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Study on Compaction Characteristics of Fine-Grained Soil

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Abstract. Compaction is the process by which mechanical energy is used to bring the densification and stabilization of the soil matrix giving the soil enough strength. The compaction characteristics can be obtained by performing Proctor Tests with varying compactive efforts. The fruitful compaction of soil is imperative towards the stability and function of structures. It is observed through different literature works that the existing relationships between compaction characteristics and physical properties of fine-grained soil, like plastic limit, have not been palatable as the plastic limit obtained from the conventional thread rolling method is prone to human error. So, an endeavor has been made to develop relations relating optimum moisture content and maximum dry unit weight with plastic limit, determined by cone penetration method, which eliminates its inclination towards human error. It has been shown in previous works that the 3.92 N-30° cone can be used to determine the plastic limit of soil. These relationships with the plastic limit have been found to relate very well with the optimum moisture content and maximum dry unit weight. Moreover, an effort has been made in this work to develop correlations between maximum dry unit weight and optimum moisture content with different compaction energy and other physical properties such as plastic limit, plasticity index, and degree of saturation at the maximum dry unit weight.

Keywords: Fine-grained soils, Compaction, Plastic limit, Correlations, Compaction energy

1 Introduction

Compaction of the soil gives the soil enough strength by filling up its voids and attaining a much denser state. The water content - dry density relationship of fine-grained soils obtained from the laboratory tests forms the basis for specification and control of field compaction. In large projects like road constructions, wide variation in compacted unit weight may result, under the same compactive effort, mainly due to the large variation in the type of borrowed material used for filling. Hence it is very difficult to obtain reliable information on compaction characteristics from limited test results. At the same time, the Standard Proctor Test is time-consuming, costly, and laborious.

Hence more thrust is given to determining Optimum Moisture Content (OMC) and Maximum Dry Unit Weight (MDUW) through correlations with the index properties of soils.

Jumikis (1946) first related compaction characteristics with the index properties of soils. Various research workers after Jumikies attempted to correlate compaction characteristics with liquid limit, plastic limit, and other index properties of soils. It is reported in the literature that the optimum moisture content has a considerably good correlation with the plastic limit in comparison with the liquid limit (Leroueil et al., 1992; Howell et al., 1997). Few researchers have attempted to compare compaction characteristics with plastic limit (Gurtug and Sridharan, 2002; Sridharan and Nagaraj, 2005). Sivrikaya et al. (2008), Prasanna H.S. (2017), and Di Matteo et al. (2009) attempted to develop a multi-linear regression model correlating the compaction characteristics with various soil properties.

Furthermore, it has been observed in the literature that many of the existing relationships between compaction characteristics and physical properties of fine-grained soil, such as the plastic limit, have not been satisfactory because the plastic limit, which is obtained from the conventional thread rolling method, is prone to human error. The Casagrande thread rolling method of determining the plastic limit of soils, according to Ballard and Weeks (1963), is prone to human error. This could be one of the reasons why the correlation of compaction characteristics with plastic limit is not always a good one. In this paper, an attempt is made to correlate the plastic limit determined by the cone penetration method (Sharma and Bora (2003) and Sharma and Bora (2004) with the compaction characteristics of soils. It is also attempted to relate maximum dry unit weight and optimum moisture content with different compaction energy and other physical properties such as plastic limit, plasticity index, and degree of saturation at the maximum dry unit weight.

2 Results and discussion

This study employs 35 natural soils from various locations in Assam, with liquid limits ranging from 27.8 percent to 72.25 percent and plastic limits ranging from 14.50 percent to 36.08 percent. Twelve sample data were generated in the laboratory for this work from the thirty-five samples; fifteen were taken from Sharma, B (2000), and eight from Sharma and Deka (2019). According to I.S. Code Standards, the soils were characterized by their physical properties and compaction characteristics. The degree of saturation (S_r) at the point of maximum dry unit weight and optimum moisture content were also determined. Table 1 summarizes the findings. The standard proctor effort was used to perform the compaction test on the thirty-five soils (IS-2720 Part-7-1980). The compaction test was also performed for the samples of Sharma and Deka (2019) for the reduced standard proctor effort, modified standard proctor effort, and reduced modified standard proctor effort. Data on soil compaction characteristics were obtained from Jyothirmayi et al. (2015), Gurtug & Sridharan (2004), Lim et al. (2014), Nagaraj et al. (2015), and Sridharan & Nagaraj (2005). The physical and compaction properties of the soil with varying compaction energy were also collected from Prasanna H.S.'s work, which included the Standard Proctor Test, Modified Proctor Test, Reduced Standard Proctor Test, and Reduced Modified Proctor Test (2017).

Table 1. Physical and compaction characteristics of soils.

Sl No.	Source	Liquid Limit (%)	Plastic Limit (%)	Specific Gravity	Maximum Dry Unit Weight (kN/m^3)	Optimum Moisture Content (%)	Degree Of Saturation at Maximum Dry Density (S_r)
1	Sharma. B (2000)	33.80	16.00	2.68	17.7	16	83.40
2		39.00	18.50	2.69	16.8	16	71.59
3		38.00	14.50	2.59	18.3	15.2	94.79
4		55.60	21.74	2.635	17	18.2	87.19
5		38.50	17.00	2.63	17.7	16	86.31
6		68.00	19.60	2.69	16.7	16.2	71.35
7		61.00	22.50	2.685	16.4	21.2	89.33
8		47.00	20.60	2.64	17.2	18.6	91.04
9		69.00	24.00	2.72	16.4	21.5	88.80
10		49.60	18.28	2.67	17.3	17	83.08
11		55.20	20.38	2.71	17.2	17.4	81.98
12		50.10	23.14	2.63	16.3	19.8	84.88
13		54.80	22.93	2.72	16.3	20	80.73
14		52.40	17.58	2.6	17.6	16.7	90.98
15		51.20	24.10	2.69	16.2	21	85.53
16	Generated data	68.18	34.43	2.65	14.6	30	96.46
17		63.58	36.08	2.69	14.5	31	70.97
18		38.74	24.32	2.65	16	21	91.50
19		32.43	17.08	2.61	17.9	13	70.50
20		48.85	27.20	2.62	15.8	22	88.70
21		58.5	18.91	2.63	16.10	16.87	74.98
22		27.8	22.2	2.6	16.96	19.62	84.87
23		34.64	27.5	2.64	14.18	25.15	76.92
24		45.43	19.6	2.78	17.57	17.53	86.75
25		33.02	19.62	2.79	16.19	18.00	80.91
26		37.71	26.58	2.81	15.73	23.96	88.47
27		58.05	17.04	2.72	17.02	14.84	77.30
28	Sharma and Deka (2019)	36.51	26.25	2.83	14.35	29.95	91.94
29		45.56	19.13	2.63	16.12	18.64	79.01
30		30.18	23.27	2.8	15.95	22.22	85.96
31		57.40	16.36	2.65	17.23	15.45	82.32
32		72.25	18.84	2.75	16.97	17.46	82.16
33		78.62	20.12	2.77	16.51	18.61	82.20
34		39.53	17.68	2.73	16.66	17.59	80.15
35		48.81	18.28	2.72	16.42	18.57	80.01

Fig. 1. shows a plot of the maximum dry unit weight versus the plastic limit of soils determined by the thread rolling method for the thirty-five natural soils used in this study, as well as data from the literature (Jyothirmayi et al. (2015); Gurtug & Sridharan (2004); Lim et al. (2014); Nagaraj et al. (2014); Sridharan & Nagaraj (2005)).

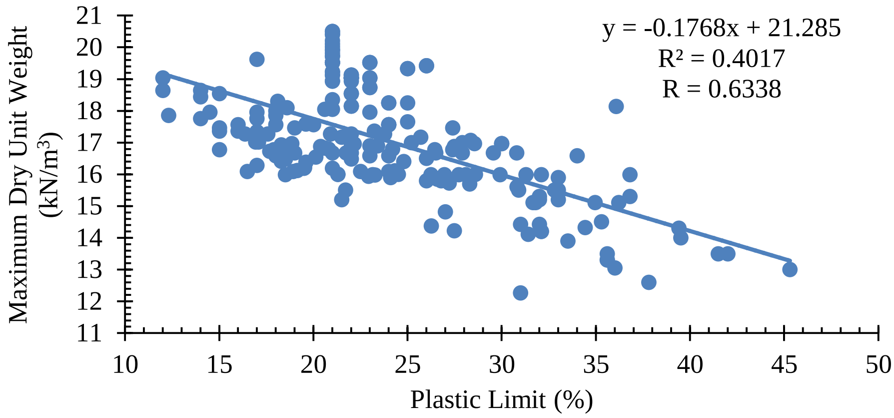

Fig. 1. Variation of Maximum Dry Unit Weight with Plastic Limit

It is observed that there is a decreasing trend of Maximum Dry Unit Weight (MDUW) with increasing Plastic Limit (PL) of the soil. The correlation of MDUW with the PL is given by the following equation, with a correlation coefficient of 0.64.

$$MDUW = 21.7 - 0.02PL \tag{1}$$

where, MDUW is in kN/m^3

In literature, however, a good correlation exists between MDUW the PL. According to H.B. Nagaraj et al. (2015), the relation between MDUW and PL for natural soils is

$$MDUW = 20.82 - 0.17PL \tag{2}$$

where, MDUW is in kN/m^3
with a correlation coefficient of 0.9.

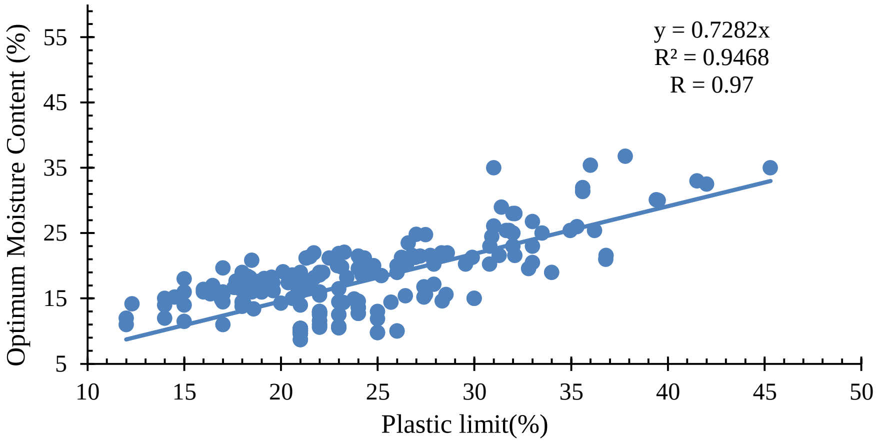

Fig. 2. Variation of Optimum Moisture Content with Plastic Limit

Fig. 2. shows the relation between the Optimum Moisture Content (OMC) and Plastic Limit (PL) of the soils. It is observed from the graph that the OMC is increasing with increasing PL. OMC is also correlating well with the PL of the soils as the correlation coefficient, R, comes out to be 0.97 with the intercept being taken as zero.

Correlation of the OMC with the PL, as seen in Fig. 2 is given by the following equation, with a correlation coefficient of 0.97

$$OMC = 0.73PL \tag{3}$$

It has been reported in literature that the correlation of the compaction characteristics with the PL is good. Sridharan and Nagaraj (2005) obtained the correlation of the OMC with the PL as

$$OMC = 0.92PL \tag{4}$$

with a correlation coefficient of 0.99.

The correlation equation between OMC and PL according to Nagaraj et al. (2015) is given by the following equation:

$$OMC = 0.76PL \tag{5}$$

The correlation coefficients in the three equations above are good but differ slightly. One important factor that can contribute to the different coefficients is the plastic limit of the soils. In the above equations, the plastic limit is used as a correlation parameter to predict the compaction characteristics of the natural soil as a whole. The plastic limit test (Atterberg's thread rolling method) is the standard test method for determining the plastic limit of soils in soil engineering practice. However, due to the human error associated with this standard test, various research workers have resorted to different methods, precisely the cone penetration method, to determine the plastic limit of soils. Such error in determining the plastic limit of the soil results in the various correlation coefficients, as shown in equations (3), (4), and (5) above. Low correlation coefficients in Fig.1 are also primarily attributable to this error. As a result, more research in this area is needed.

Sharma and Bora (2003, 2004) presented that the plastic limit could be determined using the 3.92 N-30° cone. Hansbo (1957) has shown that the penetration for a 0.98 N-30° cone is doubled by using a 3.92 N-30° cone, and the latter is thus recommended for the investigation of stiff clays. Sharma and Bora (2003, 2004) demonstrated that the undrained shear strength at the plastic limit is 100 times that at the liquid limit, and using the above cone, the water content corresponding to 4.4m penetration can be taken as the soil's plastic limit. Further research was conducted to overcome the error caused by the thread rolling method, and 15 additional samples were tested to determine their compaction characteristics. The soils' plastic limit was determined using the 3.92 N-30° cone, and the water content corresponding to 4.4m penetration was taken as the soils' plastic limit. Table 2 below summarizes the findings.

Table 2. Compaction Characteristics and Plastic limit as determined by the cone penetration method

Sl No.	Plastic Limit determined by cone penetration method	Maximum dry unit weight (kN/m^3)	Optimum moisture content (%)
1	16	1.77	16
2	17	1.768	16
3	19.6	1.67	16.2
4	18.5	1.68	16
5	14.5	1.83	15.2
6	22.5	1.64	21.2
7	20.6	1.715	18.6
8	24	1.64	21.5
9	18.28	1.725	17
10	20.38	1.72	17.4
11	23.14	1.63	19.8
12	22.93	1.625	20
13	17.58	1.76	16.7
14	24.1	1.62	21
15	21.74	1.7	18.2

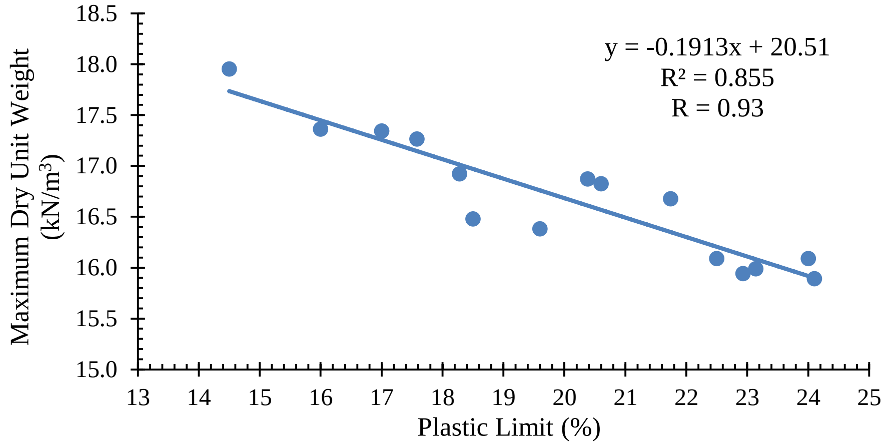

Fig. 3. Variation of Maximum Dry Unit Weight with Plastic Limit determined by Cone Penetration Method

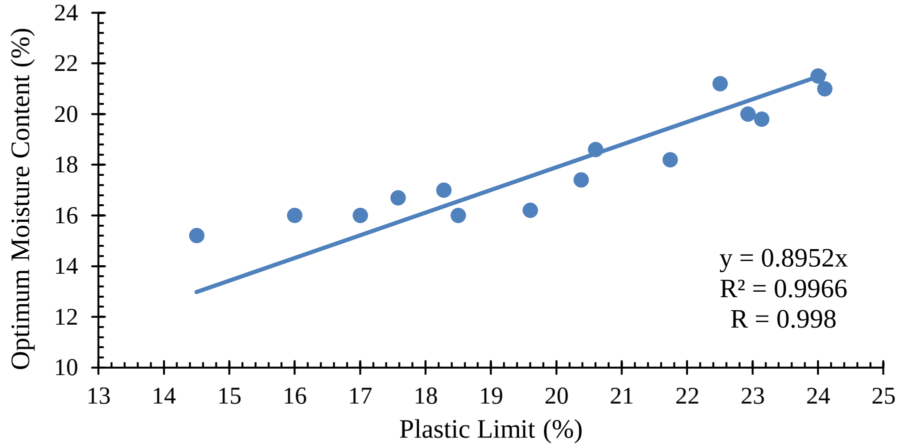

Fig. 4. Variation of Optimum Moisture Content with Plastic Limit determined by Cone Penetration Method

Fig. 3 shows the variation of MDUW with PL as determined by the cone penetration method. The correlation is given by the following equation, with a correlation coefficient of 0.93.

$$MDUW = 20.91 - 0.02PL \qquad (6)$$

This equation is again comparable with equation (2), as given by H.B. Nagaraj (2015) for natural soils.

The variation of OMC with the PL as determined by the cone penetration method is shown in Fig. 4. Correlation of the OMC with the PL is given by the following equation, with a correlation coefficient of 0.99.

$$OMC = 0.9PL \tag{7}$$

Equation (7) is now comparable with equation (4), as given by Sridharan and Nagaraj (2005).

Hence equations (6) and (7) indicate the improved correlations of MDUW and OMC with the plastic limit of the soils when the plastic limit is being determined using cone penetration method.

According to the literature, estimating MDUW using OMC obtained from the plastic limit is more reliable than directly relating MDUW to the plastic limit. Figure 5 shows a plot of experimentally determined MDUW versus OMC using data from Table 1. The figure shows that there is a strong correlation between the two compaction parameters.

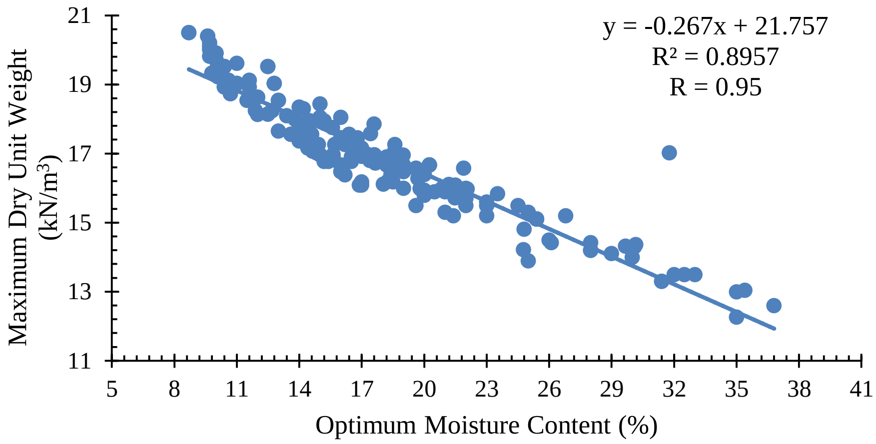

Fig. 5. Variation of Maximum Dry Density with Optimum Moisture Content.

The following expression gives the linear relation between the two compaction parameters with a correlation coefficient of 0.95.

$$MDUW = 21.7 - 0.27OMC \tag{8}$$

This work also attempted to correlate MDUW with different compaction energies. Through multiple regression analysis, the best correlation was observed when different compaction energies (E) were considered alongside other parameters such as plastic limit, plasticity index, and degree of saturation (S_r) at maximum dry unit weight. In this study, four distinct levels of compaction energies were used: Standard Proctor (E_s= 592.5 KJ/m3), Modified Proctor (E_m= 2703.88 KJ/m3), Reduced Standard Proctor (E_{rs}= 355.5 KJ/m3), and Reduced Modified Proctor (E_{rm}= 1622.33 KJ/m3). The degree of saturation at maximum dry unit weight (S_r) was found to vary approximately between 70% to 90% for the thirty-five samples shown in Table 1. Consequently, an average value of 80% has been used in the analysis.

The compaction characteristics at these four different energy levels, the physical properties, and the degree of saturation were taken from the works of Sharma and Deka (2019) and Prasanna H.S. (2017).

The correlation is obtained as –

$$MDUW = (9.97\times10^{-6})\,E + (-0.197)\,PL + (0.08)\,S_r + (0.008)\,PI + 13.88 \qquad (9)$$

with a correlation coefficient R of 0.96. For MDUW as a dependent parameter, it can be observed that there exists a good correlation when it is correlated with the parameters, viz. E, PL, PI, and S_r at MDUW.
The proposed equations will be a handy tool for quickly determining the suitability of fine-grained soils for compaction-related purposes at construction sites.

3 Conclusions

Correlations exist between compaction characteristics and the plastic limit of fine-grained inorganic soils. However, these correlations must be able to predict the compaction characteristics accurately and be rational. According to the findings of this study, the compaction characteristics, MDUW and OMC, can be accurately predicted using the soil's plastic limit (equations (6) and (7)) when the plastic limit is determined using the cone penetration method to eliminate human error. There also exists a working correlation between MDUW and OMC that can be used to predict MDUW from OMC (equation (8)). MDUW can also be expected at different compaction energies (equation (9)), which gives a good correlation of MDUW when correlated with parameters such as E, PL, PI, and S_r at MDUW.

Considering the time and effort needed to determine compaction characteristics from laboratory experiments, the proposed formulations presented here may significantly help practicing engineers.

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