VARIATION OF INITIAL SOIL SUCTION WITH COMPACTION CONDITIONS FOR CLAYEY SOILS

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ABSTRACT

In this study, the initial soil suction of as-compacted clayey soils was evaluated for various compaction conditions, covering a wide range of compaction energy and molding water content. The soil specimens were prepared by impact compaction under three levels of compaction energy. The filter paper method was used to measure the initial soil suction of as-compacted specimens. Test results indicate that the relationship between the soil suction and the molding water content is bilinear under three different compaction energies. However, the effect of compaction energy on soil suction is different for the soils with different amounts of clay fraction and is elucidated by the macro soil properties. The change of soil suction due to different compaction energies can be predicted by the void ratio and the degree of saturation.

Keywords: Soil suction, Compaction energy, Filter paper method.

1. INTRODUCTION

Compacted soils are commonly used as buffer materials in radioactive waste repositories, landfills, backfills, man-made compacted slopes, and subgrades. It is generally assumed that the compacted clayey soils are saturated during the entire life of the facility. In reality, the as-compacted clay is unsaturated and does not necessarily become saturated after the resaturation processes (Miller *et al*. [1]). Soil suction is an important property of unsaturated soils, especially for soils immediately after compaction. The initial soil suction of as-compacted soils determines their potential of absorbing and retaining water.

Numerous researchers confirmed that the mechanical and hydraulic behaviors of compacted soils are influenced by soil suction (Chen and Yu [2]; Cui and Delage [3]; Alonso *et al*. [4]; Wheeler and Sivakumar [5]; Ng and Chiu [6]; Rao and Revanasiddappa [7]; Cokca *et al*. [8]; Yang *et al*. [9]; Yang and Lin [10]). In engineering practice, the soil suction has been considered to be an important factor in the design and construction of as-compacted soils (Yang *et al*. [11]; Kung *et al*. [12]). Molding water content and compaction energy are also known to have significant influences on the subsequent mechanical and hydraulic behaviors of as-compacted clayey soils. Hence, it can be expected that the molding water content and compaction energy have certain relations with soil suction.

Chu and Mou [13] studied the effect of variations in the density, the water content, and the compaction method on the soil suction for an expansive clayey soil. Their test results showed that the soil suction of the soil that compacted at the same molding water content increased as the compaction energy increased. However, a different trend was observed by Marinho and Stuermer [14] and Rao and Revanasiddappa [15]. Their test results showed that the soil suction of a residual soil of gneiss was higher when compacted with low energy than with high compaction energy at the same molding water content. Tripathy *et al*. [16] investigated the soil suction of two residual as-compacted soils. They also found that at a given molding water content the soil suction decreased with an increase in compaction energy. Romero *et al*. [17] simultaneously found the above two behaviors: At low water content, high compaction energy leaded to high suction. On the other hand, at high molding water content, high compaction energy leaded to low suction.

From the above literature review, it is very certain that the compaction energy has significant influences on the soil suction. However, the level of influence and

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the relationship between the soil suction and the compaction energy appear to be uncertain and need further investigation. To extensively evaluate the effect of molding water content and compaction energy on the soil suction, three clayey soils were compacted using three levels of compaction energy at various water contents. Post-compaction soil suction was measured by the filter paper method. The macro soil properties were used to explain the effect of compaction energy on the soil suction. Additional test results of two other soils previously published in the literature (Tripathy *et al*. [16]) were also examined to validate the findings from this study.

2. MATERIAL AND METHODS

2.1 Soil Properties

Two residual lateritic soils (Soil 1 and Soil 2) and a residual mudstone soil (Soil 3) were used in this study. Soil 1 and Soil 2 were obtained from soil slope at two different sites of similar geologic formation in northern Taiwan, and the distance between them is about 25km. Soil 3 is the subgrade soil used in the construction of National Freeway No. 3. The construction site is located at about 80km south of Taipei. These three locally available soils have high clay fraction (CF) of about 40% to 60%.

Soil 4 and Soil 5 having low clay fraction of 11% and 22% were obtained from the reference (Tripathy *et al*. [16]). In their study, the soil specimens were also prepared by impact compaction. Basic properties of all soil types studied, including specific gravity (Gs), liquid limit (LL), plasticity index (PI), clay fraction (CF), and soil activity (A_c) are summarized in Table 1.

Table 1 Index soil properties

	Type	Gs	LL	PI	CF (%)	A_c	USCS	Source
Soil 1	Residual Lateritic Soil	2.68	49	23	60	0.38	CL	This study
Soil 2	Residual Lateritic Soil	2.71	46	19	55	0.35	CL	This study
Soil 3	Residual Mudstone Soil	2.67	37	15	42	0.36	CL	This study
Soil 4	Residual Mudstone Soil	2.71	42	14	11	1.27	CL	Tripathy *et al.*, [16]
Soil 5	Residual Sandstone Soil	2.73	53	17	22	0.77	MH	Tripathy *et al.*, [16]

Table 2 Optimum moisture content and maximum dry density

Soil	Compaction Energy	Optimum Moisture Content, OMC (%)	Maximum Dry Density (Mg/m^3)
Soil 1	Modified	19.5	1.69
	Standard	22.0	1.55
	Reduced	24.0	1.47
Soil 2	Modified	18.5	1.76
	Standard	22.5	1.67
	Reduced	24.0	1.52
Soil 3	Modified	17.0	1.80
	Standard	21.0	1.68
	Reduced	23.0	1.62
Soil 4	Modified	13.5	1.94
	Enhanced	14.5	1.89
	Standard	15.0	1.80
Soil 5	Modified	18.0	1.80
	Enhanced	18.5	1.74
	Standard	20.5	1.65

2.2 Sample Preparation

Prior to compaction, the soils were air-dried and pulverized. In order to prepare the soil specimens at the designated molding water content, an appropriate amount of distilled water was added to the previously air-dried soil and allowed to equilibrate for one week. In this study, water content is defined as the ratio of the weight of water in a sample to the weight of the dry soil. The molding water contents ranges from 4% dry of optimum (OMC − 4%) to 4% wet of optimum (OMC + 4%) under different compaction energies. Then, the soils were compacted at three energy levels: Modified Proctor (ASTM D 1557), standard Proctor (ASTM D 698), and a reduced energy. The reduced energy corresponding to one half of the standard Proctor energy was used to simulate the poor compaction quality in the field. Figure 1 shows the compaction curves for the tested soils. The maximum dry density and the optimum water content of various compaction energies determined from Fig. 1 are shown in Table 2. Table 2 also summarizes the maximum dry density and the optimum water content of the other two soils derived from the literature (Tripathy *et al*. [16]). After the compaction, the soil suction of specimens was measured by the filter paper method described below.

2.3 Filter Paper Method

The filter paper method as specified in ASTM D 5298-94 is inexpensive and relatively simple. It is the only known method covering the full range of soil suction (10kPa ~ 100MPa). This method as described by Fredlund and Rahardjo [18] is based on the assumption that a filter paper will reach equilibrium with respect to moisture flow within a soil. When using this method, the moisture content of the filter paper at equilibrium is related to soil suction through a predetermined calibration equation, Eq. (1), for the particular paper type used.

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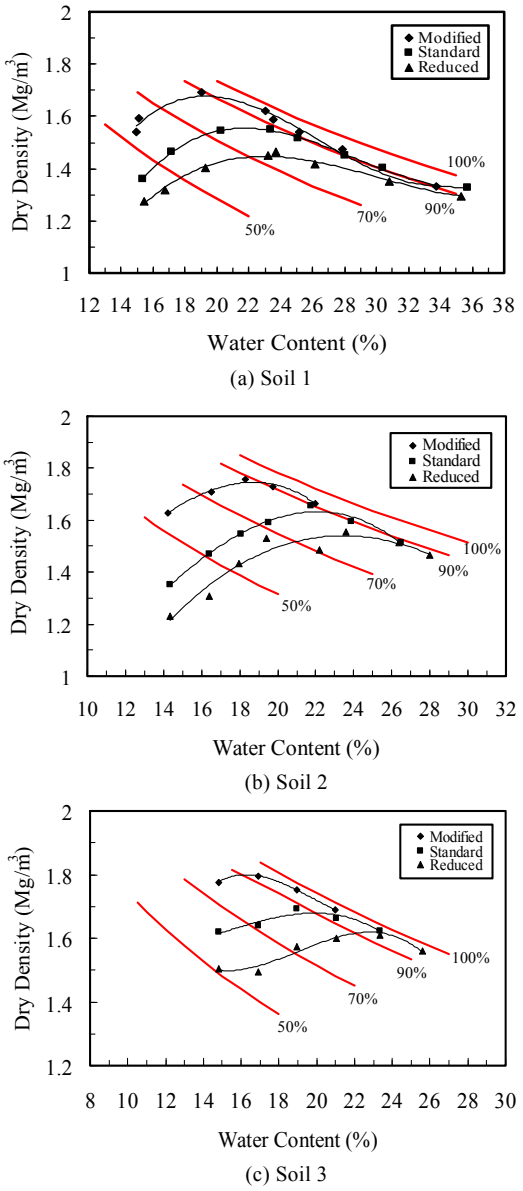


Fig. 1 Compaction curves of the tested soils using different energies

The filter paper used in this study is Whatman No. 42, ash-free quantitative Type II with a diameter of 5.5cm. Because the filter paper is used as indirect sensors, accurate measurements of suction rely on accurate calibration of the sensor properties. The calibration characteristics of filter paper vary significantly from batch to batch; hence, independent calibration on a batch-to-batch basis is strongly encouraged (Likos and Lu [19]).

The filter papers were calibrated by determining the relationship between equilibrium filter paper water content (w_{fp}) and vapor-phase relative humidity. Salt solutions of known concentrations were used to control relative humidity. In this study, NaCl solution was used for calibration. The following calibration equation based on the calibration data was used:

$$\psi = 5.467 - 0.1094\omega_{fp} \quad R^2 = 0.982 \qquad (1)$$

where ψ is soil suction (log kPa) and ω_{fp} is the filter paper water content (%).

To measure the soil suction, three stacked filter papers were placed in direct contact with the soil to determine the soil suction. For the "contact" procedure, the center filter paper is generally used for the soil suction measurement, while the outer filter papers are primarily used to protect the center paper from soil contamination.

The correct soil suction data rely upon a good contact with the specimens and maintenance of temperature during equilibrium. In order to maintain the temperature at 20°C within ±0.5°C fluctuations, a container accommodating the soil specimens and filter papers was put into an airtight box, and then placed in a temperature-controlled cabin. Usually, a 10-day period is sufficient for allowing the filter paper-soil to reach equilibrium (Yang *et al*. [11]). The moisture content of the filter paper was then determined, and the soil suction of the specimen was obtained from the calibration equation according to the moisture content of filter papers. More details on the calibration procedures and suction measurement by filter paper method can be found elsewhere (Bulut *et al*. [20]).

3. EFFECT OF COMPACTION ENERGY ON SOIL SUCTION

Various models have been proposed to represent soil water characteristic curves (SWCC), for example, the Brooks-Corey, the van Genuchten, and the Fredlund and Xing equations (Miller *et al*. [1]). However, there is still lack of models to describe the soil suction of as-compacted soils. In the following sections, a bilinear model is proposed to discuss the soil suction behavior against different molding water contents for five as-compacted clayey soils. Furthermore, the macro soil properties are used to evaluate the effect of compaction energy on the soil suction.

3.1 Bilinear Model for Soil Suction of As-Compacted Soils

Figure 2 shows the typical test results of the soil suction of the as-compacted clayey soils on a semi-log scale. In this figure, the test results of Soil 3 under standard compaction energy are used as an example to illustrate the bilinear model. In general, the soil suction decreases with increasing molding water content and the relationship between the soil suction and the molding water content exhibits bilinear behavior. From Fig. 2, the soil suction sharply increases as water content is below the breakpoint water content. At this condition, the pore water is occluded by air and the air-water interfaces, subjected to surface tension of pore water, form the meniscuses, resulting in sharply increases in the soil suction of the soil. The bilinear lines (Line *A* and Line *B*) are obtained by regression from the test results to show the feature of "rate of decrease in soil suction". These two lines can be expressed as:

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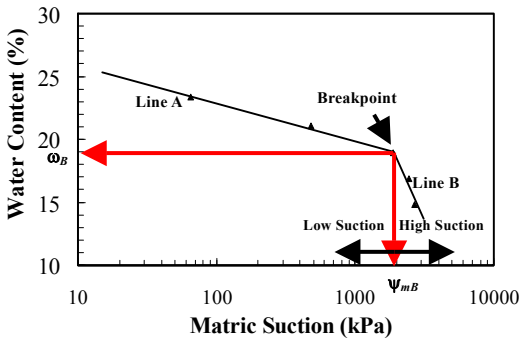


Fig. 2 Bilinear model for soil suction of as-compacted Soil 3 under standard compaction energy

$$\omega = \omega_B - K_1\left[\mathrm{Log}(\psi_B) - \mathrm{Log}(\psi)\right] \quad \text{when } \psi \le \psi_B \tag{2}$$

$$\omega = \omega_B + K_2\left[\mathrm{Log}(\psi) - \mathrm{Log}(\psi_B)\right] \quad \text{when } \psi \ge \psi_B \tag{3}$$

where ω = water content, ω_B = breakpoint water content, ψ = soil suction, ψ_B = breakpoint soil suction, K_1 = slope of Line *A*, and K_2 = slope of Line *B*. For ease of discussion, the soil suction that is lower than the breakpoint soil suction is termed the low suction. On the contrary, it is termed the high suction.

Figures 3 to 5 present the relationship between the soil suction and the as-compacted water content for Soils 1, 2, and 3 having high clay fraction. The bilinear model is used to fit the test results. These trends all fit in with the bilinear behavior well under modified, standard and reduced compaction energies. For Soil 1, Soil 2 and Soil3, breakpoint soil suction is above 1500kPa. Figures 6 and 7 present the soil suction of Soil 4 and Soil 5 having low clay fraction. Compared with the soil suction behavior of Soils 1, 2, and 3, the bilinear behavior of Soil 4 and Soil 5 is not significant, which is probably due to low clay fraction, or the fact that the soil suction in Soil 4 and Soil 5 is still in the low suction range (< 1500kPa). Additional research is needed to comprehend whether low clay fraction soils also exhibit bilinear behavior.

Table 3 summarizes the results of ω_B, ψ_B, K_1, K_2 and coefficient of determination (R^2) for Soils 1, 2, and 3 under different compaction energies. R^2 is the average of Line *A* and Line *B*. From Table 3, good correlations are observed since all the R^2 values are all above 0.9. The proposed model can be used to predict the soil suctions of the as-compacted clayey soils effectively. From Table 3, the breakpoint soil suction increases as the compaction energy increases for Soil 1 and Soil 2. On the other hand, it decreases for Soil 3. Test results also show that for Soils 1, 2, and 3 at one specific compaction energy, if the soils have higher clay fraction, the breakpoint soil suction is higher. Hence, the breakpoint soil suction and breakpoint water content can reflect the effects of compaction energy and clay fraction on the soil suction.

Table 3 Regression constants in Eqs. (2) and (3)

Soil	Compaction Energy	ω_B	ψ_B	K_1	K_2	R^2
Soil 1	Modified	17.68	3899	–1.324	–7.739	0.991
	Standard	17.89	3154	–1.267	–11.046	0.989
	Reduced	17.65	3033	–1.3108	–21.405	0.998
Soil 2	Modified	18.32	3253	–1.291	–3.675	0.921
	Standard	18.07	2630	–1.826	–14.371	0.937
	Reduced	17.94	1747	–2.082	–6.879	0.932
Soil 3	Modified	18.95	990	–1.271	–9.103	0.963
	Standard	18.95	1882	–1.296	–10.816	0.966
	Reduced	18.95	3745	–1.358	–9.184	0.965

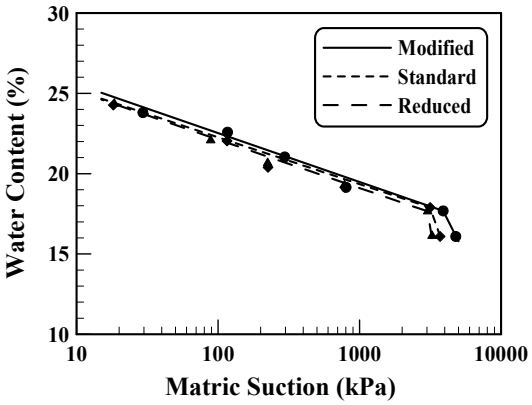


Fig. 3 Soil suction of as-compacted Soil 1

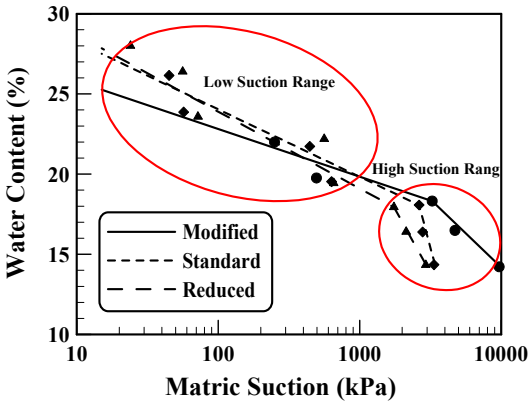


Fig. 4 Soil suction of as-compacted Soil 2

It is important to emphasize that the curves in Figs. 3 to 7 do not represent the so called soil water characteristic curve (SWCC), *i.e.* the water retention curve obtained by de-saturating the soil from saturated conditions under zero net stress. Hence, the characteristics of curves in Figs. 3 to 7 may be different from those of SWCC, since these curves do not describe the adsorption and desorption characteristics of the soils.

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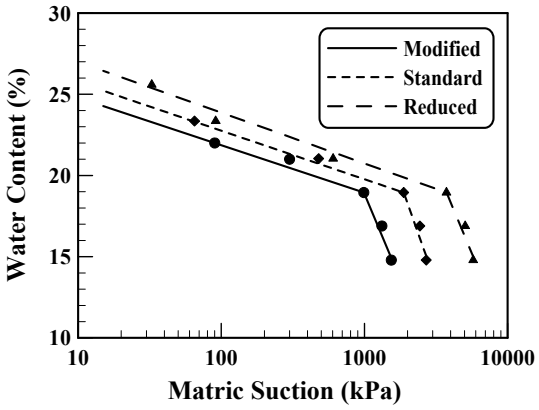


Fig. 5 Soil suction of as-compacted Soil 3

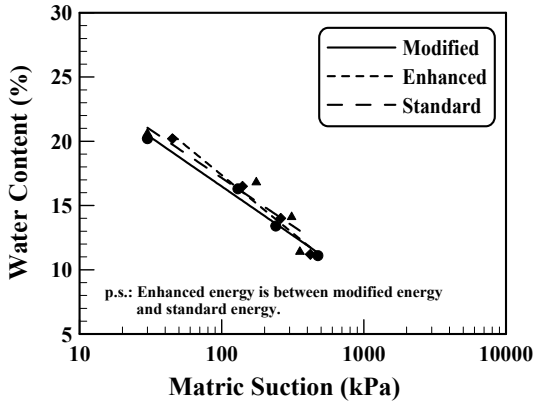


Fig. 6 Soil suction of as-compacted Soil 4

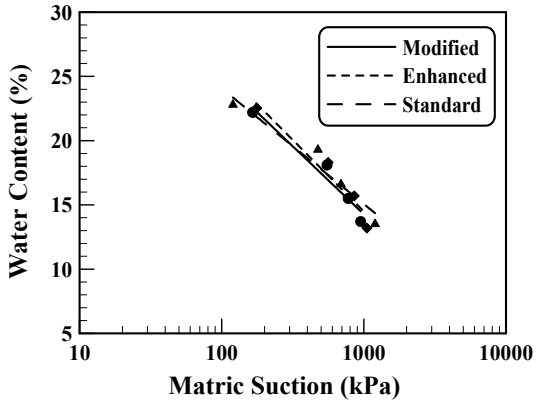


Fig. 7 Soil suction of as-compacted Soil 5

3.2 Relationship Between As-Compacted Soil Suction and Soil Properties

Test results indeed prove that the compaction energy has influences on the soil suction for the clayey soils. However, these influences are somewhat different with increasing molding water content and clay fraction.

Figures 3 and 4 show that the soil suction at a given water content for Soil 1 and Soil 2 compacted at high energy is higher than that compacted at low energy; however, this trend is totally reversed for Soil 3, as shown in Fig. 5. From Table 1, Soil 1 and Soil 2 have clay fraction larger than 50%, while Soil 3 has clay fraction lower than 50%. It seems that the clay fraction plays an important role on governing the effect of compaction energy on the soil suction.

Recall the previous discussion in introduction, Chu and Mou [13] found that the soil suction of an as-compacted clayey soil with the same initial compaction water content increases as compaction energy increases. Romero *et al*. [17] found the similar behavior at low molding water content. These two clayey soils both have clay fractions of 50%. However, Marinho and Stuermer [14], Rao and Revanasiddappa [15] and Tripathy *et al*. [16] presented reversed test results for residual soils having clay fraction of 45%, 32%, 22%, and 11%. Hence, from the study in the literature the effect of compaction energy on the soil suction for different clayey soils also reverses when clay fraction approaches 50%. Considering all of the results from this study and the literature, it seems that the clay fraction in soil provides a way to clarify the trend of influence of compaction energy on soil suction.

To clarify the above seemingly inconsistent suction behavior, further study was pursued from the point of macro soil properties. Conceptually, void ratio and saturation are two macro soil properties that can be used to evaluate soil suction in soils. At the following discussions, the changes of macro soil properties under different compaction energies were determined to evaluate the effects of compaction energy on soil suction.

The effect of compaction energy on void ratio and degree of saturation of the soils can be expected. In general, soil suction increases with decreasing the void ratio or the degree of saturation. In principle, when compaction energy increases, void ratio decreases, resulting in soil suction increase. Simultaneously degree of saturation increases resulting in soil suction decrease. The effects of these two factors are contradictory to each other. Hence, when the compaction energy increases at the same water content, if the change in void ratio (Δe) is larger than the change in degree of saturation (ΔS_r), the soil suction increases. Contrarily, the soil suction decreases. To comprehend the influence of compaction energy on the soil suction, the changes of macro soil properties, the Δe and ΔS_r, due to increasing compaction energy are examined in Figs. 8 and 9.

Figure 8 plots the Δe and ΔS_r using test results of Soil 1 and Soil 2 in the high suction range where high compaction energy results in high soil suction (Figs. 3 and 4). Each point in Fig. 8 represents the Δe and ΔS_r at a given water content due to an increase in compaction energy. For instance, for Soil 1 at the water content of 16%, the void ratios are 1.03, 0.89 and 0.63 under reduced, standard and modified compaction energy, respectively. The corresponding degrees of saturation are 0.41, 0.48 and 0.67. Hence, as the compaction energy increases from the reduced to the modified energy, the void ration decreases from 1.03 to 0.63; the degree of saturation increases from 0.41 to 0.67. In other words, the Δe is equal to –0.4 and the ΔS_r is equal to 0.26, plotted as Point A in Fig. 8. At the same water content of 16%, the Δe and ΔS_r can also be obtained by considering other two combinations of compaction

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energy, *i.e.* an increase from the reduced to the standard energy and an increase from the standard to the modified energy. Using the same approach, the data points representing the Δe and ΔS_r can be plotted in Fig. 8 at other molding water contents. If the change in void ratio equals to the change in degree of saturation, points will fall on the 45 angel degree line. It is observed that most points in Fig. 8 are below this line. In other words, the change in void ratio is larger than the change in degree of saturation with increasing compaction energy. Hence, from the macroscopic point of view the soil suction is expected to increase with compaction energy. This observation is consistent with the test results of the high suction range in Figs. 3 and 4.

Figure 9 used the same approach to show the Δe and ΔS_r of Soil 1 and Soil 2 in the low suction range, also including Soils 3, 4, and 5. Under this circumstance, high compaction energy results in low soil suction or insignificant influence on the soil suction (Figs. 5, 6, and 7). Figure 9 shows that most points are above the 45 angel degree line. It indicates that the change in degree of saturation is larger than the change in void ratio. In other words, the soil suction is expected to decrease with increasing compaction energy, when the change in degree of saturation is larger than the change in void ratio. This observation is also consistent with the test results. Besides, for Soil 5, the points shown in Fig. 9 are very close to the 45 angel degree line. It means that the change in void ratio nearly equals to the change in degree of saturation, and thus the compaction energy should have no significant influence on the soil suction, as verified by the test results shown in Fig. 7.

The level of influence of compaction energy on the soil suction can be quantitatively determined using Eq. (4). Equation (4) is used to describe the change of soil suction due to different compaction energies.

$$\Delta\psi = a_1 \Delta e + a_2 \Delta S_r + a_3 \tag{4}$$

where $\Delta\psi$ = change of soil suction (kPa), Δe = change of void ratio, ΔS_r = change of degree of saturation, and a_1, a_2, and a_3 are regression parameters. Table 4 summarizes the results of regression analysis on the test data using Eq. (4). Good correlations are observed with the coefficient of determination (R^2) ranging from 0.722 to 0.881. Hence, the Δe and ΔS_r indeed have a high correlation with the changes in soil suction when the soils are compacted at different compaction energies. In other words, the change of the soil suction can be evaluated by the change of macro soil properties.

The trends of compaction energy on the soil suction determined from all of the test results can be consistently explained both by the macro soil properties of Δe and ΔS_r. It seems to indicate that the seemingly inconsistent test results of soil suction behavior of five soils are realistic behavior. The Δe and ΔS_r can provide reasonable description of the effect of compaction energy on the soil suction. It should be pointed out that the change in the soil suction of the soils depends on the changes in the void ratio and the degree of saturation of the soils. Hence, they must be taken into account simultaneously to explain the effect of compaction energy on the soil suction.

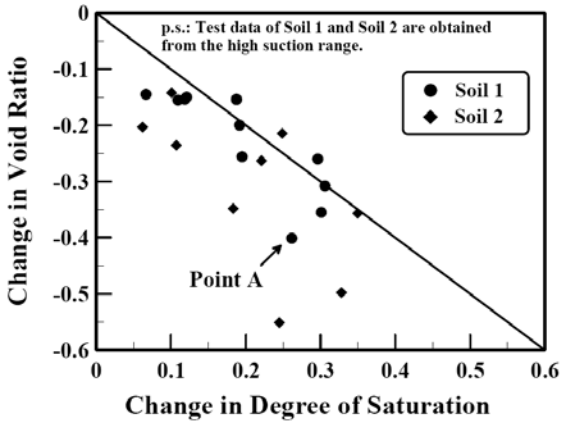


Fig. 8 Macro soil properties for high compaction energy resulting in high soil suction

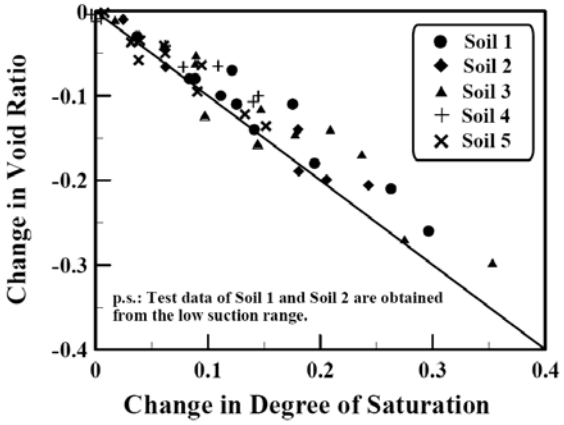


Fig. 9 Macro soil properties for high compaction energy resulting in low soil suction

Table 4 Regression constants in Eq. (5)

Soil	a_1	a_2	a_3	R^2
Soil 1	–7082.232	–5086.477	–154.792	0.728
Soil 2	–17267.000	–11952.585	–548.231	0.722
Soil 3	6930.913	–6971.069	308.108	0.824
Soil 4	–908.174	–157.294	5.929	0.881
Soil 5	–4513.595	–4547.499	42.909	0.782

4. CONCLUSIONS

In this study, extensive test results including five clayey soils and three levels of compaction energy were investigated to study the soil suction behavior of the soils compacted at various molding water content. Test re-

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sults show that the relationship between the soil suction and the molding water content is bilinear for the soils with high clay fraction. Besides, high compaction energy is accompanied by high soil suction for the residual lateritic soil, in the high suction range in particular, while high compaction energy produces low soil suction for the residual mudstone soil. For the soils with less clay fraction, the compaction energy has less influence on the soil suction. The macro soil properties were used to interpret the effects of compaction energy on the soil suction of the as-compacted soils.

Test results show that a higher compaction energy leads to a high soil suction at a given water content, if the effect of the change in void ratio on soil suction is larger than the effect of the change in degree of saturation on soil suction. On the contrary, the soil suction decreases with increasing compaction energy, if the effect of the change in degree of saturation on soil suction is larger than the effect of the change in void ratio on soil suction. Hence, the change in these two macro soil properties can also be adopted together to describe the changes in the soil suction under different compaction energies. The approach presented in this paper provides a promising way of interpreting the complicated soil suction behavior by taking into account simultaneously the changes in void ratio and the degree of saturation of soils.

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