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Compaction Characteristics of Non-Gravel and Gravelly Soils Using a Small Compaction Apparatus

ABSTRACT: The standard Proctor test has been widely used and accepted for characterizing soil compatibility for field compaction control. This paper presents a time- and cost-effective method to predict standard Proctor compaction characteristics of non-gravel and gravelly soils using a proposed small apparatus. This small apparatus is similar to the standard Proctor apparatus and easily introduced into soil mechanics laboratory. A comparison of the compaction characteristics of non-gravel soils measured from the proposed small apparatus and from the standard Proctor apparatus shows that this small apparatus can be used as an alternative to the standard Proctor apparatus and regarded as a practical tool for non-gravel soils. For gravelly soils, gravel content mainly controls compaction energy transmitted to the fine fraction and hence its compaction characteristics. A relationship between the generalized optimum water content of the fine fraction in the gravelly soil and the gravel content is established. This relationship leads to an effective method of predicting standard Proctor compaction characteristics of gravelly soils compacted in standard molds using compaction results from the proposed small apparatus. Comparisons between the predicted and the measured compaction characteristics are in very good agreement.

KEYWORDS: standard Proctor, compaction characteristics, small compaction apparatus, transmitted compaction energy

Introduction

Compaction is a classical ground improvement technique for earth structures. Every day, thousands of cubic metres of soil are compacted throughout the world. A standard Proctor test [1] is a compaction test widely used for qualifying a borrowed pit and controlling field compaction. There are two standard molds used in the standard Proctor test. They are the cylinder mold. Both molds are 116.4 mm in height. One has 101.6 mm diameter and the other has 152.4 mm diameter. The selection between these two molds is based on gravel ($\geq$4.75 mm) content in soil being compacted. If it is greater than 20 % by weight, the 152.4 mm diameter mold is recommended to replace the 101.6 mm diameter mold (Procedure C in ASTM D698-91 [1]). These standard molds are still considered large. Efforts have been devoted to shorten the compaction mold size [2,3]. Nevertheless, gaining the advantages of resizing mold comes with a limitation in size of the soil particles being able to test. It has been suggested that a ratio of the mold diameter to the largest particle size should not be less than 5 to 6 [4]. Garga and Madureira [5] suggested a ratio of 6 ~ 8 as quoted from their paper, "From a practical viewpoint, it would appear that mould diameter equal to six to eight times the maximum gravel size is acceptable." The previous small compaction apparatuses were suggested only for non-gravel soils [2,3] and are impossible for gravelly soils because of the gravel interference effect.

The compaction characteristics of gravelly soils are mainly governed by the compactability of fine fraction (<4.75 mm particles), which is generally obstructed by the gravel interference. Garga and Madureira [5] performed a series of Proctor tests on gravelly soil in Brazil to investigate the influences of the compaction mold size and gravels on the compaction characteristics. They found that at ~20–25 % gravel, the interference of coarse grains begins to affect the compaction of the fine fraction. This interfer-

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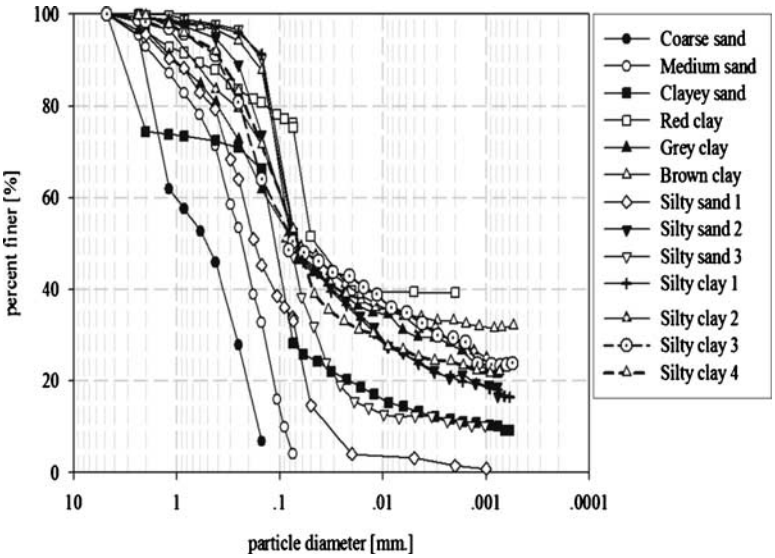

FIG. 1—*Particle size distribution curves of the tested soils.*

ence reduces the compaction energy transmitted to the fine fraction. Their results are similar to those reported by Holtz and Lowitz [6] and Jones [7]. Winter et al. [8] concluded that if the >20 mm gravels are greater than 45–50 %, these gravels determine the behavior of soil matrix. This paper attempts to develop a small compaction apparatus for both non-gravel and gravelly soils. A suggested procedure for predicting the standard Proctor compaction characteristics using this small apparatus is introduced. It is time- and cost-effective. The framework of this development is the transmitted compaction energy concept.

Materials and Test Program

Eight different soils were used in the study. Their particle size distribution curves are shown in Fig. 1. Index properties along with Unified Soil Classification System (USCS) group symbols are listed in Table 1.

The laboratory compaction tests were carried out in three different series.

- Series A: To develop a small compaction apparatus for determining the compaction characteristics of non-gravel soils under standard Proctor energy
- Series B: To verify the proposed small apparatus
- Series C: To develop a rational method of predicting the standard Proctor compaction characteristics of a gravelly soil using the proposed small apparatus

TABLE 1—*Index properties of the tested soils.*

Soil Type	*LL* (%)	*PL* (%)	*PI* (%)	G_S	Group Symbol
Coarse sand	NP	NP	NP	2.72	SP
Medium sand	NP	NP	NP	2.72	SP
clayey sand	28.7	19.4	9.3	2.72	SC
Red clay	75	24.6	50.4	2.70	CH
Grey clay	68.8	19.4	49.4	2.72	CH
Brown clay	61.6	18.7	42.9	2.74	CH
Silty sand 1	NP	NP	NP	2.67	SM
Silty sand 2	NP	NP	NP	2.69	SM
Silty sand 3	NP	NP	NP	2.68	SM
Silty clay 1	28.7	19.4	9.3	2.72	CL
Silty clay 2	37.5	15.7	21.8	2.67	CL
Silty clay 3	29.4	17.9	11.5	2.73	CL
Silty clay 4	41.4	20	21.4	2.64	CL

TABLE 2—*Compaction test program in the test program series A.*

					Rammer		
Tests Number	Mold Diameter (mm)	Rammer Diameter (mm)	Diameter Ratio	Number of Layers	Weight (kg)	Drop Height (mm)	Number of Blow
1.1	152.4	50.8	**0.33**	3	2.5	304.8	56
1.2	101.6	50.8	**0.5**	3	2.5	304.8	25
1.3	101.6	76.2	**0.75**	3	2.5	304.8	25
1.4	76.2	57.2	**0.75**	3	2.5	304.8	14
1.5	76.2	76.2	**1**	3	2.5	304.8	14
2.1	101.6	50.8	0.5	**2**	2.5	304.8	37
2.2	101.6	50.8	0.5	**3**	2.5	304.8	25
2.3	101.6	50.8	0.5	**4**	2.5	304.8	19
2.4	101.6	50.8	0.5	**5**	2.5	304.8	15
3.1	101.6	50.8	0.5	3	**4.5**	304.8	14
3.2	101.6	50.8	0.5	3	**3.2**	304.8	16
3.3	101.6	50.8	0.5	3	**2.5**	304.8	25
3.4	101.6	50.8	0.5	3	**1**	304.8	62
4.1	101.6	50.8	0.5	3	2.5	**457.2**	17
4.2	101.6	50.8	0.5	3	2.5	**381**	20
4.3	101.6	50.8	0.5	3	2.5	**304.8**	25
4.4	101.6	50.8	0.5	3	2.5	**228.6**	33

Note: Figures in bold indicate compaction characteristics being changed during the test.

A main propose of the test series A is to develop a new small compaction apparatus for non-gravel soils (<4.75 mm particles) taking the influence of the equipment characteristics into account. A small compaction apparatus can be achieved mainly by reducing volume of its compaction mold. Hence, a compaction energy needed to attain the standard Proctor energy can be reduced. Volume of a compaction mold can be reduced by decreasing either a mold diameter or a mold height. Taking the reduction of the compaction mold into account, the following equipment characteristics are investigated:

(1) A ratio of the diameter of the compaction rammer to the diameter of the compaction mold (DR): This equipment characteristic is chosen to deal with the reduction of the mold diameter.
(2) A number of compacted layers (or layer thickness): This compaction characteristic is chosen in order to deal with the reduction of the mold height.
(3) A weight of the rammer: A reduction in volume of the compaction mold might lead to a significant difference between a ratio of the rammer weight to weight of the soil in compaction mold for the standard mold and that for the small mold. While keeping the compaction mold volume constant, the ratio of the rammer weight to weight of the soil in compaction mold might alter with the weight of the rammer.
(4) A drop distance of the rammer: By concerning compaction energy per unit volume of compacted soil per drop, this factor is chosen to study. While keeping weight of the rammer and volume of the compaction mold constant, the energy per unit volume per drop alters with the drop distance of the rammer.

Table 2 summarizes compaction test program for series A. All tests have the same input of compaction energy per mold volume, equal to standard Proctor energy, even though their equipment characteristics are different. The tested soils were silty sand 1 and red clay, which represented cohesionless and cohesive soils.

In the test program series B, five different non-gravel soils were used. These soils are coarse sand, medium sand, silty sand 2, clayey sand, and silty clay 1. A compaction test according to ASTM D698-91 [1] and a compaction test using the small apparatus were conducted to each of these soils.

In the test program series C, the influence of gravel on compaction characteristic was investigated. The base soils for series C are silty sand 1, silty sand 3, silty clay 2, silty clay 3, and red clay. They were mixed with two gravel sizes (4.75–9.75 mm and 9.47–18.9 mm) at various amounts to investigate the role of gravel content and gravel size on the compaction characteristics. According to ASTM D698-91 [1], the gravel size used in the compaction test must be smaller than or equal to 18.9 mm. The gravels are random shaped and quartzitic, having their average specific gravity of 2.62. An absorbed water content is about 0.2

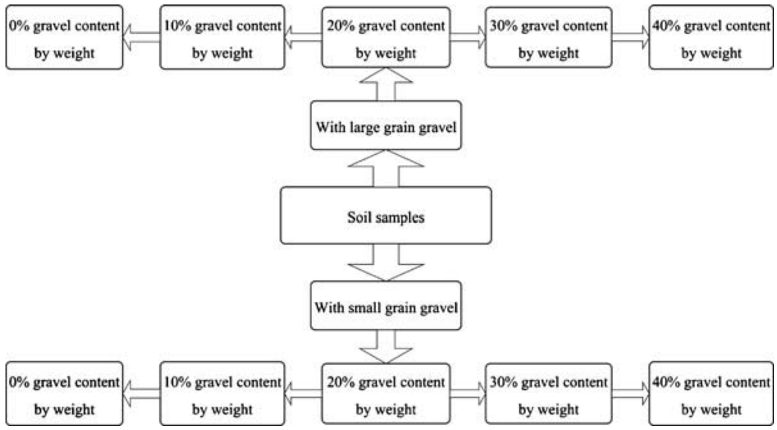

FIG. 2—*Organization of compaction tests for the test program series C.*

%, which is very low and can be omitted in this study. In the test series C, the 101.6 mm mold were used for ≤20 % gravel (4.75 mm), and the 152 mm mold were used for >20 gravel as recommended by the ASTM standards [1].

Both gravels were washed to remove any deleterious coatings. Afterward, the gravels were soaked under water for 24 hours and surface-dried before use. Each base soil was mixed with the two gravel sizes at about 0 %, 10 %, 20 %, 30 %, and 40 % by weight. While being mixed, the mixed soils were sprayed with certain amount of water to attain the desired water contents. Thereafter, the mixed soils were covered with plastic sheet for 2 days in order to achieve uniform water content. The compaction program was organized as shown in Fig. 2. In total, there were 45 standard Proctor tests (ASTM D698-91 [1]) for this test program. Table 3, along with compaction test results, provides detail information of these 45 Proctor tests. Interpreting the influence of gravel size and gravel content on the compaction energy transmitted to the fine fraction leads to the method of assessing the compaction characteristics of gravelly soils using the proposed small apparatus.

A New Small Compaction Apparatus for Non-Gravel Soils

Recently, there are two small compaction apparatuses that have been introduced [2,3]. To enhance compaction efficiency, both apparatuses assign a diameter of the rammer close to a diameter of the compaction mold, i.e. DR=1. The equipment characteristics of both apparatuses are totally different from those of the standard Proctor apparatus.

Regarding the test program series A, it is found that every test from test numbers 1.1–4.4, which are written in Table 2, gives the same compaction test results, except the test number 1.5, which is a compaction test with DR=1. Figure 3 shows the compaction characteristics of the two studied soils compacted under standard Proctor energy with four different DRs (test numbers 1.1–1.5). The optimum water content, w_{opt}, remains unchanged for every DR, while the maximum dry density, $\rho_{d\,\max}$, and the optimum degree of saturation, $S_{w_{\text{opt}}}$, are almost the same for DR=0.33–0.75 and suddenly increase when DR becomes 1. This seems to indicate that the compaction test with DR=1 is more energy efficient than the compaction test with DR=0.33–0.75 perhaps because the compaction energy can entirely distribute downward. It is concluded that for DR=0.33–0.75 and for the same input of compaction energy per mold volume, the energy transformation for different equipment characteristics is practically the same, hence the same compaction characteristics. A new small compaction apparatus is introduced based on this finding with the least change of the Proctor apparatus.

Detail of the Small Compaction Apparatus

A neat sketch of the proposed small apparatus is shown together with the standard Proctor apparatus in Fig. 4. For simple and practical development of the small apparatus, the rammer and the mold height are kept the same as those of the standard Proctor, i.e., the rammer is of cylindrical shape with 50.8 mm diameter and 114.3 mm height, having a weight of 2.5 kg and mold height of 116.4 mm. The difference

TABLE 3—*Summary of the test program series C.*

		Gravel Content					
Test Number	Soil Type	Small (%)	Large (%)	$\rho_{d\ max}$ (g/cm^3)	w_{opt} (%)	$\rho'_{d\ max}$ (g/cm^3)	w'_{opt} (%)
1.1	Silty sand 1	···	···	1.965	10.80	1.965	10.80
1.2		10	···	2.012	9.81	1.961	10.90
1.3		20	···	2.060	8.80	1.956	11.00
1.4		30.3	···	2.100	8.50	1.933	12.19
1.5		40.3	···	2.130	8.20	1.904	13.74
1.6		···	10	2.015	9.81	1.965	10.80
1.7		···	20	2.061	8.80	1.957	10.90
1.8		···	30.3	2.110	8.40	1.946	11.00
1.9		···	40.3	2.145	8.00	1.911	12.04
2.1	Silty sand 3	···	···	1.800	13.00	1.800	13.00
2.2		10	···	1.860	11.79	1.802	13.10
2.3		20	···	1.920	10.56	1.800	13.20
2.4		30.1	···	1.970	10.00	1.779	14.31
2.5		40.1	···	2.010	9.50	1.738	15.87
2.6		···	10	1.860	11.79	1.800	13.00
2.7		···	20	1.920	10. 56	1.802	13.10
2.8		···	30.1	1.975	9.90	1.786	13.20
2.9		···	40.1	2.020	9.30	1.775	14.17
3.1	Silty clay 2	···	···	1.770	16.00	1.770	16.00
3.2		10	···	1.830	14.49	1.771	16.10
3.3		20	···	1.890	13.04	1.767	16.30
3.4		30.5	···	1.925	12.40	1.724	17.84
3.5		40.6	···	1.955	11.80	1.666	19.86
3.6		···	10	1.830	14.49	1.770	16.00
3.7		···	20	1.890	13.04	1.771	16.10
3.8		···	30.5	1.940	12.20	1.767	16.30
3.9		···	40.6	1.980	11.50	1.742	17.55
4.1	Silty clay 3	···		1.890	14. 00	1.890	14. 00
4.2		10	···	1.944	12. 69	1.890	14. 10
4.3		20	···	2.000	11. 36	1.888	14. 20
4.4		30.4	···	2.040	11. 00	1.860	15. 81
4.5		40.5	···	2.070	10. 65	1.812	17. 90
4.6		···	10	1.944	12. 69	1.890	14. 00
4.7		···	20	2.000	11. 36	1.890	14. 10
4.8		···	30. 4	2.050	10. 90	1.888	14. 20
4.9		···	40. 45	2.100	10. 30	1.872	15. 67
5.1	Red clay	···	···	1.530	25. 00	1.530	25. 00
5.2		10	···	1.600	22. 59	1.534	25. 10
5.3		20	···	1.660	20. 16	1.521	25. 20
5.4		32	···	1.720	18. 50	1.481	27. 19
5.5		42.2	···	1.770	17. 00	1.419	29. 95
5.6		···	10	1.600	22. 59	1.530	25. 00
5.7		···	20	1.665	20. 16	1.534	25. 10
5.8		···	32	1.740	18. 00	1.526	25. 20
5.9		···	42. 2	1.800	16. 50	1.503	26. 46

between the proposed small apparatus and the standard Proctor apparatus is only the compaction mold diameter. The proposed small apparatus uses a mold diameter of 76.2 mm (3 in.). As such, this proposed small apparatus has a DR of 0.67, which is in the range of 0.33–0.75. The mold assembly has a base plate of 12.7 mm thickness and an extension collar of 69.8 mm height. To attain the same input of compaction energy per mold volume, the number of rammer blows is decreased to 14 blows per layer and the compaction is performed in three layers. To avoid segregation, scratches must be made on the soil between layers. The proposed small apparatus conveys an advantage over the two previously mentioned small

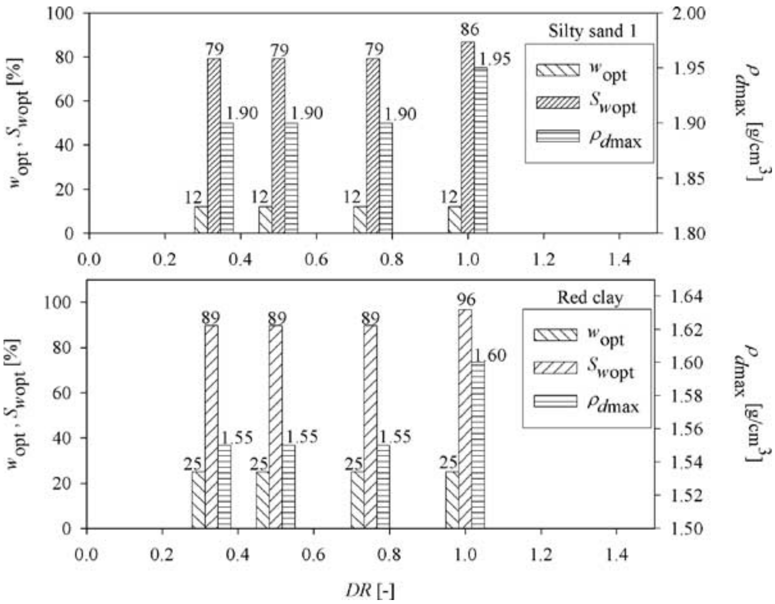

FIG. 3—*Effect of the DR on the compaction characteristics.*

compaction apparatus on easy configuration. Any laboratorian who prefers to implement this apparatus in the laboratory can modify the existing standard Proctor apparatus easily just by casting the small compaction mold in a manner described in Fig. 4.

Verification

Figure 5 shows compaction curves obtained from the proposed small apparatus along with those obtained from the standard Proctor apparatus. An identical shape is found for the same compacted soil. This is

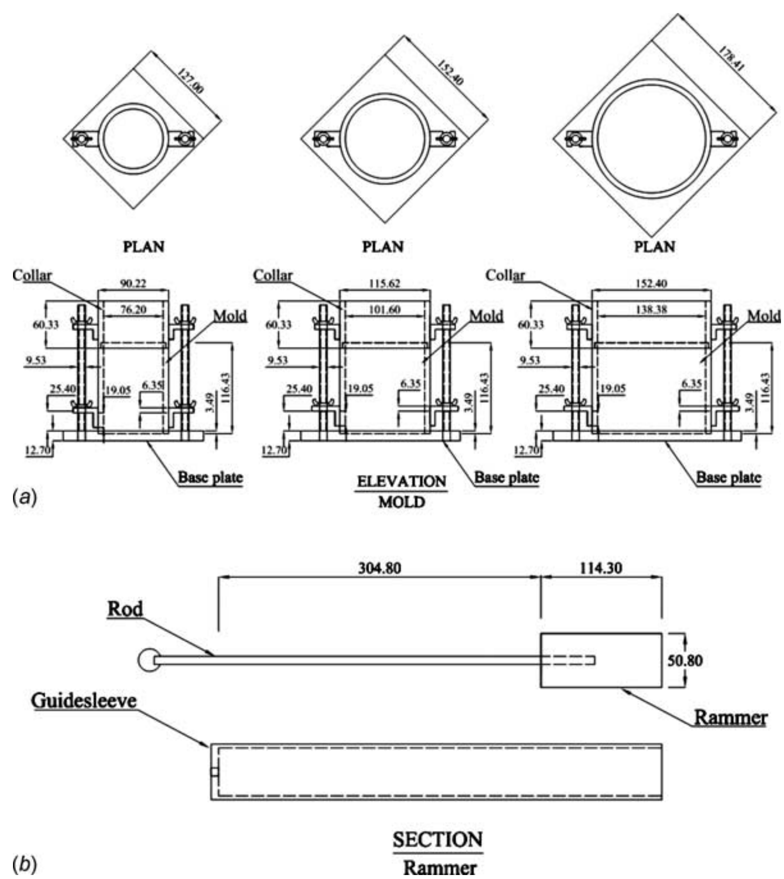

FIG. 4—*Neat sketches of (a) the Proctor apparatus and (b) the proposed small apparatus.*

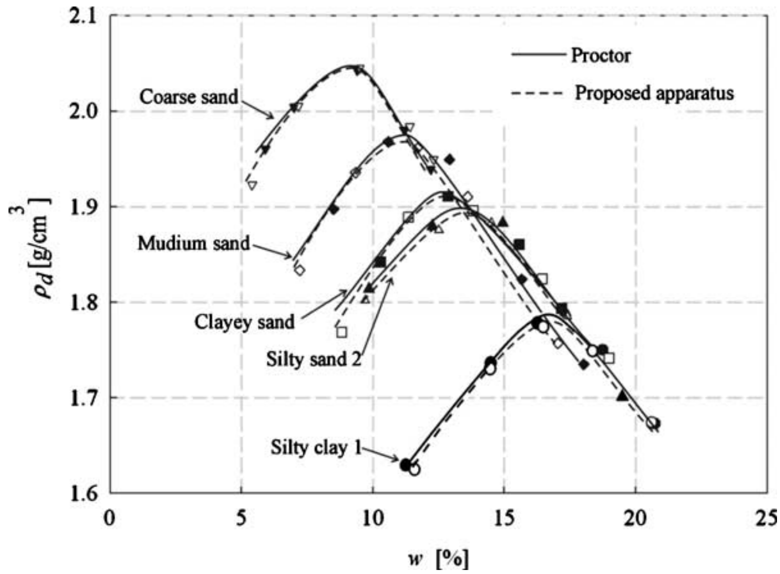

FIG. 5—*Compaction curves from the proposed small apparatus and from the standard Proctor test.*

another advantage of the proposed apparatus over the previously proposed small compaction apparatuses [2,3]. For cohesive soils, the compaction path on the wet side of the optimum obtained from the previous mentioned small compaction apparatuses generally lies above the standard Proctor compaction path. A comparison of $\rho_{d\,max}$ and w_{opt} between the proposed small apparatus and the standard Proctor apparatus is shown in Fig. 6. Both $\rho_{d\,max}$ and w_{opt} obtained from both apparatuses almost lie on the 1:1 line. This implies that these two apparatuses provide the same energy transformation for the same input of energy per mold volume, resulting in the same compaction characteristics. The proposed small apparatus can thus be used as alternative to the Proctor apparatus for non-gravel soils. To apply this small apparatus to gravelly soils, the influence of gravel content must be well understood. This influence would be examined in the next section.

Influence of Gravel Size and Gravel Content on the Standard Proctor Test Results

The gravelly soil is imaginably composed of two fractions (coarse and fine fractions) and five components. The fine fraction consists of three components: Soil particles (<4.75 mm particles), water, and air. The

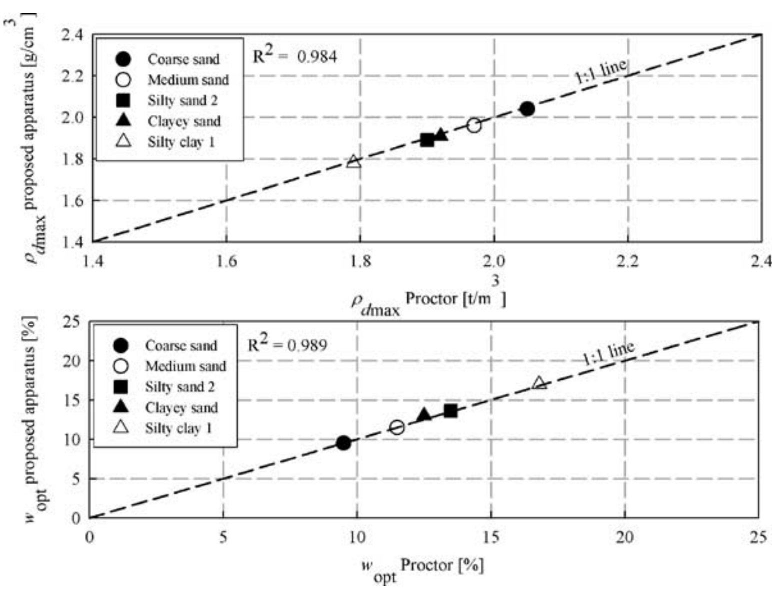

FIG. 6—*Relationships between* $\rho_{d\,max}$ *and* w_{opt} *obtained from the proposed small apparatus and the standard Proctor test.*

coarse fraction consists of two components: Gravels and absorbed water in gravels. By assuming that during compaction the fine fraction is being compacted, the coarse particles do not break down into many smaller parts. Based on a simple phase analysis, the dry density, ρ_d, and the water content, w, of gravelly soil are obtained in the form

$$\rho_d = \frac{W_s + W_g}{V_s + V_g + V_v} \tag{1}$$

$$w = \frac{W_{w,f} + W_{w,c}}{W_s + W_g} \tag{2}$$

where:

W_s=weight of soil particles,
W_g=weight of gravels,
$W_{w,f}$=weight of water in the fine fraction,
$W_{w,c}$=weight of absorbed water in gravels,
V_s=volume of soil particles,
V_g=volume of gravels, and
V_v=volume of void in the fine fraction.

Basically, $W_{w,c}$ is much less than $W_{w,f}$. Hence, $W_{w,c}$ is ignorable, and Eqs 1 and 2 become

$$\rho_d = \frac{1}{\frac{P_s}{\rho_d'} + \frac{P_g}{\rho_g}} \tag{3}$$

$$w = w' P_s \tag{4}$$

where:

ρ_d'=dry density of the fine fraction, which is equal to $W_s/(V_s+V_v)$,
w'=water content of the fine fraction, which is equal to $W_{w,f}/W_s$,
ρ_g=average density of the gravels,
P_s=ratio of the dry weight of the fine fraction to the dry weight of the gravelly soil (summation of the dry weight of the fine and coarse fractions), and
P_g=gravel content, which is the ratio of the dry weight of the gravel to the dry weight of the gravelly soil.

Both P_s and P_g are expressed as decimal fractions.

Table 3 shows the standard Proctor compaction test results of the mixed soils (series C) for different gravel contents and gravel sizes. With known gravel content, gravel density, $\rho_{d\ \max}$, and w_{opt}, the compaction characteristics of the fine fraction ($\rho_{d\ \max}'$ and w_{opt}') in the mixed soils are obtained from Eqs 5 and 6, respectively, as shown in Table 3 and Figs. 7 and 8

$$\rho_{d\ \max}' = \frac{\rho_{d\ \max}(1 - P_g)}{\left[1 - \frac{P_g \rho_{d\ \max}}{\rho_g}\right]} \tag{5}$$

$$w_{\text{opt}}' = \frac{w_{\text{opt}}}{P_s} \tag{6}$$

For the ideal condition where no gravel interference takes places, the compaction characteristics of the fine fraction in the gravelly soil ($\rho_{d\ \max}'$ and w_{opt}') would be the same as those of the fine fraction, which is solely compacted under the standard Proctor energy. Hence, the ideal maximum dry density, $\rho_{d\ \max,I}$, and the ideal optimum water content, $w_{\text{opt},I}$, of the gravelly soil can be obtained from

$$\rho_{d\ \max,I} = \frac{1}{\frac{P_s}{\rho_{d\ \max,f}} + \frac{P_g}{\rho_g}} \tag{7}$$

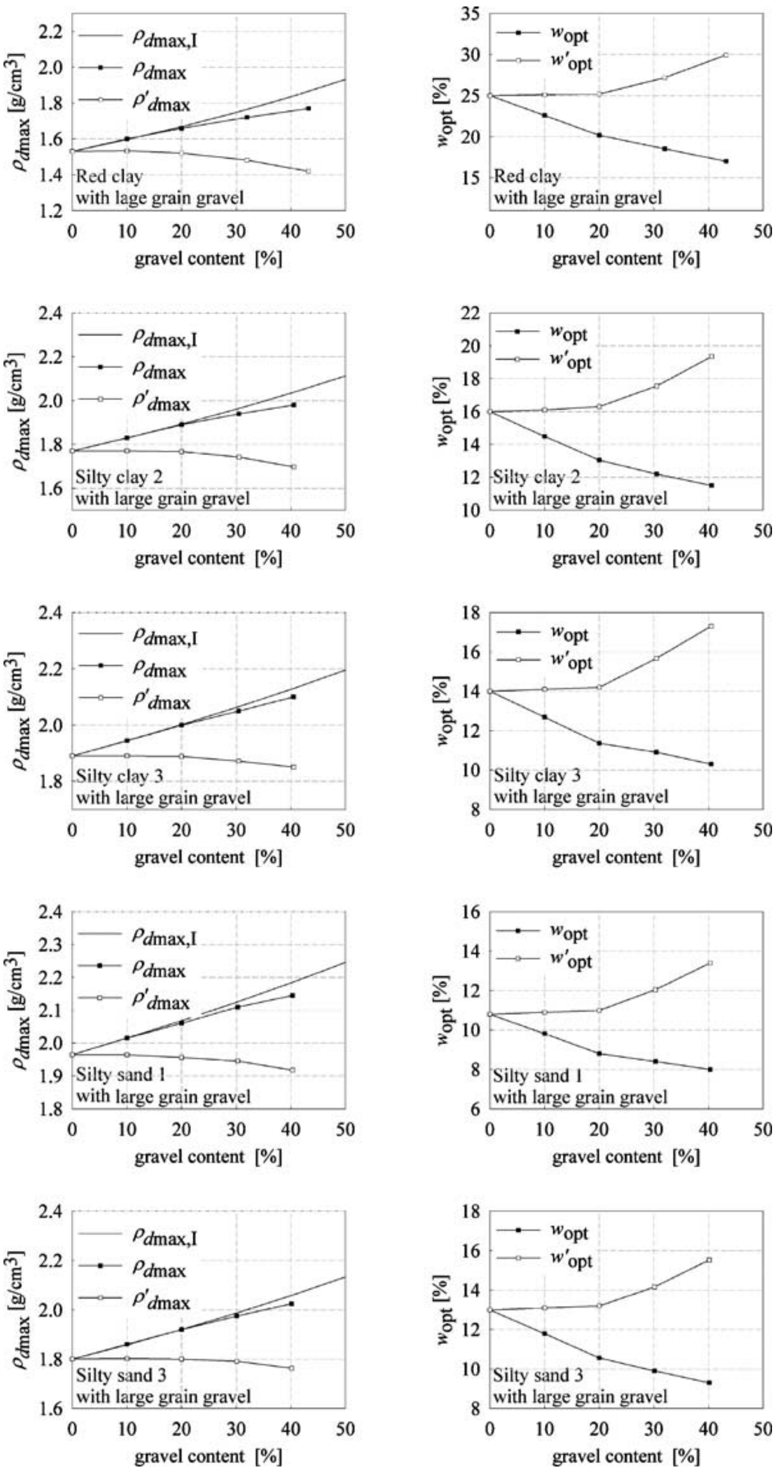

FIG. 7—*Relationships between the compaction characteristics and the gravel content for the soils mixed with large gravels.*

$$w_{\text{opt},I} = w_{\text{opt},f} P_s \tag{8}$$

where:

$\rho_{d\ \max,f}$ and $w_{\text{opt},f}$=maximum dry density and the optimum water content of the fine fraction solely compacted under standard Proctor energy, respectively.

Relationships between the maximum dry densities ($\rho_{d\ \max,I}$, $\rho_{d\ \max}$, and $\rho'_{d\ \max}$) and the gravel content for all the mixed soils are plotted in Figs. 7 and 8. It is noted that the $\rho_{d\ \max,I}$ increases continuously with increasing the gravel content. Deviation between the $\rho_{d\ \max,I}$ and the $\rho_{d\ \max}$ starts at about 20 % gravel,

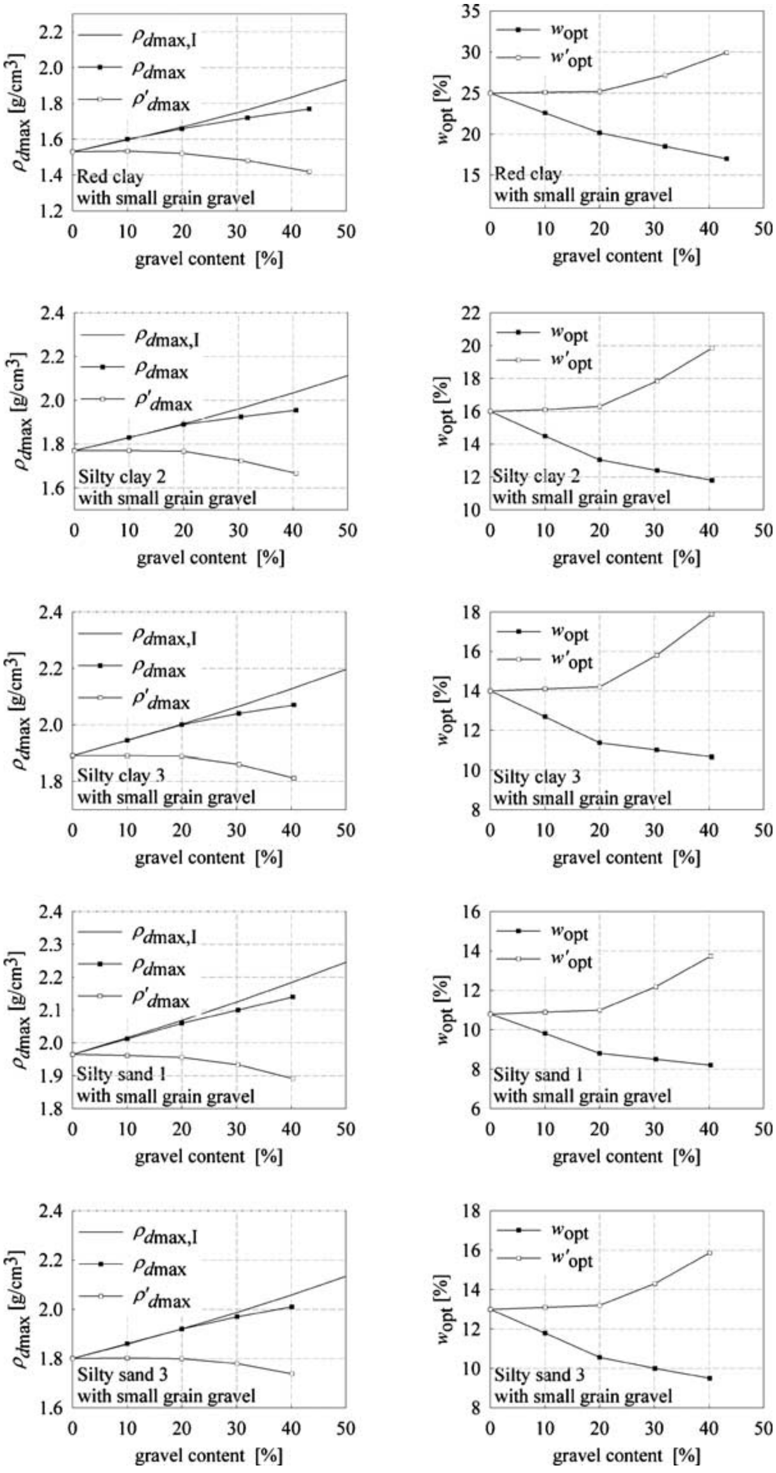

FIG. 8—*Relationships between the compaction characteristics and the gravel content for the soils mixed with small gravels.*

which indicates that the gravel interference effect starts at about 20 % gravel and is irrespective of gravel size. This finding is in agreement with Garga and Madureira's work [5].

The relationships between the optimum water contents (w'_{opt} and w_{opt}) and the gravel content for all the mixed soils are also shown in Fig. 7 and 8. The w_{opt} decreases with increasing the gravel content due to the huge difference between amount of absorbed water in gravels and amount of water in the voids of the fine matrix, whereas the w'_{opt} remains constant until gravel content reaches 20 %. Beyond gravel content of 20 %, the w'_{opt} increases with increasing gravel content. The change of the w'_{opt} also confirms that the interference effect starts when the gravel content reaches 20 %.

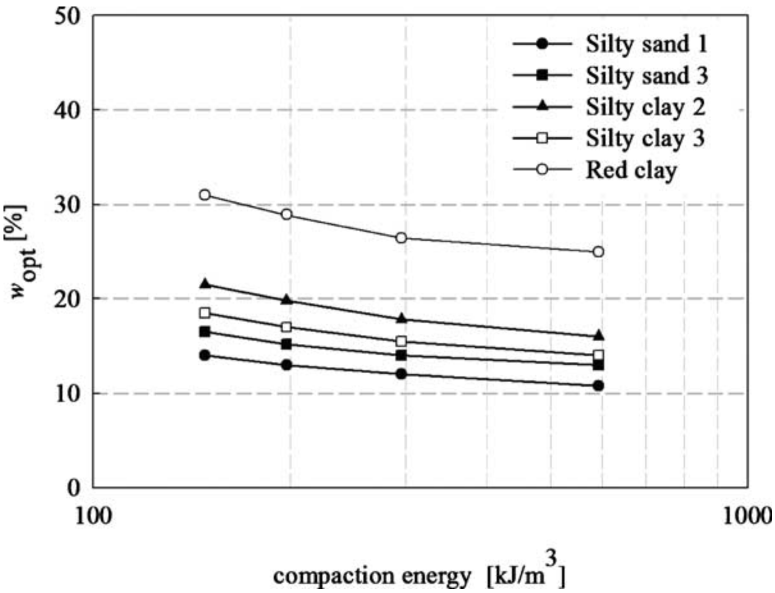

FIG. 9—*Relationship between the optimum water content and the compaction energy.*

From the above test result, it is worthwhile to conclude that for $\leq$20 % gravel where no gravel interference ($w_{opt,I}=w_{opt}$, and $\rho_{d\ max,I}=\rho_{d\ max}$), for the same standard Proctor energy, the energy transmitted to the fine fraction in a gravelly soil is as same as that in the same soil without gravel (0 % gravel). Hence, $w'_{opt}=w_{opt,f}$ and $\rho'_{d\ max}=\rho_{d\ max,f}$. For $>$20 % gravel, the gravel interference is clearly seen ($w'_{opt}>w_{opt,f}$ and $\rho'_{d\ max}<\rho_{d\ max,f}$). This implies that although the 152.4 mm mold was used instead of the 101.6 mm mold for $>$20 % gravel (ASTM D698-91 [1]) and the ratio of mold diameter to the largest particle size was greater than 8 (as recommended by Garge and Madureira [5]), the interference still happened. This interference effect can be reduced by using a larger mold. For the field compaction with the same energy as that in the laboratory, the interference effect might be minimal due to larger compacted area. This paper does not focus on the elimination of the gravel interference effect in laboratory tests but aims to develop an effective method of predicting the standard Proctor compaction characteristics of gravelly soils with different gravel contents (different gravel interference effects) using the proposed small apparatus.

Since the compaction energy directly affects the optimum water content [9–12], it is possible to determine the w'_{opt} from the transmitted compaction energy, which is mainly dependent upon gravel content. Hence, the relationship between the w'_{opt} and the gravel content can be developed. The development is now being illustrated.

A series of compaction tests at various compaction energies (148.1–592.5 kJ/m^3) was carried out with the base soils used in the test program series C, i.e., silty sand 1, silty sand 3, silty clay 2, silty clay 3, and red clay. Based on these compaction tests, the relationship between the optimum water content and the compaction energy is made, as shown in Fig. 9. With known w'_{opt} (consult Table 3) for different gravel contents and gravel sizes, the transmitted compaction energy corresponding to w'_{opt} can be obtained using Fig. 9. The relationship between the inverse of gravel content ($1/P_g$) and the transmitted compaction energy is thus developed, as shown in Fig. 10. It is shown that the relationship can be represented by a single line, indicating that the transmitted compaction energy is dependent mainly upon the gravel content and regardless of soil type and gravel size. For $\leq$20 % gravel, gravels insignificantly interfere wih the compaction of the fine fraction; therefore, the transmitted energy does not change with the gravel content and equals the standard Proctor energy. For $>$20 % gravel ($1/P_g<5$), the transmitted compaction energy decreases linearly with decreasing the inverse of gravel content.

Figure 10 shows that the relationship between the w'_{opt} and the compaction energy is dependent upon soil type, which is in agreement with the previous works [9–12]. Based on the study of Horpibulsuk et al. [11,12] on both coarse- and fine-grained soils, it has been possible to generalize the optimum water content, w_{opt} and the input of compaction energy, E_i relationship by considering the optimum water content at standard Proctor energy, $w_{opt,st}$ as a reference value. The generalized w_{opt} and E_i relationship for various soils has been expressed in the form of [12]

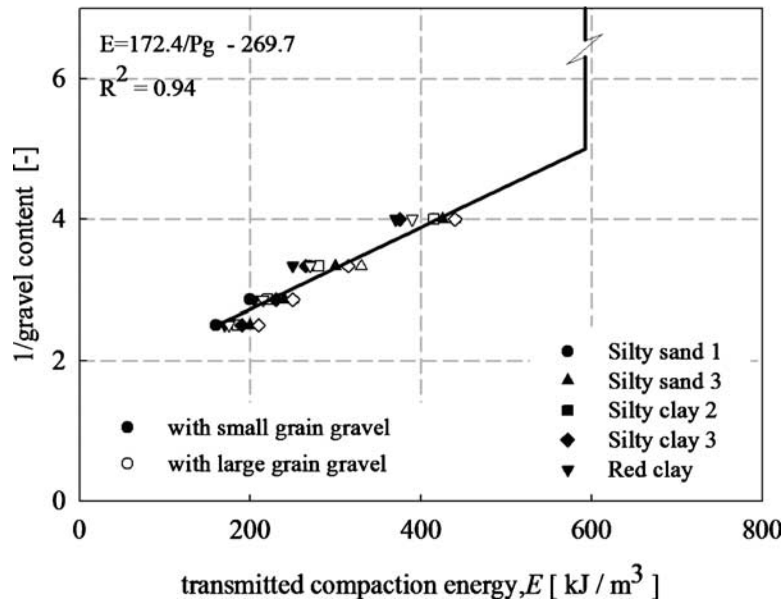

FIG. 10—*Relationship between the 1/gravel content and the transmitted compaction energy.*

$$\frac{w_{\text{opt}}}{w_{\text{opt,st}}} = 2.09 - 0.39 \log E_i \tag{9}$$

where E_i is in kJ/m^3.

By the same way, the optimum water content of the fine fraction, w'_{opt}, at any transmitted energy can be determined from the value at the standard Proctor energy, $w_{\text{opt},f}$. Since the transmitted compaction energy is directly related to the P_g (Fig. 10), the generalized w'_{opt} and P_g relationship is developed

$$\frac{w'_{\text{opt}}}{w_{\text{opt},f}} = 2.09 - 0.39 \log\left[\frac{172.4}{P_g} - 269.7\right] \tag{10}$$

This equation is very useful to determine w'_{opt} for gravelly soils with different gravel contents, P_g, when the $w_{\text{opt},f}$ is available. The $w_{\text{opt},f}$ is simply obtained from either the proposed small apparatus or the standard Proctor apparatus on the fine fraction (<4.75 mm).

From a known w'_{opt} at a particular gravel content, the w_{opt} can be estimated from Eq 6. The $\rho_{d\ \max}$ of the gravelly soil can thus be estimated from Fig. 11, which shows a unique relationship between w_{opt} and $\rho_{d\ \max}$ of different soils. Compaction test results of different coarse- and fine-grained soils, colleted from

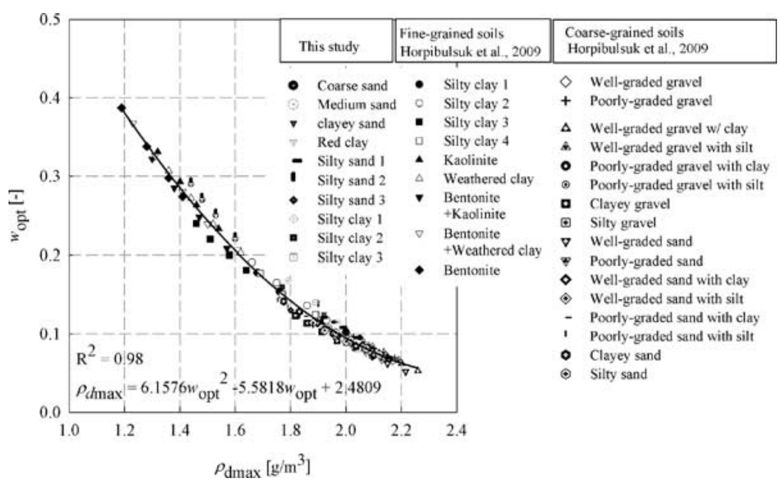

FIG. 11—*Unique relationship between the* $\rho_{d\ max}$ *and the* w_{opt} *(test data from this study and Horpibulsuk et al. [11,12]).*

the literature [11,12] and from this study, are employed to plot Fig. 11. The coarse-grained soils covered 16 soil types classified by the USCS. The fine-grained soils covered nine clays, which were from non- to high-swelling types with low to high plasticity.

Prediction of Compaction Characteristics of Gravelly Soils

From this study, the standard Proctor compaction characteristics and compaction curves of non-gravel soils can be alternatively obtained from the proposed small apparatus. This small apparatus provides practically the same results as the standard Proctor apparatus with less amount of soil and compaction energy. It is thus regarded as a practical tool for non-gravel soils. The following stepwise procedure is presented for predicting the compaction characteristics of a gravelly soil. The procedure consists of two categories: Category A is for ≤ 20 % gravel, and category B is for >20 % gravel.

Category A: For ≤ 20 % Gravel

(1) Separate the coarse and the fine fractions from the gravelly soil and then determine P_s and P_g.
(2) Compact the fine fraction in the small apparatus and determine its maximum dry density, $\rho_{d\ \max,f}$, and optimum water content, $w_{\text{opt},f}$.
(3) Determine the compaction characteristics of the gravelly soil from

$$\rho_{d\ \max} = \frac{1}{\dfrac{P_s}{\rho_{d\ \max,f}} + \dfrac{P_g}{\rho_g}} \tag{11}$$

$$w_{\text{opt}} = w_{\text{opt},f} P_s \tag{12}$$

It is worth mentioning here that Eqs 11 and 12 are similar to those written in ASTM D4718-87 [13].

Category B: For >20 % Gravel

(1) Separate the coarse and the fine fractions from the gravelly soil and then determine P_s and P_g.
(2) Compact the fine fraction in the small apparatus and determine its optimum water content, $w_{\text{opt},f}$.
(3) Determine the optimum water content of the fine fraction in the gravelly soil, w'_{opt}, from $w_{\text{opt},f}$ and P_g using Eq 10.
(4) Determine the optimum water content of the gravelly soil, w_{opt}, from

$$w_{\text{opt}} = w'_{\text{opt}} P_s \tag{13}$$

(5) Determine the maximum dry density of the gravelly soil, $\rho_{d\ \max}$, from w_{opt} using Fig. 11.

To verify the proposed method of predicting compaction characteristics, a comparison between the predicted $\rho_{d\max}$ and standard Proctor $\rho_{d\max}$ and between the predicted w_{opt} and standard Proctor w_{opt} is presented in Fig. 12. Seven different gravelly soils were taken for this verification. They were the mixture of non-gravel soils and gravels (see Fig. 12). The non-gravel soils were silty clay 1, silty clay 4, silty sand 2, and medium sand. The gravels were gathered from different sources, mixed together and sieved to obtain the small (4.75–9.75 mm) and the large (9.47–18.9 mm) gravels. A very good agreement between the prediction and the Proctor test results is found. This reinforces the applicability of the proposed method. This method can be employed for rapidly and economically assessing the compaction characteristics of gravelly soils.

Conclusions

A small compaction apparatus and a transmitted compaction energy concept are introduced for non-gravel and gravelly soils. For a simple introduction of the proposed small apparatus into a soil mechanics laboratory, this apparatus is most similar to the standard Proctor apparatus. This small apparatus uses the rammer of the standard Proctor apparatus and a mold diameter of 76.2 mm (3 in.). Consequently, its DR is 0.67, which is in the range of 0.33–0.75, while the DRs for the standard Proctor mold are 0.5 and 0.33 for 101.6 and 152.4 mm diameters, respectively. For this DR range, the compaction molds with different

Symbol	Soil samples	Gravel mix.	
		Small [%]	Large [%]
△	Medium sand	-	35
◇	Grey clay	12	28
▽	Brown clay	15	15
○	Silty clay 1	-	30
⊙	Silty clay 1	-	30
□	Silty sand 2	-	30
◈	Silty sand 2	-	30
⊕	Silty clay 4	12	18
⬡	Silty clay 4	16	24

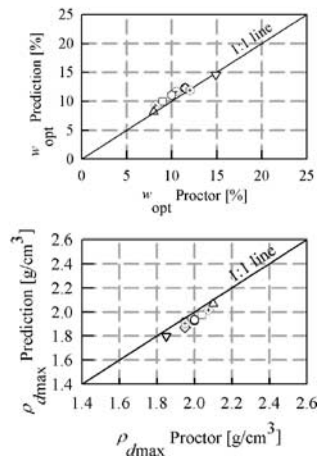

FIG. 12—*Comparisons between the prediction and the standard Proctor test results.*

equipment characteristics provide the same compaction test results for the same input of energy per mold volume. Thus, this small apparatus can be used as alternative to the standard Proctor one for non-gravel soils.

For gravelly soils, the gravel interference occurs when gravel content is in excess of 20%. This interference reduces the energy transmitted to the fine fraction; hence, the $w'_{opt} > w_{opt,f}$ and $\rho'_{d\,max} < \rho_{d\,max,f}$. The transmitted energy is mainly dependent upon the gravel content and irrespective of gravel size. Based on the relationship between the transmitted energy and gravel content, the generalized w'_{opt} and gravel content relationship is developed. It is used for determining the compaction characteristics of gravelly soils with different gravel contents. Finally, this paper presents the method that accommodates the transmitted compaction energy concept to the proposed small apparatus for predicting the compaction characteristics of non-gravel and gravelly soils. Comparisons between the prediction and the Proctor test results are in very good agreement. As such, the proposed method can be considered as an alternative for determining soil standard compaction characteristics. The results can be used for field compaction control. This proposed method is very useful in terms of engineering and economic viewpoints.

Acknowledgments

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