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Research Article

Estimation of Soil-Water Characteristic Curve for Cohesive Soils with Methylene Blue Value

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This study described a new methylene blue test to measure the methylene blue value (MBV) for 15 cohesive soils and established the relationship between MBV and plasticity index (PI) and between MBV and percent passing No. 200 sieve (P_{200}), respectively. Thereafter, the soil-water characteristic curves (SWCCs) for 15 cohesive soils based on Fredlund and Xing's model were generated by the pressure plate test. Then, regression equations for determining the four fitting parameters in a previously developed SWCC equation by using the measured MBV were utilized to generate the SWCC for the cohesive soils. At the same time, the slope parameter, b_f, in the SWCC equations was found to be associated with the moisture susceptibility of cohesive soils. A higher b_f value indicates that the material is more moisture susceptible. In addition, a lower MBV/PI/P_{200} shows a lower suction at the same degree of saturation; on the other hand, a higher MBV/PI/P_{200} presents a higher suction. Therefore, the moisture-holding capacity of cohesive soils increases with increasing MBV, PI, and P_{200}. Finally, the proposed estimation method was validated by a comparison between the four determined fitting parameters from MBV and the pressure plate test.

1. Introduction

The soil-water characteristic curve (SWCC) is a graphical relationship between the matric suction and the water content. It is one of the basic characteristics of partially unsaturated soils, and as such, it is useful for estimating the other properties of soil, when solving engineering problems in these three classic areas: fluid flow, compressibility, and shear strength [1]. For example, when modeling unsaturated moisture flow beneath a highway pavement, the hydraulic conductivity of the base course and subgrade materials, as a function of moisture content, must be known. Since the experimental procedures, in which a filter paper or pressure plate test, adopted for determining the matric suction-water content relationship, is time-consuming and cost-intensive [2, 3], recent research has placed a major focus on an estimation method to predict the SWCC using some mathematical functions [1, 4, 5]. However, the shape of the curve depends on many basic soil properties, such as the percent passing No. 200 sieve (P_{200}), plasticity index (PI), and environmentally induced factors that determine the stress state, compaction level, and temperature. It is difficult to find a valid and convenient mathematical expression to describe it. However, several analytical functions for predicting the SWCC can be found in some literatures [6–9]. The predicting variables, including sieve analysis and index properties, display extensive variability in those literatures [10]. Some time-consuming and material-consuming experiments are still necessary, including sieve analysis and Atterberg limits. Under this circumstance, Hakan Sahin et al. proposed a new estimation method to determine SWCC for unbound aggregate mixtures based on the methylene blue value (MBV) and percent fines content (PFC) [11–13].

The methylene blue has a large polar organic molecule $C_{16}H_{18}N_3S^+$ that can be adsorbed onto the negatively charged surfaces of clay minerals. The amount of adsorbed methylene blue depends on the amount of the surface area of the clay particles. The more the methylene blue adsorbed by the clay particles, the brighter the methylene blue solution will be. The adsorbed methylene blue is able to be quantified by assessing the color change of the methylene blue solution. At the same time, SWCCs for cohesive soils reveal their water-holding capacity which depends on the specific surface area of the clay particles [9,14–18]. Based on the above description about the methylene test, MBV reflects the specific surface area of soil particles. Therefore, SWCCs for cohesive soils can be predicted using the methylene blue value. Once the relationship between the four fitting coefficients of Fredlund and Xing's model, which are shown in (1), and the MBV is built, SWCCs for cohesive soils will be determined:

$$\theta_\omega = C(h) \times \frac{\theta_s}{\left\{\ln\left[\exp(1) + (h/a_f)^{b_f}\right]\right\}^{c_f}},$$
$$C(h) = 1 - \frac{\ln(1 + (h/h_r))}{\ln(1 + (10^6/h_r))}, \quad (1)$$

where θ_ω is the volumetric water content; θ_s is the saturated volumetric water content; h is the matric suction; and a_f, b_f, c_f, and h_r are fitting coefficients, which are primarily a function of the air entry value, rate of water extraction from the soil, residual water content, and suction at which the residual water content occurs, respectively. Once these four fitting parameters are determined, the SWCC for a specific soil can be established automatically.

This study is organized as follows: The forthcoming section introduces a new methylene blue test method, and the methylene blue tests of 15 cohesive soils were completed. Subsequently, the correlation between PI and MBV and between P_{200} and MBV was proposed and analyzed, respectively. The next section builds the correlations between the four fitting parameters of Fredlund and Xing's model and the MBV, which were validated subsequently. The final section summarizes the major findings of this study.

2. Experiments and Materials

Based on the preceding discussions, this section presents the laboratory experiments and materials required to develop the fitting models for the SWCCs.

2.1. Laboratory Experiments. The sieve test and Atterberg limit test were employed to determine the particle distribution and plasticity index, respectively. At the same time, the maximum dry density and optimum moisture content, which were utilized to mold the soil samples for the pressure plate test, were gained according to the Proctor test. Thereafter, the pressure plate test was used to measure the matric suction for different moisture contents. In addition, the methylene blue test was used to detect the amount of fine particles in 15 cohesive soils. The pressure plate test and methylene blue test are briefly introduced in the following sections.

2.2. New Methylene Blue Test. A traditional methylene blue test, specified in ASTMC837 [19], was used to determine the active clay content in fine materials by measuring the methylene blue dye content adsorbed by clay particles. This traditional test method contains an empirical check criterion, in which the test procedures need to be repeated until a light blue ring is found. It is time-consuming and requires experienced personnel to operate the test, which is similar to the method of the current specification of *Test Methods of Aggregate for Highway Engineering* in China. Recently, a new test method, which measures the MBV of soils by using the methylene blue solution with a colorimeter, was proposed by W.R. Grace Inc. The advantage of this new test method is that it is relatively simple, inexpensive, and repeatable. Figure 1 shows the apparatus which consists of a colorimeter, a 150 μL pipette with a resolution of 1 μL, a dropper, a 3 mL syringe, two 50 mL plastic bottles, two sample bottles, methylene blue solution, and distilled water. In addition, a 0.20 μm filter of the syringe, a portable balance with a resolution of 0.01 g, a standard sieve, and a small glass tube are also needed.

Firstly, the sample was passed through a 2 mm sieve, and 20.00 g sample was taken as the initial amount. The sample was added to a plastic bottle with 30.00 mL calibrated methylene blue solution. The mixture was shaken for 1 min, rested for 3 min, and shaken again for 1 more min. Thereafter, the mixture was filtered through a 2.0 μm filter by using a syringe. And the mixture passing the filter was used for the rest of the experiment. Subsequently, 30.00 mL of the filtered solution was added to a plastic bottle and filled with distilled water until a total of 45.00 g is collected. The newly mixed solution was put into a small glass tube plugged into the colorimeter, and the MBV can be measured by using the colorimeter. It is considered that 20.00 g is a valid sample amount, and the value of reading is valid, if the MBV reading is smaller than 7.50 mg/g. The sample size must be halved to 10.00 g, and the test procedure should be repeated, if the MBV is higher than 7.50 mg/g. It is worth mentioning that the total test time for a measurement is less than 10 min. The methylene blue value (mg/g) can be calculated by (2) after the methylene blue tests were completed:

$$\text{MBV} = \frac{(C_i - C_f) \times M_{MB}}{M_{FM}} \times 1000 \text{ mg/g}, \quad (2)$$

where C_i is the initial concentration of the methylene blue solution; C_f is the final concentration of the methylene blue solution; M_{MB} is the weight of the methylene blue solution; and M_{FM} is the weight of the soil samples. The average value of three tests for one soil is selected as the final MBV.

Table 1 shows the soil amount and the corresponding valid MBV range. It should be noted that the method using the methylene blue solution with a colorimeter is not suitable for soils in the case that the MBV is larger than 60 mg/g. For this case, the traditional method to measure the MBV should be adopted [19, 20].

2.3. Pressure Plate Test. The pressure plate consists of a high-pressure nitrogen gas bottle, a reducing valve, a pressure cooker, a ceramic plate, and so on, which is used to measure both matric and total suction with respect to the moisture

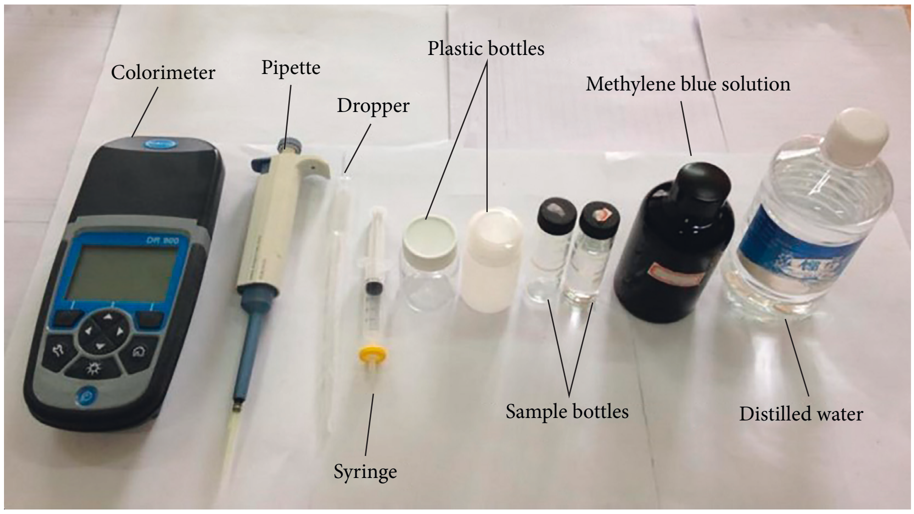

Figure 1: Apparatus.

Table 1: Soil amount and corresponding valid MBV range.

Soil weight (g)	MBV range (mg/g)
20	$0 < \text{MBV} < 7.5$
10	$7.5 \leq \text{MBV} < 15$
5	$15 \leq \text{MBV} < 30$
2.5	$30 \leq \text{MBV} < 60$

content of the sample. For this test, soil samples of 618 mm diameter and 100 mm height were made by a cutting ring at compacted degree of 90% and at the optimum moisture content. Then, the samples were put into a vacuum saturator and were taken out 48 hours later for equilibrating the internal moisture content. Thereafter, the mass was recorded when there is no water on the surface of samples. Subsequently, the ceramic plate was put into the pressure cooker and saturated. The following step was to put the saturated sample into the pressure plate and add air pressure until reaching a balanced state. After that, the moisture content of the sample was measured and the pressure was read. By repeating the above steps, the SWCC for the soil sample can be developed.

2.4. Materials. Fifteen cohesive soils were taken from different field sites of Hunan Province in this study, which is located in South China [21]. Table 2 summarizes the results for laboratory testing. Since the MBV of the soil samples S13 and S14 is larger than 60 mg/g, it was measured by the traditional method [19, 20].

3. Correlations between MBV and PI and between P_{200} and MBV

The four fitting coefficients of Fredlund and Xing's model can be predicted by P_{200} and PI, based on the available database. Thus, it is necessary to analyze the relationship between the MBV and PI and between MBV and P_{200}, respectively. Figure 2 presents the relationship between the MBV and PI for the selected cohesive soils and the solid line represents a trend line. A correlation equation is observed between PI and MBV, as shown in (3). Witczak et al. [22, 23] suggested subjective criteria for goodness predictions based on the coefficient of determination (R^2) values. An excellent fit can be defined as $R^2 \geq 0.9$, a good fit covers the R^2 range of 0.7–0.89, and a fair fit is defined as $0.4 \leq R^2 \leq 0.69$. Therefore, (3) is a good fit for selected cohesive soils and can provide a relatively satisfactory correlation. This equation indicates that the MBV also has the ability to classify the plasticity of cohesive soils and the positive correlation with PI:

$$\text{PI} = e^{(2.525+0.008\,\text{MBV})} \quad \left(R^2 = 0.72\right). \tag{3}$$

Simultaneously, the relationship between the P_{200} and MBV was gained according to Figure 3. The data of S2, S11, and S12 were not considered because of their large variability. Equation (4) shows their mathematical formula, which is a good fit:

$$P_{200} = 44.66 \ln(\text{MBV} + 21.73) - 115.52 \quad \left(R^2 = 0.79\right). \tag{4}$$

Many studies have reported that the clay mineral is a key factor that affects the suction variation of a soil, and clay minerals are known to have a much higher P_{200} than other small mineral particles. Thus, as can be seen from the above, MBV and P_{200} are positively correlated. It indicates that the higher clay mineral content corresponds to higher MBV for soil sample, since the MBV is positively correlated with P_{200}.

4. Regression Analysis and Validation

4.1. Regression Analysis. The SWCCs for 15 cohesive soils were measured by the pressure plate test, which are presented in Figure 4. The slope of the SWCC in the middle stage represented the suction loss ratio with increasing moisture content in this figure. The steeper suction slopes represent that soil sample is more moisture susceptible. "Moisture susceptibility" describes the rate of loss of subgrade strength, stiffness, and resistance to permanent

Table 2: Testing results.

Soil sample	Liquid limit (%)	Plastic limit (%)	PI (%)	Optimum moisture content (%)	Maximum dry density (g/cm^3)	P_{200} (%)	MBV (mg/g)	Classification
S1	43.30	26.10	17.20	11.20	1.84	52.14	18.98	ML
S2	36.10	22.70	13.40	14.00	1.88	66.80	20.18	CLS
S3	33.60	19.80	13.80	11.90	1.93	54.00	22.38	MLS
S4	35.90	19.10	16.80	11.20	1.84	51.60	27.33	CLS
S5	36.60	21.50	15.10	18.90	1.68	56.50	31.87	CLS
S6	42.50	25.00	17.50	17.20	1.75	79.10	34.64	CL
S7	44.70	28.50	16.20	15.50	1.85	73.10	37.12	CLS
S8	42.30	22.00	20.30	14.00	1.86	59.80	38.27	CLS
S9	35.80	19.30	16.50	16.00	1.92	68.70	40.45	CLS
S10	39.80	26.80	13.00	18.00	1.80	72.30	44.13	CLS
S11	35.70	16.00	19.70	11.40	1.98	64.30	54.11	CLS
S12	35.80	17.00	18.80	15.50	1.84	94.20	57.34	CL
S13	46.10	22.10	24.00	17.00	1.84	93.10	80.33	CLS
S14	56.50	30.10	26.40	23.50	1.56	95.08	94.00	CH
S15	40.90	21.60	19.30	14.80	1.87	64.30	39.97	CLS

Note. M denotes silt; C denotes clay; S denotes soils with sand; L and H denote soils with a low liquid limit (no more than 50%) and a high liquid limit (larger than 50%).

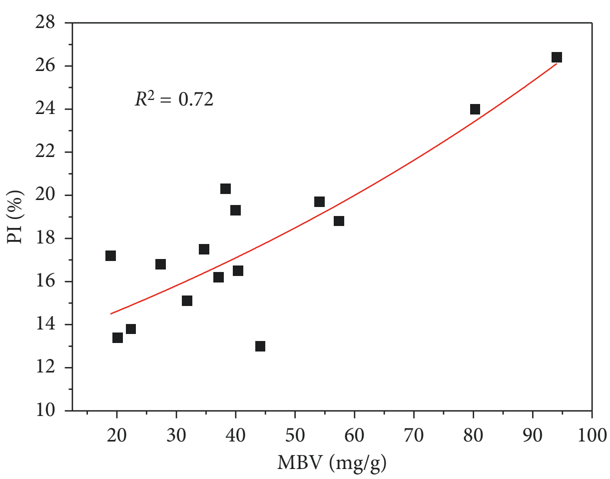

Figure 2: Correlation between MBV and PI.

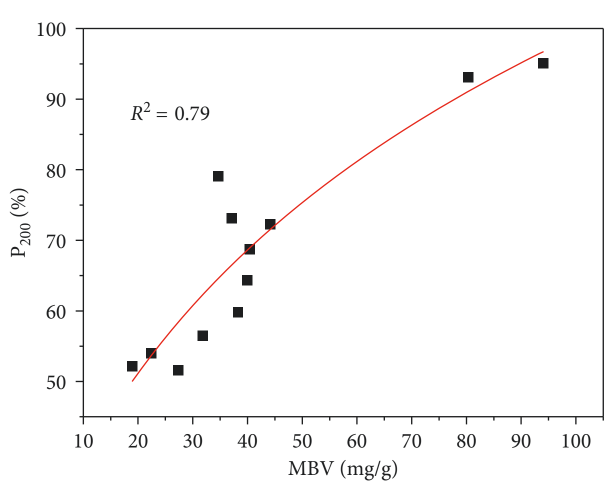

Figure 3: Correlation between MBV and P_{200}.

deformation with increasing moisture. Therefore, the slope of the SWCCs can also be used to evaluate the moisture susceptibility of subgrade soils. The moisture susceptibility

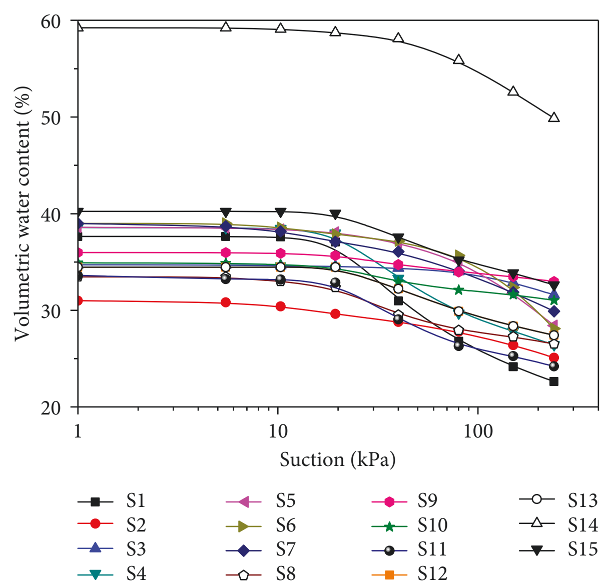

Figure 4: SWCCs of cohesive soils.

of the selected soils is ranked as follows: S1 > S2 > S3 > S4 > S5 > S6 > S7 > S8 > S15 > S9 > S10 > S11 > S12 > S13 > S14, according to the comparison of the slope values of SWCCs, as shown in Figure 4.

The four coefficients of Fredlund and Xing's model were gained, according to the results of the pressure plate test, as shown in Table 3.

To investigate the correlation between the four fitting parameters and the MBV, the regression analysis was performed for soil samples S1~S14. In addition, the soil sample S15 was used to validate the rationality of the correlations. Each fitting parameter had a unique equation to describe its relationship with the MBV, as presented in (5)–(8). The air entry value of soil, a_f, is formulated in (5). The rate of water extraction of the soil exceeding the air entry value, b_f, is formulated based on the MBV given in (6). The mathematical relationship describing the residual

Table 3: Fitting coefficients of Fredlund and Xing's model.

Soil sample	a_f (kPa)	b_f	c_f	h_r (kPa)
S1	28.55	1.28	2.72	941.39
S2	30.86	1.26	2.67	1097.66
S3	34.78	1.22	2.58	1361.42
S4	42.33	1.13	2.4	1870.75
S5	48.15	1.06	2.24	2262.48
S6	51.30	1.01	2.15	2474.93
S7	53.91	0.98	2.07	2651.18
S8	55.07	0.96	2.04	2728.95
S9	57.16	0.93	1.97	2870.17
S10	60.46	0.88	1.86	3092.12
S11	68.17	0.76	1.60	3611.81
S12	70.36	0.72	1.53	3759.60
S13	83.11	0.51	1.08	4618.98
S14	89.05	0.42	0.88	5019.56
S15	56.71	0.94	1.98	2839.74

water content of the soil, c_f, is given in (7). The mathematical formula describing the suction value at the residual water content, h_r, is given in (8):

$$a_f = 27.4 \ln(\mathrm{MBV} - 9.9) - 34.7 \quad (R^2 = 0.90), \tag{5}$$

$$b_f = 1.66 e^{(-0.014\,\mathrm{MBV})} \quad (R^2 = 0.72), \tag{6}$$

$$c_f = 0.729 e^{(-0.057\,\mathrm{MBV})} + 0.12 \quad (R^2 = 0.73), \tag{7}$$

$$h_r = 2221.59 \ln(\mathrm{MBV} - 4.78) - 5024 \quad (R^2 = 0.90). \tag{8}$$

According to the above description, (5) and (8) are excellent fits and (6) and (7) are good fits according to the research results of Witczak et al. Those equations can provide a relatively satisfactory correlation. In addition, a_f and h_r have a positive relationship with the MBV, which increase with the increasing MBV. On the other hand, b_f and c_f have a negative relationship with the MBV, which mean that these two fitting coefficients decrease with the increasing MBV. Among the four parameters, b_f is a special one. It represents not only the moisture susceptibility but also the slope of the SWCC.

4.2. Validation. In order to verify the rationality of the prediction method for cohesive soils in this study, the four fitting coefficients of SWCC from the pressure plate test and MBV measured for soil sample S15 were compared, as shown in Table 4. For soil sample S15, the MBV was 39.97 mg/g and the four fitting coefficients a_f, b_f, c_f, and h_r gained from (5)–(8) are 51.06, 0.94, 0.20, and 2839.74, respectively, and they are 51.34, 0.95, 0.25, and 2736.15 according to the pressure plate test. Therefore, the difference is negligible for the fitting coefficients between the pressure plate test and new prediction method by the methylene blue test, except the residual suction value h_r. However, this difference in the residual suction values will not affect the whole curve of the SWCCs, as shown in Figure 5. It can be seen from Figure 5 that there is a little difference for the initial stage with a low suction, and subsequently, two curves

Table 4: Fitting parameters from test and estimation using MBV.

Soil sample S15	MBV (mg/g)	a_f (kPa)	b_f	c_f	h_r (kPa)
Parameters from MBV	39.97	51.06	0.94	0.20	2839.74
Parameters from the pressure plate test		51.34	0.95	0.25	2736.15

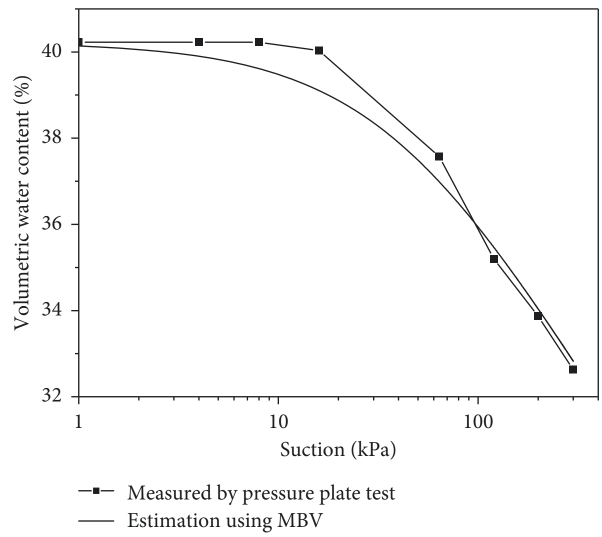

Figure 5: SWCCs from test and estimation methods.

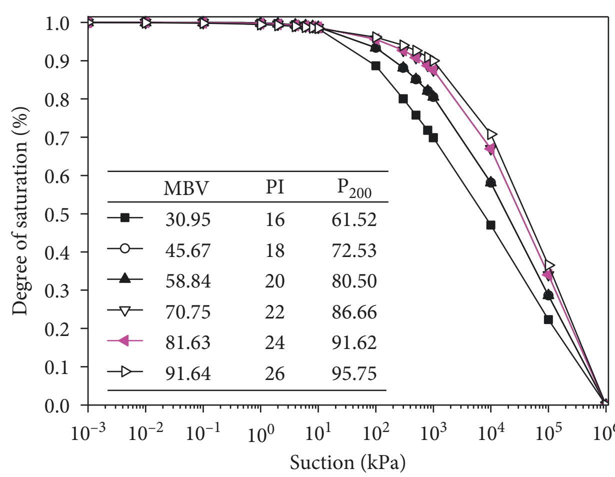

Figure 6: SWCCs with different methylene blue values.

are almost consistent with the increasing suctions. Thus, the accuracy of the prediction method for cohesive soils based on the MBV is acceptable.

5. SWCCs Predicted Using the Methylene Blue Test

Figure 6 shows the suction change with the degree of saturation under six different methylene blue values. It is noted that the suction decreases with decreasing MBV under the same degree of saturation; on the other hand, a higher MBV shows a higher suction under the same degree of saturation, which means a high moisture-holding capacity. Therefore, the moisture-holding capacity of cohesive soils increases with the increasing MBV.

And at the same time, the four fitting parameters can be expressed in terms of PI and P_{200}, by substituting (3) and (4) into (5)–(8). The PI and P_{200} values and the corresponding MBV are also given in Figure 6. Since the MBV has a positive correlation with them, the moisture-holding capacity of cohesive soils increases with the increasing PI and P_{200}. As mentioned above, lower PI or P_{200} values correspond to lower plasticity soils and higher PI or P_{200} values are associated with higher plasticity soils, which has the same law reflected in Figure 6.

This study indicates that there is a relationship between the four fitting parameters of Fredlund and Xing's model and the MBV for cohesive soils. The MBV is easy to be measured in a practical engineering. However, the pressure plate test or filter paper, adopted for determining the SWCC, is time-consuming and cost-intensive. Therefore, the four parameters of Fredlund and Xing's model can be predicted by MBV in a very short time compared to other experimental procedures. And this method can generate the SWCCs for cohesive soils far more efficiently with an acceptable accuracy. Meanwhile, it can even be used in field investigations since the methylene blue test only requires limited portable test equipment.

6. Conclusions and Discussions

In order to more effectively determine the MBV for 15 cohesive soils, a new methylene blue test was proved. Then, the mathematical formulations between the four fitting coefficients of Fredlund and Xing's model and the MBV were developed and verified. The major conclusions are drawn as follows:

(1) Compared to other experimental procedures, the new methylene blue test with a colorimeter required fewer experimental tools and soil samples. At the same time, the colorimeter provided an objective way to assess the color change of the methylene blue solution. It greatly reduces the subjective error.

(2) P_{200} and PI were positively related to MBV, which indicates that the higher clay mineral content corresponds to higher PI or MBV for soil sample.

(3) The fitting parameters a_f and $h_{r'}$ were directly proportional to the MBV, which increase with the increasing MBV, and b_f and c_f were negatively related to the MBV, which means that these two fitting coefficients decrease with the increasing MBV. When the MBV was measured, the four fitting parameters can be calculated using (5)–(8), and its accuracy was proved to be acceptable. It was more efficient to describe the SWCC based on Fredlund and Xing's model by the methylene blue test compared to other experimental procedures.

(4) The slope parameter b_f was suitable to evaluate the moisture susceptibility of cohesive soils. Therefore, the MBV can also be used to describe the moisture susceptibility of cohesive soils, which can be gained much more easily and quickly than b_f.

(5) It was seen that the correlation coefficients of the mathematical formulations between the four fitting coefficients and the MBV were not high enough. More cohesive soils need to be selected to modify the formulations in the future research. In spite of this, the difference in the results of the pressure plate test and the prediction method using MBV was acceptable.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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