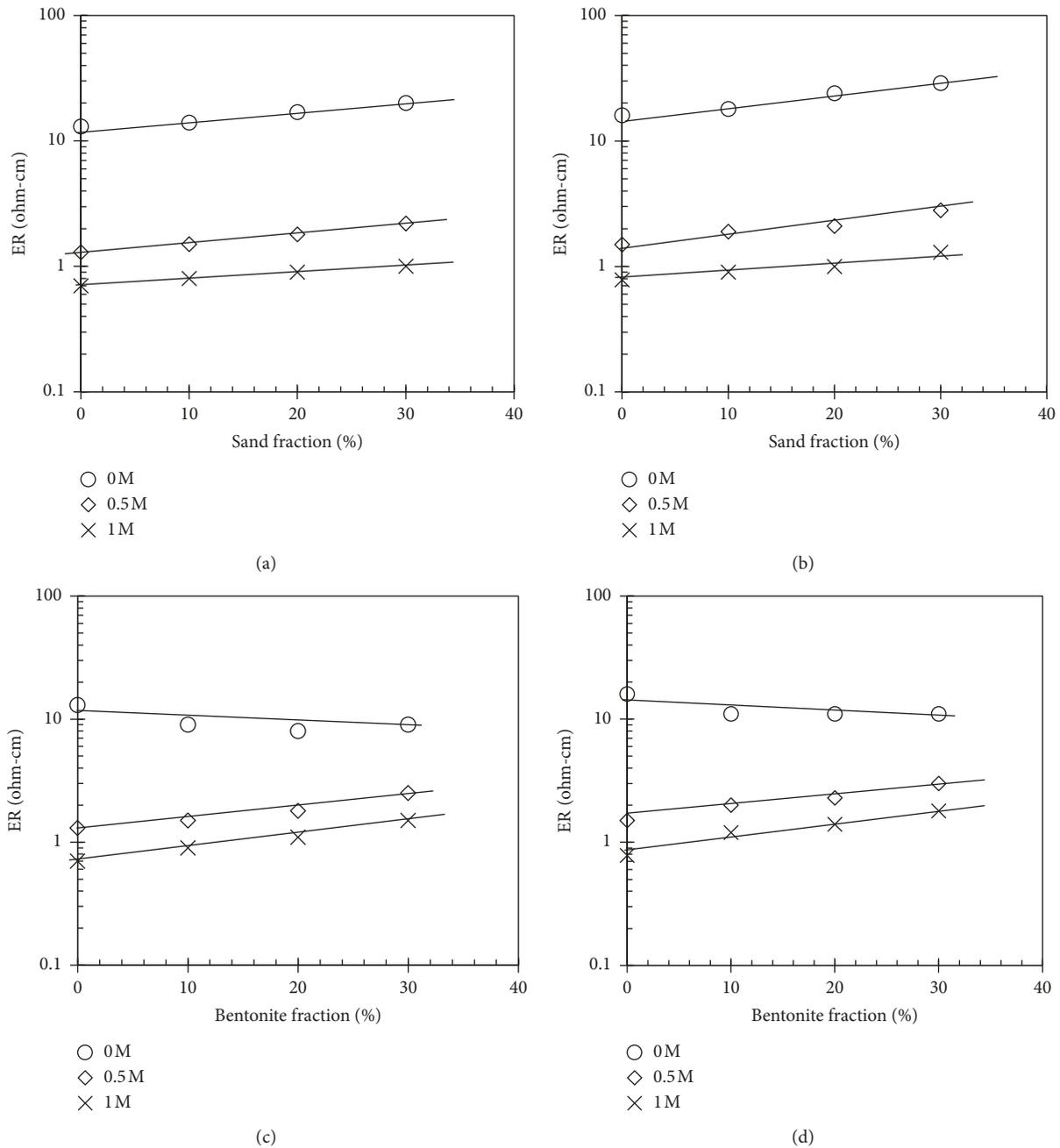


FIGURE 10: Comparisons of ER at two different dry densities (1.4 g/cm^3 and 1.6 g/cm^3) for different sand/bentonite fractions at 20% water content. (a) $W_c = 20\%$, $\rho_d = 1.6 \text{ (g/cm}^3\text{)}$. (b) $W_c = 20\%$, $\rho_d = 1.4 \text{ (g/cm}^3\text{)}$. (c) $W_c = 20\%$, $\rho_d = 1.6 \text{ (g/cm}^3\text{)}$. (d) $W_c = 20\%$, $\rho_d = 1.4 \text{ (g/cm}^3\text{)}$.

bentonite content and pore-water salinity changed. The results indicate that increasing the dry density would decrease ER. However, the overall ER change behaviour as the bentonite content and pore-water salinity change stayed the same.

4. Conclusions

The influence of pore-water salinity on the ER of three types of kaolin-dominant CCL specimens (kaolin, kaolin-sand, and kaolin-bentonite) has been experimentally investigated. The study was conducted by constituting CCL specimens at

different NaCl concentrations of water (0 M, 0.5 M, and 1 M) corresponding to seven types of soil mixtures, different dry densities (ρ_d), water contents (W_c), sand/bentonite fractions, and degree of saturation (%Sr). A typical constitutive electrical resistivity surface (CERS) based on a statistical approach was established in order to understand the correlation between the ER, W_c , and ρ_d at different pore-water salinities and soil plasticity. The test results, in general, demonstrate that the ERs of the CCL specimens decrease nonlinearly with increasing dry densities, moisture contents, or pore-water salinities. However, at constant density and water content, the increased salt concentrations had an

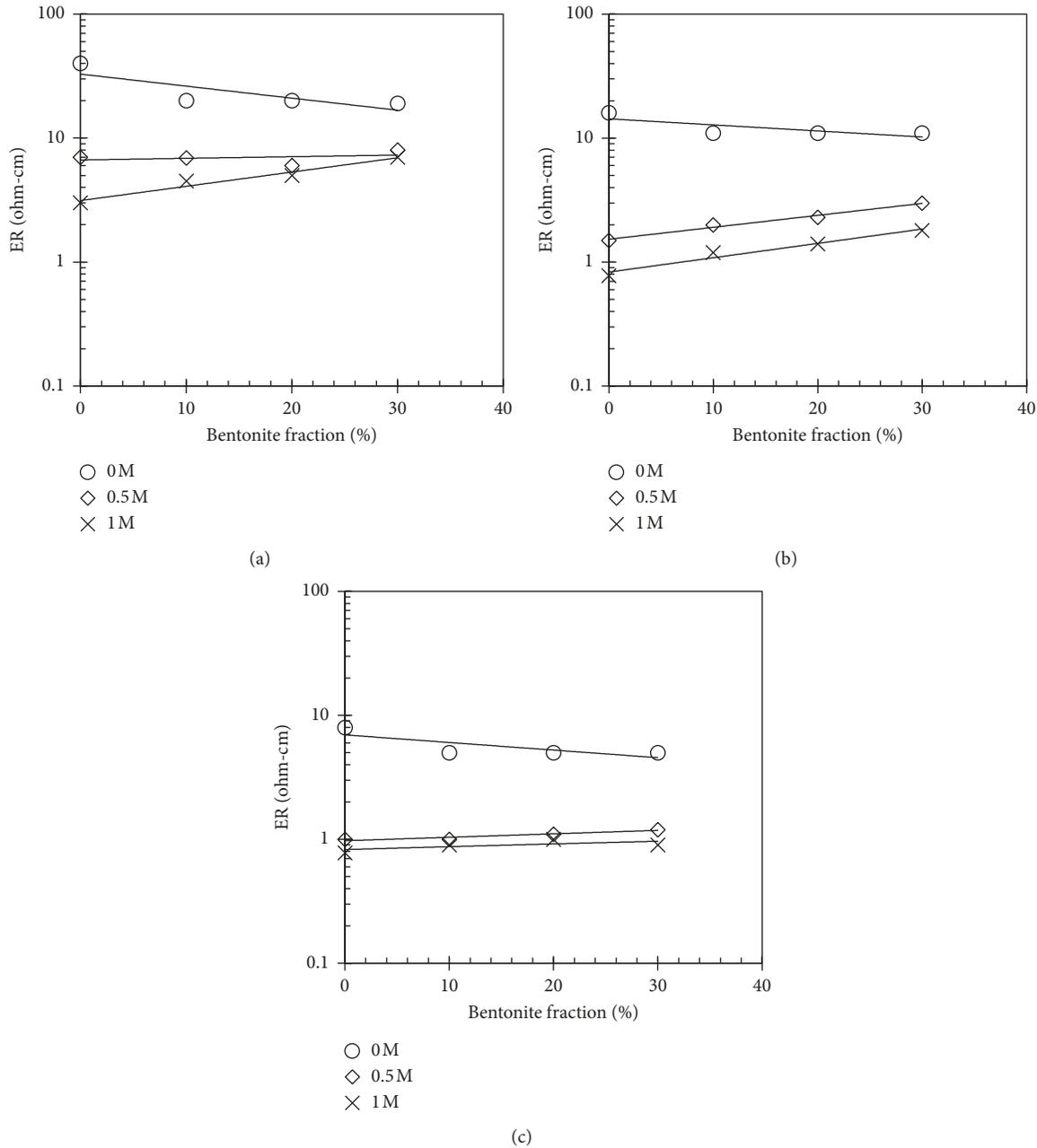


FIGURE 11: ER against bentonite fraction in NaCl solutions (0 M, 0.5 M, and 1 M) at (a) $W_c = 15\%$, $\rho_d = 1.4 \text{ (g/cm}^3\text{)}$, (b) $W_c = 20\%$, $\rho_d = 1.4 \text{ (g/cm}^3\text{)}$, and (c) $W_c = 25\%$, $\rho_d = 1.4 \text{ (g/cm}^3\text{)}$ water contents.

insignificant impact on conductivity as the ERs increased if the sand fraction increased in the tested specimens. This behaviour can be attributed to sand's lower surface conduction compared to that of kaolin. Consequently, bentonite has higher surface conduction than kaolin, and hence, the ERs of kaolin-bentonite declined abruptly if bentonite fraction increased concurrently in the CCL specimens, constituted using distilled water. Nevertheless, it was also found that ERs of the kaolin-bentonite increased surprisingly despite increasing bentonite fraction at 0.5 M and 1 M of NaCl concentrations. A conceivable explanation for this result can be interpreted in terms of the aggregated

microstructure of bentonite (bimodal pore size) and shortage of water available for the hydration process of bentonite, which weakens the connectivity of pore water, leading to a reduction in the number and area of the interparticle contacts.

Data Availability

No data were used to support this study. The research is mostly experimental, which was validated by numerical presentation and theoretical explanation. Proper references have been cited throughout the research article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

- [1] R. K. Rowe, "Long-term performance of contaminant barrier systems," *Géotechnique*, vol. 55, no. 9, pp. 631–678, 2005.
- [2] S. Kumar and W.-L. Yong, "Effect of bentonite on compacted clay landfill barriers," *Soil and Sediment Contamination: An International Journal*, vol. 11, no. 1, pp. 71–89, 2002.
- [3] J. R. Booker, *Clayey Barrier Systems for Waste Disposal Facilities*, CRC Press, Boca Raton, FL, USA, 1st edition, 2014.
- [4] Y. Lu, H. Abuel-Naga, and A. Bouazza, "Water retention curve of GCLs using a modified sample holder in a chilled-mirror dew-point device," *Geotextiles and Geomembranes*, vol. 45, no. 1, pp. 23–28, 2017.
- [5] Y. Lu, H. Abuel-Naga, E.-C. Leong, A. Bouazza, and P. Lock, "Effect of water salinity on the water retention curve of geosynthetic clay liners," *Geotextiles and Geomembranes*, vol. 46, no. 6, pp. 707–714, 2018.
- [6] M. A. Budihardjo, "The influence of salt solution on morphological changes in a geosynthetic clay liner," *Advances in Materials Science and Engineering*, vol. 2016, Article ID 6349407, 8 pages, 2016.
- [7] A. Bouazza, "Geosynthetic clay liners," *Geotextiles and Geomembranes*, vol. 20, no. 1, pp. 3–17, 2002.
- [8] L. M. S. Pandey and S. K. Shukla, "Effect of state of compaction on the electrical resistivity of sand-bentonite lining materials," *Journal of Applied Geophysics*, vol. 155, pp. 208–216, 2018.
- [9] Q. Zhao, H. Choo, A. Bhatt, S. E. Burns, and B. Bate, "Review of the fundamental geochemical and physical behaviors of organoclays in barrier applications," *Applied Clay Science*, vol. 142, pp. 2–20, 2017.
- [10] G. Di Emidio, T. Katsumi, N. Touze-Foltz, and A. Bouazza, "Special issue: modified clays for barriers," *Applied Clay Science*, vol. 142, p. 1, 2017.
- [11] J. K. Mitchell and K. Soga, *Fundamentals of Soil Behavior*, John Wiley & Sons, Hoboken, NJ, USA, 3rd edition, 2005.
- [12] M. A. Dafalla, "The compressibility and swell of mixtures for sand-clay liners," *Advances in Materials Science and Engineering*, vol. 2017, Article ID 3181794, 9 pages, 2017.
- [13] G. P. Karunarajne, S. H. Chew, S. L. Lee, and A. N. Sinha, "Bentonite:Kaolinite clay liner," *Geosynthetics International*, vol. 8, no. 2, pp. 113–133, 2001.
- [14] M. A. Dafalla, "Effects of clay and moisture content on direct shear tests for clay-sand mixtures," *Advances in Materials Science and Engineering*, vol. 2013, Article ID 562726, 8 pages, 2013.
- [15] H. Lu, Q. Zhang, Y. Dong, J. Li, and X. Zhang, "The adsorption capacity, pore structure, and thermal behavior of the modified clay containing SSA," *Advances in Materials Science and Engineering*, vol. 2016, Article ID 9894657, 7 pages, 2016.
- [16] R. Polanský, P. Kadlec, Z. Kolská, and V. Švorčík, "Influence of dehydration on the dielectric and structural properties of organically modified montmorillonite and halloysite nanotubes," *Applied Clay Science*, vol. 147, pp. 19–27, 2017.
- [17] Z. Li, Q. Xue, T. Katsumi, and T. Inui, "Electric-hydraulic-chemical coupled modeling of solute transport through landfill clay liners," *Applied Clay Science*, vol. 101, pp. 541–552, 2014.
- [18] Y. Watabe, K. Yamada, and K. Saitoh, "Hydraulic conductivity and compressibility of mixtures of Nagoya clay with sand or bentonite," *Géotechnique*, vol. 61, no. 3, pp. 211–219, 2011.
- [19] Y. Deng, Z. Wu, Y. Cui, S. Liu, and Q. Wang, "Sand fraction effect on hydro-mechanical behavior of sand-clay mixture," *Applied Clay Science*, vol. 135, pp. 355–361, 2017.
- [20] M. Dafalla, A. Al-Mahbashi, and M. Al-Shamrani, "Trends of moisture and electrical conductivity in clay liners," *Geofluids*, vol. 2018, Article ID 8391830, 7 pages, 2018.
- [21] W. M. Telford, L. P. Geldart, and R. E. Sheriff, *Applied Geophysics*, Cambridge University Press, Cambridge, UK, 2nd edition, 2001.
- [22] J. M. Reynolds, *An Introduction to Applied and Environmental Geophysics*, John Wiley, Chichester, NY, USA, 1997.
- [23] Z. S. Abu-Hassanein, C. H. Benson, and L. R. Blotz, "Electrical resistivity of compacted clays," *Journal of Geotechnical Engineering*, vol. 122, pp. 397–406, 1996.
- [24] D. Zhang, Z. Cao, L. Fan, S. Liu, and W. Liu, "Evaluation of the influence of salt concentration on cement stabilized clay by electrical resistivity measurement method," *Engineering Geology*, vol. 170, pp. 80–88, 2014.
- [25] R. Chhabra, *Soil Salinity and Water Quality*, Routledge, Abingdon, UK, 1st edition, 2017.
- [26] Q. A. AL Rashid, H. M. Abuel-Naga, E.-C. Leong, Y. Lu, and H. Al Abadi, "Experimental-artificial intelligence approach for characterizing electrical resistivity of partially saturated clay liners," *Applied Clay Science*, vol. 156, pp. 1–10, 2018.
- [27] M. F. Hasan, H. Abuel-Naga, P. Broadbridge, and E.-C. Leong, "Series-parallel structure-oriented electrical conductivity model of saturated clays," *Applied Clay Science*, vol. 162, pp. 239–251, 2018.
- [28] M. A. Mojid, D. A. Rose, and G. C. L. Wyseure, "A model incorporating the diffuse double layer to predict the electrical conductivity of bulk soil," *European Journal of Soil Science*, vol. 58, no. 3, pp. 560–572, 2007.
- [29] ASTM D422-63e2, *Standard Test Methods for Particle Size Analysis of Soils*, Annual Book of ASTM Standards, West Conshohocken, PA, USA, 2007.
- [30] ASTM D4253-16, *Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table*, ASTM International, West Conshohocken, PA, USA, 2016.
- [31] ASTM D4254-16, *Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density*, ASTM International, West Conshohocken, PA, USA, 2016.
- [32] ASTM D4318-10e1, *Standard Test Methods for Liquid Limit, Plastic Limit and Plasticity Index of Soils*, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, USA, 2010.
- [33] E.-C. Leong and H. Abuel-Naga, "Contribution of osmotic suction to shear strength of unsaturated high plasticity silty soil," *Geomechanics for Energy and the Environment*, vol. 15, pp. 65–73, 2018.
- [34] A. M. Elsharief and M. Sufian, "Time rate of swelling of compacted highly plastic clay soil from Sudan," *MATEC Web of Conferences*, vol. 149, p. 02032, 2018.
- [35] D. Sangrey and R. Mitchell, *Soil Specimen Preparation for Laboratory Testing*, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 1976.
- [36] F. Wenner, "A method for measuring earth resistivity," *Journal of the Franklin Institute*, vol. 180, no. 3, pp. 373–375, 1915.
- [37] L. D. Suits, T. C. Sheahan, J. H. Kim et al., "Four electrode resistivity probe for porosity evaluation," *Geotechnical Testing Journal*, vol. 34, no. 6, article 102866, 2011.

- [38] Y. Cui, M. Yahia-Aissa, and P. Delage, "A model for the volume change behavior of heavily compacted swelling clays," *Engineering Geology*, vol. 64, no. 2-3, pp. 233–250, 2002.
- [39] E. Castellanos, M. V. Villar, E. Romero, A. Lloret, and A. Gens, "Chemical impact on the hydro-mechanical behaviour of high-density FEBEX bentonite," *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 33, pp. S516–S526, 2008.
- [40] Q. Wang, Y.-J. Cui, A. M. Tang, P. Delage, B. Gatmiri, and W.-M. Ye, "Long-term effect of water chemistry on the swelling pressure of a bentonite-based material," *Applied Clay Science*, vol. 87, pp. 157–162, 2014.
- [41] K. Norrish, "The swelling of montmorillonite," *Discussions of the Faraday Society*, vol. 18, p. 120, 1954.
- [42] M. Holmboe, S. Wold, and M. Jonsson, "Porosity investigation of compacted bentonite using XRD profile modeling," *Journal of Contaminant Hydrology*, vol. 128, no. 1–4, pp. 19–32, 2012.
- [43] N. Mokni, E. Romero, and S. Olivella, "Chemo-hydro-mechanical behaviour of compacted Boom Clay: joint effects of osmotic and matric suctions," *Géotechnique*, vol. 64, no. 9, pp. 681–693, 2014.
- [44] T. Thyagaraj and U. Salini, "Effect of pore fluid osmotic suction on matric and total suctions of compacted clay," *Géotechnique*, vol. 65, no. 11, pp. 952–960, 2015.
- [45] D. Manca, A. Ferrari, and L. Laloui, "Fabric evolution and the related swelling behavior of a sand/bentonite mixture upon hydro-chemo-mechanical loadings," *Geotechnique*, vol. 66, no. 1, pp. 41–57, 2016.

