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RESEARCH ARTICLE - CIVIL ENGINEERING

Prediction of Compaction Characteristics of Fine-Grained Soils Using Consistency Limits

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Abstract Evaluation of laboratory compaction parameters, i.e., maximum dry unit weight (γ_{dmax}) and optimum moisture content (OMC) of a soil, is an essential task in controlling field compaction for all earthworks construction. Laboratory determination of compaction parameters requires considerable time and effort which can be saved through the use of empirical correlations during early stages of a project. In this paper, correlations between consistency limits, compactive effort (CE) and compaction parameters, i.e., γ_{dmax} and OMC, for fine-grained soils have been proposed. In order to develop the correlations, 105 soil samples of fine-grained soils representing various classification groups were collected from different areas of Punjab province of Pakistan. Besides classification tests, standard and modified proctor compaction tests were performed on the selected samples. Based on the classification test results, the selected samples are classified as CH, CL, CL-ML, ML with gravel fraction in the range of 0–12 %, sand fraction from 2 to 48 % and silt clay fraction from 50 to 95 %. The laboratory standard and modified compaction tests on the selected samples indicate the γ_{dmax} in the range of 15.8–19.7 kN/m^3 with OMC varying from 9 to 19.5 %. Multiple regression analyses were performed on the experimental data, and correlations have been proposed to predict the compaction parameters (γ_{dmax} and OMC) in terms of LL, PI and CE. In order to validate the proposed equations, an independent data set of 37 samples was used for the validation purpose. The comparative results showed that the variation between experimental and predicted values of γ_{dmax} is within ±2.5 % and that of the OMC (%) is within ±9.5 % at 95 % confidence interval. Based on the correlations developed, predictive curves corresponding to standard and modified proctor energy are proposed for quick estimation of γ_{dmax} and OMC based on LL and PI without performing the laboratory compaction tests.

Keywords Correlation · Compaction parameters · Fine-grained soils · Liquid limit · Plasticity index · Compactive effort · Maximum dry unitweight · Optimum moisture content

1 Introduction

In earthwork construction, filed compaction is an important process whereby soil particles are brought closer to each other by imparting compactive effort resulting in the increase in shear strength, decrease in compressibility and permeability of the soil mass. Engineering projects such as road embankments, earthen dams, river dykes, railway formations require borrow materials to be compacted for the formation of earth embankment, and to avoid failure of these earthen structures, field compaction control of the borrow materials after placement is must. Maximum dry unit weight (γ_{dmax}) and optimum moisture content (OMC) are the two parameters which are determined in the laboratory by performing either standard proctor or modified proctor compaction test. These parameters are used to check the relative compaction requirements as mentioned in the project specifications. The γ_{dmax} and the OMC of coarse-grained soils as determined through laboratory compaction tests are an explicit function of grain size distribution, index properties and the mineralogical composition of the soil samples [1]. However, for fine-grained soils, consistency limits have considerable effects on the compaction characteristics. The objective of this research is to develop a model in case of fine-grained soils for the pre-

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diction of compaction characteristics by using consistency limits. Such a model which can efficiently predict compaction characteristics of soils is a beneficial tool in the preliminary/prefeasibility stages of a project for facilitating engineering decisions and also save time and efforts required to conduct complete testing program. Many researchers in the past have proposed models to predict the compaction characteristics of both coarse-grained and fine-grained soils using gradational parameters and index properties of the soils without conducting laboratory compaction tests. Few of them include Korfiatis and Manikopoulos [1], Mujtaba et al. [2], Omar et al. [3] in case of coarse-grained soils, and Blotz et al. [4], Gurtug and Sridharan [5], Sridharan and Nagaraj [6], Gurtug and Sridharan [7], Noor et al. [8] are notable in case of fine-grained soils.

Joslin [9] proposed 26 typical standard proctor curves, known as Ohio curves, representing a wide range of soils encountered in earthworks construction based on large data bank of laboratory compaction tests. These curves provide a quick method for identifying an approximate compaction curve of a given soil encountered in the earthwork. That research was extended by Horpibulsuk et al. [10] who carried out laboratory compaction tests on 16 coarse-grained and 9 fine-grained soils for compaction energies varying in the range of 296.3, 592.5, 1346.6 and 2693.3 kJ/m^3 and proposed a set of compaction curves designated as "Modified Ohio's curves". Based on an extensive laboratory compaction test data, Blotz et al. [4] proposed relationship to estimate γ_{dmax} and OMC for fine-grained soils based on liquid limit and logarithm of compaction energy (log CE) as given in Eqs. (1) and (2).

$$\gamma_{\mathrm{dmax}}\,(\mathrm{kN/m^3}) = (2.27 \times \log \mathrm{LL} - 0.94) \times \log(\mathrm{CE}) - 0.16\mathrm{LL} + 17.02 \quad (1)$$

$$\mathrm{OMC}\,(\%) = (12.39 - 12.21 \times \log \mathrm{LL}) \times \log(\mathrm{CE}) + 0.67\mathrm{LL} + 9.21 \quad (2)$$

Gurtug and Sridharan [5] suggested a correlation for clayey soils: γ_{dmax} is 0.98 times the dry unit weight of soil at plastic limit water content, and OMC is 0.92 times the plastic limit. Sridharan and Nagaraj [6] developed the correlations given by Eqs. (3) and (4) to predict the compaction characteristics of standard compaction test by using the plastic limit (PL) as an independent variable and γ_{dmax} and OMC as dependent variables.

$$\gamma_{\mathrm{dmax}}\,(\mathrm{kN/m^3}) = 0.23(93.3 - \mathrm{PL}) \quad (3)$$

$$\mathrm{OMC}\,(\%) = 0.92 \times \mathrm{PL} \quad (4)$$

Gurtug and Sridharan [7] based on a series of compaction tests on fine-grained soil presented the correlations as given by Eqs. (5) and (6) to predict the compaction characteristics for different values of CE based on the plastic limit of the soils.

$$\gamma_{\mathrm{dmax}}\,(\mathrm{kN/m^3}) = 22.68\mathrm{e}^{-0.0183(\mathrm{OMC})} \quad (5)$$

$$\mathrm{OMC}\,(\%) = \left[1.95 - 0.38 \log(\mathrm{CE})\right] \times \mathrm{PL} \quad (6)$$

Noor et al. [8] performed the work on fine-grained soils of India and proposed the correlations of compaction characteristics for standard compaction test based on three independent variables plastic limit, plasticity index and specific gravity (G_{s}).

$$\gamma_{\mathrm{dmax}}\,(\mathrm{kN/m^3}) = 27 - (\mathrm{PL})^{0.60} - (\mathrm{PI})^{0.33} - (G_{\mathrm{s}})/2.7 \quad (7)$$

$$\mathrm{OMC}\,(\%) = 0.55(\mathrm{PL}) + 0.36(\mathrm{PI}) - (G_{\mathrm{s}})/2.7 \quad (8)$$

By using compaction characteristics and plastic limit, another correlation is presented by Nagaraj et al. [11] given in Eqs. (9) and (10).

$$\gamma_{\mathrm{dmax}}\,(\mathrm{kN/m^3}) = 20.82 - 0.17w_p \quad (9)$$

$$\mathrm{OMC}\,(\%) = 0.76(w_p) \quad (10)$$

Omar et al. [3] presented the model to predict the compaction characteristics of sandy soils based on three independent variables (specific gravity, liquid limit and % retained on sieve # 4) given in Eqs. (11) and (12).

$$\rho_{\mathrm{d,max}}\,(\mathrm{kg/m^3}) = [4804574G_{\mathrm{s}} - 195.55(\mathrm{LL}^2) + 156971(R\#4)^{0.5} - 9527830]^{0.5} \quad (11)$$

$$\ln(w_o) = 1.195 \times 10^{-4}(\mathrm{LL}^2) - 1.964G_{\mathrm{s}} - 6.617 \times 10^{-3}(R\#4) - 7.651) \quad (12)$$

Mujtaba et al. [2] developed correlation between gradational parameters and compaction characteristics of sandy soils by performing classification tests and both standard and modified proctor tests. They proposed the model presented in Eqs. (13) and (14). These models are based on uniformity coefficient and compaction energy.

$$\gamma_{\mathrm{dmax}}\,(\mathrm{kN/m^3}) = 4.49 \times \log(C_u) + 1.51 \times \log(\mathrm{CE}) + 10.2 \quad (13)$$

$$\log \mathrm{OMC}\,(\%) = 1.67 - 0.193 \times \log(C_u) - 0.153 \times \log(\mathrm{CE}) \quad (14)$$

This study was aimed to establish the empirical correlations between the compaction characteristics and the consistency limits of fine-grained soils present at various locations of Punjab (Pakistan) for both standard and modified proctor compaction efforts.

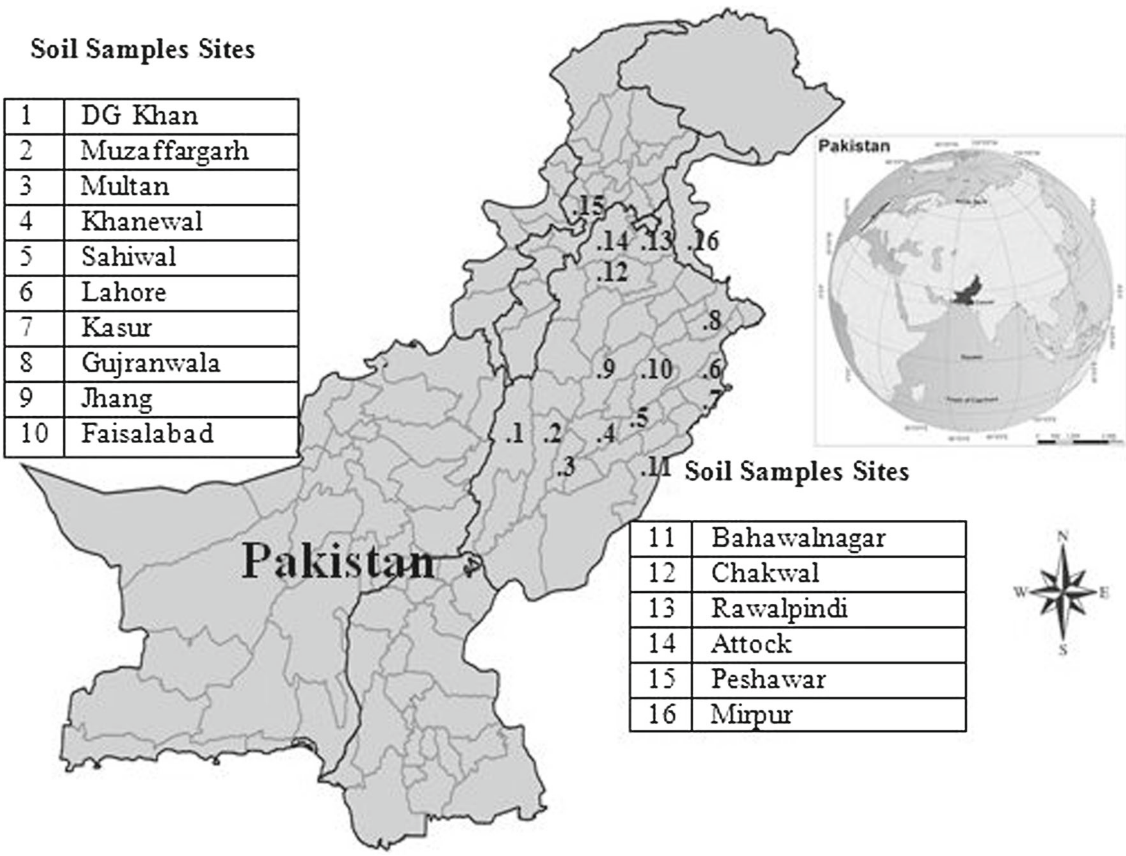

Fig. 1 Pakistan Map indicating locations of the selected soil samples collected from the different areas of Punjab province

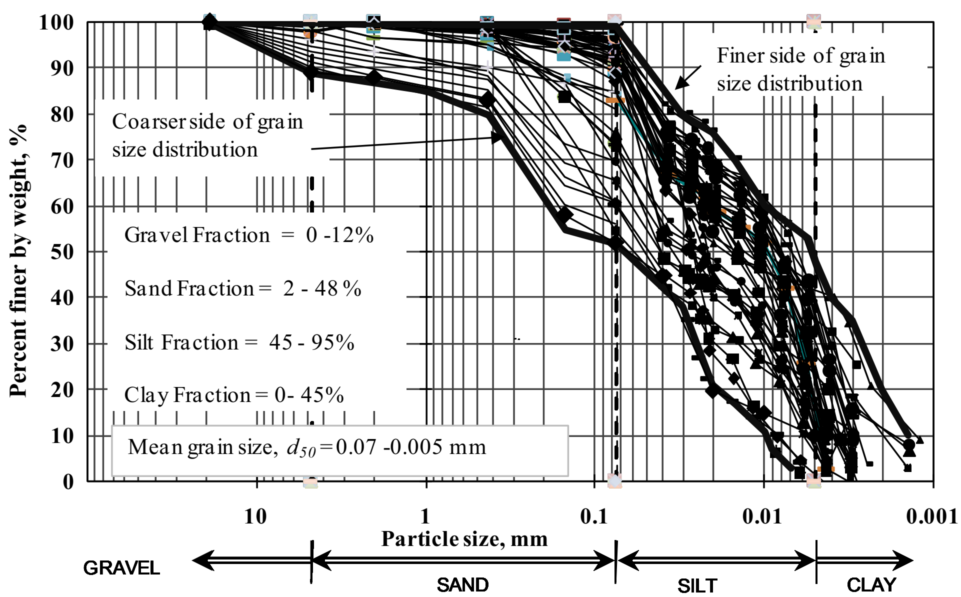

Fig. 2 Grain size distribution curves of selected samples

2 Test Materials and Laboratory Testing

The soil samples used in the experimental program were collected from different areas of Punjab province of Pakistan; specifically, the sampling locations, marked in Fig. 1, include the areas of districts: Dera Gazi Khan, Muzaffargarh, Multan, Khanewal, Rawalpindi, Sahiwal, Mirpur, Attock, Peshawar, Lahore, Gujranwala and Chakwal. From these locations, the representative disturbed soil samples were procured from test pits excavated to 3–4 ft depth below natural surface level, generally the shallow foundation depths. The procured samples were properly packed in plastic bags duly labeled and transported to the testing laboratory of the University of Engineering and Technology, Lahore, Pakistan, for experimental investigation.

The following tests were conducted on the selected samples according to the standard procedures.

i. Grain size analysis (ASTM D-422 and 4221)
ii. Atterberg limit test (ASTM D-4318)
iii. Specific gravity test (ASTM D-854)
iv. Standard proctor compaction test (ASTM D-698)
v. Modified proctor compaction test (ASTM D-1557)

The grain size distribution analysis was performed through wet sieve analysis and hydrometer analysis. The sieve analysis included the US standard sieves of 3/4″, #4, #10, #40, #100 and #200, whereas the hydrometer analysis was performed on fraction passing #200 sieve. The consistency limit tests were performed on air-dried sample fraction finer than 0.425 mm. The standard and modified proctor tests were performed on all the samples using Method A of the relevant ASTM procedure. In these methods, the compaction is done in a mold with 10.16 cm internal diameter and 944 cm^3 volume with samples compacted in three and five layers by imparting compactive efforts of 592 and 2696 kN-m/m^3, respectively, for standard and modified proctor tests. In the experimental program reported herein, 68 fine-grained soil samples were selected for the development of the proposed correlations and 37 similar samples were selected for validation purposes.

3 Results and Discussion

Grain size distribution (GSD) curves of all the soil samples used in this research are plotted in Fig. 2. The data set of sixty eight samples used for the development of correlations is presented in Table 1, whereas Table 2 presents the data used for validation of the correlations. Based on GSD curves, Tables 1 and 2, it is inferred that the selected samples contain gravel fraction (percent coarser than 4.75 mm) in the range varying from 0 to 12 %, sand fraction (percent finer than 4.75 mm and coarser than 0.075 mm) varying between 2 and 48 %, silt fraction (percent finer than 0.075 mm and coarser than 0.005 mm) between 45 and 95 % and the clay fraction (percent finer than 0.005 mm) between 0 and 45 %. The fines (percent finer than 0.075 mm) present in the samples are non-plastic to high plastic in nature on the basis of Atterberg limit test results reported in Tables 1 and 2. The liquid limit of the samples varies between 19 and 70 %, whereas the plasticity index ranges from NP to 46. The specific gravity of the tested samples falls in the range of 2.65–2.78. According to Unified Soil Classification System (USCS) as per ASTM D-2487,

Table 1 Summary of test results of samples (used for development of correlation)

No. of samples	Classification symbols	Grain size distribution				LL	PI	G_s	Standard proctor (ASTM D-698)		Modified proctor (ASTM D-1557)	
	USCS	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	(%)			OMC (%)	γ_{dmax} (KN/m^3)	OMC (%)	γ_{dmax} (KN/m^3)
17	ML	4–5	4–45	44–95	0–30	20–25	NP–3	2.65–2.75	11.5–15.5	16.7–18.4	9.0–11.5	18.7–19.7
10	CL-ML	5–8	5–7	60–74	10–20	19–27	4–7	2.66–2.77	13.5–16.5	17.3–18.0	10.0–12.0	18.7–19.3
36	CL	0–12	1–39	51–80	15–42	23–48	8–26	2.65–2.78	11.0–18.5	16.3–18.2	10.0–14.0	17.8–19.6
5	CH	0	2–4	49–54	43–48	52–70	27–46	2.67–2.73	15.5–19.5	15.8–17.0	13.5–15.0	17.9–18.3

Table 2 Summary of test results of samples (used for validation of correlation)

No. of samples	Classification symbols USCS	Grain size distribution				LL (%)	PI	Standard proctor (ASTM D-698)		Modified proctor (ASTM D-1557)	
		Gravels (%)	Sand (%)	Silt (%)	Clay (%)			OMC (%)	γ_{dmax} (KN/m^3)	OMC (%)	γ_{dmax} (KN/m^3)
5	ML	0–1	15–45	50–80	5–14	20–25	NP	11.5–15.5	17.0–17.5	9.0–11	18.7–19.7
5	CL–ML	0–3	8–30	55–77	15-25	19–24	4–6	13.5–15.5	17.3–18.0	10.0–11.50	18.7–19.3
22	CL	0–10	0–39	45–70	16–30	23–48	9–26	12.0–18.5	16.5–18.2	10.5–12.5	17.8–19.6
5	CH	0	6–12	45–50	43–44	53–70	38–46	15.5–18.0	16.5–17.0	13.5–14.5	17.9–18.3

the soil samples are classified into various soil classification groups, i.e., fat clay (CH), lean clay (CL), silty clay (CL-ML) and silt (ML).

The results of modified proctor and standard proctor compaction tests in the form of compaction curves of all the samples are shown in Figs. 3 and 4, respectively. The compaction characteristics corresponding to modified proctor, i.e., γ_{dmax} and *OMC*, are generally in the range of 17.8–19.7 kN/m^3 and 9.0–15.0 %, respectively. As shown in Fig. 3, the above-mentioned range of γ_{dmax} is further subdivided for individual soil classification group, i.e., ML, CL-ML, CL and CH. The value of γ_{dmax} for CL samples varies between 17.8 and 19.6 kN/m^3, for ML/CL-ML in the range of 18.7–19.7 kN/m^3 and for CH in the range of 17.9–18.3 kN/m^3. Similarly, the standard proctor parameters (γ_{dmax} and *OMC*) are generally in the range of 15.8–18.4 kN/m^3 and 11.0–19.5 %, respectively. Specifically in Fig. 4, CL samples have γ_{dS} between 16.3 and 18.2 kN/m^3, while for the soil groups ML/ CL-ML and CH, the value of γ_{dmax} is 16.7–18.4 and 15.8–17.0 kN/m^3, respectively.

From Figs. 3 and 4, it can be clearly observed that the γ_{dmax} for ML samples is on the higher side followed by CL-ML, CL and CH samples in decreasing order of course with some overlap. The *OMC* values for ML samples are on the lower side and gradually increases for CL-ML, CL and CH soil groups. This implies that γ_{dmax} has decreasing trend with increasing LL and PI of the soil samples, whereas the OMC increases with increase in LL and PI of fine-grained soils.

4 Development of Correlations

In order to develop the correlation, experimental data are divided into two groups of dependent and independent variables. Dependent variables consist of maximum dry unit weight and OMC, while the independent variables are liquid limit, plasticity index, fines fraction, specific gravity and compaction effort. Initially five independent variables were selected, i.e., liquid limit, plasticity index, fines fraction, specific gravity and compaction effort. Stepwise regression analysis was carried out by computer program Statistical Product and Service Solution (SPSS), and the above-mentioned five independent variables are used to develop the correlations. It is observed that out of five, three variables, i.e., liquid limit (LL), plasticity index (PI) and compactive effort (CE), have significant effect on values of maximum dry unit weight and the OMC. Hence, they are selected and fine fraction and specific gravity are not included in the model formulation. The final best-fit models obtained are given by Eqs. (15) and (16).

$$\gamma_{dmax}\ (\text{kN/m}^3) = -0.055(\text{LL}) + 0.014(\text{PI}) + 2.21 \times \log(\text{CE}) + 12.84 \quad (15)$$

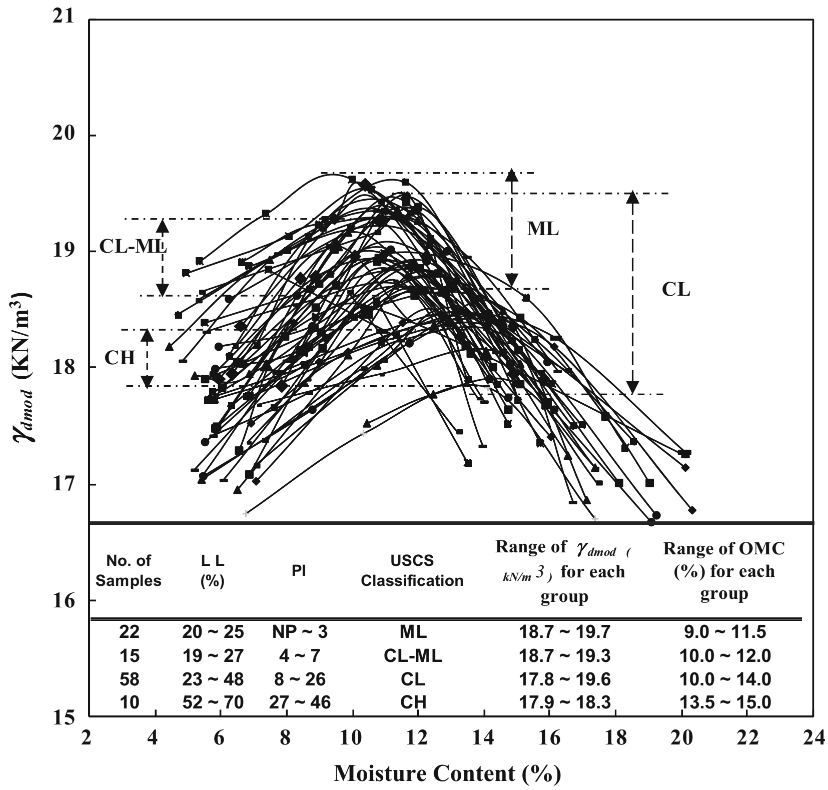

Fig. 3 Modified proctor compaction curves of selected samples

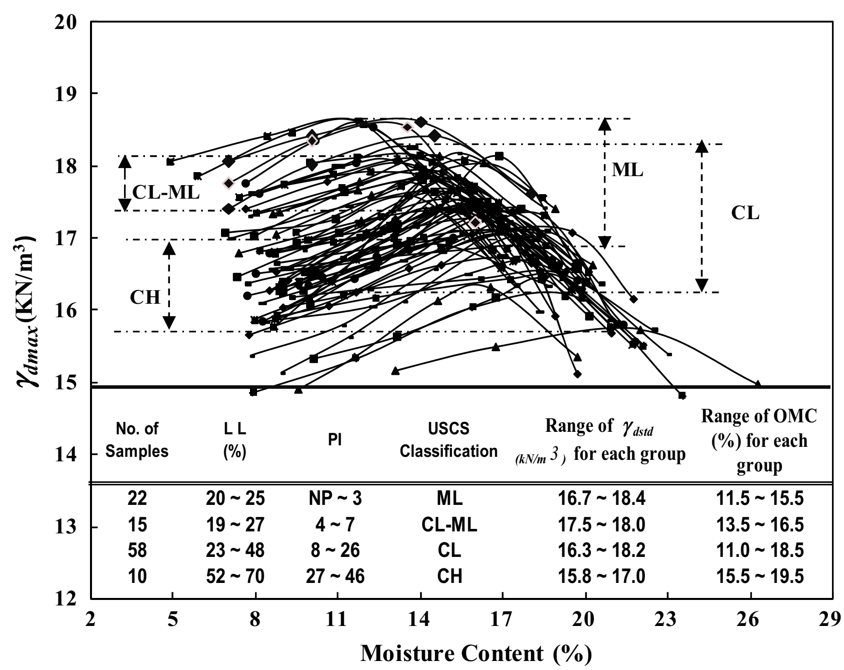

Fig. 4 Standard proctor compaction curves of selected samples

$$\text{OMC}\,(\%) = 0.133(\text{LL}) + 0.02(\text{PI}) - 5.99 \times \log(\text{CE}) + 28.60 \quad (16)$$

A good and reliable correlation must have high value of correlation coefficient (R) and low value of standard error of estimate (SEE) and passes F and t tests statistics with preselected confidence interval of about 95 %. Value of R is 0.89 for Eq. (15) and 0.88 for Eq. (16). These are rated as reasonable correlation coefficient in geotechnical engineering. The prediction accuracy of the proposed models is also checked by plotting experimental values versus predicted values of γ_{dmax} and *OMC* using Eqs. (15) and (16), respectively.

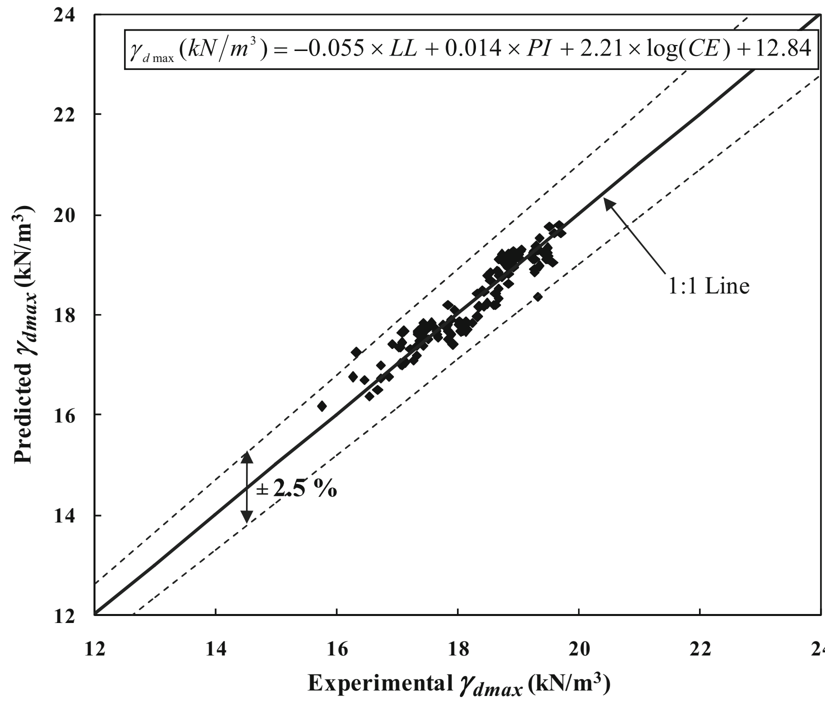

Fig. 5 Experimental versus predicted γ_{dmax} by Eq. (15)

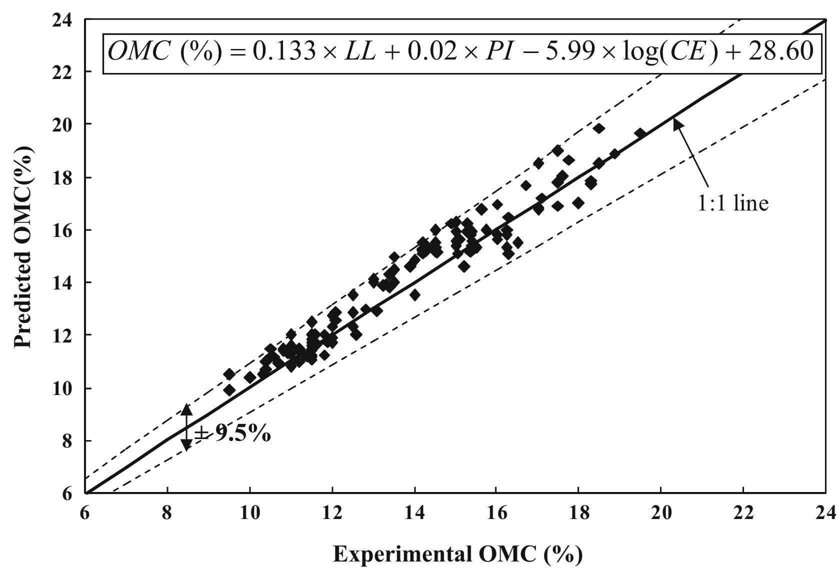

Fig. 6 Experimental versus predicted OMC by Eq. (16)

These variations between experimental and predicted values are presented in Figs. 5 and 6, respectively. These plots show that the prediction accuracy is within ±2.5 % for γ_{dmax} and is ±9.5 % for *OMC*.

The SEE for Eqs. (15) and (16) is 0.29 and 0.86, respectively, indicating the good prediction capability of the model. Regression outputs of both these equations are given in Table 3. Analysis of variance (ANOVA) is carried out to determine *F* statistic for output parameters and *t* statistics for input parameters. As indicated in Table 3, the model *F* value for both γ_{dmax} and *OMC* is greater than critical *F*, indicating that Eqs. (15) and (16) are significant. Similarly, absolute *t* statistics for input parameters is greater than *t* significance of the model indicating that the input parameters pass *t* test.

5 Validation of the Correlations

An independent data set of 37 samples was used to validate the proposed correlations. Further, the proposed predictive equations were also compared with similar equations already available in literature. Out of 37 data points, ten samples were taken from a research publication of Benson and Trast [12].

Table 3 Regression output for Eqs. (15) and (16)

	Equation (15)			Equation (16)		
Variable Y	γ_{dmax}			OMC		
Units		KN/m^3			%	
Regression constant		12.84			28.6	
SEE		0.29			0.86	
Model F value		345.9			292.9	
Model F significance		0			0	
Correlation coefficient		0.89			0.88	
No. of observation		136			136	
Degree of freedom		132			132	
Variable X	LL	PI	log CE	LL	PI	log CE
Coefficient of X	−0.055	0.014	2.21	0.113	0.02	−5.99
Absolute t value	−12.8	2.68	27.38	8.9	1.35	−24.25
t significance	0	0.008	0	0	0.18	0

Validation graphs are plotted between the experimental and predicted values of γ_{dmax} and OMC as shown in Figs. 7 and 8. It can be observed from the figures that the estimated values of γ_{dmax} and OMC using Eqs. (15) and (16) fall within ±2.5 and ±9.5 % of the measured values, respectively. The predictive equations proposed by Blotz et al. [4] and Gurtug and Sridharan [7] were also used to estimate compaction characteristics of these 37 samples and are also plotted in Figs. 7 and 8. It can be observed from Fig. 7 that the estimated value of γ_{dmax} using Blotz et al. [4] model is within ±7.5 % accuracy, i.e., 25 estimations out of 37 lie outside the ±2.5 % band, and for OMC 11 predicted data points fall out of the envelope ±9.5 %, i.e., deviation is ±13.5 %. Similarly, predictions made by Gurtug and Sridharan [7] model show 11 predictions out of 37 falls outside ±2.5 % for γ_{dmax} and for OMC 12 out of 37 estimations fall out of ±9.5 %. The probable reason for these variations in estimation may be due to the reason that Blotz et al. [4] equations are based on liquid limit and the estimations using these equations for plastic soils are not reliable. Similarly, Gurtug and Sridharan [7] model can be used only for plastic soil, and for non-plastic soils, the predictions are not reliable. Therefore, caution is needed when using the models presented in Eqs. (1), (2), (5) and (6) for the prediction of γ_{dmax} and OMC.

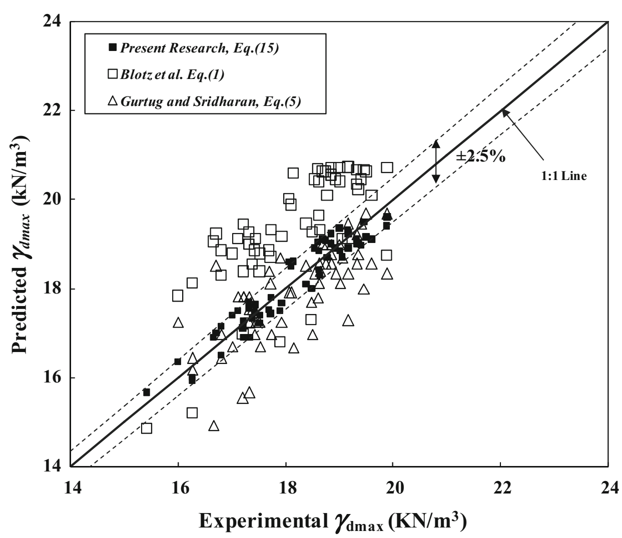

Fig. 7 Comparison of experimental versus predicted values of γ_{dmax} by Eqs. (1), (5) and (15)

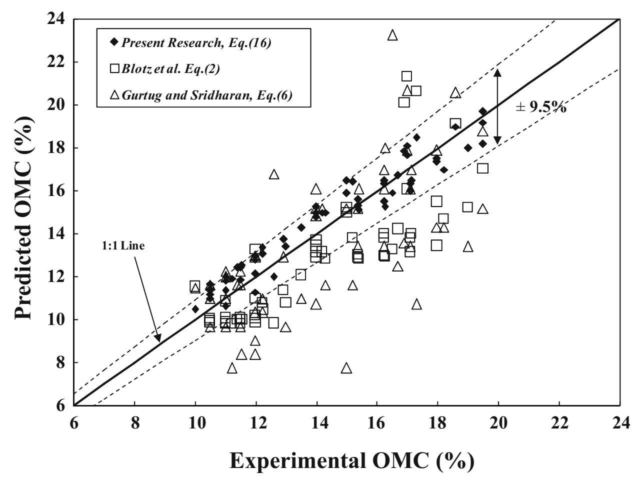

Fig. 8 Comparison of experimental versus predicted values of OMC for Eqs. (2), (6) and (16)

6 Model Implications

It is generally difficult to predict accurately the values of compaction parameters (γ_{dmax} and OMC) due to the involvement of too many variables, mostly related to consistency limits, affecting the compaction mechanism. However, the simple

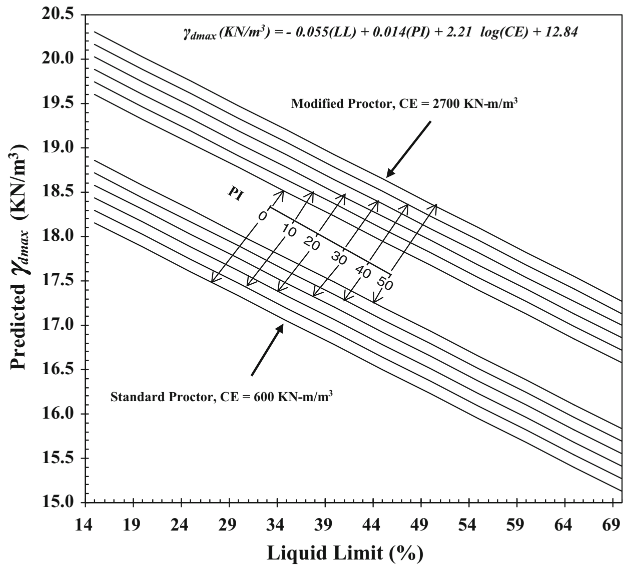

Fig. 9 Predictive curves for estimation of γ_{dmax}(KN/m^3), for fine-grained soils

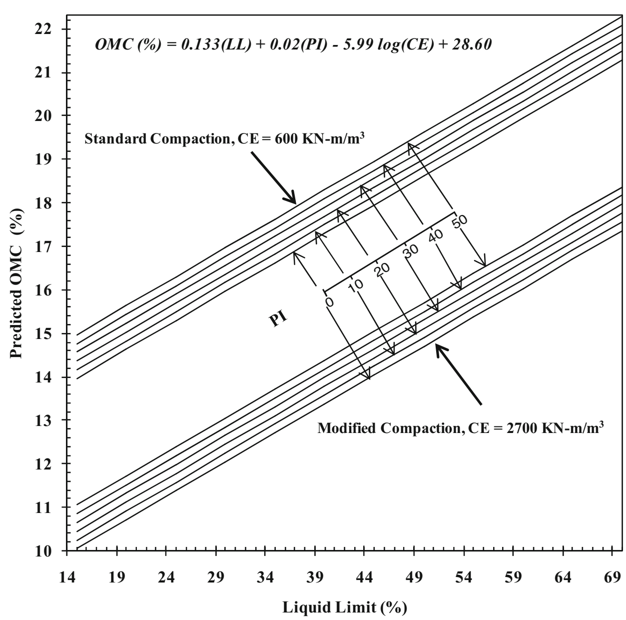

Fig. 10 Predictive curves for estimation of OMC (%), for fine-grained soils

predictive model presented in this paper can be used with reasonable accuracy to predict the values of γ_{dmax} and the OMC for fine-grained soils using consistency limit data. The proposed correlations would be very useful in quick estimation of their compaction characteristics without performing the laboratory compaction tests during early stages of the projects. To simplify the use of the model equations, Eqs. (15) and (16) are presented in graphical form as Figs. 9 and 10, respectively. These graphs are very simple to use and have the accuracy same as that of the proposed correlations.

7 Conclusions

On the basis of the above research, the following conclusions can be made:

- Based on the results of laboratory compaction tests, the maximum dry unit weight (γ_{dmax}) determined through the modified proctor compaction test is 7–8 % more than γ_{dmax} determined through the standard proctor compaction test.
- The optimum moisture content (OMC, %) determined through standard compaction test is 1.20–1.25 times more than that determined through modified compaction test for the same samples.
- The estimation of γ_{dmax} based on liquid limit (*LL*), plasticity index (*PI*) and the logarithm of compactive effort (*CE*) can be made using the predictive equation:

$$\gamma_{\mathrm{dmax}}\,(\mathrm{kN/m^3}) = -0.055(\mathrm{LL}) + 0.014(\mathrm{PI}) + 2.21 \times \log(\mathrm{CE}) + 12.84.$$

  The prediction accuracy of the proposed relation is ±2.5 % at 95 % confidence interval.
- Based on the data of Atterberg limits and the compaction tests, the optimum moisture content of fine-grained soils can be estimated by using the correlation:

$$\mathrm{OMC}\,(\%) = 0.133(\mathrm{LL}) + 0.02(\mathrm{PI}) - 5.99 \times \log(\mathrm{CE}) + 28.60$$

The variation between experimental versus predicted values of OMC is within ±9.5 %. at confidence interval of 95 %

- The proposed correlations and the predictive curves presented in this study are valid for fine-grained soils having gravel fraction up to 10 % and sand fraction maximum up to 40 % and further liquid limit and plasticity index values up to 19–70 % and NP–46, respectively.

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