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TECHNICAL NOTE

Predicting Compaction Characteristics of Fine-Grained Soils in Terms of Atterberg Limits

Ankurjyoti Saikia[1] · Debankur Baruah[1] · Kaushik Das[1] · Hirak Jyoti Rabha[1] · Anirjit Dutta[1] · Anupjyoti Saharia[1]

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Abstract This study presents a set of regression models for predicting maximum dry unit weight (γ_{dmax}) and optimum moisture content (OMC) of fine-grained soils in terms of their consistency limits. The empirical models were developed by performing experimental investigation on forty (40) natural fine-grained soils, encompassing a wide range of liquid limit (LL) and plastic limit (PL). The compaction characteristics were determined by conducting IS light compaction test (standard Proctor equivalent in Indian standards). Observation shows that γ_{dmax} linearly decreases and in contrast, OMC increases in the same fashion with increase in LL or PL. However, in terms of regression coefficient, LL exhibits a superior correlation with γ_{dmax} and OMC than PL does. The observed variation trend of compaction characteristics with LL and PL is affirmed by a few previous studies in the domain. A set of two independent models are finally developed for predicting γ_{dmax} and OMC of soils taking both LL and PL into account. Reasonably good regression coefficients are obtained in case of both the models ($R^2=0.90$ in case of γ_{dmax} and $R^2=0.86$ in case of OMC model). The models are validated by predicting γ_{dmax} and OMC and comparing with actually measured values in a published study as well as present study. The root-mean-square error (RMSE) in case of γ_{dmax} prediction is 2.1% against the measured values of present study and 7.4–7.5% against measured values in literature. The RMSE involved in case of OMC prediction model is 7% against present values and 17.5–28.2% against measured values in literature.

Keywords Maximum dry unit weight (γ_{dmax}) · Optimum moisture content (OMC) · Liquid limit (LL) · Plastic limit (PL) · Regression model

✉ Ankurjyoti Saikia
asaikia@tezu.ernet.in; saikia.ankurjyoti@gmail.com

Debankur Baruah
debtezu@gmail.com

Kaushik Das
kaushikdas195@gmail.com

Hirak Jyoti Rabha
hirak.jrabha@gmail.com

Anirjit Dutta
anirjit_dutta@rediffmail.com

Anupjyoti Saharia
anupjyotisaharia63@gmail.com

[1] Department of Civil Engineering, Tezpur University, Tezpur, Assam 784028, India

Introduction

Compaction is the process of application of mechanical energy to soil in order to rearrange its particles causing reduction in void ratio. The primary objectives of compaction are to increase the shear strength and bearing capacity, to decrease settlement, and to decrease the permeability of soil. Compaction has wide applications almost in all civil engineering works such as improving the properties of an existing soil, in the process of placing fills, and to prepare a level surface such as in the construction of buildings. So, from civil engineering viewpoint, it is very essential to know the compaction characteristics of soils to assess their suitability as a construction material.

Two basic compaction characteristics of a soil obtained from a laboratory compaction test are maximum dry unit weight (γ_{dmax}) and optimum moisture content (OMC). These two parameters are determined either by performing standard Proctor or modified Proctor test which requires considerable time and effort. Therefore, in preliminary estimation of the compaction parameters, it is convenient to use correlations with soil index properties. The γ_{dmax} and OMC of coarse-grained soils are explicit functions of grain-size distribution, index properties, and the mineralogical composition of the samples [1]. However, compaction characteristics of a fine-grained soil are largely governed by its consistency limits.

Limited attempts have been made in the past to develop empirical models for predicting compaction characteristics despite of their practical significance. Joslin [2] made an early attempt proposing a set of typical standard Proctor curves, known as Ohio curves, representing a wide range of soils encountered based on a large number of experimental results. Johnson and Sallberg [3] contributed a chart to estimate OMC by performing a series of standard compaction tests on various soils. However, this chart is a useful only for predicting the OMC soil from its liquid limit (LL) and plastic limit (PL). In several investigations, prediction models were developed in terms of LL in conjunction with other parameters such as compaction energy, clay content, grain characteristics etc. Al-Khafaji [4] investigated the role of Atterberg limits and clay content on compaction parameters of soil and proposed a simple method to predict OMC and γ_{dmax} of soil based on its clay content and LL. Pandian et al. [5] proposed a method to determine the path of compaction for a specific compactive effort in terms of density-water content-liquid limit relationship relationship. Blotz et al. [6] proposed empirical methods to estimate γ_{dmax} and OMC of fine-grained soils based on LL and compaction energy. Al-Badran and Schanz [7] recently developed a theoretical model for constituting the entire compaction curve of fine-grained soils at varying compaction efforts and proposed a chart correlating γ_{dmax} and OMC with LL. Significance of LL in predicting compaction characteristics of soils is also noted in the investigation of Günaydın [8] and Dokovic et al. [9].

In a few other investigations, PL of soil is shown to provide better correlation with γ_{dmax} and OMC than does LL. Gurtug and Sridharan [10] suggested empirical correlations for predicting OMC and γ_{dmax} of clayey soils from PL with special reference to compaction energy. Another study on standard Proctor test on plastic clays [11] shows that both γ_{dmax} and OMC exhibits a superior correlation with PL than LL and finally proposed empirical models in terms of PL. Sivrikaya et al. [12] developed empirical equations correlating γ_{dmax} and OMC of fine-grained soils obtained from standard and modified Proctor tests to index parameters. In this study, models were developed correlating LL and PL of soils independently and PL was shown to provide better correlation than liquid limit. Nagaraj et al. [13] conducted a recent study on different sandy and clayey soils to correlate compaction characteristics with modified plastic limit at standard Proctor compactive effort.

In few recent studies, effort was made to develop empirical models for predicting compaction characteristics of coarse-grained soils. Investigation of Mujtaba et al. [14] on gradational parameters of soil and compaction energy, Sivrikaya et al. [15] that correlates compaction characteristics with grain-size characteristics and consistency limits are two such attempts. Compaction characteristics of coarse-grained soils are, however, out of scope of the present study.

So far as fine-grained soils are concerned, efforts were mostly made to correlate γ_{dmax} and OMC especially either with LL or PL. In few investigations, special emphasis was laid on compaction energy. Limited attempts have been made in the domain to correlate γ_{dmax} and OMC with LL in conjunction with PL or plasticity index (PI). Di Matteo et al. [16] developed regression models compaction characteristics of fine-grained soils in terms of consistency limits and physical properties but are limited to for modified Proctor energy level only. Another attempt was made by Gu¨naydın [8] taking both sandy and clayey soils into account. The γ_{dmax} and OMC of fine-grained soils are largely governed by its consistency limits. In contrast, compaction characteristics of coarse-grained soils are also governed by their grain-size distribution and index properties apart from consistency limits. Hence a common prediction model for estimating γ_{dmax} and OMC of coarse-grained and fine-grained soils seems to have potential drawback. Recently, Farooq et al. [17] conducted an extensive study on fine-grained soils and developed correlations for predicting γ_{dmax} and OMC of fine-grained soils in terms of LL, PI, and compaction energy.

Review of previous studies shows that limited efforts [8, 16, 17] have been made to develop prediction models for compaction parameters of fine-grained soil in terms of both LL and PL and scope of few such models are limited as already explained [8, 16]. Predicting compaction parameters from LL or PL alone has got technical limitations and therefore, it is more logical to have a model which takes both the consistency limits into account. Moreover, the variations of compaction characteristics with Atterberg limits are not fully understood. In few investigations, LL of soil was observed to bear better correlation with compaction characteristics than PL [4, 8, 9]. Contrastingly, in few other studies, PL was shown to provide a better correlation than LL [10–13]. Furthermore, prediction models are not expected to be unique and may have dependency on the place of origin of soils. These pin-points the necessity of a further study to understand the behavior of compaction characteristics with consistency limits of fine-grained soils. Therefore, an extensive laboratory investigation has been carried out to study the variation pattern of γ_{dmax} and OMC of fine-grained soils at standard Proctor energy level as functions of their LL and PL values aiming at developing an improved correlation among these parameters.

Methods and Materials

This study is performed 40 natural fine-grained soil samples collected from different parts of Assam (India). The physical properties of these soils were determined as per the guidelines laid down in relevant Indian standards. The classification tests include determination of specific gravity (G_s), grain-size distribution, liquid and plastic limits. IS light compaction test was further performed on these samples to determine the respective γ_{dmax} and OMC values.

The Atterberg limit tests were carried out on oven-dried samples considering the fraction finer than 0.425 mm. The liquid limit tests are performed using mechanical liquid limit device [18]. Plastic limits are determined by roll and thread method [18] and average of three trials is reported as the plastic limit.

The particle size distribution was carried out by wet sieving [19] on oven-dried samples. The objective was to determine the relative proportions of constituent fractions (gravel, sand, and finer content) and accordingly no hydrometer analysis was performed on the finer fraction. The samples were finally classified as per Indian standard plasticity chart as per IS: 1498–1970 [20]. Physical characteristics and classification of the samples are shown in Table 1.

Compaction parameters of the soils were determined by performing IS light compaction test as per standard guidelines [21]. IS light compaction test (mass of hammer: 2.6 kg, height of fall: 31 cm, number of layers: 3, blows per layer: 25, volume of mould: 1000 cc) is Indian equivalent of standard Proctor test which delivers compaction energy of 594 kJ/m^3 which is same as delivered in standard Proctor test [22]. Readers may refer to Shukla [23] for comparison of Indian and ASTM standards for compaction of soils. Compaction curves were generated with minimum six data points at altered water contents.

Results and Discussions

IS light compaction tests were carried out on the samples as per the methodology discussed in previous section and their compaction characteristics are summarized in Table 2. The summary of soil types and key soil parameters are furnished in Table 3. It can be observed from Table 3 that the soils under investigation has LL ranging from 20.8–56.2%, PL lying in the range of 10.0–29.9%, and PI in the range of 3.9–28.4%.

Variation of γ_{dmax} and OMC Versus LL

In order to study the variation trend of compaction characteristics with LL, the γ_{dmax} and OMC values are plotted treating LL as independent variable in Fig. 1a, b. It can be seen that both γ_{dmax} and OMC of a fine-grained soil are linearly dependent on its LL. MDD decreases and OMC increases in contrast, with increasing LL. Regression models developed in few published literature [8, 9, 11] are also plotted for comparison where similar trend of variations are noted. The differences in present trend and published models could be attributed to the differences in soil types and their places of origin. Another reason could be the inclusion of both sandy and clayey soils [8] in contrast to the inclusion of only fine-grained soils in the present model.

The linear regression equations obtained from the data points of present study are expressed in Eqs. 1a and 1b as follows:

$$\gamma_{dmax} = 20.97 - 0.127LL \quad \left(R^2 = 0.90\right) \tag{1a}$$

$$OMC = 0.42LL + 7.104 \quad (R^2 = 0.85) \tag{1b}$$

LL exhibits a somewhat better correlation with γ_{dmax} than OMC does (R^2=0.90 with γ_{dmax} in contrast to 0.85 with OMC). The regression coefficient obtained in either case is more convincing than the previous models [8, 9, 11]. The significance of LL in predicting compaction parameters is noted in several earlier studies [6, 8, 9, 16].

The γ_{dmax} and OMC values as predicted by the present models are plotted against the corresponding measured values in Fig. 2a, b. The errors involved in the predicted values are expressed in terms of root-mean-square error (RMSE) in percentages. Considerably good agreement is observed between the measured and predicted values with RMSE values of 2.1% (in case of γ_{dmax} with LL) and 7.2% (in case of OMC with LL).

Variation of γ_{dmax} and OMC Versus PL

In this case, γ_{dmax} and OMC are plotted treating PL as independent variable as depicted in Fig. 3a, b. Compared to LL, PL bears a noticeably weaker correlation with both γ_{dmax} and OMC (R^2=0.67 with γ_{dmax} and 0.69 with OMC). However, the trend is still linear as observed in a few previous studies. The regression coefficients are better than few previous studies [8, 9] but differ considerably from few other investigations [11, 12]. Differences in soil types and their place of origin could be the reason behind the differences in present and previous models as stated in previous section.

The empirical expressions obtained from the best-fit trend lines are expressed in Eqs. 2a and 2b as follows:

$$\gamma_{dmax} = 20.94 - 0.215PL \quad \left(R^2 = 0.67\right) \tag{2a}$$

Table 1 Physical characteristics and classification of the samples under investigation

Sample no.	Grain-size distribution			G_s	LL (%)	PL (%)	PI (%)	Group symbol
	% Gravel	% Sand	% Finer					
1	0	11.1	88.9	2.78	36.2	21.8	14.4	CI
2	0	35.8	64.2	2.70	26.9	17.8	9.1	CL
3	0	36.1	63.9	2.80	25.5	14.6	10.9	CL
4	0	19.1	80.9	2.72	29.6	22.4	7.2	CL
5	0	28.0	72.0	2.78	22.0	16.9	5.1	CL-ML
6	0	45.1	54.9	2.75	20.4	15.4	5.0	CL-ML
7	0	16.2	83.8	2.74	31.3	16.2	15.1	CL
8	0	22.2	77.8	2.77	29.2	16.5	12.7	CL
9	0	4.7	95.3	2.76	33.9	22.6	11.3	CL
10	0	7.6	92.4	2.72	43.3	22.6	20.7	CI
11	0	13.8	86.2	2.72	28.2	21.8	6.4	CL-ML
12	0	9.3	90.7	2.70	25.7	14.6	11.1	CL
13	0	15.2	84.8	2.66	30.8	17.1	13.7	CL
14	0	47.0	53.0	2.78	25.2	16.3	8.9	CL
15	0	27.4	72.6	2.79	33.4	14.3	19.1	CL
16	0	10.6	89.4	2.65	29.8	19.0	10.8	CL
17	0	12.2	87.8	2.74	25.1	16.6	8.5	CL
18	0	27.1	72.9	2.72	25.8	12.3	13.5	CL
19	0	4.7	95.3	2.67	37.3	19.0	18.3	CI
20	0	13.8	86.2	2.67	40.0	19.6	20.4	CI
21	0	11.4	88.6	2.70	32.6	19.5	13.1	CL
22	0	21.4	78.6	2.73	54.9	29.9	25.0	MH
23	1.1	13.2	85.7	2.87	40.0	21.4	18.6	CI
24	0	11.1	88.9	2.75	38.6	21.6	17.0	CI
25	0	26.7	73.3	2.71	20.8	16.9	3.9	ML
26	0	21.5	78.5	2.67	21.2	10.0	11.2	CL
27	0	1.5	98.5	2.72	38.6	22.6	16.0	CI
28	0	6.4	93.6	2.74	31.7	18.3	13.4	CL
29	0	13.5	86.5	2.73	38.7	21.7	17.0	CI
30	0	17.3	82.7	2.76	23.5	18.9	4.6	CL-ML
31	0	27.9	72.1	2.71	26.3	12.4	13.9	CL
32	0	24.3	75.7	2.77	28.9	18.2	10.7	CL
33	0	20.3	79.7	2.79	32.1	19.1	13.0	CL
34	0	8.4	91.6	2.81	56.2	27.8	28.4	CH
35	0	9.8	90.2	2.74	32.3	18.0	14.3	CL
36	0	7.9	92.1	2.73	34.5	20.2	14.3	CL
37	0	3.7	96.3	2.76	36.1	19.0	17.1	CI
38	0	3.0	97.0	2.75	47.1	29.0	18.1	MI
39	0	6.6	93.4	2.71	39.3	26.1	13.2	MI
40	0	8.1	91.9	2.70	48.2	25.2	23.0	CI

G_s Specific gravity, *LL* Liquid limit, *PL* Plastic limit, *PI* Plasticity index, CI and MI respectively signifies inorganic clays and inorganic silts of intermediate plasticity (LL in the range of 35–50%) as per Indian standards

$$OMC = 0.742PL + 6.64 \quad (R^2 = 0.69) \tag{2b}$$

The predicted values of γ_{dmax} and OMC by the present set of models are plotted against the corresponding measured values in Fig. 4a, b. The RMSE values in case of γ_{dmax} prediction model is 3.9% and 11.5% for the case of OMC model. However, it is recommended that if γ_{dmax} and OMC of a fine-grained soil is to be predicted either from its plastic or liquid limit, one must use the latter for better accuracy.

Table 2 Compaction characteristics of the samples under investigation

Sample no.	Compaction characteristics		Sample no.	Compaction characteristics	
	γ_{dmax} (kN/m^3)	OMC (%)		γ_{dmax} (kN/m^3)	OMC (%)
1	15.80	25.5	21	17.10	19.1
2	17.80	19.0	22	14.70	28.1
3	17.90	18.4	23	15.70	25.3
4	16.85	21.8	24	16.50	21.0
5	18.50	14.5	25	18.00	15.1
6	18.90	15.4	26	18.55	15.5
7	16.55	20.5	27	15.35	26.4
8	17.20	21.4	28	17.25	17.8
9	16.25	22.3	29	16.12	25.0
10	15.10	24.0	30	18.00	17.9
11	17.25	20.5	31	17.65	18.1
12	18.20	16.8	32	16.85	19.8
13	16.85	21.0	33	17.25	19.8
14	18.18	17.3	34	13.80	31.0
15	17.20	18.8	35	16.35	23.0
16	16.65	19.7	36	16.65	22.5
17	18.00	15.8	37	16.55	21.0
18	17.30	17.0	38	15.25	25.2
19	16.10	23.3	39	15.80	25.5
20	16.40	22.5	40	15.00	27.5

γ_{dmax} Maximum dry unit weight, *OMC* Optimum moisture content

Table 3 Summary of test results

Soil type	Nos.	Range of				
		LL (%)	PL (%)	PI (%)	γ_{dmax} (kN/m^3)	OMC (%)
ML	1	20.8	16.9	3.9	18.00	15.1
CL-ML	4	20.4–28.2	15.4–21.8	4.6–6.4	18.90–17.25	14.5–20.5
MI	2	39.3–47.1	26.1–29.0	13.2–18.1	15.25–15.80	25.2–25.5
MH	1	54.9	29.9	25.0	14.70	28.1
CL	21	21.2–34.5	10.0–22.6	7.2–19.1	16.25–18.55	15.5–23.0
CI	10	36.1–48.2	19.0–25.2	14.4–23.0	15.00–16.55	21.0–27.5
CH	1	56.2	27.8	28.4	13.80	31.0

LL Liquid limit, *PL* Plastic limit, *PI* Plasticity index, γ_{dmax} Maximum dry unit weight, *OMC* Optimum moisture content, CI and MI respectively signifies inorganic clays and inorganic silts of intermediate plasticity (LL in the range of 35–50%) as per Indian standards

Regression Model in Terms of LL and PL

Predicting compaction characteristics of a fine-grained soil solely in terms of liquid or plastic limit may have potential drawback and therefore, it is more rational to have a model in terms of both the consistency limits. To take both the consistency limits into account, liquid limit and plastic limit are considered as independent variables treating γ_{dmax} and OMC as dependent variables. A set of models are finally developed using multivariable linear regression tool in excel and are expressed in Eqs. 3a and 3b as follows:

$$\gamma_{dmax} = 21.07 - 0.119LL - 0.02PL \quad \left(R^2 = 0.90\right) \tag{3a}$$

$$OMC = 0.35LL + 0.163PL + 6.26 \quad \left(R^2 = 0.86\right) \tag{3b}$$

Reasonably good regression coefficients are obtained in both the models ($R^2 = 0.90$ for γ_{dmax} and 0.86 for OMC). The R^2 values obtained in present context are better than few previous models [8, 9, 17]. The accuracy of the models are verified by comparing predicted γ_{dmax} and OMC values of soils with their actually measured values in present study and published works [8, 11] as shown in Fig. 5a, b.

The RMSE values involved in the prediction of γ_{dmax} is 2.1% against present study and 7.4–7.5% against measured values in literature. The RMSE values obtained in

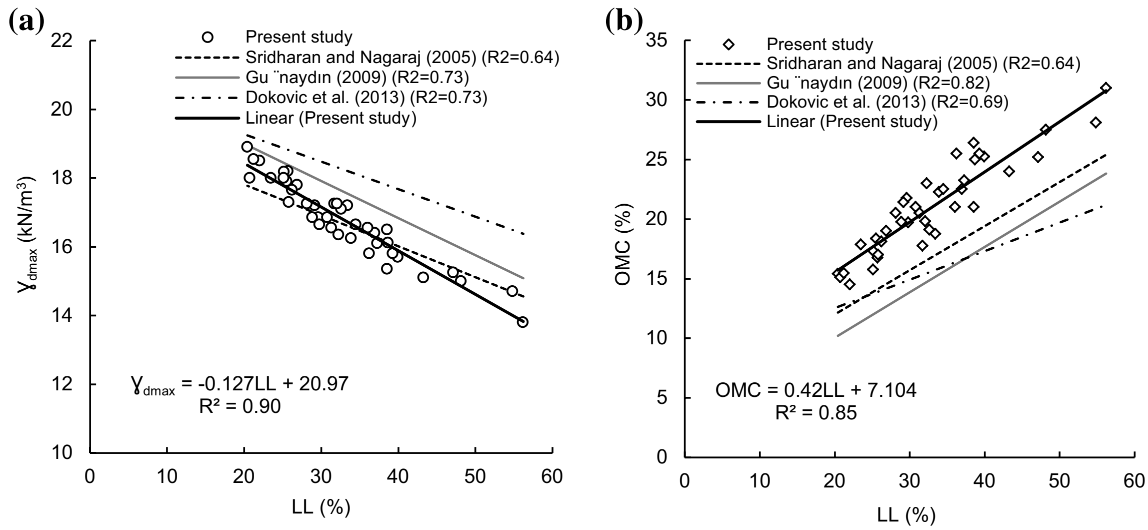

Fig. 1 **a** Variation of γ_{dmax} with LL and **b** variation of OMC with LL

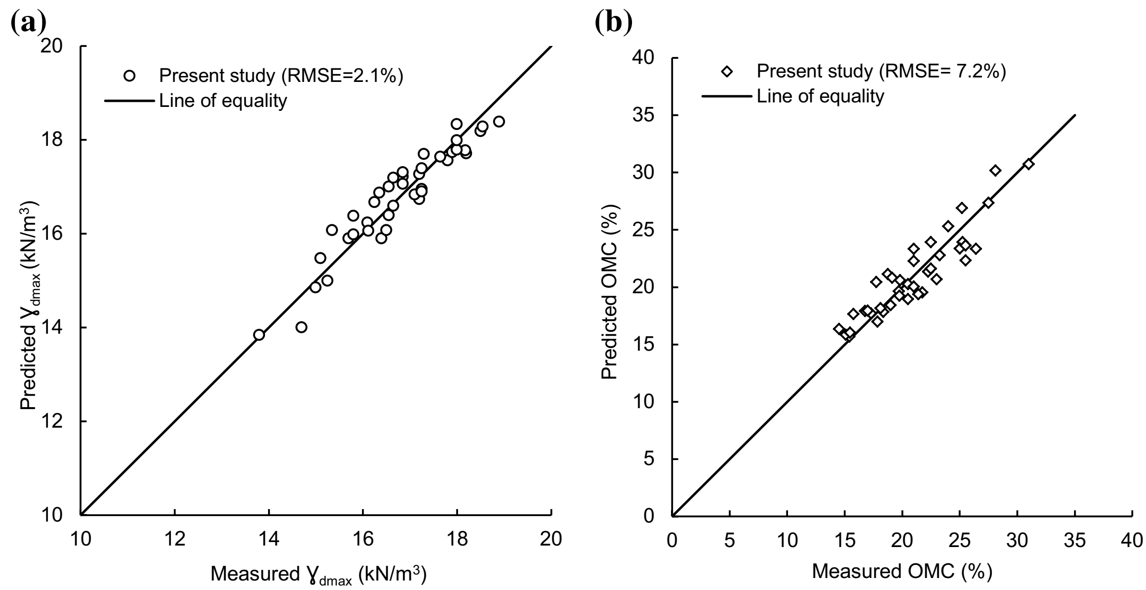

Fig. 2 **a** Predicted γ_{dmax} using LL relationship versus measured values and **b** predicted OMC using LL relationship versus measured values

the prediction of OMC is 7% against present study and 17.5–28.2% against measured values in literature. This has been observed that error involved with the OMC model is higher than the γ_{dmax} model, implying that γ_{dmax} is more dependent on the consistency limits compared to OMC. In addition, more variation is noted in case of values measured in literature than present study, especially in case of OMC model. It may be hence be concluded that application of such empirical models are more appropriate to the place of investigation as there is a possibility of variation depending on the place of origin of soils.

Conclusions

An extensive experimental study was carried out on 40 natural fine-grained soils to investigate the variation pattern of γ_{dmax} and OMC against their consistency limits. The salient observations of this study can be summarized as follows:

- The γ_{dmax} of soils linearly decreases and OMC increases in contrast, with increasing LL. However, γ_{dmax} bears a somewhat superior correlation with LL ($R^2 = 0.90$) than OMC does ($R^2 = 0.85$). The measured and predicted val-

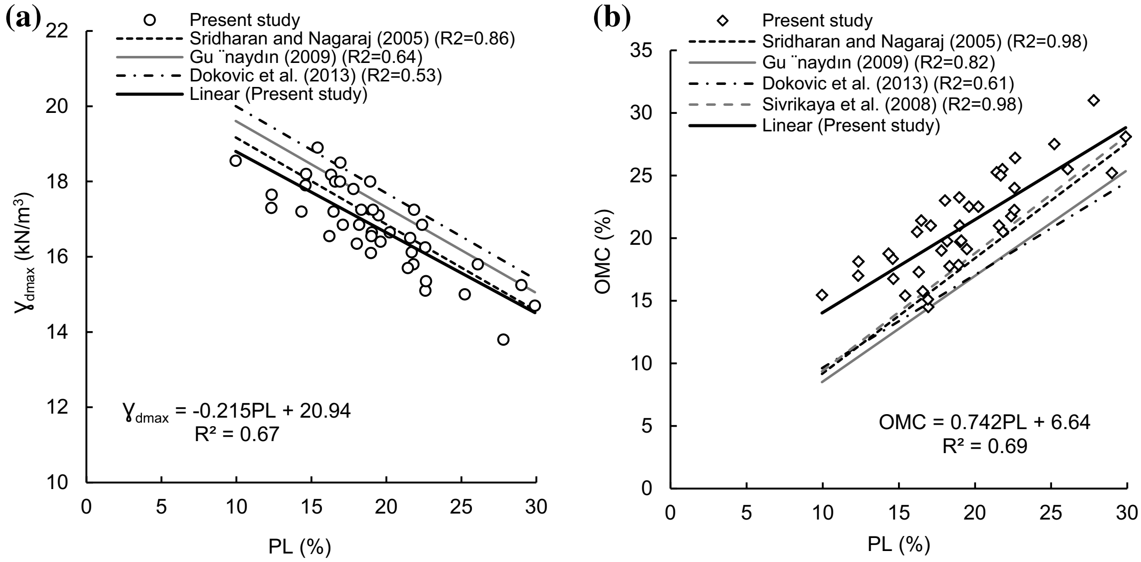

Fig. 3 **a** Variation of γ_{dmax} with PL and **b** variation of OMC with PL

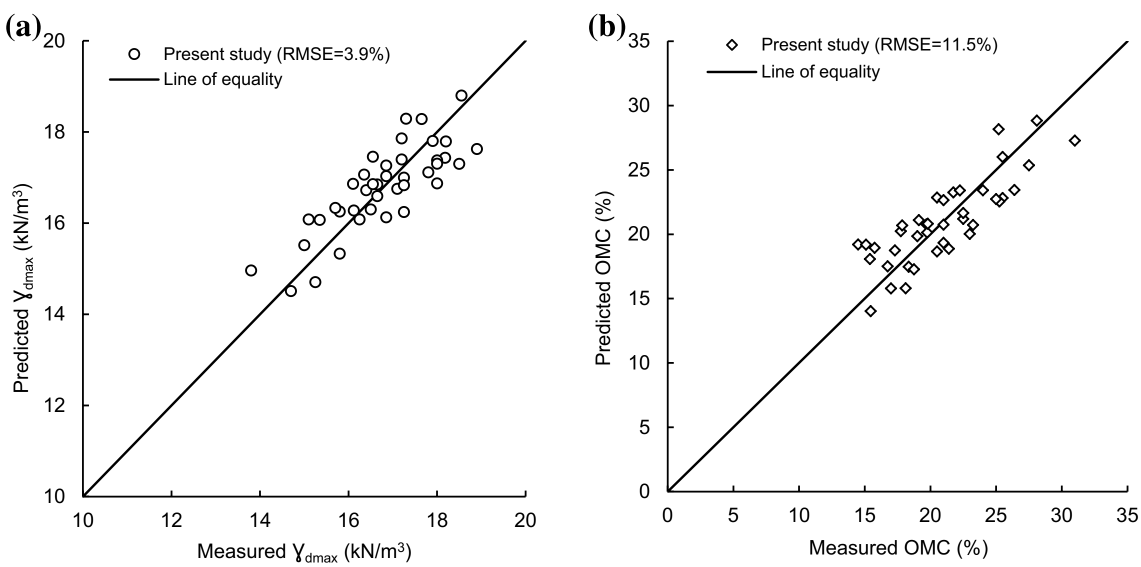

Fig. 4 **a** Predicted γ_{dmax} using PL relationship versus measured values and **b** predicted OMC using PL relationship versus measured values

ues of γ_{dmax} and OMC of present study were found to be in reasonable agreement with RMSE of 2.1% (in case of γ_{dmax}) and 7.2% (in case of OMC).

- Plots of γ_{dmax} and OMC versus PL of soils also exhibit a linear correlation but less convincing than LL does. Therefore, if the γ_{dmax} and OMC is to be predicted solely in terms of either LL or PL, one must use LL for higher accuracy.
- The prediction models finally developed in terms of both LL and PL exhibit convincingly good regression coefficients ($R^2=0.90$ in case of γ_{dmax} and $R^2=0.86$ in case of OMC model). The RMSE in case of γ_{dmax} prediction is 2.1% against the measured values of present study and 7.4–7.5% against measured values in literature. The RMSE involved in case of OMC prediction is 7% against present values and 17.5–28.2% against measured values in literature.
- Proposed correlations are valid only for standard Proctor energy level and the range of the consistency limits observed in this study. Moreover, the relationships would be more appropriate for clayey soils of Assam

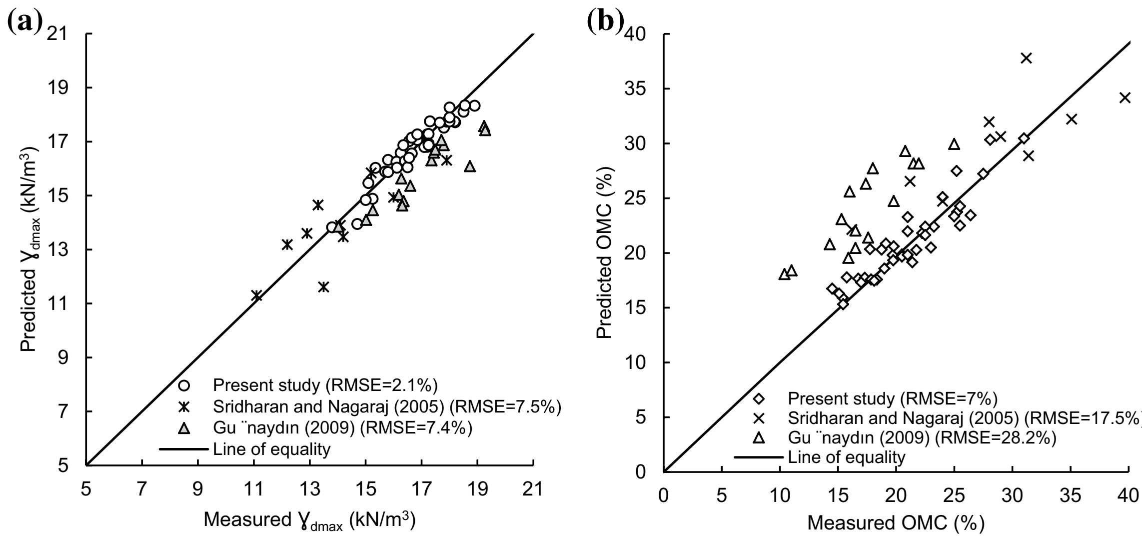

Fig. 5 **a** Predicted γ_{dmax} using Eq. 3a versus measured values and **b** Predicted OMC using Eq. 3b versus measured values

(India) as more variation is noted depending on the place of origin of soils.

Proposed empirical models may be useful in predicting γ_{dmax} and OMC of fine-grained soils in absence of laboratory data. It may be also useful in deciding the trial water content to begin with a compaction test as OMC can be predicted beforehand. Investigation on highly plastic clays (kaolinite, bentonite, black cotton soil etc.) at altered compactive effort may be pursued as a future scope of this study.

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