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Evaluation of compaction parameters of fine-grained soils using standard and modified efforts

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Abstract

Compaction characteristics of the soil have the great importance for practically achieving the desired strength, permeability and compressibility of soil during the construction. Standard compaction test (SCT) and modified compaction test (MCT) are two very famous laboratory test methods to determine the compaction characteristics of soils worldwide. Modest efforts have been made in the past to correlate the compaction parameters drawn from these two tests with each other. In the present study, authors are established the models to predict the modified compaction parameters ($\gamma_{dmax(m)}$ and $w_{opt(m)}$) by using standard compaction parameters ($\gamma_{dmax(s)}$ and $w_{opt(s)}$) or vice versa for the fine-grained soils. Such models can extricate from performing additional tedious and laborious compaction tests. Moreover, the effect of plasticity on the compaction parameters obtained using standard and modified effort is also discussed. Total 156 disturbed fine-grained soil samples were collected from different areas of Pakistan. The index properties tests and laboratory compaction tests were performed using these soil samples. On the basis of index properties tests, these soil samples were classified into different sub-groups of fine-grained soil as per the Unified Soil Classification System. Relationships between the plasticity index (I_p) and compaction parameters of both MCT and SCT were also accomplished. Out of 156 soil samples, test results of 126 samples are used to develop the correlations and test results data of 30 samples was used to validate the developed correlations. The percentage error in the correlation between $\gamma_{dmax(m)}$ and $\gamma_{dmax(s)}$ is observed to be only $\pm 0.4\%$ and for the correlation between $w_{opt(m)}$ and $w_{opt(s)}$ the percentage error is observed to be $\pm 2.7\%$.

Keywords: Compaction, Fine-grained soil, Maximum dry unit weight, Optimum water content, Correlation

Introduction

Densification is a tool to improve the mechanical characteristics of soil for the various civil engineering projects. In the field, compaction is the best rapid method to improve the unit weight, strength, permeability and compressibility of soil during the construction by removing the air voids. Densification of soil through compaction depends upon the two factors, such as moisture content and compaction effort. A number of compaction tests are established to determine the unit weight of soil in the field and laboratory. In the laboratory, modified compaction test (MCT) and standard compaction test (SCT)

are two major tests which are used to find out the compaction parameters i.e. maximum dry unit weight (γ_{dmax}) and optimum water content (w_{opt}). Standard compaction parameters are used for the light-weight infrastructures, and modified compaction parameters are used for the heavy-weight infrastructures. The compaction parameters obtained from different tests have a great significance for the ground improvement and are also used to satisfy the relative compaction requirements as per project specifications. However, the laboratory compaction tests require considerable time and effort. Therefore, to minimize the effort and to save the time, many researchers have proposed the regression models to predict the compaction parameters based on the physical properties of soils. Among them, these studies [1–16] are the most significant. The maximum dry density and optimum water content obtained depend on several soil parameters such as (a) the percent of fines, (b) specific gravity of soil solids (G_s), (c) amount of fine-grained soils, (d) liquid limit and plasticity index, (e) grain size distribution and shape factor of grains in the case of granular soils, and (f) compaction effort imported to the soil [17]. Blotz et al. [1] proposed a model to estimate the maximum dry unit weight (γ_{dmax}) and optimum water content (w_{opt}) of fine-grained soils (FGS) at any compaction effort (CE) based on the liquid limit (w_L) of the soils. Gurtug and Sridharan [2], Sridharan and Nagaraj [4] and Nagaraj et al. [18] discussed the dependence of standard compaction parameters ($w_{opt(s)}$ and $\gamma_{dmax(s)}$) on the plastic limit and also discussed the relationship among them. Omar et al. [17] worked on the sandy soils of UAE and tested the three hundred and fifty sandy soils in the laboratory. The models for compaction parameters proposed by Omar et al. [17] depended upon the three independent parameters such as liquid limit, specific gravity (G_s) and retention on sieve no. 04. However, their proposed model was only applicable for the modified compaction parameters ($w_{opt(m)}$ and $\gamma_{dmax(m)}$). Gurtug and Sridharan [3] proposed a model for the approximation of compaction parameters of cohesive soils with respect to compaction effort and plastic limit. Matteo et al. [6] developed a model to predict the compaction parameters of the modified compaction test by using the three independent variables liquid limit, plasticity index and specific gravity. Noor et al. [8] also established a model to predict the standard compaction characteristics of fine-grained soils with three variables such as plastic limit, plasticity index and specific gravity. Mujtaba et al. [9] collected 110 samples of sandy soils and developed the correlations of compaction parameters with uniformity coefficient (C_u) and compaction effort and validated these correlations by using the results of 40 similar samples. Moreover, modest efforts have also been made to apprehend the effect of plasticity on compaction parameters of the fine grained soils. Laskar and Kumar [19] discussed the effect of plasticity index on the optimum water content. Plasticity index and optimum water content were found to be directly proportional to each other [19]. In addition, further detailed discussions are required to briefly apprehend the effect of the plasticity of the fine-grained soil on compaction parameters based on the variety of fine-grained soils.

Many researchers have developed the models to predict the compaction parameters for both MCT and SCT with index properties as discussed in the above section. However, the modest efforts have been made to correlate the compaction parameters obtained from SCT and MCT with each other. Such correlations are proved to be very helpful in reducing the time and compaction effort, as the compaction effort required for one trial of MCT and SCT is 2700 kN-m/m³ and 600 kN-m/m³ respectively. It renders

that the compaction effort required for MCT is 4.5 times higher than SCT. Rabaiotti et al. [7], and Mujtaba et al. [10] have focused in this area of research for coarse-grained soils. During the revision of the Swiss standard “SN 670 330 b” for Swiss Federal Institute of technology, Rabaiotti et al. [7] collected coarse-grained soil samples and performed MCT and SCT on them. Based on the test results, a correlation was developed to predict the density for different types of coarse-grained soils as given in Eq. 1.

$$\eta = \frac{\text{Dry density according to AASHTO standard}}{\text{Dry density according to AASHTO modified}} \quad (1)$$

The value of η was proposed to be 0.93 to 0.97 for different soils. Mujtaba et al. [10] tested 120 sandy samples and developed the bivariate correlations between modified compaction parameters and standard compaction parameters for different types of coarse-grained soils. The general form of these correlations is presented in Eqs. 2–3.

$$\gamma_{dmax(m)} \text{ (kN/m}^3\text{)} = \alpha \times \gamma_{dmax(s)} \quad (2)$$

$$w_{opt(m)} \text{ (\%)} = \beta \times w_{opt(s)} \quad (3)$$

The values of α and β for poorly graded sand (SP) were proposed to be 1.067 and 0.800, for poorly graded sand (SP-SM) with silt 1.072 and 0.804, for silty sand (SM) 1.062 and 1.054 and for well graded sand (SW/SW-SM) 0.785 and 0.787 respectively.

According to Farooq et al. [12], the maximum dry unit weight (γ_{dmax}) determined through the modified compaction test is 7–8% more than γ_{dmax} determined through the standard compaction test for the fine-grained soils. Whereas, the optimum water content (w_{opt}) determined through standard compaction test is 1.20–1.25 times more than that determined through modified compaction test. Humdani [20] performed laboratory compaction tests on fine-grained soil samples and proposed the correlations to predict the modified compaction parameters with the standard compaction parameters. These correlations are presented in Eqs. 4–5.

$$\gamma_{dmax(m)} \text{ (pcf)} = 0.02 \times (\gamma_{dmax(s)})^2 - 3.79 \times \gamma_{dmax(s)} + 293.4 \quad (4)$$

$$w_{opt(m)} \text{ (\%)} = -0.036 \times (w_{opt(s)})^2 + 1.754 \times w_{opt(s)} - 5.564 \quad (5)$$

However, these correlations were based on a small number of soil samples and only medium plastic fine grained soils were tested in this study. Moreover, not enough efforts have been made to correlate the standard compaction parameters ($\gamma_{dmax(s)}$ and $w_{opt(s)}$) with the modified compaction parameters ($\gamma_{dmax(m)}$ and $w_{opt(m)}$) for a variety of fine-grained soils. Whereas, the parameters obtained from both compaction tests are most widely used for the desirable densification of soil in the field. These tests are tedious and laborious, especially in the developing countries, where automatic types of compaction equipment are commonly unavailable at construction sites and in the geotechnical laboratories. Hence, for the quick prediction of compaction parameters based on one performed test, predictive models are required. Moreover, it is also very important to apprehend the effect of the plasticity of fine-grained soil on the compaction parameters

to have a quick idea of compaction parameters based on the plasticity of fine-grained soils. Therefore, the aims of the present study are to develop the relationship between modified compaction parameters and standard compaction parameters based on the variety of fine-grained soils and also to examine the effect of plasticity index on compaction parameters.

Materials and experimental program

For the present study, total 156 fine-grained samples were collected with different soil properties from the twenty districts of Pakistan as shown in Fig. 1. These were disturbed soil samples and were collected from 1 to 2 m depth below the ground surface. Out of 156 samples, test results of 126 soils were used to develop the correlations between the modified compaction parameters and standard compaction parameters, and test results of other 30 soils were used to validate the developed correlations. Following laboratory tests were performed to investigate the soil characteristics:

- Grain size distribution analysis (ASTM D-422 [21]).
- Atterberg’s limit test (ASTM D-4318-95A [22]).
- Specific gravity test (ASTM D-854 [23]).
- Soil classification (ASTM D-2487 [24]).

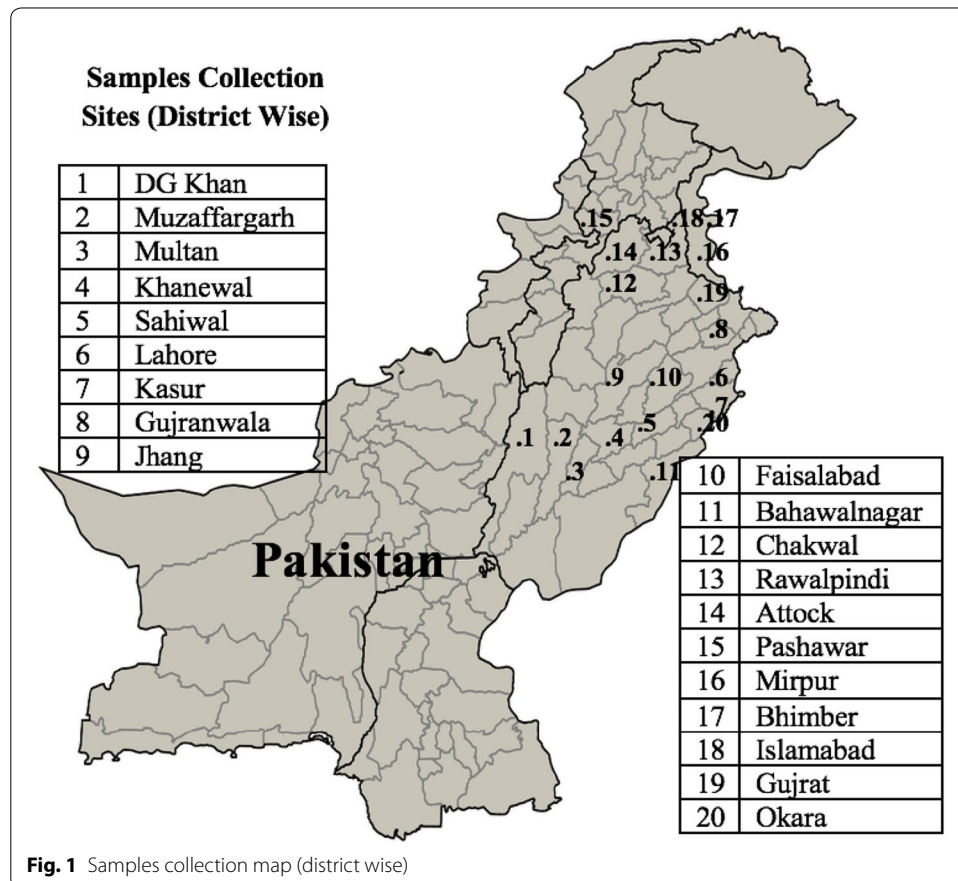


Fig. 1 Samples collection map (district wise)

- Standard proctor compaction test (ASTM D-698 [25]).
- Modified proctor compaction test (ASTM D-1557 [26]).

The aforementioned tests were performed to determine the index properties and compaction parameters. The index properties were used to classify the samples according to Unified Soil Classification System (ASTM D-2487) and these samples were classified as low plastic silt (ML), silty clay (ML), lean clay (CL) and fat clay (CH). Hence, a variety of fine-grained soils, with a wide range of plasticity and grain size were tested in the present study. Compaction tests results were utilized to develop the predictive models. Test results are summarized in Table 1.

Test results

According to grain-size distribution results, all the collected soil samples were classified as the fine-grained soils and percentages of gravels, sand, silt and clay fractions fell in the range of 0–24%, 0–50%, 42–90% and 0–57% respectively. Atterberg's limit test results are presented in Fig. 2 and liquid limit (w_L) and plasticity index (I_p) of soil samples were 15% to 78% and non-plastic (N.P.) to 60% respectively. But overall ranges of w_L and I_p were classified in to sub-ranges of ML, CL-ML, CL and CH soils. The ranges of w_L and I_p for the ML group were 15 to 29% and N.P.–5% respectively. The CL-ML samples had w_L between 19% to 28% and the I_p fell within 4% to 7%. The CL samples had the w_L and I_p in the ranges of 30% to 48% and 7.7% and 26.5% respectively and the ranges of w_L and I_p for CH were 52% to 78% and 27.5% to 60% respectively.

Figure 3 presents the results of modified compaction tests. The modified compaction parameters, i.e., $\gamma_{dmax(m)}$ and $w_{opt(m)}$ were in the range of 16–20.4 kN/m³ and 8.4–16.6%, respectively. The ranges of $\gamma_{dmax(m)}$ were also further divided for each soil group, i.e., CL, ML, CL-ML and CH. The value of $\gamma_{dmax(m)}$ for CL samples varied between 16.6–20.4 kN/m³, for ML, between 17.8–20 kN/m³, for CL-ML and CH samples, it fell in the range of 18–20.4 kN/m³ and 16–18.3 kN/m³ respectively. The values of $w_{opt(m)}$ for CL, ML, CL-ML and CH were in the ranges of 9–16.6%, 8.4–13.5%, 8.4–13% and 12.8–16% respectively. The compaction curves of all samples for standard compaction test are shown in Fig. 4. The $\gamma_{dmax(s)}$ and $w_{opt(s)}$ were in the range of 13.5–19.5 kN/m³ and 10–26% respectively. The value of $\gamma_{dmax(s)}$ fell in the range of 14.3–18.8 kN/m³, 15.9–19.3 kN/m³, 16.3–19.5 kN/m³ and 13.5–16.7 kN/m³ for CL, ML, CL-ML and CH soils respectively. The CL samples had $w_{opt(s)}$ between 11–21.8%, while for the soil groups ML, CL-ML and CH, the value of $w_{opt(s)}$ was 10.5–19.9%, 10–18.9% and 14.5–25%, respectively.

Test results analysis and discussion

Effect of plasticity index on compaction parameters

Figures 5 and 7 show that at a given compaction effort, the plasticity of fine-grained soil had a definite impact on the compaction parameters (γ_{dmax} and w_{opt}) and compaction curve. For a subjected compaction effort, it was relatively easier to remove air voids for the low plastic fine-grained soil than the high plastic soil, because it had a low moisture content anyway, and had soft soil lumps, therefore, a tighter grain position was easily achieved for the given matrix. Thus, a high unit weight was achieved for the low-plastic fine grained soils, at a subjected compaction effort. Moreover, it can also be observed

Table 1 Summary of index properties and compaction parameters of 156 samples

Soil classification (ASTM D-2487 [24])	No. of samples	Grain size distribution (ASTM D-698 [21])			Atterberg's limit (ASTM D-4318 [22])	Sp. Gravity (ASTM D-854 [23])	Standard compaction (ASTM D-698 [25])		Modified compaction (ASTM D-1557 [26])		
		Gravel (%)	Sand (%)	Silt (%)			w_L (%)	I_p (%)	G_s	$w_{opt(s)}$ (%)	$\gamma_{dmax(s)}$ (kN/m ³)
CL	80	0-24	0-44	47-80	30-48	7.7-26.5	2.67-2.75	11.0-21.8	14.3-18.8	9-16.6	16.6-20.4
ML	33	0-12	3-46.1	58-90	15-29	N.P-5	2.55-2.76	10.5-19.9	15.9-19.3	8.4-13.5	17.8-20
CL-ML	26	0-18	4.0-50	53-83	19-28	4.0-7	2.60-2.78	10-18.9	16.3-19.5	8.4-13	18-20.4
CH	17	0	0-6	42-56	52-78	27.5-60	2.67-2.74	14.5-25	13.5-16.7	12.8-16	16-18.3
Overall range	156	0-24	0-50	42-90	15-78	N.P-60	2.55-2.78	10.0-26	13.5-19.7	8.4-16.6	16-20.4

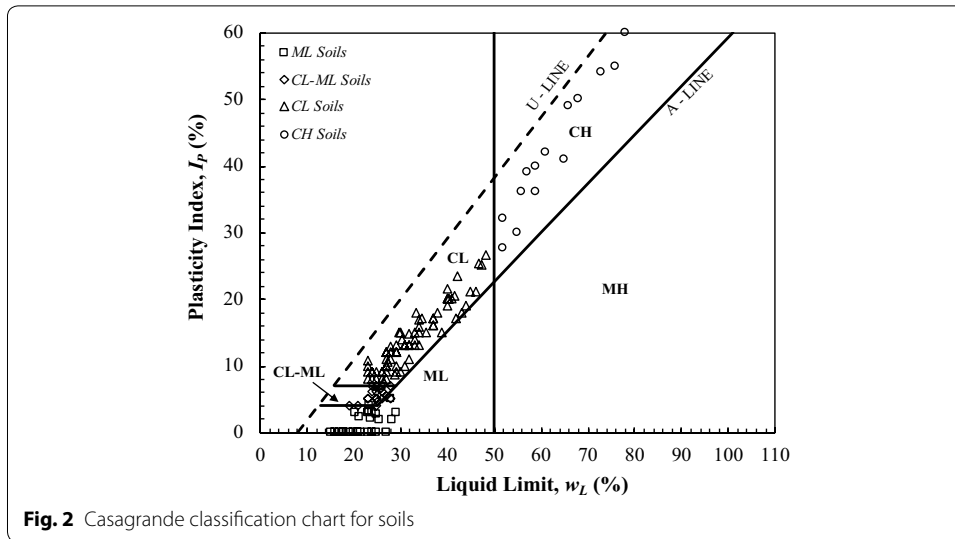


Fig. 2 Casagrande classification chart for soils

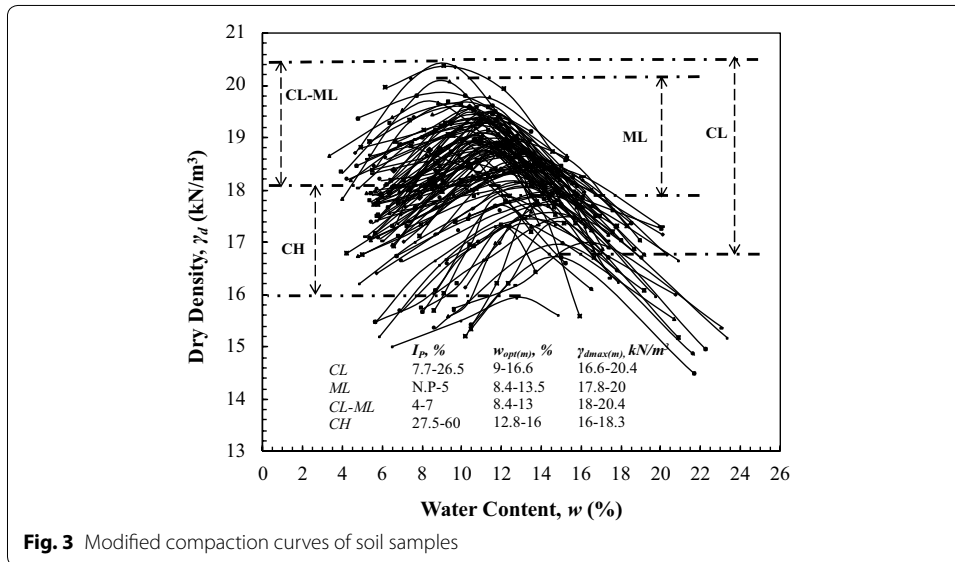


Fig. 3 Modified compaction curves of soil samples

that at a given compaction effort, the compaction curves were relatively flatter for the high plastic fine-grained soil than the low plastic fine-grained soil, because of its relatively higher water retaining capacity, which restrained the sudden drop down of water content after crossing the optimum water content, in comparison with the low plastic fine-grained soil (Figs. 3 and 4).

Statistical analysis was also done on the test data to quantify the effect of plasticity index (I_p) on compaction parameters of both MCT and SCT. The effect of I_p was observed on the different sub groups of fine-grained soils which were classified as per USCS. The average values of γ_{dmax} and w_{opt} of all the samples associated with a specific soil group were analyzed (Figs. 5 and 6) respectively. Figure 5 shows the variation of average values of $\gamma_{dmax(m)}$ and $\gamma_{dmax(s)}$ with average I_p -values of samples and these curves were divided into sub-soil groups. The values of γ_{dmax} for both MCT and

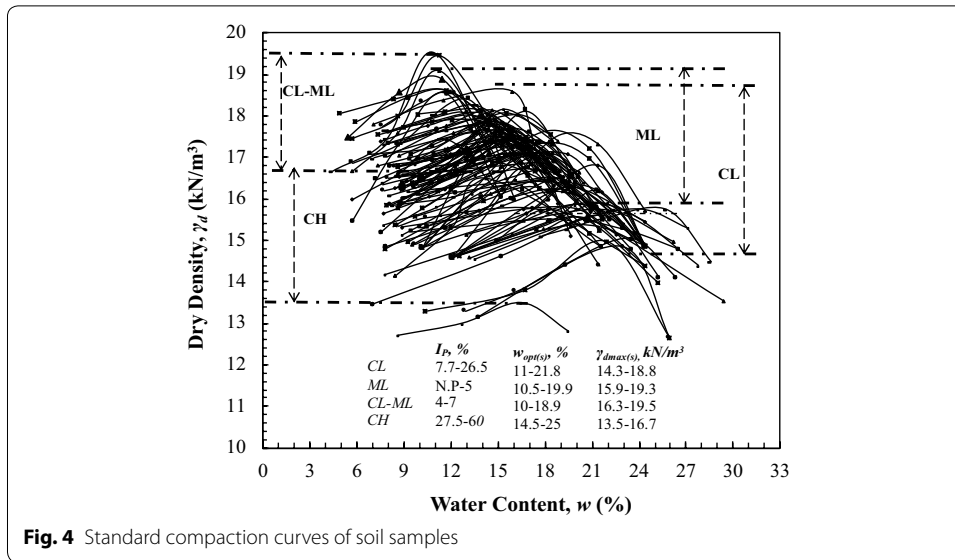


Fig. 4 Standard compaction curves of soil samples

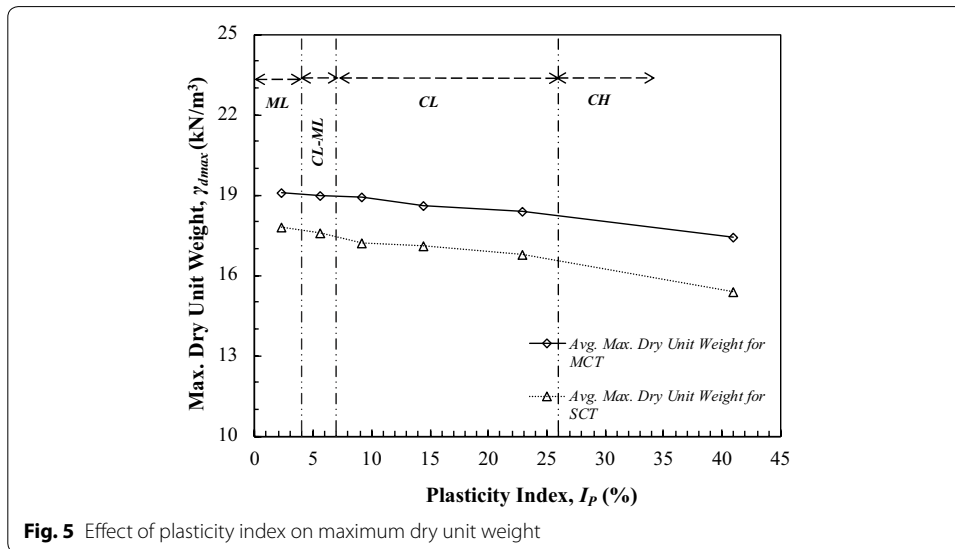


Fig. 5 Effect of plasticity index on maximum dry unit weight

SCT decreased with increasing the I_p -value. The values of $\gamma_{dmax(m)}$ and $\gamma_{dmax(s)}$ were 19.1 kN/m^3 and 17.8 kN/m^3 respectively at 2.3% of I_p -value and the values of $\gamma_{dmax(m)}$ and $\gamma_{dmax(s)}$ were 17.4 kN/m^3 and 15.4 kN/m^3 respectively at 41% of I_p -value which showed that the reduction in $\gamma_{dmax(m)}$ and $\gamma_{dmax(s)}$ were 8.9% and 13.5% respectively with the increment of 38.7% in plasticity index. Based on the results of compaction tests, value of $\gamma_{dmax(m)}$ was 7% more than the value of $\gamma_{dmax(s)}$ in the region of ML soils where the average value of plasticity was 2.3% and the differences between the values of $\gamma_{dmax(m)}$ and $\gamma_{dmax(s)}$ were 8.6% and 11.5% in the regions of CL and CH soils respectively. Value of $\gamma_{dmax(m)}$ was 7% to 11.5% more than the $\gamma_{dmax(s)}$ value with an increase in the value of I_p from 2.3% to 41% as presented in Fig. 5.

Effect of plasticity index on optimum water content (w_{opt}) can be observed in Fig. 6. Figure 6 is also divided into the different regions according to soil groups. The curves were

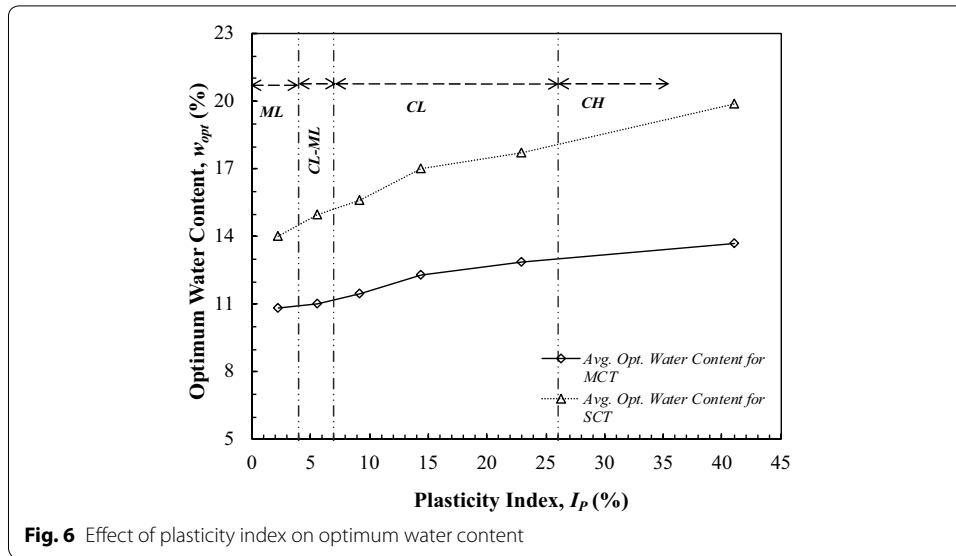


Fig. 6 Effect of plasticity index on optimum water content

drawn between the average values of I_p and average values of $w_{opt(m)}$ and $w_{opt(s)}$. The values of $w_{opt(m)}$ and $w_{opt(s)}$ increased with increasing the plasticity index. The values of $w_{opt(m)}$ and $w_{opt(s)}$ were 10.8% and 14% respectively at 2.3% of I_p -value and the values of $w_{opt(m)}$ and $w_{opt(s)}$ were 13.7% and 19.9% respectively at 41% of I_p -value, which showed that $w_{opt(m)}$ and $w_{opt(s)}$ values increased 21.2% and 29.6% respectively with the increment of 38.7% in the plasticity index. Based on the results of compaction tests, it can also be observed that w_{opt} of standard compaction test was more than the w_{opt} of modified compaction test and the difference between them increased with the increment of plasticity index. The value of $w_{opt(m)}$ was 22.8% less than the value of $w_{opt(s)}$ in the region of ML soils where the average value of plasticity was 2.3% and the difference between the $w_{opt(s)}$ and $w_{opt(m)}$ was 27% and 31.2% in the regions of CL and CH soils respectively. The $w_{opt(m)}$ value was 22.8% to 31.2% less than $w_{opt(s)}$ value with the increment in the value of I_p from 2.3% to 41%.

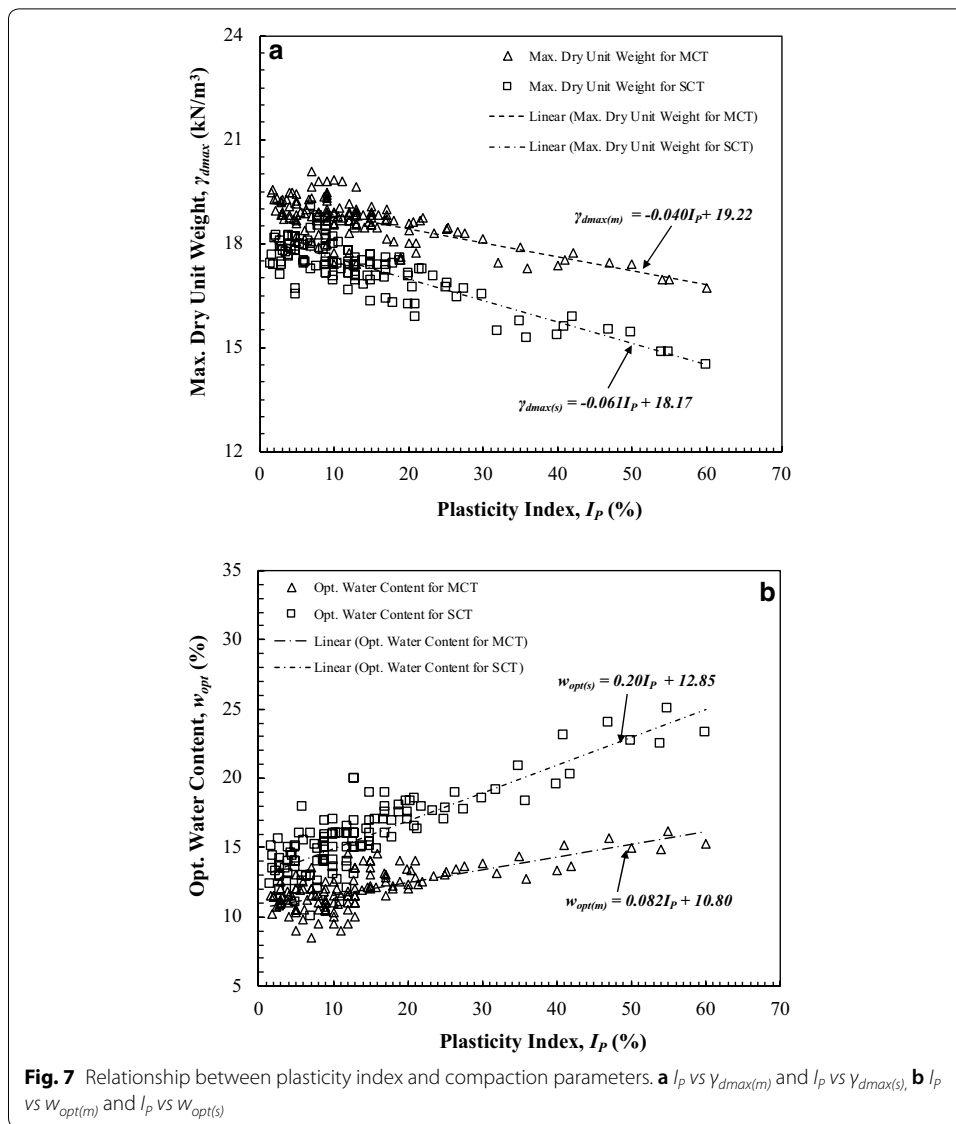
Relationships were also established between compaction parameters (γ_{dmax} and w_{opt}) obtained from different tests (SCT and MCT) and plasticity index based on the complete dataset (Fig. 7a, b). In general, the γ_{dmax} showed a decreasing trend with an increase in the plasticity, whereas, a vice versa trend was observed for the w_{opt} . Different mathematical equations were developed as follows, which can give a quick and brief idea of the response of the compaction parameters with the plasticity index of the fine-grained soils:

$$\gamma_{dmax(s)} \left(\frac{\text{kN}}{\text{m}^3} \right) = -0.061I_p + 18.17 \tag{6}$$

$$\gamma_{dmax(m)} \left(\frac{\text{kN}}{\text{m}^3} \right) = -0.40I_p + 19.22 \tag{7}$$

$$w_{opt(s)} (\%) = 0.20I_p + 12.85 \tag{8}$$

$$w_{opt(m)} (\%) = 0.082I_p + 10.80 \tag{9}$$



It can be inferred from the above analysis that plasticity of the soils has a significant impact on the compaction characteristics. Plasticity index increases with the increment of clay mineral which causes the enhancement of specific surface area and interaction between soil grains. To break this interaction and move soil grains relative to each other, more water is required, which tends to cause increase in the w_{opt} of soil. Clay minerals form a gel due to the increase in water content of the soil that is called double diffused layer, which causes the enlargement of the size of voids between the soil particles. This phenomenon tends to decrease the dry density of soils.

Development of correlations between MCT and SCT parameters

This research is carried out to develop the predictive correlation models of modified compaction parameters ($\gamma_{dmax(m)}$ and $w_{opt(m)}$) based on standard compaction parameters ($\gamma_{dmax(s)}$ and $w_{opt(s)}$). The $\gamma_{dmax(s)}$ and $w_{opt(s)}$ were treated as independent variables

Table 2 Correlations of modified compaction parameters ($w_{opt(m)}$ and $\gamma_{dmax(m)}$) with standard compaction parameters ($w_{opt(s)}$ and $\gamma_{dmax(s)}$)

FGS type	Model	R ²	Model	R ²
ML	$w_{opt(m)} = 0.4447w_{opt(s)} + 4.49$	0.78	$\gamma_{dmax(m)} = 0.5951\gamma_{dmax(s)} + 8.56$	0.78
CL-ML	$w_{opt(m)} = 0.4972w_{opt(s)} + 3.67$	0.94	$\gamma_{dmax(m)} = 0.7363\gamma_{dmax(s)} + 6.04$	0.98
CL	$w_{opt(m)} = 0.488w_{opt(s)} + 3.95$	0.91	$\gamma_{dmax(m)} = 0.7335\gamma_{dmax(s)} + 6.124$	0.91
CH	$w_{opt(m)} = 0.4724w_{opt(s)} + 4.28$	0.93	$\gamma_{dmax(m)} = 0.7233\gamma_{dmax(s)} + 6.25$	0.99
Combined model of FGS	$w_{opt(m)} = 0.4901w_{opt(s)} + 3.87$	0.94	$\gamma_{dmax(m)} = 0.716\gamma_{dmax(s)} + 6.36$	0.94

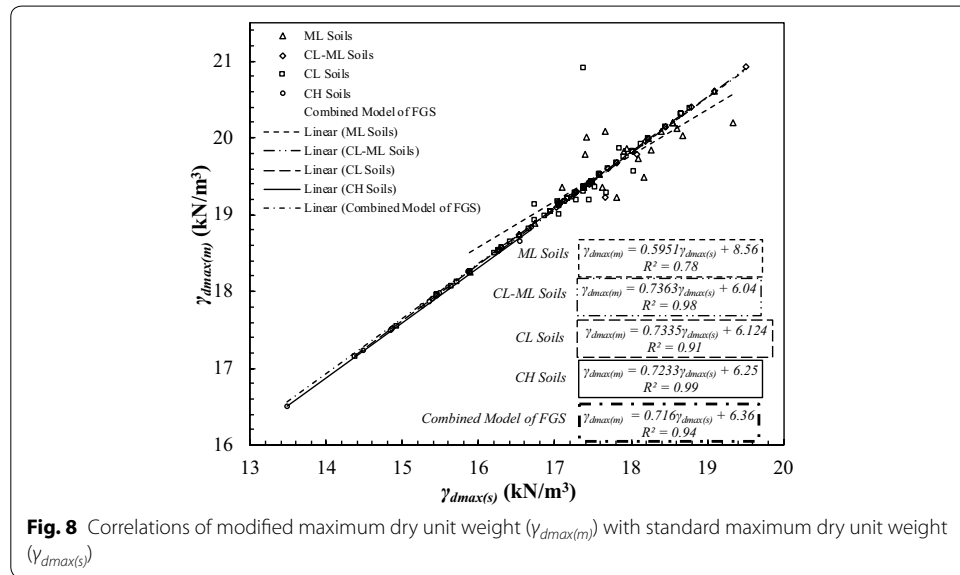


Fig. 8 Correlations of modified maximum dry unit weight ($\gamma_{dmax(m)}$) with standard maximum dry unit weight ($\gamma_{dmax(s)}$)

and the $\gamma_{dmax(m)}$ and $w_{opt(m)}$ were used as dependent variables in these correlations. Fine-grained soil samples were divided into different sub-groups as given in Table 1. The linear-regression analysis was executed on 126 samples to develop the correlations as presented in Table 2. Firstly, models were developed for the sub-groups of fine-grained soil to predict $\gamma_{dmax(m)}$ and $w_{opt(m)}$ based on $\gamma_{dmax(s)}$ and $w_{opt(s)}$ respectively and then combined models were established between modified compaction parameters and standard compaction parameters for wide range of fine-grained soils as presented in Figs. 8 and 9.

A good and reliable correlation must have a high value of correlation coefficient (R^2). The correlation coefficient (R^2) is an index of the goodness of fit between the predictive correlation and sample data used to develop that correlation. It provides a quantitative index of association between measured and predicted values and indicate the accuracy for the future predictions [9, 27]. For $\gamma_{dmax(m)}$ models, the value of R^2 varied from 0.78 to 0.99 and the R^2 value was 0.78 to 0.94 for $w_{opt(m)}$ models as shown in Figs. 8 and 9.

Figures 10 and 11 show the experimental vs predicted values of $\gamma_{dmax(m)}$ and $w_{opt(m)}$ respectively. Percentage deviation from 45⁰-line (called equality line), which is referred to as the percentage error of the predictive models was calculated by given formula;

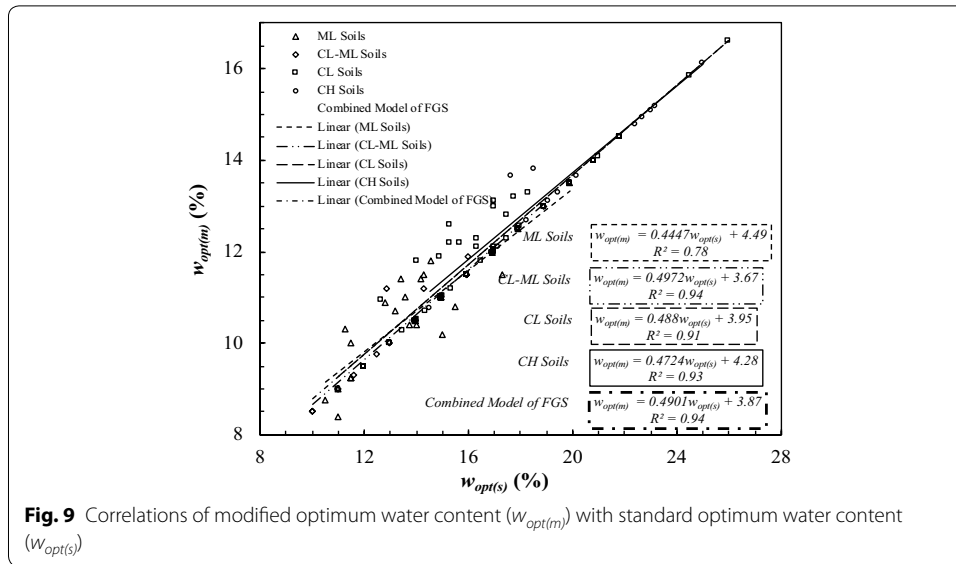


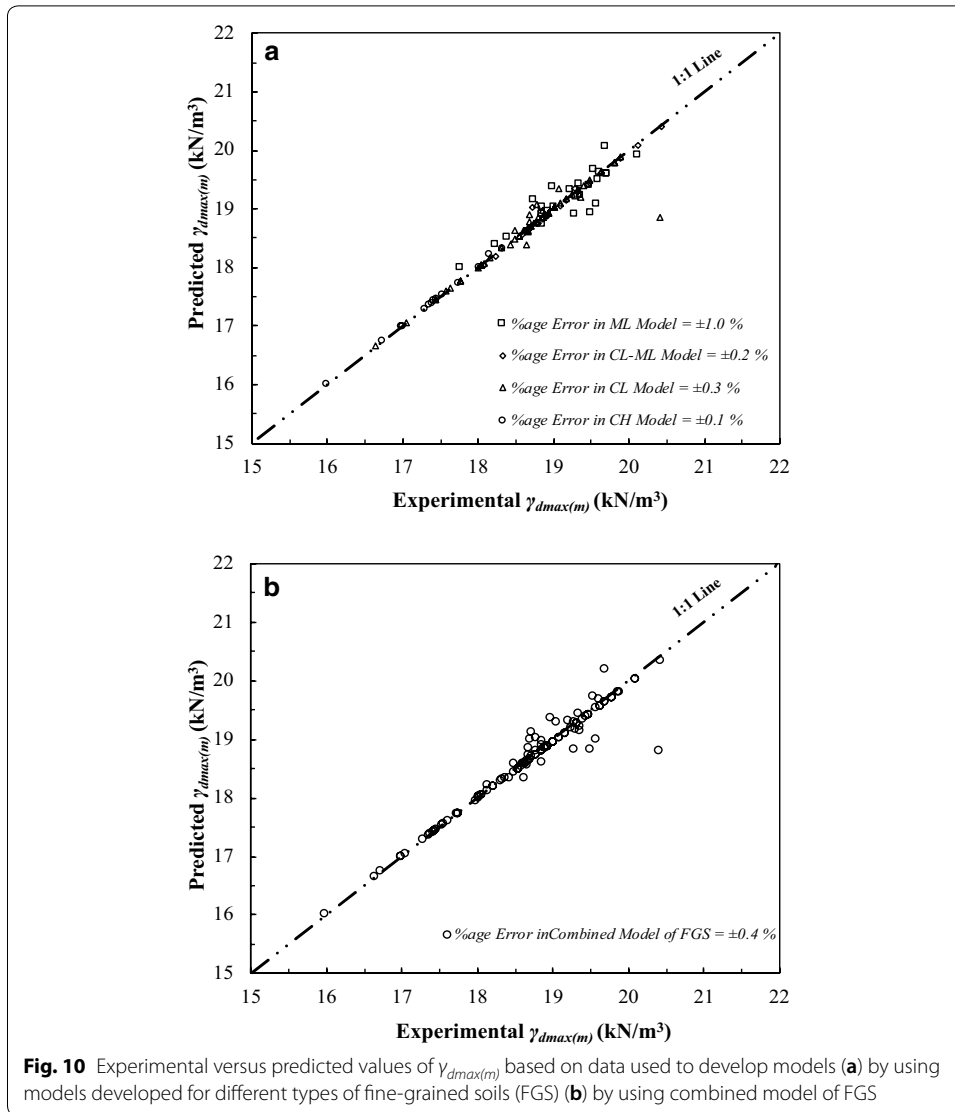
Fig. 9 Correlations of modified optimum water content ($w_{opt(m)}$) with standard optimum water content ($w_{opt(s)}$)

$$Error (\%) = \frac{100}{n} \sum_{t=1}^n \left(\frac{A_t - P_t}{A_t} \right) \tag{10}$$

where A_t =actual value, P_t =predicted value and n =number of values. Moreover, the percentage error of the model is calculated based on data used for the development of correlation, in this stage. For $\gamma_{dmax(m)}$, the percentage errors of ML, CL, CL-ML and CH models are about $\pm 1.0\%$, $\pm 0.3\%$, $\pm 0.2\%$ and $\pm 0.1\%$ respectively, as shown in Fig. 10a and the percentage error in the prediction by the combined model which applicable to all sub-groups of FGS is $\pm 0.4\%$ as presented in Fig. 10b. For $w_{opt(m)}$, the percentage errors of ML, CL, CL-ML and CH models are $\pm 4.4\%$, $\pm 2.5\%$, $\pm 1.7\%$ and $\pm 2.0\%$, respectively, as shown in Fig. 11a and the percentage error of the combined model is $\pm 2.6\%$ as presented in Fig. 11b. The average percentage error of $\gamma_{dmax(m)}$ is about $\pm 0.4\%$ of sub-group models which is equal to combined model of FGS. Similarly, the average percentage error of $w_{opt(m)}$ is $\pm 2.65\%$ which is almost equal to the combined model of FGS. Hence, the combined models can reasonably be applicable to predict the compaction parameters for all type of FGS instead of sub-group models.

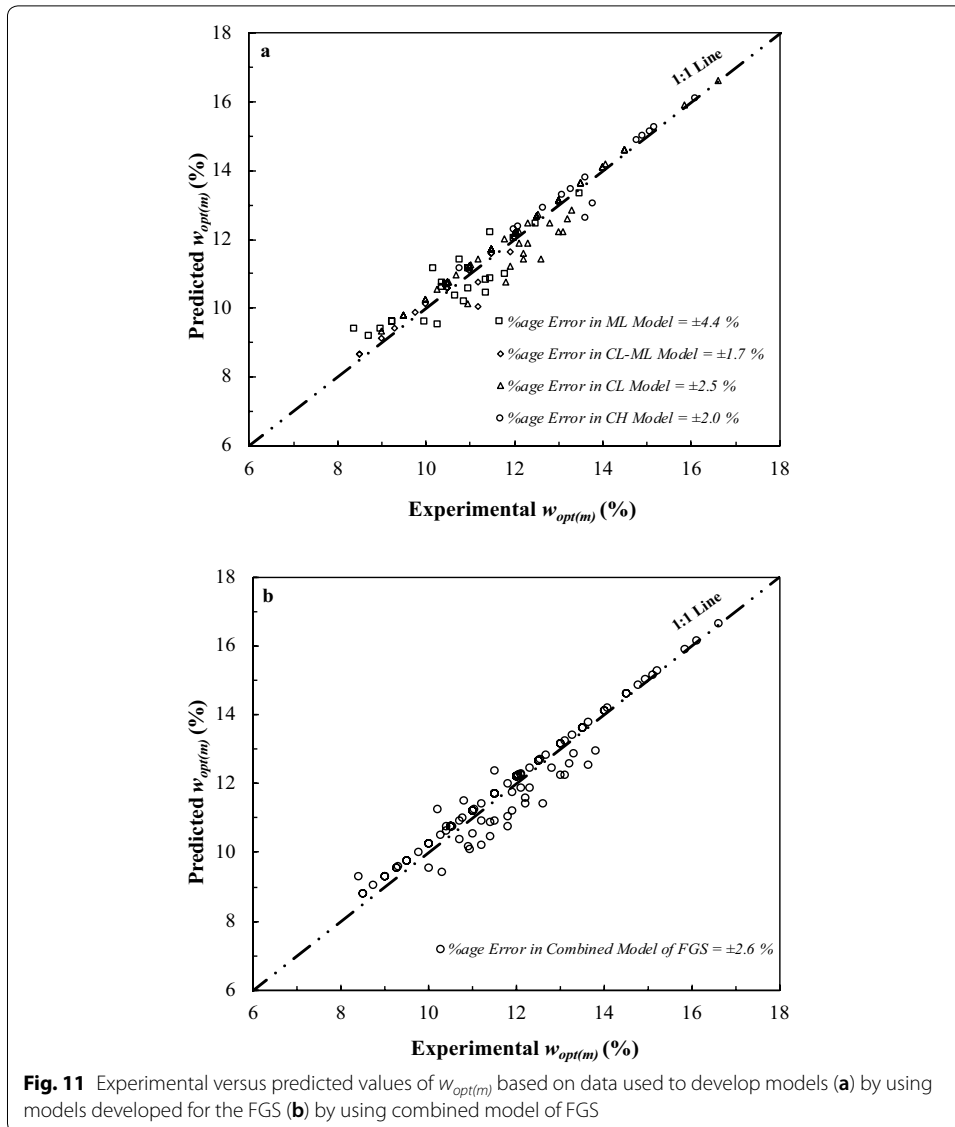
Validation of correlations

Validation of any developed model with an independent data is the most important part to check the effectiveness of the model. For this step, the dataset of 30 samples was used. Figures 12 and 13 presented the graphs between experimental vs predicted values of modified compaction parameters ($\gamma_{dmax(m)}$ and $w_{opt(m)}$). In the Figs. 12 and 13, the accuracy of the different combined models is compared with the accuracy Humdani [20] model. To compare the accuracy of the models, the $\pm 0.4\%$ standardize error envelope is drawn in Fig. 12 for $\gamma_{dmax(m)}$ and for $w_{opt(m)}$, standardized error envelope of $\pm 2.6\%$ is drawn in Fig. 13. These standardize error envelop values are taken as the parentage error



in the models based on data used to develop the correlation, as determined in the previous section.

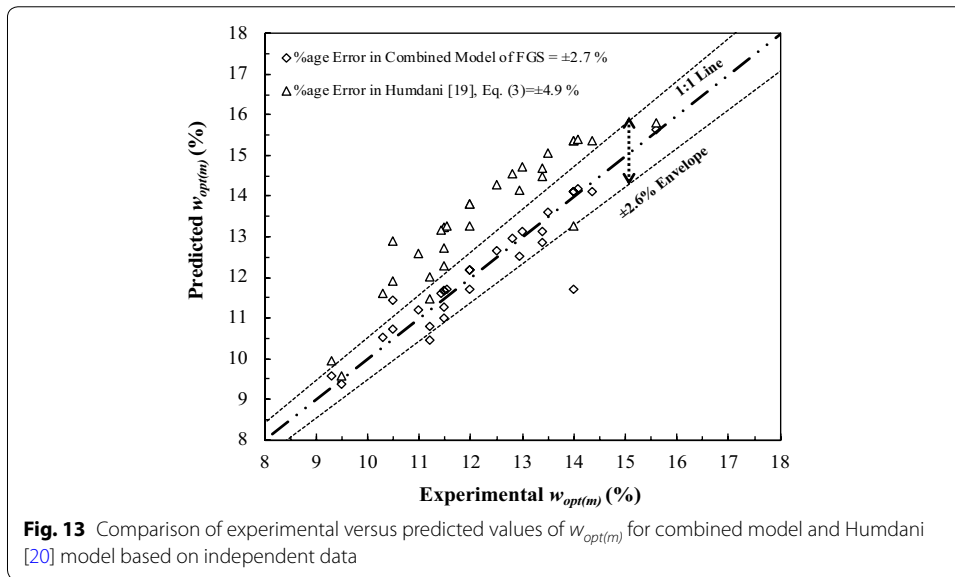
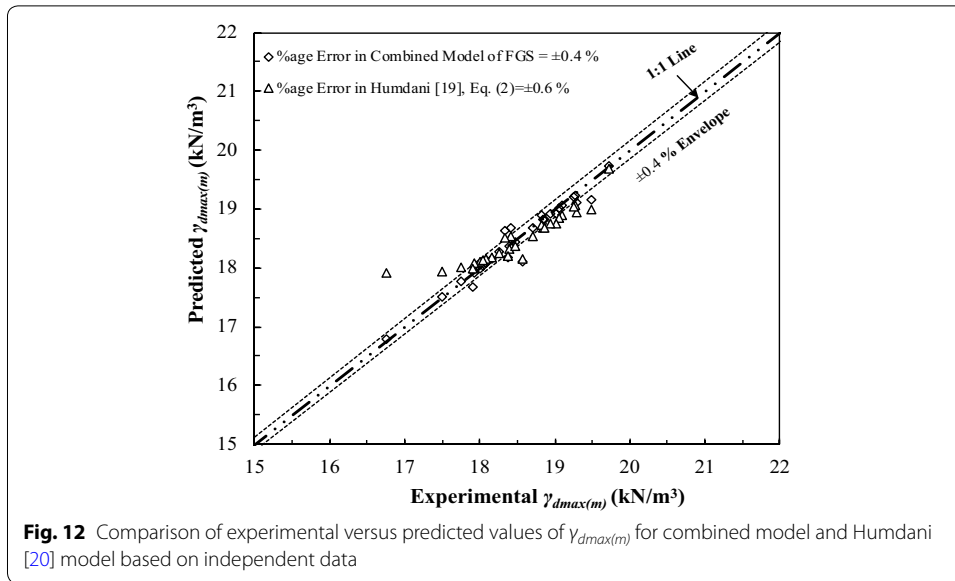
Percentage error in Humdani [20] model is about $\pm 0.6\%$ for $\gamma_{dmax(m)}$ and 6 out of 30 points fell outside the standardized envelope as shown in Fig. 12. The error in the developed combined model of $\gamma_{dmax(m)}$ was $\pm 0.4\%$ which is less than the Humdani [20] model and only one data point is out of the $\pm 0.4\%$ envelope. For $w_{opt(m)}$, the percentage error in Humdani [20] model is around $\pm 4.9\%$ and out of 30 data points, 22 points are failed to remain in the standardized envelope of $\pm 2.6\%$. On the other hand, the percentage error in the combined model of $w_{opt(m)}$ is $\pm 2.7\%$, which is almost equal to percentage error of standardized envelope and only one point fell out of the error envelope (Fig. 13). Humdani [20] model is found to be less reliable for the locally available fine-grained soils especially for $w_{opt(m)}$ as compared with the developed models of the present study. Such validity rendered that model reliability can be enhanced by widening the range of sample characteristics.



Conclusions

This study presents the correlations to predict the modified compaction parameters ($\gamma_{dmax(m)}$ and $w_{opt(m)}$) on the basis of standard compaction parameters ($\gamma_{dmax(s)}$ and $w_{opt(s)}$). The effect of the change in the plasticity index on the maximum dry unit weight and optimum water content is also discussed. The following conclusions are made on the basis of the aforementioned discussion:

- 1 Based on the results of the compaction tests using standard and modified efforts, the $\gamma_{dmax(m)}$ is almost 7% to 11.5% more than $\gamma_{dmax(s)}$ and the $w_{opt(s)}$ is 22.8% to 31.8% more than $w_{opt(m)}$ for the fine-grained soil.
- 2 Quantitatively, with an increase in the plasticity index (I_p) of fine-grained soils from 2.3% to 41%, the $\gamma_{dmax(m)}$ and $\gamma_{dmax(s)}$ are almost decreased from 20.4 kN/m³ to 16 kN/m³ and 19.5 kN/m³ to 13.5 kN/m³ respectively. Similarly, $w_{opt(m)}$ and $w_{opt(s)}$ are almost increased from 8.4% to 16.6% and 10% to 25%, respectively.



- 3 A correlation is established to predict the modified maximum dry unit weight ($\gamma_{dmax(m)}$) by using standard maximum dry unit weight ($\gamma_{dmax(s)}$) as the independent variable for the fine-grained soil: $\gamma_{dmax(m)} = 0.716\gamma_{dmax(s)} + 6.36$. This correlation has a reliable value of correlation coefficient (R^2) and has percentage error of around $\pm 0.4\%$, which indicate the good accuracy of the model.
- 4 A correlation is also developed to predict the modified optimum water content ($w_{opt(m)}$) by using standard optimum water content ($w_{opt(s)}$) as the independent variable for fine-grained soils: $w_{opt(m)} = 0.4901w_{opt(s)} + 3.87$. This correlation has a reliable value of R^2 and has only $\pm 2.7\%$ error in the predictive values.
- 5 The proposed correlation models are valid for fine-grained soils, having $\gamma_{dmax(s)}$ and $w_{opt(s)}$ up to 19.5 kN/m^3 and 25% respectively.

Authors' contributions

UK designed and executed the laboratory test plan, developed the empirical models, and drafted the manuscript. ZR analysed the test results, checked the validity of empirical models and presented the discussion along with illustrative examples in the manuscript. Both authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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