J. Cent. South Univ. (2012) 19: 2991−2998
DOI: 10.1007/s11771-012-1368-8

Key parameters controlling electrical resistivity and strength of cement treated soils

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Abstract: The improvement of question soils with cement shows great technical, economic and environmental advantages. And interest in introducing electrical resistivity measurement to assess the quality of cement treated soils has increased markedly recently due to its economical, non-destructive, and relatively non-invasive advantages. This work aims to quantify the effect of cement content (a_w), porosity (n_t), and curing time(T) on the electrical resistivity (ρ) and unconfined compression strength (UCS) of cement treated soil. A series of electrical resistivity tests and UCS tests of cement treated soil specimen after various curing periods were carried out. A modified Archie empirical law was proposed taking into account the effect of cement content and curing period on the electrical resistivity of cement treated soil. The results show that $n_t/(a_w \cdot T)$ and $n_t/(a_w \cdot T^{1/2})$ ratio are appropriate parameters to assess electrical resistivity and UCS of cement treated soil, respectively. Finally, the relationship between UCS and electrical resistivity was also established.

Key words: cement treated soil; electrical resistivity; unconfined compression strength; cement content; porosity; curing time

1 Introduction

Portland cement is used worldwide in the improvement of question soils due to the great technical, economic and environmental advantages. The treatment of soil with cement is an attractive technique in the construction of highway and railway subgrades, a support layer of shallow foundations, and soft soil improvement. In any case, the final performance of the cement treated soil depends on the quality of stabilization obtained in the field, especially the strength of cement treated soils. Therefore, assessing and controlling the quality during the stabilization process is of fundamental importance to obtain good performance.

Recently, the interest in introducing electrical resistivity measurement to assess the quality of cement treated soil has increased markedly due to its economical, non-destructive, and relatively non-invasive advantages. The electrical resistivity of a material is a measure of how well the material retards the flow of electrical current. Resistivity is a material fundamental property and does not depend upon the media geometry. The electrical resistivities of soils and rocks have been extensively reported by numerous researchers [1]. From past works, the reported factors affecting electrical resistivity of soils and rocks are porosity, degree of saturation, ionic concentration of pore fluid, composition of the solids, soil structure and fabric, and temperature. The aforementioned parameters also have a significant influence on the mechanical behaviour of cement treated soils. Therefore, numerous researchers discussed the potential application of electrical resistivity to evaluate cement stabilization process. For instance, TAYLOR and ARULANADAN [2], TASHIRO et al [3], and McCARTER et al [4] observed the electrical responses of the cementitious hydration systems using an alternating current impedance spectroscopy. LI et al [5] and XIAO and LI [6] used a noncontact electrical resistivity measurement method to understand the cement hydration mechanism and to correlate electric resistivity to concrete setting time. KOMINE [7] investigated electrical resistivity as a means of evaluating the quality of soils solidified by chemical grouting and found that the volume ratio of grout occupying the void space of the improved ground is an useful parameter to assess the electrical resistivity of soils solidified by chemical grouting. LIU et al [8] studied the electrical resistivity of laboratory prepared soil-cement admixtures and indicated that it had a good relationship with UCS. LIU et al [9] evaluated the uniformity of deep mixed soil-cement columns with electrical resistivity method.

Foundation item: Project(BK2011618) supported by the Natural Science Foundation of Jiangsu Province, China; Project(51108288) supported by the National Natural Science Foundation of China
Received date: 2011−09−22; **Accepted date:** 2012−03−06
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DONG et al [10−11] evaluated the relations between electrical resistivity and various parameters of soil-cement blocks polluted by various solutions.

Even though many works have been focused on this issue, the essential parameters controlling of electrical resistivity and strength of cement treated soil is still not well understood. The objective of this work therefore focused on quantifying the effect of cement content, the porosity, and curing period on the electrical resistivity and UCS of cement treated soil. The general Archie's law, which includes the effect of water content and porosity, was modified to evaluate the effect of cement content and curing periods on the electrical resistivity of cement stabilized soil. Therefore, a series of electrical resistivity tests and UCS tests of cement stabilized soil specimen after various curing periods were carried out. The test results and discussion will be presented in this work. In summary, the scope of the current investigation is 1) to identify the effect of cement content and curing periods on the electrical resistivity of cement treated soils, and 2) to find appropriate parameters to characterize the electrical resistivity and strength of cement treated soils.

2 Background of soil electrical resistivity

For most geotechnical and geophysical applications, bulk electrical resistivity of the soil is often measured, which represents the composite resistivities of the pore fluid, soil particles, and matrix structure [12]. Electrical measurements in soils are sometimes also represented as electrical conductivity, which is defined as the reciprocal of electrical resistivity. Conduction of electricity through porous media occurs by two mechanisms [13]. The primary mode of conduction of soils arises from the motion of ions in the soil water occupying the larger void spaces, which are displaced from their original position by an applied electric field. Conduction also takes place through the movement of surface charges at the interface between the soil particles and the pore water, referred to as surface conductivity [14].

The electrical resistivity of soils and rocks is evaluated as an integration of resistivity of solid, liquid and air by a parallel model, series model or a combination model of these two models [7]. ARCHIE [15] developed an empirical relationship that relates the electrical resistivity of saturated sand (ρ) to the electrical resistivity of its pore fluid ($\rho_{\rm w}$), and the geometry of the porosity (n) in the soil.

$$\frac{\rho}{\rho_{\rm w}}=n^{-m} \tag{1}$$

where m is the material-dependent empirical exponent, which is a measure of pore tortuosity and the inter-connectivity of the pore network. ARCHIE [15] suggested a value of m=1.8−2.0 for consolidated sandstones and m=1.3 for clean loose sands. FRIEDMAN and SEATON [16] suggested a value of m=1.38−2.3 for saturated sand and 0.3−0.49 for rocks with porosity. RINALDI and CUESTAS [14] suggested a value of m=2.49 for saturated compacted Argentinean silty clay.

The original Archie model assumed a fully saturated media consisting of a single conducting phase distributed within a non-conducting phase. The Archie model was later extended to partially saturated porous media by KELLER and FRISCHKNECHT [17], which is given as

$$\frac{\rho}{\rho_{\rm w}}=a\cdot n^{-m}S_{\rm r}^{-p} \tag{2}$$

where $S_{\rm r}$ is the degree of saturation, a is a constant, and p is the saturation exponent. The constant a reported in literature has no theoretical basis and is based on empirical observations [13]. The saturation exponent (p) reflects the interstitial water in the soil matrix. ARCHIE [15] suggested a value of p=2; however, other published values of p range from 1.4 to 4.6, depending on the soil and whether a given saturation is reached by wetting or by drainage [1]. The a, m, and p values are typically found from regression analyses.

It should be pointed out that these two models are oversimplification of the mechanisms influencing electrical measurements in soils and rocks, and they do not take into account the effect of cement stabilization process. In other words, the effect of cement content and curing period cannot be reflected on these models. Therefore, the potential applications of Archie model into the cement treated soils need to be verified.

3 Materials and method

3.1 Material

Soils used in this work were artificially obtained by mixing 85% commercial silicon sand and 15% pulverized kaolin by oven-dried weight. The commercial silicon sand particle size is less than 1 mm and the pulverized kaolin particle size is less than 45 μm. In order to minish the effect of surface electrical charge of clay particles, low proportion of pulverized kaolin is adopted in this work. The physical properties of kaolin are presented in Table 1. The soil particles distribution curve is shown in Fig. 1. The optimum water content and maximum dry density of kaolin-sand soil are $w_{\rm opt}$=10% and $\gamma_{\rm d,\,max}$=1 955 kg/m^3, respectively, with the standard proctor compaction test procedure, in accordance with ASTM D968-07.

Cement, which is made in Nanjing Yuhua Cement Company and is equivalent to Portland cement Type I, was used to stabilize the soil. Various cement contents

Table 1 Physical properties of kaolin

w/%	G_s	pH	w_p/%	w_L/%	Clay particle fraction (<2 μm)/%	Silt particle fraction (2−75 μm)/%
<1.5%	2.72	6−8.5	32	68	20	80

Note: w is water content; G_s is specific gravity; w_p is plastic limit; w_L is liquid limit.

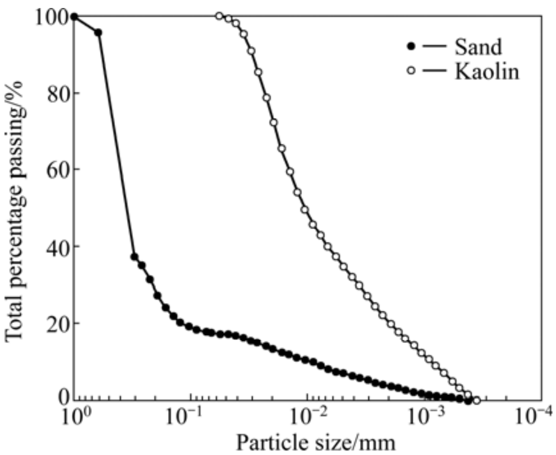

Fig. 1 Soil particles distribution curve

(the ratio of cement weight to weight of the dry soil, termed as a_w) were used to investigate the effect of cement content on the electrical resistivity and strength of cement treated soil.

3.2 Sample preparation

In order to eliminate the effect of difference in water content, the samples were prepared to be the same water content of 10% (i.e. the optimum water content) by adding the distilled water in soil. In the specimen preparation, kaolin-sand soil was mixed with 5%, 7.5% and 10% cement content by mass of dry soil, respectively. Kitchen stand mixers were used to mix the cement into the soil for a total mixing time of 10 min until a homogenous soil-cement mixture was attained. To ensure thorough mixing, the sides of the bowl were continuously scraped and the mixer was stopped as often as needed to scrape off any materials packed onto the bottom of the bowl. Upon completion of mixing, the soil was compacted into plastic tubes having an internal diameter of 50 mm and height of 100 mm with the maximum dry density obtained from the standard proctor compaction test procedure. After standing without disturbance in the moulds for 3 h, the specimens were carefully removed from the moulds by using a jack, wrapped in vinyl and were cured at temperature of about 20 °C and humidity of 95% for the desired curing periods. All the specimens were prepared in triplicate for measurement of physical properties, electrical resistivity and UCS.

3.3 Test methods

The electrical resistivity measurement and UCS tests were run on specimens after curing periods of 1, 7, 14, 28, 56 and 90 d. Before the electrical resistivity measurement and UCS test, the diameter, height and mass of specimens were measured with accuracies of about 0.1 mm and 0.01 g.

The electrical resistivity tests were run on specimens using a Gwinstek LCR-816 apparatus with a plate two-electrode method. Two copper electrodes, with a diameter 50 mm and thickness of 2 mm, were placed on the top and at the bottom of the cylinder specimens during the measurement of the electrical resistivity. A vertical pressure of 2 kPa was applied on the copper probes to create an ideal contact condition between the copper electrodes and specimens. This pressure was found to have a negligible effect on the shear strength of the samples. The frequency used to measure the resistivity of the specimen was 2 kHz in order to avoid electrode polarization effects [15, 18] and double layer relaxation effects [13]. All of the measurements of the electrical resistivity were performed under the controlled temperature of (20±2) °C.

The schematic diagram of this test method is shown in Fig. 2, and the electrical resistivity of specimen, ρ (Ω·m), is calculated based on the following equation:

$$\rho = \frac{\Delta U}{I} \cdot \frac{A}{L} \tag{3}$$

where ΔU is the electrical voltage applied to the soil (V), I is the electrical current (A), A is the cross-section area through which electrical current conducts (m^2), and L is the length of the specimen parallel to the electrical current (m).

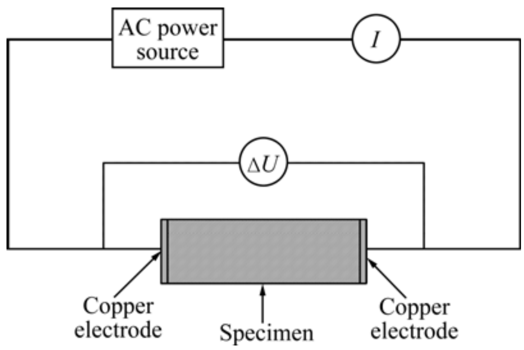

Fig. 2 Schematic diagram of two electrode probe method

Upon completion of electrical resistivity measurement, the UCS tests were carried out according to the procedure of ASTM D2166—06 at a strain rate of 1% per minute. After the UCS tests, small part of the mixtures was taken for moisture content determination.

Table 2 summarizes the specimen number, cement content, curing periods of specimens subjected electrical resistivity and UCS tests. Each test was identified in the forms CxxTyy by the cement content (xx) and curing periods (yy).

Table 2 Summary of samples for tests

Specimen No.	a_w/%	T/d	n_0	n_t	S_r
C5.0T1	5.0	1	0.327	0.324	0.952
C7.5T1	7.5	1	0.324	0.321	0.950
C10T1	10.0	1	0.317	0.312	0.925
C5.0T7	5.0	7	0.327	0.322	0.938
C7.5T7	7.5	7	0.324	0.315	0.865
C10T7	10.0	7	0.317	0.306	0.830
C5.0T14	5.0	14	0.327	0.320	0.890
C7.5T14	7.5	14	0.324	0.313	0.845
C10T14	10.0	14	0.317	0.306	0.825
C5.0T28	5.0	28	0.327	0.320	0.890
C7.5T28	7.5	28	0.324	0.310	0.810
C10T28	10.0	28	0.317	0.302	0.790
C5.0T56	5.0	56	0.327	0.313	0.790
C7.5T56	7.5	56	0.324	0.305	0.720
C10T56	10.0	56	0.317	0.293	0.625
C5.0T90	5.0	90	0.327	0.307	0.710
C7.5T90	7.5	90	0.324	0.296	0.600
C10T90	10.0	90	0.317	0.287	0.525

3.4 Data analysis methods

In order to assess the effectiveness of Archie's law in the application of cement treated soils, the porosity (n) of soils at various curing periods were determined using void ratio (e) using Eq. (4), which can be determined using the solid−liquid−air phase concept by Eq. (5) with the predetermined indices of specific gravity (G_s), water content (w), and bulk density (γ). The bulk density (γ) is calculated according to the dimensions of specimen measured before the UCS test. A composite specific gravity (G_s), based on the soil and cement mass percentages in the specimen, was used. The specific gravity value cement is 3.10.

$$n=\frac{e}{1+e} \tag{4}$$

$$e=\frac{(1+w)G_s\gamma_w}{\gamma}-1 \tag{5}$$

where e is void ratio; w is water content; G_s is composite specific gravity of the treated soil; γ is unit weight of the treated soil (kN/m^3); and γ_w is unit weight of water (kN/m^3).

4 Test results and discussion

4.1 Effect of porosity and degree of saturation on electrical resistivity

Figure 3 shows the raw data of electrical resistivity as a function of the initial porosity, which is defined as the porosity without curing time, where each data point represents the mean of three specimens. It can be observed that the initial porosity has a great effect on the electrical resistivity of this cement treated soil. An addition of cement results in a decreasing in initial porosity, which represents a larger electrical resistivity. The initial porosity, however, does not account for the effect of curing time; it accounts for only the initial condition of mixing, but not the final condition of the cured treated soil.

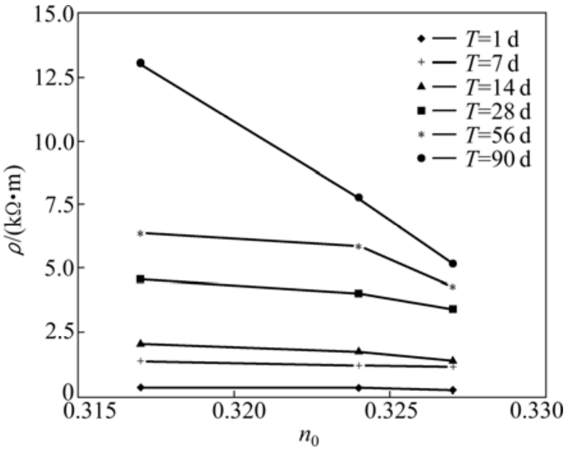

Fig. 3 Electrical resistivity versus initial porosity

Since the after-curing porosity would reflect the after-curing condition, the after-curing porosity was adapted in this work to supersede the initial porosity parameter. The after-curing void ratio (e_t) and after-curing porosity (n_t) were calculated using Eqs. (4) and (5) and the results are given in Table 2. Figure 4 shows the relationship between the electrical resistivity and after-curing porosity (n_t). Generally, an increase in electrical resistivity is observed with the reduction in after-curing porosity of cement treated soils. The best fitting line between electrical resistivity and after-curing porosity shows a power function, which shows similar trends with Archie's tests result, perhaps indicating similar characteristics, although the tests of Archie [15] were carried out from the saturated soil without cement treated process. This kind of behaviour has also been reported by other researchers [15]. However, it can be seen that there is a larger scatter of data around the best fitting curve and the effect of cement content is not reflected on the after-curing porosity parameter, as demonstrated in Fig. 4. This is expected because the

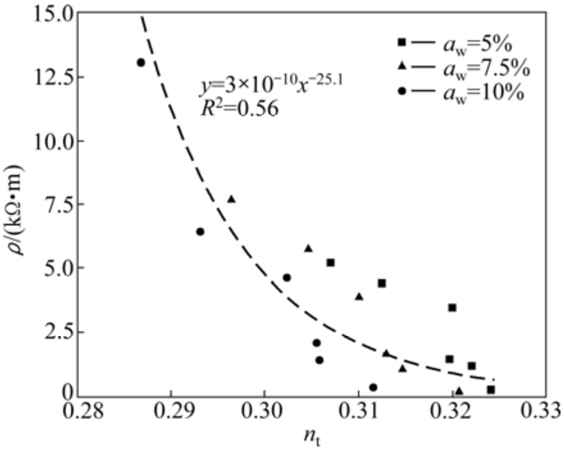

Fig. 4 Electrical resistivity versus after-curing porosity

hydration process of cement and pozzolanic reaction between hydration products and clay cannot be fully reflected by after-curing porosity parameter.

KELLER and FRISCHKNECHT [17] reported that the degree of saturation has a key effect on the electrical resistivity of soil. Figure 5 shows how the degree of saturation affects the electrical resistivity of the soil-cement studied. It can be seen that the electrical resistivity increases exponentially with the decrease of degree of saturation. Although the best fitting curve in Fig. 5 presents a higher correlation coefficient than that obtained between electrical resistivity and after-curing porosity, it can be seen that there is a larger scatter of data around the best fitting curve as before. The porosity has been found insufficient to characterize the electrical resistivity of cement treated soils since the effect of stabilization process had not been included.

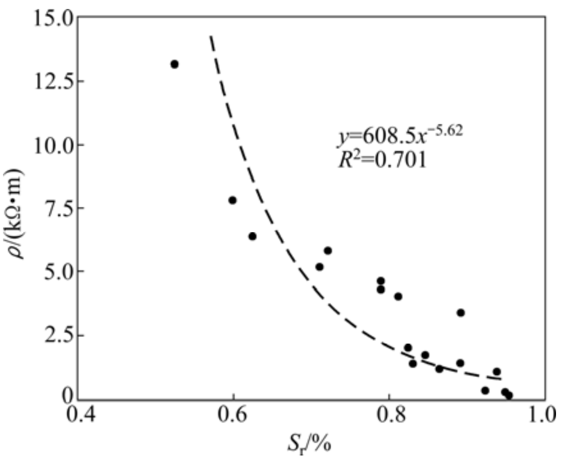

Fig. 5 Relationship between electrical resistivity and degree of saturation

4.2 Effect of cement content on electrical resistivity

The plot of electrical resistivity of cement treated soil versus cement content at varying curing times is shown in Fig. 6. As expected, the cement content has a great effect on the electrical resistivity of soil-cement. The measured electrical resistivity of cement treated soils increases with the increase of cement content. This can be interpreted by the hydration reactions of cement. For a given curing time, higher cement content yields greater amount of hydration compounds such as calcium silicate hydrate and calcium aluminate hydrates gels as a result of hydration processes. The hydration compounds fill in pore spaces and intersect each other to form solid networking resulting in a denser structure. Meanwhile, the free water space and porosity decrease, and tortuosity increases with electric current. Consequently, electrical resistivity increases more significantly [9, 19].

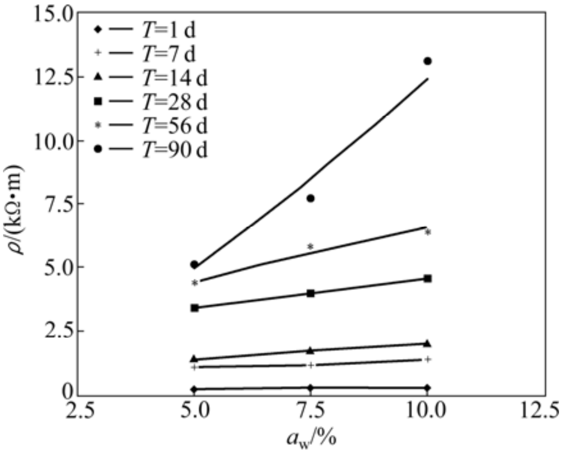

Fig. 6 Relationship between electrical resistivity and cement content

Another feature that can be seen in Fig. 6 is the increase in the electrical resistivity with the increase of curing periods. The effect of curing periods has been reported by several researchers [9, 19]. The mechanism by which the curing periods influence the cement treated soil electrical resistivity is also related to the hydration process of cement and pozzolanic reaction between hydration products and clay.

In order to clearly comprehend the effect of after-curing porosity and cement content, the electrical resistivity of cement treated soils is plotted with the ratio of after-curing porosity/cement content, as shown in Fig. 7. Generally, an increase of electrical resistivity is observed with the reduction in after-curing porosity/cement content ratio. However, the effect of curing time is still not reflected on the after-curing porosity/cement content ratio parameter.

4.3 Parameter controlling electrical resistivity of cement treated soil

As mentioned earlier, the electrical resistivity of cement treated soil is primarily dependent on the water content, cement content and curing time. The after-curing porosity (n_t), which takes into account primarily

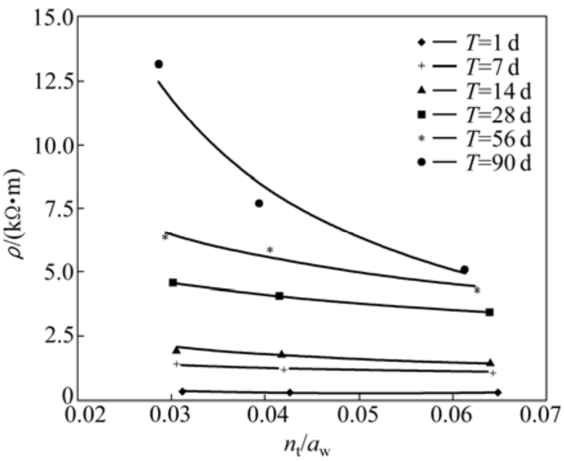

Fig. 7 Electrical resistivity versus after-curing porosity/cement content ratio

the after-curing situation of cement treated soil, was adapted in this work to supersede the initial porosity. Since the electrical resistivity of cement treated soil is also dependent on the cement content and curing time, it is logical to utilize a synthetic parameter that combines together the effects of those factors. Therefore, a new parameter, termed as after-curing porosity/cement content-curing time ratio, $n_t/(a_w \cdot T)$, was proposed to relate the electrical resistivity values and those factors.

Figure 8 demonstrates that the ratio of after-curing porosity/cement content-curing time, $n_t/(a_w \cdot T)$, has fairly combined together these effects of porosity, cement content and curing time on the electrical resistivity of cement treated soil. A good correlation (coefficient of determination, R^2=0.981 7) can be observed between this ratio and the electrical resistivity of cement treated soil, which can be expressed as Eq. (6).

$$\rho = A\left(\frac{n_t}{a_w T}\right)^{-B} \tag{6}$$

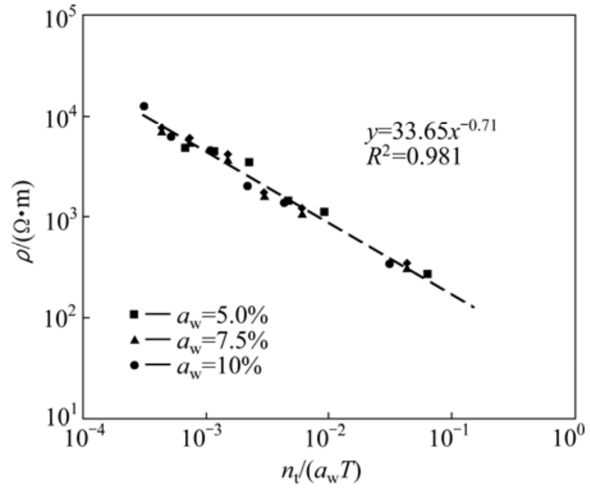

Fig. 8 Electrical resistivity versus $n_t/(a_wT)$

where A and B are dimensionless constants. Based on the test results presented, for the kaolin-sand soil mixed with cement, the constants are A=33.65 and B=0.71.

Comparing Eqs. (1) and (6), it is interesting that this study results in an empirical relationship similar to that developed by ARCHIE [15]. In other words, the Archie's empirical relationship can be applied to the cement treated soils using a synthetic parameter, termed as after-curing porosity/cement content-curing time, $n_t/(a_w \cdot T)$.

The result shows that a unique power function adapts well electrical resistivity value with the ratio. The results therefore suggest that the ratio of porosity/cement content-curing time is a fundamental parameter sufficient to characterize the electrical resistivity of cement treated soils.

4.4 Parameter controlling UCS of cement treated soil

Figure 9 shows the UCS versus porosity of the cement treated soils. The change tendency of UCS with various cement content and curing time is very similar to that of electrical resistivity (as shown in Figs. 3 and 4). In general, the increase in cement content yields an increasing gain in strength, indicating a great amount of

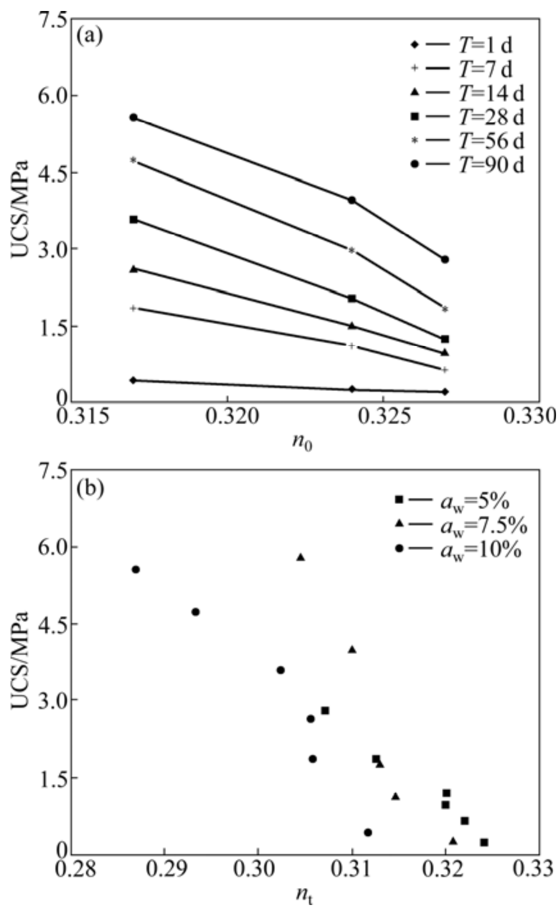

Fig. 9 Electrical resistivity versus porosity: (a) Initial porosity; (b) After-curing porosity

new compounds such as calcium silicate hydrate and calcium aluminate hydrates gels are formed as a result of hydration processes and a continuous pozzolanic reactions which subsequently crystallize to bind the structure together. The test results also demonstrate a more scatter relationship between UCS and porosity of cement treated soil than that between electrical resistivity and porosity.

Figure 10 shows the UCS of the cement treated soils versus cement content. As expected, the increase in cement content yields an increasing gain in strength, indicating a great amount of new compounds are formed, which subsequently crystallize to bind the soil particles together. The test results also demonstrate the strong influence of curing time on the UCS of cement treated soil.

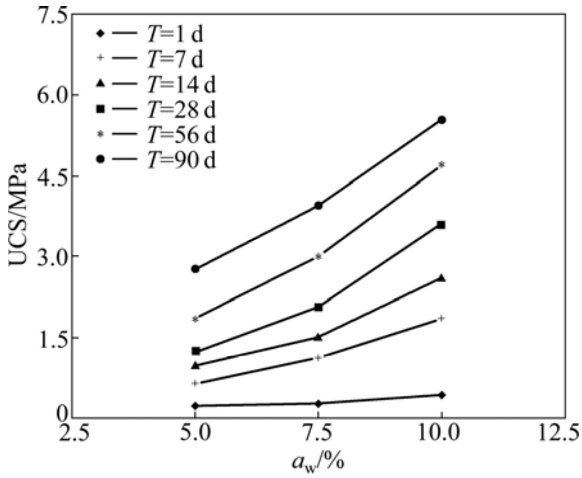

Fig. 10 UCS versus cement content

LORENZO and BERGADO [20] demonstrated that the ratio of after-curing void ratio and cement content was sufficient to characterize the UCS of cement treated soil with high water content. The plots of UCS against the ratio of porosity of specimen in this work is shown in Fig. 11, where UCS reasonably follows a function of the ratio (n_t/a_w) at a certain curing time. The parameter n_t/a_w has been demonstrated to generalize the strength development at a certain curing time of cement treated soil. This plot confirmed the research conclusion drawn by LORENZO and BERGADO [20] and CONSOLI et al [21]. However, the effect of curing time is not included in parameter n_t/a_w, being similar to the electrical resistivity results.

For the relationship between UCS and after-curing porosity, cement content and curing time, it was found that the optimum fit could be obtained applying a power equal to 0.5 to the curing time as shown in Fig. 12. A good correlation (coefficient of determination R^2=0.981 6) can be observed between $n_t/(a_w \cdot T^{1/2})$ and the UCS of cement treated soil studied, which can be expressed as Eq. (7).

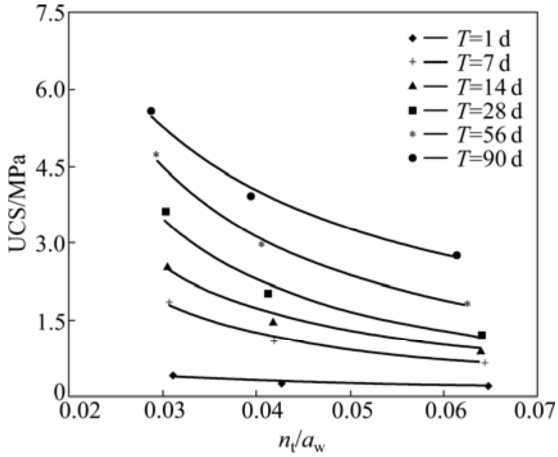

Fig. 11 UCS versus ratio of after-curing porosity/cement content

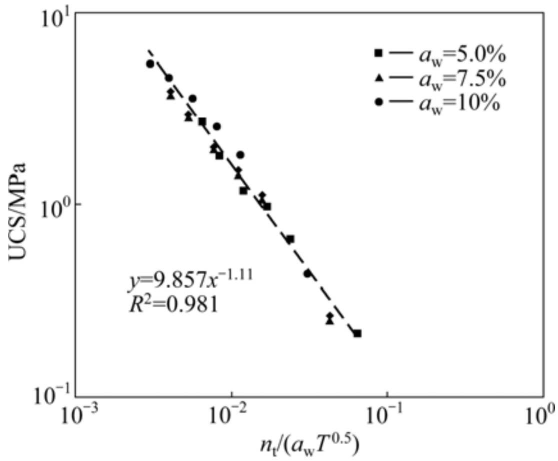

Fig. 12 UCS versus $n_t/(a_w \cdot T^{1/2})$

$$q_u = C\left(\frac{n_t}{a_w\sqrt{T}}\right)^{-D} \tag{7}$$

where C and D are dimensionless constants. Based on the test results presented, for the kaolin-sand soil mixed with cement, the constants are C=9.857 8 and D=1.114.

The results presented in this work therefore suggest that the ratio $n_t/(a_w \cdot T^{1/2})$ is an appropriate parameter to characterize the UCS of cement treated soil.

4.5 Relationship between electrical resistivity and UCS of cement treated soil

By examining Figs. 7 and 12, as well as Eqs. (6) and (7), it can be seen that the electrical resistivity and UCS of cement treated soil present similar trends. Therefore, the relationship between electrical resistivity (ρ) and UCS (q_u) for the cement treated soil can be obtained by dividing Eqs. (6) and (7), which yields the ratio

$$\frac{\rho}{q_{\mathrm{u}}}=3.414\frac{n_{\mathrm{t}}^{0.402}\cdot T^{0.155}}{a_{\mathrm{w}}^{0.402}} \tag{8}$$

It can be seen in Eq. (8) that ρ/q_{u} is not a scalar, being dependent of the after-curing porosity, cement content and curing time. This finding is different from the results of LIU et al [9], who reported that there is a linear relationship between UCS and electrical resistivity, being independent of cement content and curing time. In fact, the strength of cement treated soil primarily depends on the soil structure and chemical reactions products. However, the electrical resistivity of soil primarily depends on the ions concentration in the pore fluid, pore tortuosity, degree of saturation and surface charges of soil particles. The different controlling parameters of electrical resistivity and strength could interpret the nonlinear relationship between electrical resistivity and strength of cement treated soil.

5 Conclusions

1) The electrical resistivity and UCS of cement treated soils increase with the increase of cement content and curing time.

2) A power function well adapts the relationship between electrical resistivity of cement treated soil and the after-curing porosity/cement content-curing time ratio. In other words, the Archie's empirical relationship can be applied to the cement treated soils using a synthetic parameter, $n_{\mathrm{t}}/(a_{\mathrm{w}}\cdot T)$, replacing of the porosity (n).

3) A power function well adapts the relationship between UCS of cement treated soil and the ratio $n_{\mathrm{t}}/(a_{\mathrm{w}}\cdot T^{1/2})$.

4) The electrical resistivity and UCS ratio is not a scalar, being dependent of after-curing porosity, cement content and curing time.

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(Edited by HE Yun-bin)