

## Compaction Curves of Fine-Grained Soils

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**Abstract :** This paper deals with the development of a phenomenological model to assess the laboratory compaction curves of fine-grained soils. It is found that for a given fine-grained soil compacted at a particular compaction energy, the  $w/S^{B_d}$  and  $w/S^{B_w}$  (where  $w$  is water content,  $S$  is degree of saturation, and  $B_d$  and  $B_w$  are constant) are practically constant for dry and wet sides of optimum, respectively, even with the change in water content and dry unit weight. The  $B_d$  and  $B_w$  values and the optimum degree of saturation are mainly dependent upon soil type and irrespective of compaction energy. The  $w/S^{B_d}$  and  $w/S^{B_w}$  increase with logarithm of compaction energy and their decrease rate is practically the same for any compacted fine-grained soil. These aspects lead to the simple and practical method to assess the compaction curve wherein the compaction energy varies over a wide range by using a one point test (a single test).

### 1. Introduction

Attempts to model the soil compaction have been made since early 1940s. Most of these modeling attempts included correlation equations for estimating the compaction characteristics (optimum water content,  $OWC$  and maximum dry unit weight,  $\gamma_{dmax}$ ) of soil in terms of soil index properties and grain size distribution [1]. Ramiah et al. [2] correlated both  $OWC$  and  $\gamma_{dmax}$  solely to liquid limit. Gurtug and Sridharan [3 and 4] correlated the  $OWC$  and  $\gamma_{dmax}$  of fine grained soils compacted by various compaction energy proctor to

plastic limit. Jeng and Strohm [5] correlated the standard energy proctor  $OWC$  and  $\gamma_{dmax}$  to index properties of 85 soils. Blotz et al. [6] used Proctor compaction data from 22 fine-grained soils to correlate the  $OWC$  and  $\gamma_{dmax}$  with liquid limit and compaction energy.

Most of the previous research has focused on the prediction of the compaction characteristics whereas very few models have been generated to predict the entire compaction curve. The entire curve is very important since it delineates the soil behavior at all attainable levels of water content both wet and dry sides of optimum. The knowledge of the exact shape of the laboratory compaction curve provides a means for quality control of compaction on site by offering a good understanding of the sensitivity of soil to water. An early study by Joslin [7] on a large number of compaction curves yielded 26 typical standard proctor curves (named the Ohio curves) that are presumed to approximately resemble most of the soil encountered in earth construction. These curves provide a quick method for identifying an approximate compaction curve of a given soil using one water content – bulk density data point determined from the standard proctor penetration needle.

Pandian et al. [8] developed a phenomenological model that enables the determination of the density and water content relationship of fine-grained soils separately for dry and wet sides of optimum based on liquid limit and specific gravity. However, their model can be applied only to the standard proctor test. This model yielded two portions

of the compaction curve, which intersect to form a sharp angle at the optimum compaction point. Thus, the curve is an inverted V shape, not the well-known bell-shape. Their study gave a set of curves, which closely approximated the results of Joslin [7].

Over long period of field and laboratory experience, it has been realized that compaction test, with standard Proctor and other compaction energies, have become important to compaction curve. Carrying out compaction test at any energy level takes sufficiently long time and effort. Recently, Nagaraj et al. [9], perhaps the only paper, attempt to predict the compaction curves from liquid limit. They introduce an ideal pore model to formulate a method for rapid estimation of compaction curves of fine-grained soils under different compaction energies. The pores in the soil are assumed as cylindrical shape with equal length. Based on the ideal model, they propose two state parameters,  $w/S^{0.5}$ , and  $w/S^2$ , for dry and wet sides of optimum, respectively. The prediction method based on the two parameters and liquid limit has then been presented. Their method gives the same optimum degree of saturation (*ODS*) for different clays at the same compaction energy. In fact, the shape and distribution of the pores might deviate from the idealization dependent upon soil type. This results in the difference in the state parameters and the optimum degree of saturation (*ODS*) for different clays. Thus, additional investigation attempting to examine the prime parameters and the optimum degree of saturation is a desirable issue for better understanding the compaction behavior and hence predicting the compaction curves at various compaction energy levels. In this paper, an attempt has been made to meet this goal.

**2. Laboratory Investigation**

**2.1 Soil sample**

The study of the physicochemical behavior has indicated that all fine-grained soils could be classified into either non-expanding lattice type soils (kaolinitic soils) or

expanding lattice type soils (montmorillonitic soils) [10]. The nine clays which cover these two soil types were used for this investigation. They are Silty clay 1, Silty clay 2, Silty clay 3, Silty clay 4, weathered clay, kaolinite, bentonite, and two mixed clays, which are bentonite + kaolinite (2:1 by dry weight), and bentonite + weathered clay (4:1 by dry weight). The purpose of mixing is to reduce liquid limit and swelling potential of the bentonite. The soil expansivity and probably dominant clay mineral of the tested clays were investigated by the free swell test proposed by Prakash and Sridharan [11] since it is a simple methodology giving fairly satisfactory prediction of dominant clay mineralogy of soil [12]. The free swell ratio, FSR, is defined as the ratio of equilibrium sediment volume of 10-g oven-dried soil passing a 425µm sieve in distilled water ( $V_d$ ) to that in carbon tetra chloride or kerosene ( $V_k$ ). The silty clays were collected from different locations in Muang district, Nakhon Ratchasima province, Thailand. They are classified as low to moderately swelling type. The weathered clay was sampled at a depth of 1-2 m from Rangsit district (closed to Asian Institute of Technology), Pathumthani, Thailand. It is classified as a low swelling type. The kaolinite and bentonite were obtained from a soil testing company. They are classified as non- and high swelling types, respectively. Their chemical compounds are tabulated in Table 1.

Table 1 Chemical compounds of bentonite and kaolinite.

Chemical Compounds	Bentonite	Kaolinite
SiO <sub>2</sub>	77.695	59.786
Al <sub>2</sub> O <sub>3</sub>	10.631	31.843
Fe <sub>2</sub> O <sub>3</sub>	3.736	1.592
CaO	2.964	-
MgO	0.775	-
SO <sub>3</sub>	-	0.0469
Na <sub>2</sub> O	-	-
K <sub>2</sub> O	0.545	3.048

The bentonite + weathered clay and the bentonite + kaolinite are classified as moderately swelling type. Basic properties,

soil classification according to the Unified Soil Classification (USCS) and grain size distribution of the tested clays are presented in Figure 1 and Table 2. Due to low swelling potential and high amount of > 2µm particles of the four silty clays, their liquid and plastic limits are lowest compared to the other clays. The tested clays are non- to high swelling type with low to high plasticity, which cover a wide variation in swelling potential and plasticity.

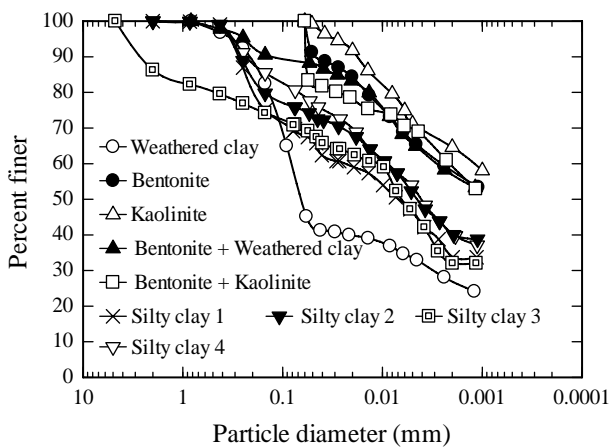


Figure 1 Grain size distribution of the tested soils.

**2.2 Methodology**

All the tested clays were passed through a 19-mm sieve to remove coarser particles. Since 20% or less by mass of all tested clays is retained on the 4.75-mm sieve, they were compacted in the standard 100-mm diameter mold according to the recommendation of the

American Society for Testing and Materials (ASTM) standards. The clays were air-dried for at least three days and then the water content was measured. A 3-kg sample of the air-dried clay was needed for one compaction point (at least five compaction points for each clay). For each point, the air-dried clay was thoroughly mixed with water by hand and kept in a plastic bag for 24 hours to achieve uniform water content and the water content was measured before compaction. The clays were compacted under four energy levels i.e. 296.3, 592.5, 1346.6 and 2693.3 kJ/m<sup>3</sup>, which are equal to the energy of half standard, standard, half modified and modified Proctor, respectively. To attain the required compaction energy, the soils are compacted with the pattern as summarized in Table 3. For each tested point, at least three samples were tested under the same condition for the consistency of the test. In most cases, the results under the same testing condition were repeatable. All test results were analyzed to generate a simple and rational method of assessing compaction curves of different fine-grained soils at various compaction energies.

Finally, test results of two compacted fine-grained soils compiled from the literature have been taken to verify the proposed method. The results were from Proctor [13]; and Bell [14].

Table 2 Basic properties of the tested soils.

Soils	Soil composition				LL (%)	PL (%)	G <sub>s</sub>	UCSC	Swelling type
	Gravel (%)	Sand (%)	Silt (%)	Clay (%)					
Silty clay 1	-	30.8	35.3	33.9	39.7	7.7	2.70	CL	Moderate
Silty clay 2	-	24.2	35.3	40.5	42.3	6.1	2.69	CL	Moderate
Silty clay 3	13.3	15.7	38.7	32.3	47.5	15.8	2.64	CL	Low
Silty clay 4	-	19.3	40.1	40.6	49.3	7.4	2.65	CL	Moderate
Kaolinite	-	-	35.4	64.6	52.0	34.8	2.62	CH	Non
Weathered clay	-	44.3	28.8	26.9	63.5	32.6	2.63	CH	Low
Bentonite + Kaolinite	-	-	40.6	59.4	150.5	39.2	2.58	CH	Moderate
Bentonite + Weathered clay	-	11.3	32.1	56.6	152.8	48.2	2.60	CH	Moderate
Bentonite	-	-	41.9	58.1	256.3	39.2	2.66	CH	High

Table 3 Summary of the compaction pattern to attain the required energy.

Energy per Volume (kJ/m <sup>3</sup> )	Weight of Hammer (N)	Number of Layer	Number of Blows/Layer	Height of Hammer drop (m)
296.3	24.46	3	13	0.3048
592.5	24.46	3	25	0.3048
1346.6	44.48	5	13	0.4572
2693.3	44.48	5	25	0.4572

**3. Test Results**

Figure 2 shows typical compaction curves of Silty clay 1 under the four levels of compaction energy. The compaction characteristics ( $\gamma_{dmax}$ , *OWC*, and *ODS*) of the tested clays at the four compaction energy levels are summarized in Table 4. It is noted that even though *ODS* values are different for different clays, they are within a narrow range (from 81.3 to 90.6%). This range is consistent with the finding of Holtz and Kovacs [15] that the optimum water content of most fine-grained soils corresponds to a degree of saturation of about 80%. The *ODS* is dependent upon the clay type. For a given clay, the *ODS* is practically constant for all the compaction energy levels. This finding contradicts the prediction method proposed by Nagaraj et al. [9].

Table 4 Compaction characteristics of all the tested soils.

Soils	<i>E</i> (kJ/m <sup>3</sup> )	Test Results		
		<i>OWC</i> (%)	$\gamma_{dmax}$ (kJ/m <sup>3</sup> )	<i>ODS</i> (%)
Silty Clay 1	296.3	17.8	16.8	83.5
	592.5	15.6	17.6	83.1
	1346.6	11.7	19.2	83.5
	2693.3	10.8	20.0	84.2
Silty clay 2	296.3	19.1	16.6	86.8
	592.5	16.5	17.5	87.0
	1346.6	13.6	18.6	86.9
	2693.3	11.9	19.3	86.3
Silty clay 3	296.3	24.0	14.6	81.7
	592.5	22.0	15.1	81.7
	1346.6	20.0	15.8	82.2
	2693.3	18.1	16.4	82.4
Silty clay 4	296.3	20.5	16.1	88.5
	592.5	17.7	16.9	87.4
	1346.6	15.0	17.7	85.7
	2693.3	12.4	18.9	87.2
Kaolinite	296.3	33.1	13.2	91.5
	592.5	29.3	14.0	91.2
	1346.6	26.3	14.6	91.1
	2693.3	23.3	15.4	90.8
Weathered clay	296.3	30.7	13.6	89.6
	592.5	27.2	14.4	89.7
	1346.6	23.9	15.2	89.8
	2693.3	20.3	16.2	89.8
Bentonite + Kaolinite	296.3	32.2	13.0	87.2
	592.5	28.5	13.8	87.7
	1346.6	24.8	14.7	88.0
Bentonite + Weathered clay	296.3	36.8	12.3	89.1
	592.5	32.6	13.1	89.5
	1346.6	28.0	14.1	89.7
Bentonite	296.3	38.7	11.9	85.6
	592.5	33.8	12.8	86.4
	1346.6	29.8	13.6	85.7
	2693.3	27.4	14.1	85.8

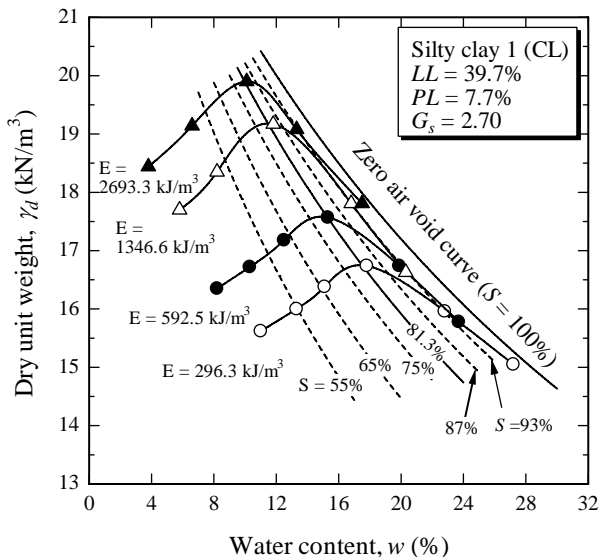


Figure 2 Compaction curves of Silty clay 1.

Recent work on the microstructural model for compacted fine-grained soils [9] reveals that for a particular compaction energy,

even though the water content changes with degree of saturation (*vide* Figure 2), the state parameters  $w/S^{0.5}$  and  $w/S^2$  are constant for the compaction paths on the dry and the wet sides of optimum, respectively. In the present study, it is however found that the proposed state parameters cannot be applied to the tested clays which have widely various soil characteristics. In other words, the parameters  $w/S^{0.5}$  and  $w/S^2$  are not constant for all clay types. A more general relationship between the water content and the degree of saturation at a particular compaction energy is now proposed as a power function of the form:

$$w = A_d S^{B_d} \quad \text{for the dry side} \quad (1)$$

$$w = A_w S^{B_w} \quad \text{for the wet side} \quad (2)$$

where  $A_d$ ,  $B_d$ ,  $A_w$  and  $B_w$  are constants. The  $w$  and  $S$  are expressed as percentage and decimal fraction, respectively.

Figure 3 shows the relationship between water content and degree of saturation of Silty clay 1 as an example. The  $(w, S)$  points were obtained from the compaction curves shown in Figure 2. The parameters  $A_d$ ,  $B_d$ ,  $A_w$  and  $B_w$  are obtained using curve fitting (Eqs. (1) and (2)). The optimum degree of saturation (*ODS*) is determined from the point of intersection of the two proposed relationships.

The values of  $A_d$ ,  $B_d$ ,  $A_w$ , and  $B_w$  for all tested soils are summarized in Table 5. These parameters are mainly dependent upon the soil type. For a given soil, the  $A_d$  and  $A_w$  values decrease with increasing compaction energy. Whereas the  $B_d$  and  $B_w$  values are practically constant for all compaction energy levels. In other words, they are irrespective of compaction energy. The  $B_d$  value varies from 0.70 to 0.86 and the  $B_w$  value from 1.50 to 2.72. This contradicts the assumption of Nagaraj et al. [9] (assuming  $B_d = 0.5$  and  $B_w = 2.0$  for all clays). It is noted that even though the parameters  $A_d$ ,  $B_d$ ,  $A_w$ , and  $B_w$  are different for different clay, the ratios  $A_d/A_{dst}$  and  $A_w/A_{wst}$  (where  $A_{dst}$  and  $A_{wst}$  are  $A_d$  and  $A_w$  values at standard Proctor energy, respectively) are almost the same for all the tested clays and are

very closed to the ratio  $OWC/OWC_{st}$  (*vide* Table 4). This is to be expected because  $B_d$  and  $B_w$  values are practically constant for different compaction energy levels; hence, the change in *OWC* ( $w$  at  $S = ODS$ ) with compaction energy is mainly controlled by  $A_d$  and  $A_w$ . From the present study, the normalized *OWC* and compaction energy relationship for compaction energy ranging from 296.3 to 2693.3  $\text{kJ/m}^3$  can be presented in the following form:

$$\frac{OWC}{OWC_{st}} = 2.09 - 0.39 \log E \quad (3)$$

with a high degree of correlation of 0.970. This equation is useful for rapidly predicting compaction characteristics (*OWC*,  $\gamma_{dmax}$ ). The applicability and verification of this equation is illustrated by Horpibulsuk et al. [16].

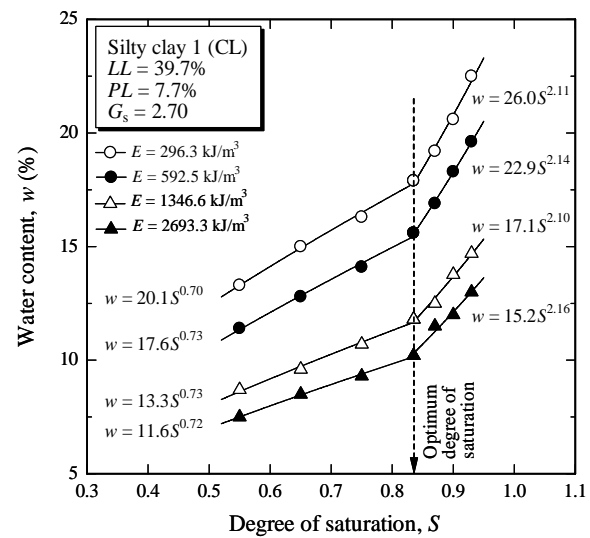


Figure 3 Relationship between water content and degree of saturation at different compaction energies of Silty clay 1.

### 5. SUGGESTED APPROACH FOR ASSESSMENT OF COMPACTION CURVES

The characteristic of compaction curves of fine-grained soils has been analyzed using the two power relationships between water content and degree of saturation (Eqs. (1) and (2)). The compaction paths on both the dry and the wet sides of optimum can now be drawn

using these two relationships. Given a known compaction curve of any fine-grained soil under a particular compaction energy, the following procedure is suggested for assessing the compaction curves under any compaction energy.

1. From the known compaction curve for a particular compaction energy, determine  $A_d$ ,  $B_d$ ,  $A_w$  and  $B_w$  values and the compaction characteristics ( $\gamma_{dmax}$ ,  $OWC$  and  $ODS$ ) using Eqs. (1) and (2).
2. From the calculated  $OWC$  and  $ODS$  values, determine the  $OWC_{st}$  value using Eq. (3), and hence  $(\gamma_{dmax})_{st}$  by assuming that the

$ODS$  value is the same for all compaction energy levels.

3. Determine the optimum compaction point ( $\gamma_{dmax}$ ,  $OWC$ ) for the required compaction energy by substituting the  $OWC_{st}$  value into Eq. (3).
4. Determine  $A_d$  and  $A_w$  values for the required compaction energy from the  $OWC$  value using the following equations

$$A_d = \frac{OWC}{ODS^{B_d}} \tag{4}$$

$$A_w = \frac{OWC}{ODS^{B_w}} \tag{5}$$

Table 5: Values of  $A_d$ ,  $A_w$ ,  $B_d$  and  $B_w$  for all the tested soils.

Soils	$E$ (kJ/m <sup>3</sup> )	$A_d$	$B_d$	$A_w$	$B_w$	$A_d/A_{dst}$	$A_w/A_{wst}$	$OWC/OWC_{st}$
Silty clay 1	296.3	20.14	0.70	25.96	2.11	1.14	1.13	1.15
	592.5	17.65	0.73	22.90	2.14	1.00	1.00	1.00
	1346.6	13.30	0.72	17.07	2.10	0.75	0.75	0.76
	2693.3	11.56	0.72	15.20	2.16	0.65	0.66	0.66
Silty clay 2	296.3	21.26	0.75	24.40	1.72	1.16	1.16	1.16
	592.5	18.29	0.75	20.96	1.73	1.00	1.00	1.00
	1346.6	15.10	0.75	17.33	1.73	0.82	0.82	0.82
	2693.3	13.13	0.76	15.17	1.74	0.72	0.72	0.71
Silty clay 3	296.3	28.25	0.80	33.26	1.61	1.10	1.10	1.09
	592.5	25.84	0.80	30.37	1.60	1.00	1.00	1.00
	1346.6	23.44	0.80	27.47	1.61	0.90	0.90	0.91
	2693.3	21.07	0.79	24.64	1.60	0.81	0.81	0.82
Silty clay 4	296.3	22.36	0.70	24.69	1.51	1.15	1.14	1.16
	592.5	19.49	0.71	21.68	1.50	1.00	1.00	1.00
	1346.6	16.79	0.72	18.94	1.50	0.86	0.87	0.85
	2693.3	13.63	0.71	15.21	1.51	0.70	0.70	0.70
Kaolinite	296.3	35.48	0.79	42.05	2.71	1.12	1.12	1.13
	592.5	31.54	0.80	37.54	2.70	1.00	1.00	1.00
	1346.6	28.34	0.81	33.80	2.71	0.90	0.90	0.90
	2693.3	25.21	0.80	30.35	2.72	0.80	0.80	0.80
Weathered clay	296.3	33.60	0.81	40.21	2.45	1.13	1.13	1.13
	592.5	29.68	0.80	35.44	2.43	1.00	1.00	1.00
	1346.6	26.05	0.81	31.06	2.45	0.87	0.87	0.88
	2693.3	22.18	0.81	26.43	2.44	0.75	0.75	0.75
Bentonite + Kaolinite	296.3	35.70	0.75	40.78	1.72	1.13	1.13	1.13
	592.5	31.53	0.76	35.78	1.72	1.00	1.00	1.00
	1346.6	27.30	0.76	30.86	1.72	0.86	0.86	0.87
	2693.3	22.94	0.75	26.05	1.72	0.77	0.73	0.73
Bentonite + Weathered clay	296.3	40.33	0.80	45.92	1.92	1.13	1.13	1.13
	592.5	35.70	0.81	40.43	1.93	1.00	1.00	1.00
	1346.6	30.57	0.81	34.49	1.92	0.85	0.85	0.86
	2693.3	26.24	0.81	29.88	1.92	0.74	0.74	0.73
Bentonite	296.3	44.19	0.86	49.66	1.61	1.15	1.16	1.14
	592.5	38.31	0.85	42.87	1.62	1.00	1.00	1.00
	1346.6	34.04	0.86	38.21	1.61	0.89	0.89	0.88
	2693.3	31.22	0.85	35.14	1.62	0.81	0.82	0.81

5. Determine  $w$  for both the dry and wet sides of optimum at different values of degree of saturation using Eqs. (4) and (5).
6. Draw a curve connecting  $(\gamma_d, w)$  points obtained from step (5).

the predicted and the measured curves are in very good agreement with errors acceptable for engineering purpose. This reinforces the application of the proposed method in assessing the compaction curves.

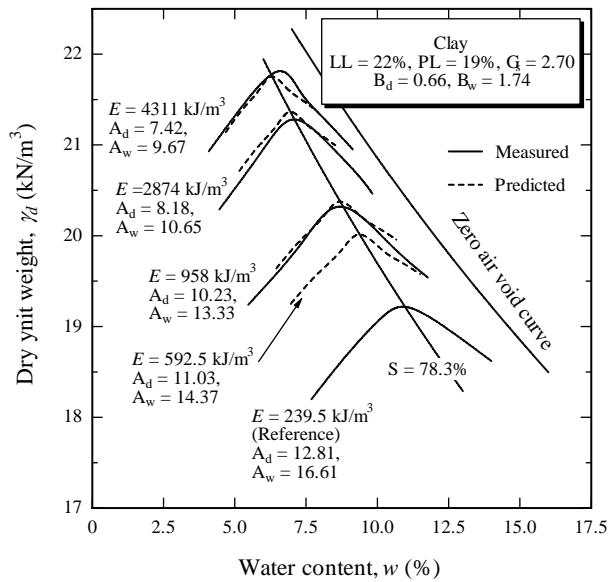


Figure 4 Predicted and measured compaction curves of clay (data from Proctor [13]).

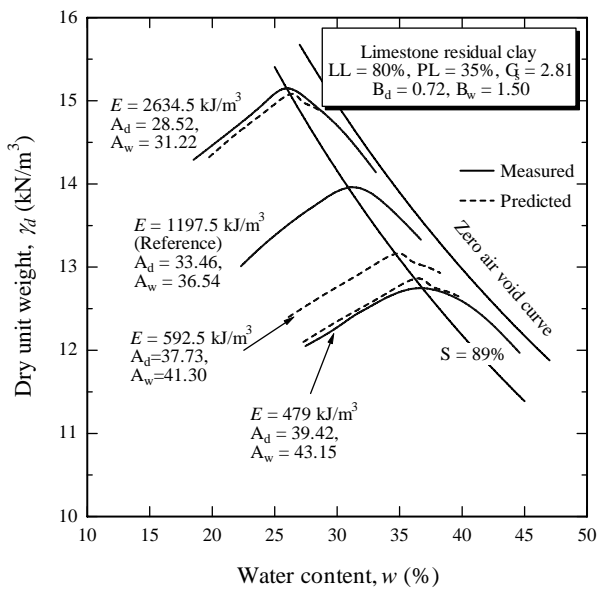


Figure 5 Predicted and measured compaction curves of limestone residual clay (data from Bell [14]).

Figures 4 and 5 show the predicted and the measured compaction curves of the clays compiled from the literature. It is found that

## 6. Conclusions

The present paper deals with the characteristics of compaction curves for fine-grained soils. A method of assessing the compaction curves based on a one point test is presented. The following conclusions can be drawn.

1. On the dry and the wet sides of optimum, the relationships between the water content ( $w$ ) and the degree of saturation ( $S$ ) at a particular compaction energy are represented by the power function as follows:

$$w = A_d S^{B_d} \text{ for the dry side of optimum}$$

$$w = A_w S^{B_w} \text{ for the wet side of optimum}$$

The parameters  $A_d$  and  $A_w$  control the maximum dry unit weight. The maximum dry unit weight increases (optimum water content decreases) with decreasing values of  $A_d$  and  $A_w$ . The constants  $B_d$  and  $B_w$  are dependent upon soil type and regardless of compaction energy. The parameters  $A_d$ ,  $B_d$ ,  $A_w$  and  $B_w$  can capture compaction curves of various fine-grained soils.

2. A simple and rational method for assessing the laboratory compaction curves of fine-grained soils wherein the compaction energy varies over a wide range using a one point test has been proposed. The verification and the applicability of this method are illustrated in this paper.

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