Journal of Marine Science and Technology

Volume 23 | Issue 3 Article 2

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Shu-Rong Yang
Department of Civil Engineering, National Pingtung University of Science and Technology, Pingtung, Taiwan, R.O.C.

Wei-Hsing Huang
Department of Civil Engineering, National Central University, Taoyuan, Taiwan, R.O.C., t321655@ncu.edu.tw

Shao-Hung Chung
Department of Civil Engineering and Environmental Informatics, Minghsin University of Science and Technology, Hsinchu, Taiwan, R.O.C.

Recommended Citation
Yang, Shu-Rong; Huang, Wei-Hsing; and Chung, Shao-Hung (2015) "COMBINED EFFECTS OF TEMPERATURE AND MOISTURE CONTENT ON SOIL SUCTION OF COMPACTED BENTONITE," *Journal of Marine Science and Technology*: Vol. 23: Iss. 3, Article 2.
DOI: 10.6119/JMST-014-0326-2
Available at: https://jmstt.ntou.edu.tw/journal/vol23/iss3/2

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Acknowledgements

This study was supported under project No. NSC 100- 2221-E-008-109 and NSC 101-2218-E-020-002 by the National Science Council of the Republic of China, Taiwan.

Journal of Marine Science and Technology, Vol. 23, No. 3, pp. 281-287 (2015)
DOI: 10.6119/JMST-014-0326-2

COMBINED EFFECTS OF TEMPERATURE AND MOISTURE CONTENT ON SOIL SUCTION OF COMPACTED BENTONITE

Shu-Rong Yang[1], Wei-Hsing Huang[2], and Shao-Hung Chung[3]

Key words: soil suction, compacted bentonite, filter paper method, thermocouple psychrometer, expansive soils.

ABSTRACT

Based on experimental determination of soil suctions of two clayey soils, this study investigated the combined effects of temperature and moisture content on soil suction. First, two clayey soils were statically compacted at target moisture contents ranging from 5% to 20%, such that a broad spectrum of compaction conditions can be evaluated. Then, filter paper method and thermocouple psychrometer were adopted to measure soil suction, including total and matric suctions, at temperatures ranging from 10°C to 60°C. It was found that soil suctions of expansive soils vary with compaction parameters such as compaction moisture content and compaction effort, and that temperature is influential on soil suction also. As moisture content increases, the effects of compaction effort and temperature on suction become less significant. Formulations developed using multiple regression were established for predicting the soil suction of as-compacted expansive soils.

I. INTRODUCTION

Clayey soils are used as buffer material in an engineered barrier system for isolation of high-level radioactive wastes (HLW) in a repository. The safety of a deep geological repository depends upon the stability of engineering barriers. Being a major component in the barrier system, buffer material is expected to create an impermeable zone around the high level waste canisters. Compacted bentonites have been considered by many countries as the prime candidate for buffer material due to their sealing capacity.

In the current proposal for deep geological disposal of the high-level radioactive wastes in Taiwan, compacted bentonite is used to contain the metallic waste canisters and separate the waste from the host rock and backfill materials. The major roles of the buffer material are to reduce the groundwater flow, to protect the overpack from degradation, and to minimize the migration of radionuclides.

In a HLW repository, after emplacement of the buffer material, groundwater begins to be taken from the surrounding rock by the buffer and the buffer becomes saturated gradually. Groundwater intrusion is taken as an important scenario in the performance assessment of a geological repository. The resaturation of the buffer is considered a hydro-process occurring at elevated temperatures in the near-field of a repository. Soil suction affects this resaturation process because soil suction describes the potential with which a given soil adsorbs and retains pore water, at given moisture contents. Soil-water characteristic curve (SWCC) describes the relationship between soil suction and moisture content, and is an important physical behavior of unsaturated soils. With the knowledge of soil suction, the mechanism of groundwater penetration into buffer material can be understood.

Groundwater flow through buffer is coupled with the mechanical changes induced by in-situ stresses and the thermal loading resulting from heat generated by the radioactive waste. Recent studies have widely discussed the influences of temperature on the SWCC of unsaturated soils (Börgesson et al., 2001; Romero et al., 2003; Tang and Cui, 2005; Arifin et al., 2006). Tang and Cui (2005) determined the SWCC of MX-80 clay. They found that at a given moisture content the suction decreased as temperature increased. Börgesson et al. (2001) indicated that the effects of temperature on SWCC were small for compacted bentonite. Besides, the effects of compaction effort on soil suction have also been widely discussed (Chu and Mou, 1981; Marinho and Stuermer, 2000; Yang et al., 2012; Yang et al., 2013). Chu and Mou (1981) observed that matric suction of compacted soils with the same moisture content increased with increasing compaction effort. However, Marinho and Stuermer (2000) proposed an adverse argument. They indicated that the soil suction increased as compaction

Paper submitted 11/30/13; revised 02/26/14; accepted 03/26/14. Author for correspondence: Wei-Hsing Huang (e-mail: t321655@ncu.edu.tw).
[1] *Department of Civil Engineering, National Pingtung University of Science and Technology, Pingtung, Taiwan, R.O.C.*
[2] *Department of Civil Engineering, National Central University, Taoyuan, Taiwan, R.O.C.*
[3] *Department of Civil Engineering and Environmental Informatics, Minghsin University of Science and Technology, Hsinchu, Taiwan, R.O.C.*

Table 1. Chemical composition of the two soils.

Components	BH Bentonite	Zhisin Clay
	Percentage (%)	
SiO_2	64.55	55.43
Al_2O_3	17.53	20.11
Fe_2O_3	3.85	5.54
CaO	1.42	2.55
MgO	1.31	1.71
Na_2O	2.24	0.72
K_2O	0.40	1.35
SO_3	0.3	2.5

Table 2. Cation exchange capacity (CEC).

Cation	BH Bentonite	Zhisin Clay
	(meq/100 g)	
K^+	4.8	1.4
Na^+	56.7	23.1
Ca^{2+}	19.6	38.7
Mg^{2+}	1.1	6.8
CEC	82	70
Ratio of Na^+/Ca^{2+}	2.89	0.60

Table 3. Basic Soil Properties.

Soil Properties	BH Bentonite	Zhisin Clay
Gs	2.69	2.67
LL	434	67
PI	380	49
Activity (Ac)	5.85	1.88
Clay Content (%) (< 0.002 mm)	65	26
USCS Classification	CH	CH

effort decreased. Rational models were proposed by Yang et al. (2012) to explain the two kinds of soil suction behaviors.

In this study, the suction of two clayey soils was determined for various initial compaction conditions, covering a wide range of moisture contents and dry unit weights. The combined effects of temperature and moisture content on soil suction were investigated in the laboratory. The total suction and matric suction of the compacted clayey soils were obtained using filter paper method and thermocouple psychrometer. The measured suction data were used to establish multiple regression formulations for predicting soil suction, at varying temperature and compaction criteria, of as-compacted clayey buffer materials.

II. MATERIALS AND METHODS

1. Material Characteristics

In the study, two industrial clays were investigated, namely Black Hill bentonite (BH bentonite) and Zhisin clay. BH

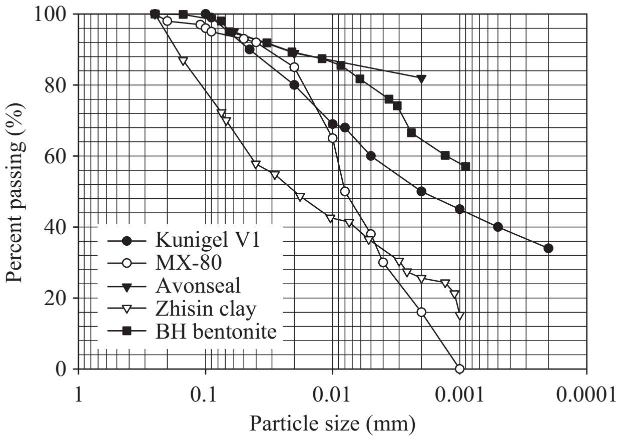


Fig. 1. Particle size analysis for the 2 tested clays.

bentonite is produced by Black Hills company in Wyoming while Zhisin clay is a locally available clayey soil, with an estimated deposit of over a million tons in Eastern Taiwan. Both clays are highly plastic and have potential for being used as a possible engineering barrier for disposal of high-level nuclear waste.

Table 1 shows the chemical composition of the two expansive clays. Table 2 presents the cation exchange capacity (CEC). It shows that BH bentonite is a Na-bentonite and Zhisin clay is identified as a Ca-bentonite. Their basic soil properties are summarized in Table 3. BH bentonite was found to be more plastic than Zhisin clay. The grain size curve is given in Fig. 1. It shows that BH bentonite has a higher percentage of fines than Zhisin clay. Also shown in Fig. 1 is the grain size distribution of MX-80 bentonite which is a widely used reference material for engineered barrier for the final disposal of radioactive wastes.

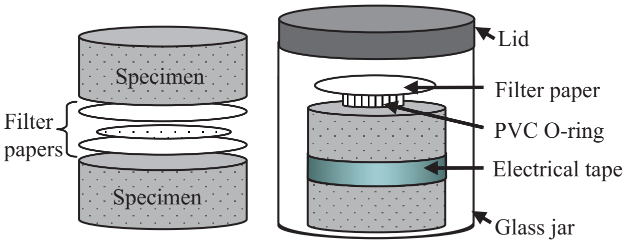
All specimens used in this study were statically compacted to 60 mm in diameter and 30 mm in height, and prepared in a single layer using a constant volume mold at different unit weights and moisture contents, and then suction measurements were made at the temperature range of 10°C to 60°C.

2. Suction Measurement

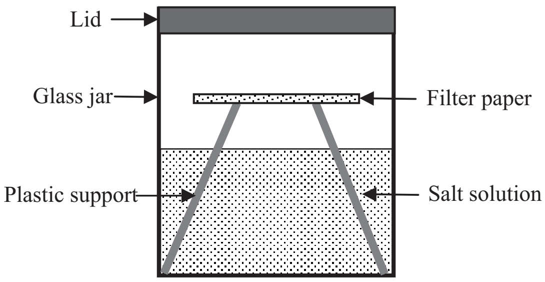
The filter paper method and thermocouple psychrometer were adopted to measure soil suction of as-compacted Zhisin clay and BH bentonite. The thermocouple psychrometer measures the total suction, which is the sum of the matric suction and osmotic suction. The filter paper method is capable of determining the matric suction or total suction depending on the contact or non-contact of the filter paper with the soil.

1) Filter Paper Method

The filter paper method was conducted in accordance with ASTM D 5298-94 (2000), which is a relatively simple and inexpensive test method. It is the only known method that can measure the full range of soil suction, and it is also the only



(a) Soil suction measurement by filter paper



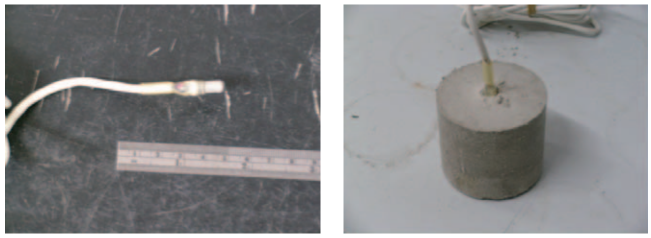
(b) Calibration of filter paper method

Fig. 2. Filter paper method configuration.

method to measure total suction and matric suction simultaneously. Fredlund and Rahardjo (1993) indicated that the filter paper method is based on the assumption that a filter paper will reach equilibrium with respect to moisture flow within the soil.

Figs. 2(a) and (b) show the sketch of filter paper method for measuring soil suction and calibration of filter paper, respectively. To determine the matric suction of a soil, three stacked filter papers were placed in direct contact with the soil. For the “contact” procedure, the center filter paper is generally used for the suction measurement, while the outer filter papers are primarily used to protect the center paper from soil contamination. The “noncontact” procedure can be used by placing a dry filter paper on a disk above the soil to determine the total suction of soil. Accurate determinations of matric suction rely upon a good contact of the paper with the soil sample and maintenance of constant temperature. In order to maintain the temperature within ±0.1°C fluctuations, a container accommodating soil samples and filter papers was put into an ice box, and then placed in a temperature-controlled cabin. A 10-day period was allowed for the filter paper-soil to reach equilibrium.

Common types of filter paper for suction testing include Whatman No. 42, Schleicher, Schuell No. 589 White Ribbon, and Fisherbrand 9-790A, as suggested by ASTM D 5298. The filter paper used in this study was Whatman No. 42, ash-free quantitative Type II with a diameter of 5.5 cm. The moisture content of the filter paper at equilibrium is related to soil suction through a predetermined calibration curve for the particular paper type used. The filter papers were calibrated by determining the relationship between equilibrium filter paper moisture content (w_{fp}) and total suction (ψ_t), and the suction of the specimen was obtained from the calibration curve



(a) Probe (b) Soil specimen

Fig. 3. Measurement of total suction using thermocouple psychrometer.

according to the moisture content of the filter paper. Salt solutions of known concentrations were used to control relative humidity. This study used a NaCl solution at different concentrations. The relationship between the total suction and the relative humidity of the pore water vapor is described by Kelvin’s equation:

$$\psi_t = \frac{RT}{V}\ln\left(\frac{P}{P_0}\right) \tag{1}$$

where ψ_t = total suction (kPa), R = universal gas constant [8.31432 J/(mol K)], T = absolute temperature (K), V = molecular volume of water (m^3/kmol), P/P_0 = relative humidity (percent), P = partial pressure of pore water vapor (kPa), and P_0 = saturation pressure of water vapor over a flat surface of pure water at the same temperature (kPa). The following calibration equation, based on the calibration data, was used:

$$\psi_t = 5.467 - 0.1094\omega_{fp} \qquad R^2 = 0.982 \tag{2}$$

where ψ_t is total suction (log kPa) and w_{fp} is the filter paper moisture content (%).

2) Thermocouple Psychrometer

Thermocouple psychrometer can provide very positive and reliable suction measurement in the laboratory and for field applications (Tsai and Petry, 1995). Besides, it has quick response time and the durability of the steel shield compared favorably with the ceramic tipped alternative (Skierucha, 2005). In this study, soil suction was measured using an eight-channel thermocouple psychrometer (WESCOR PSYPRO Water Potential System).

The thermocouple psychrometer used is a commercially available item (Wescor PST-55-30-SF), as shown in Fig. 3(a). The operating temperature range of thermocouple psychrometer is between 0°C and 60°C. A thermocouple psychrometer measures the dewpoint of the water vapor within the probe that is placed in the soil sample, as shown in Fig. 3(b). Thermocouple psychrometer method relies on Peltier cooling and Seebeck effects, which are two physical phenomena describing the psychrometric method of soil suction measurements. More details on the theories and operations of psychrometer can be found elsewhere (Lu and Likos, 2004; Skierucha, 2005).

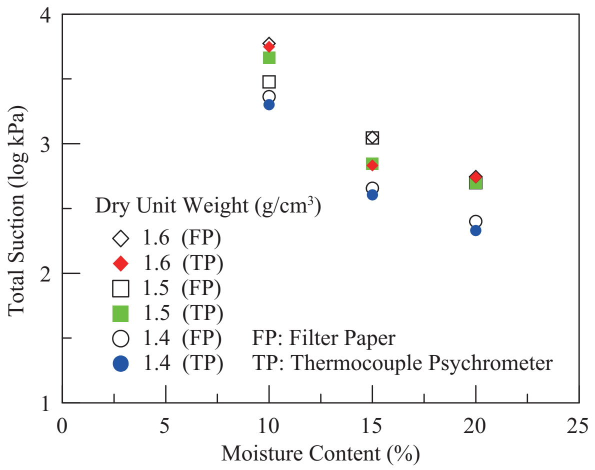


Fig. 4. Total suction of Zhisin clay measured by filter paper method and thermocouple psychrometer.

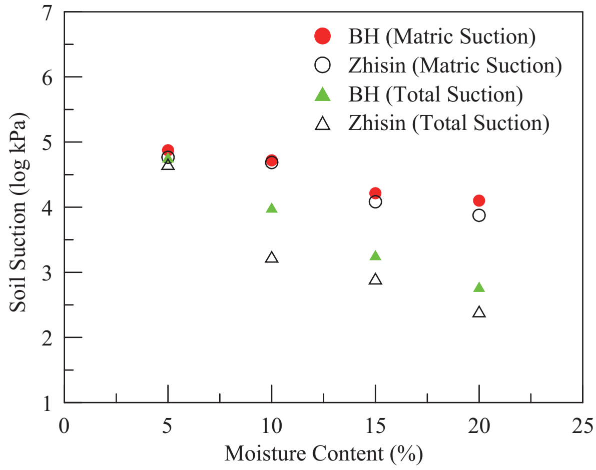


Fig. 5. Suctions of Zhisin clay and BH bentonite measured by filter paper method at a dry unit weight of 1.7 g/cm^3.

Thermocouple psychrometer method also requires calibration procedures to evaluate the suction. Calibration is performed with salt solutions of various known molarities that produce a given relative humidity. In the present study, solution of NaCl at five different concentrations with molarities of 0.1, 0.2, 0.55, 0.70 and 1.2 was used to establish the calibration curve. The following calibration equation was developed:

$$\psi_{t1} = 1.011\psi_{t2} \qquad R^2 = 0.994 \tag{3}$$

where ψ_{t1} is total suction as calculated using Eq. (1) at specific concentration and ψ_{t2} is total suction measured by thermocouple psychrometer at specific concentration corresponding to ψ_{t1}. The correction factor of 1.011 is used to set the proper conversion for thermocouple psychrometer.

III. DISCUSSION OF TEST RESULTS

1. Effect of Compaction Moisture Content on Soil Suction

In general, filter paper method is considered as a high uncertainty technique when measuring soil suction (Likos and Lu, 2002). Thermocouple psychrometer is generally able to provide reliable suction measurements because of the availability of advanced electronic components of high accuracy and microcontroller supervision (Tsai and Petry, 1995; Skierucha, 2005). To evaluate the accuracy of filter paper method, the total suction measured by filter paper was compared with that measured by thermocouple psychrometer.

Fig. 4 presents the total suction of Zhisin clay using filter paper method and thermocouple psychrometer at moisture contents of 10, 15 and 20% and dry unit weights of 1.4, 1.5 and 1.6 g/cm^3. Test results show that the filter paper method and thermocouple psychrometer measure nearly the same total suction for specimens having the same compaction conditions. It reveals that the filter paper method gives reliable soil suction measurements, if the method is carried out appropriately. Tsai and Petry (1995) also confirmed that the suction measured by filter paper method and thermocouple psychrometer was close.

Fig. 5 presents the total suction and matric suction of BH bentonite and Zhisin clay at dry unit weight of 1.7 g/cm^3. The suction of BH bentonite is higher than that of Zhisin clay, especially at high moisture content, because BH bentonite has higher clay content. Besides, the suctions of both soils decrease as moisture content increases, and the change rate in suction with increasing moisture content is observed to be lower for BH bentonite than for Zhisin clay. Therefore, BH bentonite has a better capacity of water holding than Zhisin clay.

2. Combined Effects of Moisture Content and Dry Unit Weight on Soil Suction

Fig. 6 and Fig. 7 show the total suction and matric suction of Zhisin clay at different compaction moisture contents and dry unit weights using filter paper method. It is found that the total suction and matric suction decrease as the compaction moisture content of the soil increases, especially at high dry unit weight. It is also found that an increase in the dry unit weight at similar compaction moisture content results in an increase in total suction and matric suction. Hence, the total suction and matric suction of the compacted clayey soils at the same moisture content increases with increasing compaction effort. However, the effect of compaction effort on soil suction becomes less significant with increasing compaction moisture content.

Fig. 8 and Fig. 9 show the relationship between the soil suction and compaction moisture content at various dry unit weights for BH bentonite. Suction characteristics of BH bentonite are similar to those of Zhisin clay. The total suction and matric suction decrease as moisture content increases. In addition, the total suction and matric suction of the soil with the same moisture content increases as compaction effort increases. Both total suction and matric suction are influenced by compaction effort, but the influence is not significant at high compaction moisture content.

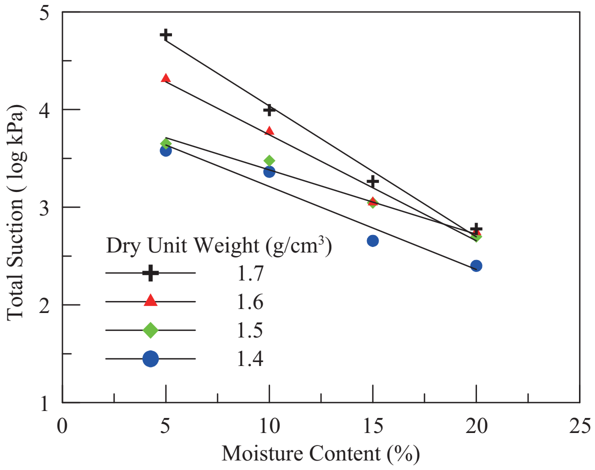


Fig. 6. Combined effects of moisture content and dry unit weight on total suction of Zhisin clay.

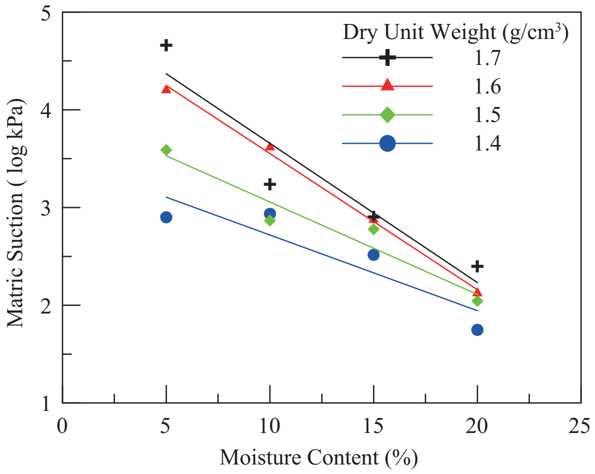


Fig. 7. Combined effects of moisture content and dry unit weight on matric suction of Zhisin clay.

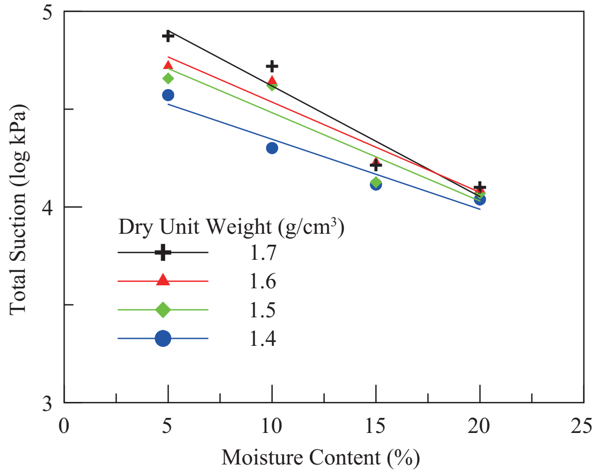


Fig. 8. Combined effects of moisture content and dry unit weight on total suction of BH bentonite.

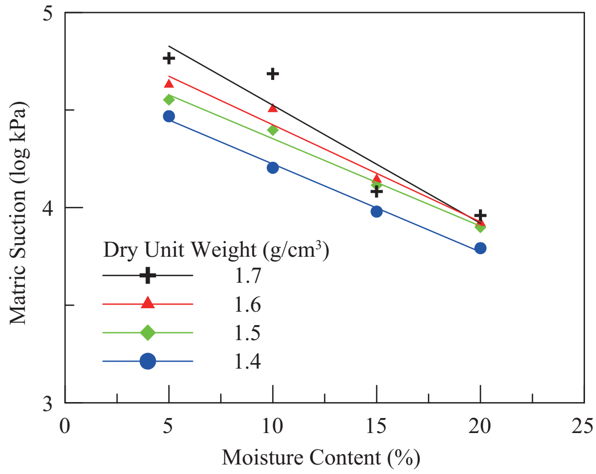


Fig. 9. Combined effects of moisture content and dry unit weight on matric suction of BH bentonite.

For compacted soils, compaction moisture content (ω) and dry unit weight (γ_d) are most two important factors influencing soil behaviors. In addition, these two parameters are easily obtained from soil compaction tests. Hence, compaction moisture content (ω) and dry unit weight (γ_d) were used to predict the total suction and matric suction. Based on suction data presented in Fig. 6 to Fig. 9, a multiple regression analysis was conducted to establish correlations between soil suction, compaction moisture content (ω) and dry unit weight (γ_d). Eqs. (4) and (5) were derived to predict the total suction and matric suction of as-compacted clayey soils with varying compaction moisture contents.

$$\log \psi_T = a_1 + a_2\omega + a_3\gamma_d \tag{4}$$

$$\log \psi_M = b_1 + b_2\omega + b_3\gamma_d \tag{5}$$

where ψ_T = total suction (kPa), ψ_M = total suction (kPa), ω = compaction moisture content (%), γ_d = dry unit weight (g/cm^3), a_1, a_2, a_3, b_1, b_2 and b_3 are regression constants. Tables 4 and 5 summarize the results of regression analysis on the total suction and matric suction test data. Fig. 10 plots the predicted total suction and matric suction calculated by Eqs. (4) and (5) against the measured suction. It is shown that Eqs. (4) and (5) predict the soil suction of the compacted soil effectively.

3. Combined Effects of Temperature and Moisture Content on Soil Suction

Test results obtained from filter paper method and thermocouple psychrometer were used in this study to assess the effect of temperature on the suction of compacted soil at different dry unit weights and moisture contents. In Fig. 11, measurements of total suction were conducted at 10°C, 25°C, 35°C, and 50°C using the thermocouple psychrometer on Zhisin clay. The soil specimens were compacted at dry unit weight of 1.6 g/cm^3 and moisture contents of 10%, 15% and

Table 4. Regression constants in Eq. (4).

Soil	Total Suction		
	a_1	a_2	a_3
Zhisin Clay	0.924	-0.098	2.356
BH Bentonite	3.850	-0.046	0.713

Table 5. Regression constants in Eq. (5).

Soil	Matric Suction		
	b_1	b_2	b_3
Zhisin Clay	0.182	-0.113	2.708
BH Bentonite	3.570	-0.050	0.846

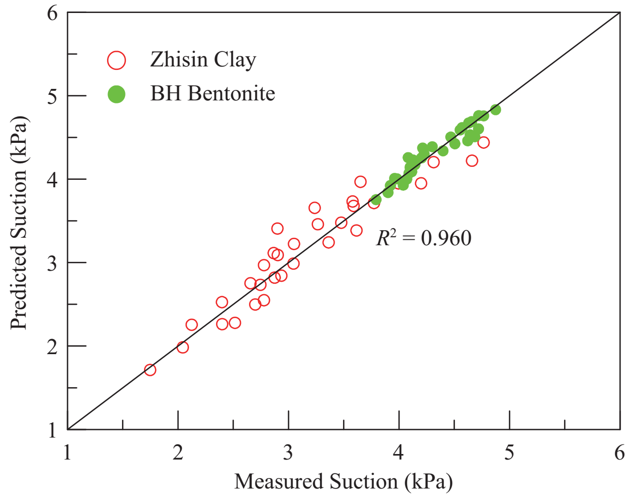


Fig. 10. Predicted versus measured suction using Eqs. (4) and (5).

20%. Test results show that temperature does influence the total suction of compacted clayey soils. At the same moisture content, the total suction of soil specimen at higher temperature is less than that at lower temperature. Hence, an increase in temperature results in a decrease in the total suction of compacted clays.

At temperature of 10°C, the measured total suction is about 3.88 log kPa, or 7600 kPa, for Zhisin clay with moisture content of 10%. The suction drops to about 3.32 log kPa (2100 kPa) when the temperature rises to 50°C. Similarly, at moisture content of 20%, the total suction is about 2.98 log kPa (950 kPa) at temperature of 10°C. As temperature increases to 50°C, the total suction is about 2.54 log kPa (350 kPa). It is calculated that the change rate in suction with increasing temperature ($\Delta\psi_T/\Delta T$) were approximately –136.91 and –15.59 (kPa/°C) for moisture contents of 10% and 20%, respectively. To summarize, the total suction decreases sharply with increasing temperature at low moisture content. However, at high moisture content, the change rate in suction with the rise of temperature reaches a constant. Hence, the effect of temperature on total suction is much smaller at high moisture content than at low moisture content.

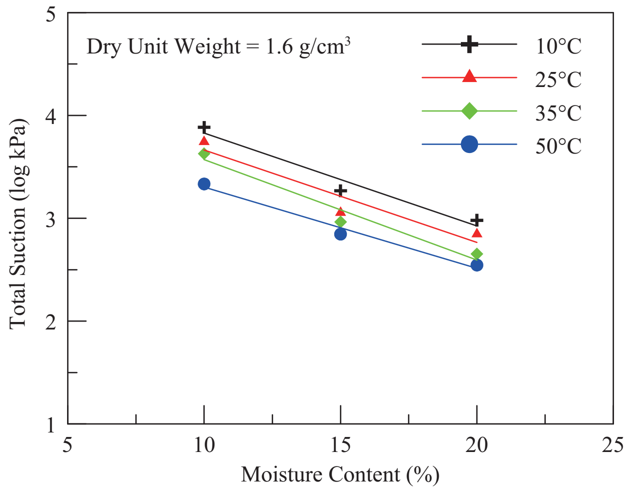


Fig. 11. Combined effects of temperature and moisture content on total suction of Zhisin clay measured by TP.

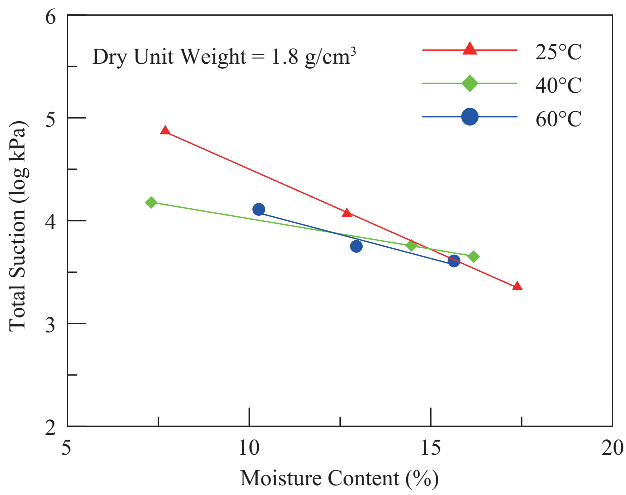


Fig. 12. Combined effects of temperature and moisture content on total suction of Zhisin clay measured by FP.

Filter paper method was carried out for suction determinations of Zhisin clay compacted at dry unit weight of 1.8 g/cm^3, as the suction measuring range exceeds the capacity of thermocouple psychrometer. Test results are presented in Fig. 12. It shows similar trend as that obtained from the thermocouple psychrometer in that: (a) the total suction of the compacted clayey soils decreases as temperature increases; (b) at low moisture content, total suction decreases sharply as temperature increases. Notably, as the moisture content is higher than 15%, it is found the total suction is no longer affected by temperature.

Fig. 13 shows the total suction of BH bentonite conducted at 25°C, 40°C, and 60°C using the filter paper method. The soil specimens were compacted at dry unit weight of 1.8 g/cm^3 and moisture contents of 10%, 15% and 20%. It is also found that the total suction was observed to decrease as temperature increases. The change rate in suction with increasing temperature

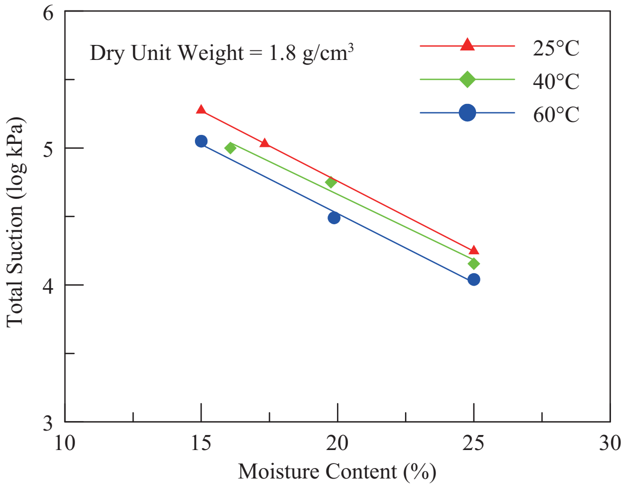


Fig. 13. Combined effects of temperature and moisture content on total suction of BH bentonite measured by FP.

($\Delta\psi_T/\Delta T$) were approximately –2174.85 and –191.31 (kPa/°C) for moisture contents of 15% and 20%, respectively. Hence, effect of temperature on total suction is low at high moisture content. Comparing with Zhisin clay, the total suction of BH bentonite is found to be more sensitive to temperature. Nevertheless, temperature effect on total suction characteristics of BH bentonite is similar to that of Zhisin clay.

IV. CONCLUSIONS

Due to the wide range of total suction and matric suction exhibited by expansive soils, the two suction measurement techniques, filter paper method and thermocouple psychrometer, were found to be applicable to specific suction measurement ranges. Incorporation of the two suction measurement techniques improves the covered range and measured accuracy. The combined effects of compaction moisture content, compaction effort, and temperature on compacted clayey soils, namely BH bentonite and Zhisin clay, were investigated. Based on the test results and discussions presented, the following conclusions are drawn:

(1) Test results confirm that both total suction and matric suction are significantly influenced by changes in the moisture content of compacted BH bentonite and Zhisin clay. In addition, the soil suction of BH bentonite is higher than Zhisin clay, and the change rate in suction with increasing moisture content is lower for BH bentonite than for Zhisin clay, indicating that BH bentonite has a better capacity of water holding than Zhisin clay.

(2) It was found that total suction and matric suction of BH bentonite and Zhisin clay are significantly influenced by compaction effort at low moisture content. Soils compacted to a higher dry unit weight have greater soil suction than those with low dry unit weight. However, at high moisture content, the effects of compaction effort on suction become limited.

(3) Soil suction of BH bentonite and Zhisin clay was conducted at temperatures ranging from 10°C to 60°C. Test results show that soil suction decreases as temperature increases. Besides, BH bentonite was found to be more sensitive to temperature than Zhisin clay.

(4) The multiple regression formulations, incorporating moisture content and dry unit weight, were developed for predicting the matric suction and total suction of compacted Zhisin clay and BH bentonite. It is shown that the developed formulations predict the suction of the compacted soil effectively.

ACKNOWLEDGMENTS

This study was supported under project No. NSC 100-2221-E-008-109 and NSC 101-2218-E-020-002 by the National Science Council of the Republic of China, Taiwan.

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