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Simple Regression Models to Estimate the Standard and Modified Proctor Characteristics of Specific Compacted Fine-Grained Soils

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Abstract – This study is formed to obtain regression models both for the prediction of Standard compaction and Modified compaction characteristics of cohesive soils with the use of simple laboratory tests. For this purpose, a sequential research process has been performed considering both experimental applications and empirical prediction steps to interpret the relationship between the obtained optimum water content and maximum dry unit weight values of cohesive soils via the conducted standard proctor and modified proctor tests. The simple material characteristics of the soils have been obtained by performing sieve analysis and consistency limit tests. With an aim to relate the grain size characteristics and consistency parameters with both of the compaction test outputs two dimensional regression analyses have been conducted. In addition, the availability of Modified Proctor test results in terms of the Standard Proctor test were also investigated. Consequently, mathematical expressions have been achieved to determine both the compaction characteristics in terms of fine content ratio and liquid limit values and also the results of the Modified Proctor tests were obtained with high accuracy by the use of Standard Proctor tests.

***Keywords*:** Standard Proctor test (SP), Modified Proctor test (MP), compacted fine-grained soils, parameter prediction.

1. Introduction

Compaction is defined as a mechanical improvement technique that is applied to remoulded unsaturated soils and includes the increase of the soil unit weight by decreasing the volume of the air existing within the soil medium, without any apparent change in the water content [1]. This process is significantly prevalent in filling processes that were conducted during the construction of embankments, highways, retaining structures, airways and etc. The compaction behaviour characteristics are generally specified in terms of the soil type, the natural water content, and the maximum dry density. The value of the possessed maximum dry density of any type of soil can be achieved by performing laboratory compaction tests which can be applied in two different ways depending on the processed energy. Standard and especially Modified Proctor tests necessitate considerable effort, time, and experience to perform. Therefore, nowadays, the prediction of both standard and modified compaction characteristics with different methods in terms of easily applicable basic geotechnical tests continues to be an under research subject. Besides, the estimation of modified proctor testing outcomes from the results of the applied standard proctor tests is still investigated for different types of soils by various researchers. In this context, there are many studies conducted by evaluating current technological developments in order to estimate soil compaction parameters, especially in recent years. Gurtug and Sridharan (2002) presented a technical note to achieve the standard compaction test parameters of fine-grained soils with the use of plastic limit value [2]. Sivrikaya et al. (2013) have studied the prediction process of compaction parameters considering the energy for coarse-grained soils. The authors have used the genetic expression programming and multilinear regression analysis to derive expressions of the maximum dry unit weight and optimum water content that were achieved from both the Standard and Modified Proctor tests [3]. Mujtaba et al. (2013) have used 110 sandy soil samples to derive a predictive model in order to define the compaction behaviour. The authors have used the uniformity coefficient and the compaction energy as the input parameters of the multiple regression analysis to predict the maximum dry unit weight and optimum water content values [4]. Farooq et al. (2016) have investigated 105 fine-grained soil samples to obtain laboratory compaction parameters utilizing multiple regression analysis. The authors were focused on the liquid limit and plasticity index values as the input parameters of the regression studies [5]. Saikia et al. (2017)

presented regression models to estimate the compaction properties of fine-grained soils depending on their index properties. The study is gain in individuality through the attainment of the compaction properties by performing light compression tests depending on Indian Standards [6]. Karimpour-Fard et al. (2019) have used artificial neural networks and multilinear regression analysis to estimate the compaction characteristics of soils through the search of the influence of the results of geotechnical engineering laboratory tests such as sieve analysis, consistency limits, specific gravity [7]. Wand and Yin (2020) have used multi-expression programming as a tool to define the compaction parameters of a wide range of soils. The authors defended that the plastic limit and the fine content ratio have a more significant effect to determine the compaction parameters and the compaction energy can also be calculated depending on the necessitated values of compaction characteristics [8]. Kurnaz and Kaya (2020) have estimated compaction parameters of the selected soils from the literature with the use of four different soft computing methods considering the standard proctor test results [9]. Verma and Kumar (2020) reviewed the studies conducted considering the prediction process of compaction properties of soils till the last six decades and evaluated the used methods and the significance of the selected input parameters throughout the derivation process [10]. Consequently, the aforementioned studies establish several relationships to predict the maximum dry density and the optimum water content of the compacted soils considering especially the grain size characteristics, consistency limits, specific gravity values and energy effort performed during the tests. The significant challenge of the use of the mentioned expressions is that the relationships are generally derived for a specific localization or for the same geological structured soils. Therefore, the utilization of the suggested expressions for a field that is located outside of the identification area can lead to determining important differences between the real and computed compaction parameters. In this context, it is required to be suspicious while the use of the envisaged compaction parameters calculated by the use of empirical expressions or it will be a proper solution to derive an appropriate insight with the use of representative tests of the investigated field. In order to evaluate the second point of view, an estimation process was carried out by using the sieve analysis, consistency limits, standard proctor and modified proctor tests applied on the soil samples taken from the Boyalık district of Arnavutköy, Istanbul, within the scope of this study. Totally 105 soil samples have been used to define the characteristic properties of dominant soils existing in Boyalık locality considering sieve analysis, consistency limit tests, and both types of compaction tests. Based on the univariate regression analyses performed to obtain the compaction properties, satisfactory representative expressions have been achieved in terms of the consistency limits and fine content ratios. In addition, the results of modified proctor tests have been achieved via the outputs of standard proctor tests with an acceptable applicability ratio by controlling the coefficient of determination values.

2. Materials and Methods

The location of the Boyalık that has been investigated in the context of this study is given in Figure 1. Boyalık is a neighbourhood in the Arnavutköy district of Istanbul province and is adjacent to the new Istanbul airport. Depending on the site investigation program which was conducted at the site that to design a primary school, the relevant department of the Republic of Turkey Governorship of Istanbul performed 150 laboratory tests to define the characteristic properties of soils that were dominated in the field.

Figure 1. The map of Boyalık, Istanbul indicating the location of the foreseen soil samples

The laboratory testing program has included sieve analysis [11], consistency limit tests [12], the organic content specification, and both standard and modified proctor tests [13, 14]. In the context of this study, it is aimed to find some representative geotechnical parameter relations considering basic simple laboratory tests of geotechnical engineering discipline by utilizing the most known simple regression analyses. It is preferred to search the univariate parameter relations by Microsoft Excel software. The limited number of experiments in the actual data set created by the application of laboratory experiments enabled rapid analysis with many different parameter combinations. In this way, it has also been possible to investigate which parameters play a more effective role in defining compaction behaviour. Because the Proctor tests could be controlled with all possible parameter combinations and it was seen that there are four marginal data that distort the data distribution and create deviation. Accordingly, when the qualities of the mentioned four data were examined, it was seen that these data had relatively more granular content. By eliminating these 4 data that disrupts the data distribution network, the analyses have been reconstructed with a total of 11 data in two and three dimensions. The obtained properties of the mentioned 11 soils are given in Table 1. Data distribution visualizations were made with 11 data included in the evaluation, but no regression was made for parameter relationships that did not show a tendency to interpret compaction behaviour. Some novel terms and abbreviations have been used in this study to define special conditions. In this context, the maximum dry density and the optimum water content values that are obtained for standard and modified effort were defined by MDD_s, OMC_s, MDD_m, OMC_m respectively. The liquid limit, plastic limit, and plasticity index values were abbreviated by LL, PL, and Ip respectively. In addition, the fine content ratio obtained from the sieve analyses was abbreviated as No 200.

Table 1. The results of the conducted laboratory tests

Specimen	Sieve Analysis						Modified Proctor Test		Standard Proctor Test		Consistency Limits		
	3/4" (%)	3/8" (%)	No.4 (%)	No.10 (%)	No.40 (%)	No.200 (%)	OMC_m (%)	MDD_m (gr/cm³)	OMC_s (%)	MDD_s (gr/cm³)	LL (%)	PL (%)	I_p (%)
1	100	97.70	90.00	71.80	33.00	20.10	12.60	1.92	15.52	1.77	42	22	20
S 2	100	99.10	98.80	97.80	95.90	71.00	16.00	1.74	19.40	1.62	41	20	21
S 3	100	100.00	100.00	100.00	99.00	90.80	16.70	1.70	20.30	1.56	41	21	20
S 4	100	100.00	97.90	95.30	88.30	67.70	13.90	1.78	16.50	1.69	69	30	39
S 5	100	98.60	94.90	89.50	82.20	76.80	15.00	1.77	18.60	1.68	81	30	51
S 6	100	100.00	100.00	99.30	97.20	89.40	15.70	1.75	19.20	1.57	45	18	27
S 7	100	98.80	93.70	81.80	58.00	30.00	13.30	1.88	15.80	1.77	33	20	13
S 8	100	100.00	100.00	99.60	97.50	94.50	17.20	1.71	20.10	1.58	65	23	42
S 9	100	100.00	100.00	95.80	68.70	23.60	13.40	1.86	15.71	1.76	29	18	11
S 10	100	89.80	81.20	62.20	46.10	36.00	15.90	1.83	19.50	1.68	46	25	21
S 11	100	96.70	92.20	83.20	62.50	31.40	12.80	1.86	15.00	1.77	41	18	23

3. Results and Discussion

The laboratory test results have been interpreted by the use of regression analysis that can be counted as one of the popular methods in the geotechnical engineering discipline from last years. The univariate regression analysis can be defined as a simple analysis that presents a relationship between one dependent variable and the response variable [15]. Within this manner, in the context of this study, univariate regression analyses were conducted to predict the compaction parameters such as the maximum dry unit weight and the optimum water content. The dependent values are used individually as the liquid limit, plastic limit, plasticity index, and the fine content ratio of the soil. Totally 11 couples of standard and modified compaction tests have been used to form the univariate relations and several curve fitting options have been used as linear, polynomial, exponential, or logarithmical to obtain an appropriate expression of the evaluated relations. In Figure 2, the change of compaction characteristics with the achieved liquid limit values is given. Figure 2a and Figure 2c are related to the modified compaction tests however, Figure 2b and Figure 2d is related to the standard compaction tests. The evaluation criterion of the derived expressions has been assumed to be the coefficient of determination value that can be abbreviated by the R^2 term. Davis (1971) and Lewis (1982) have been defined the correlation strength depending on the coefficient of determination values [16, 17]. The R^2 values between 0.70-1.00 are assumed to be very strong, 0.50-0.69 are strong, 0.30-0.49 are moderate, 0.10-0.29 are weak and 0.01-0.09 are very weak. In Figure 2, the liquid limit values have tried to be associated with MDD and OMC values but it can be clearly seen that depending on the mentioned value ranges, the identified polynomial quadratic and cubic expressions could be classified as weak or moderate. Therefore, it will be appropriate to say that the usage of only liquid limit value can’t represent the compaction behavior of the considered type of special soils. A similar manner has been adopted for the case to investigate if there is a significant relationship between the compaction parameters and the plastic limit value. In Figure 3, the change of the compaction parameters is given depending on PL. In this situation, polynomial fitting options have given the biggest values of coefficient of determination values. If the strength of the achieved expressions has been controlled depending on the determined R^2 values, it can be true to classify the relation of PL vs compaction parameters as weak or very weak. Besides, in Figure 4, the change in MDD and OMC are evaluated depending on I_p values. The investigated relationships were obtained with the use of the polynomial regression quadratic option. The obtained R^2 values haven't been found satisfactory to be used to define the compaction parameters in terms of the plasticity index properties. The interpretation of Figure 2, Figure 3, and Figure 4 show that the consistency limit values cannot be individualistically used to determine the compaction parameters. Another step of this study is to investigate the compaction parameters by using grain size distribution relationships. Starting from this point, the fine content (No 200) ratios of the envisaged tests were taken into consideration in Figure 5 depending on the change of compaction characteristics. In Figure 5a, the change of OMC_m against the fine content ratio is given based on linear relation, in Figure 5b, the change of OMC_m against the fine content ratio is given based on polynomial relation with quadratic option. In terms of the determined R^2 values, it is possible to state the optimum moisture content value of the modified proctor test in terms of fine content with a linear regression relation depending on the slight difference between the R^2 values determined for polynomial and linear regression. In Figure 5c, the change of OMC_s against the fine content ratio is given based on logarithmic relation, in Figure 5d, the change of OMC_s against the fine content ratio is given based on linear relation. Similar to the modified test results, the optimum moisture content value of standard compaction parameters can be predicted in terms of fine content with a linear regression relation depending on the slight difference between the R^2 values determined for logarithmic and linear regression. The correlation strength values based on the calculated R^2 values of the defined relations can be classified as strong (0.50-0.69) [16, 17]. In the context of the study, the maximum dry density is predicted depending on the change of the fine content ratio too. In Figure 6a and Figure 6b, the change of the MDD values against No200 is given for modified compaction tests and in addition, in Figure 6c and Figure 6d the change of MDD values against No200 is given for standard compaction tests with different regression options. The obtained R^2 values are satisfactory and have a very strong correlation strength to be applied to predict the MDD values in terms of the fine content ratio with the utilization of linear regression relation. In addition to all these, univariate regression analyses have been also conducted to search for a proper relation between the modified proctor and standard proctor test results. In Figure 7a, MDD_m has been predicted in terms of MDD_S, and in Figure 7b, OMC_m has been predicted in terms of OMC_s. In this context, Equation 1 gives the opportunity to derive the maximum dry density value of the modified test in terms of the standard proctor test. Also, Equation 2 is derived to predict the optimum moisture content of the modified test in terms of the standard proctor test. The correlation strength of the related expressions has been achieved very strong and seemed to be applicable in geotechnical prediction processes.

$$MDD_m = -2.2926 x MDD_s + 55.522 \quad (1)$$

$$OMC_m = 0.7776 x OMC_s + 0.9437 \quad (2)$$

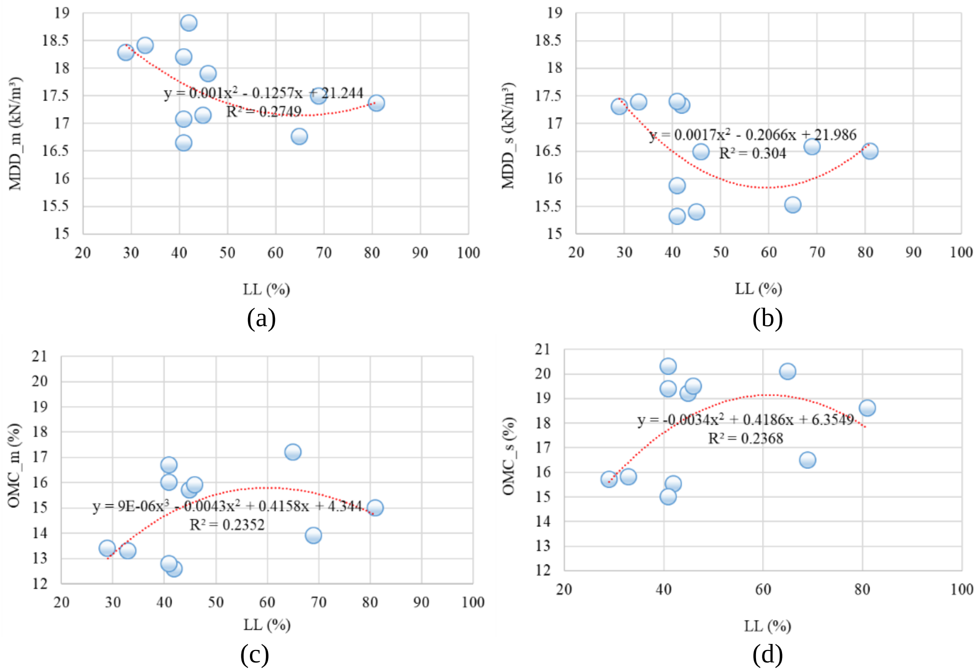

Figure 2. The change of compaction parameters against the liquid limit a) MDD_m and LL, b) MDD_s and LL, c) OMC_m and LL, d) OMC_s and LL

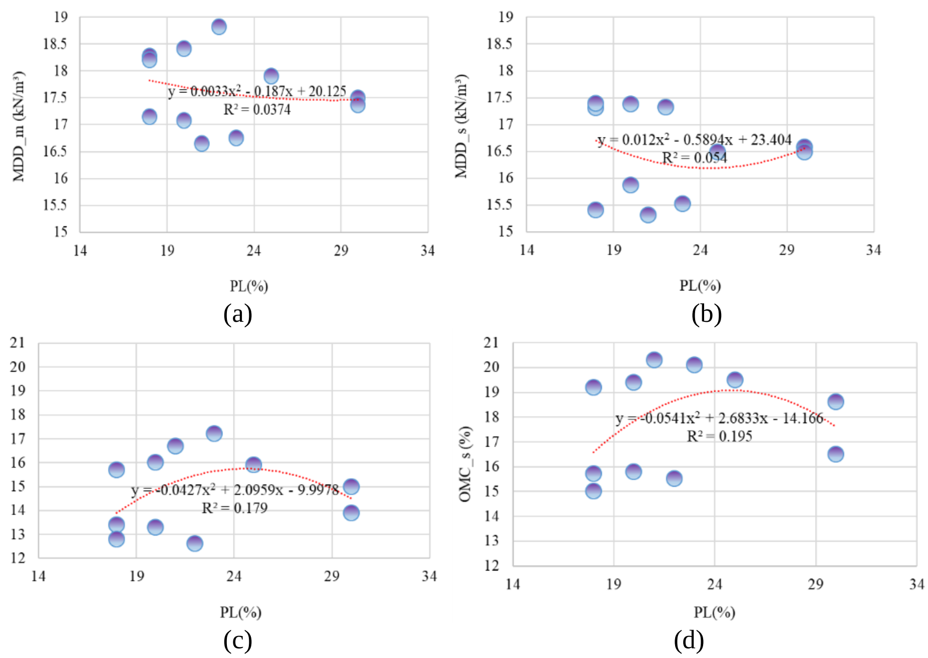

Figure 3. The change of compaction parameters against the plastic limit a) MDD_m and PL, b) MDD_s and PL, c) OMC_m and PL, d) OMC_s and PL

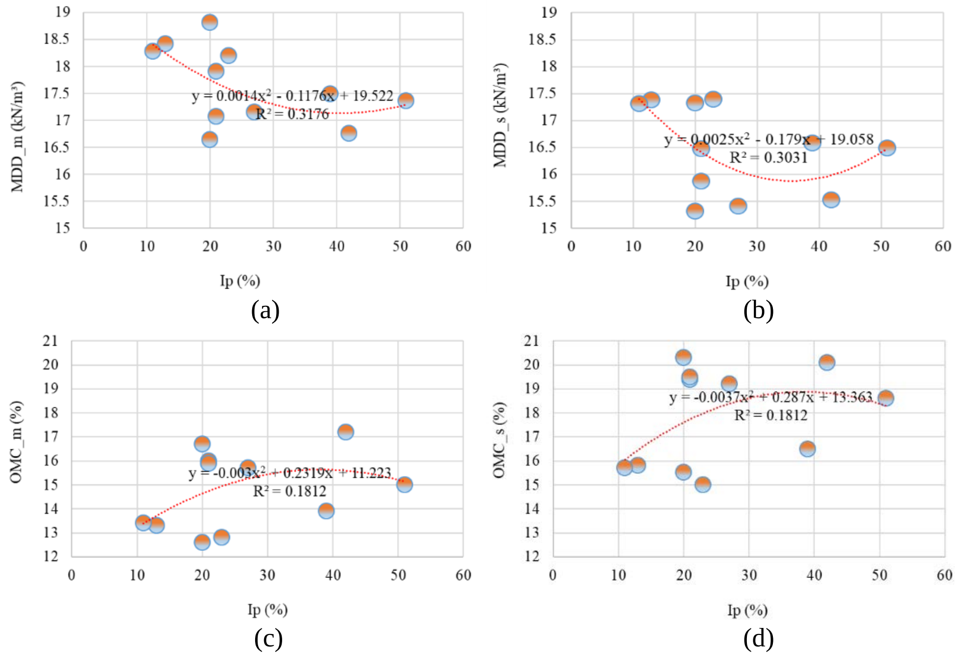

Figure 4. The change of compaction parameters against the plasticity index a) MDD_m and I_p, b) MDD_s and I_p, c) OMC_m and I_p, d) OMC_s and I_p

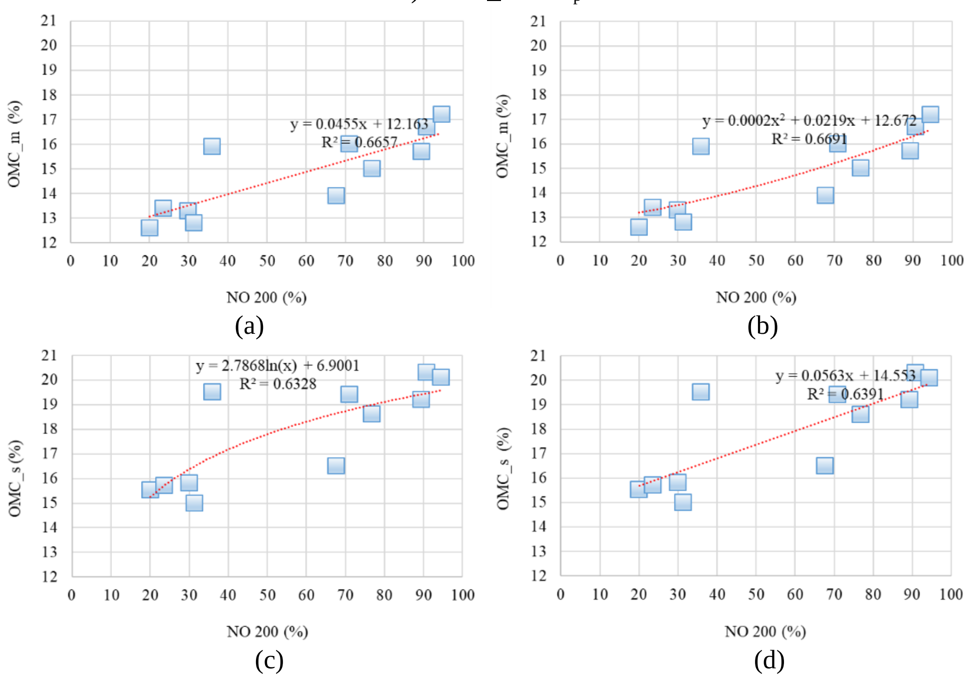

Figure 5. The change of compaction parameters against the fine content ratio a) OMC_m and No200 (linear relation), b) OMC_m and No200 (polynomial relation), c) OMC_s and No200 (logarithmic relation), d) OMC_s and No200 (linear relation)

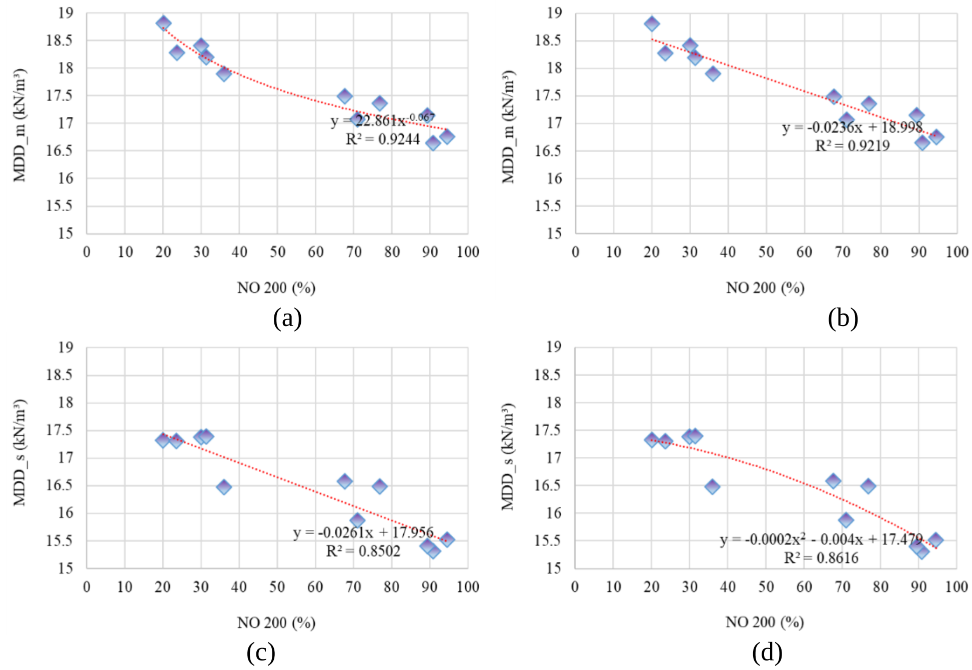

Figure 6. The change of compaction parameters against the fine content ratio a) MDD_m and No200 (exponential relation), b) MDD_m and No200 (linear relation), c) MDD_s and No200 (linear relation), d) MDD_s and No200 (polynomial relation)

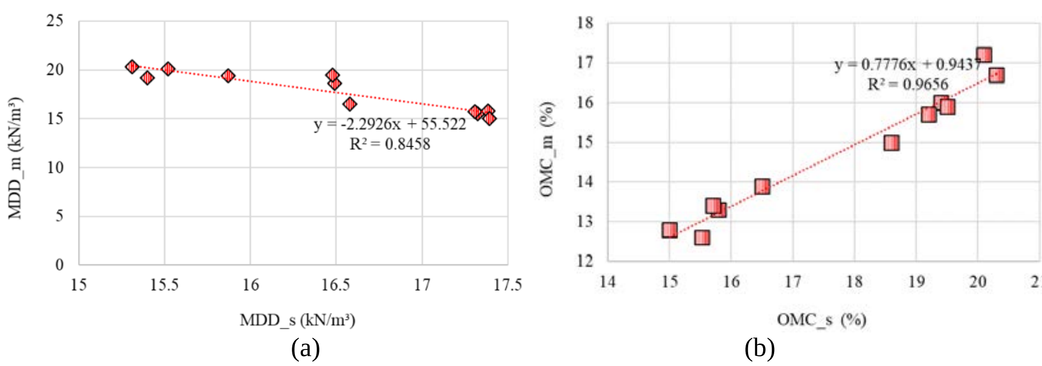

Figure 7. The relation of modified proctor test parameters against standard proctor test results

The obtained relations in order to reach the compaction characteristics have been given in Table 2 for the standard effort and the prediction models have been given in Table 3 for modified effort. In addition, the estimation of modified MDD against modified OMC and the prediction of standard MDD against modified OMC is given in Table 4. The mentioned tables were effective in evaluating the representability capability of the suggested relations. In Table 2, the usage of only the fine content ratio to define the standard compaction parameters gives reasonable prediction models to determine both MDD and OMC with a linear variation. In Table 3, the usage of only the fine content ratio to define the standard compaction parameters gives reasonable prediction models to determine both MDD and OMC with a linear variation again. In addition, the determination of the modified properties in terms of standard parameters have been given in Table 4 and the R^2 values obtained for linear relation ensure strong prediction capability.

Table 2. The results of the univariate analyses for standard effort

Standard Effort				
Parameter	Variant	Curve Fitting Option	R^2	Mathematical Expression
MDD_s	LL	Polynomial	0.304	$y = 0.0017x^2 - 0.2066x + 21.986$
OMC_s	LL	Polynomial	0.2368	$y = -0.0034x^2 + 0.4186x + 6.3549$
MDD_s	PI	Polynomial	0.3031	$y = 0.0025x^2 - 0.179x + 19.058$
OMC_s	PI	Polynomial	0.1812	$y = -0.0037x^2 + 0.287x + 13.363$
MDD_s	PL	Polynomial	0.054	$y = 0.012x^2 - 0.5894x + 23.404$
OMC_s	PL	Polynomial	0.195	$y = -0.0541x^2 + 2.6833x - 14.166$
OMC_s	No 200	Logarithmic	0.6328	$y = 2.7868\ln(x) + 6.9001$
OMC_s	No 200	Linear	0.6391	$y = 0.0563x + 14.553$
MDD_s	No 200	Linear	0.8502	$y = -0.0261x + 17.956$
MDD_s	No 200	Linear	0.8502	$y = -0.0261x + 17.956$
MDD_s	OMC_s	Linear	0.8458	$y = -0.3689x + 23.022$
MDD_s	OMC_s	Exponential	0.8361	$y = 50.866x^{-0.393}$

Table 3. The results of the univariate analyses for modified effort

Modified Effort				
Parameter	Variant	Curve Fitting Option	R^2	Mathematical Expression
MDD_m	LL	Polynomial	0.2749	$y = 0.001x^2 - 0.1257x + 21.244$
OMC_m	LL	Polynomial	0.2352	$y = 9E\text{-}06x^3 - 0.0043x^2 + 0.4158x + 4.344$
MDD_m	PI	Polynomial	0.3176	$y = 0.0014x^2 - 0.1176x + 19.522$
OMC_m	PI	Polynomial	0.1812	$y = -0.003x^2 + 0.2319x + 11.223$
MDD_m	PL	Polynomial	0.0374	$y = 0.0033x^2 - 0.187x + 20.125$
OMC_m	PL	Polynomial	0.179	$y = -0.0427x^2 + 2.0959x - 9.9978$
OMC_m	No 200	Linear	0.6657	$y = 0.0455x + 12.163$
OMC_m	No 200	Polynomial	0.6691	$y = 0.0002x^2 + 0.0219x + 12.672$
MDD_m	No 200	Exponential	0.9244	$y = 22.861x^{-0.067}$
MDD_m	No 200	Linear	0.9219	$y = -0.0236x + 18.998$

Table 4. The Standard and Modified Proctor test predictions

Parameter	Variant	Curve Fitting Option	R^2	Mathematical Expression
MDD_m	MDD_s	Linear	0.8458	$y = -2.2926x + 55.522$
OMC_m	OMC_s	Linear	0.9656	$y = 0.7776x + 0.9437$

4. Conclusion

As the laboratory tests to determine the key parameters of geotechnical characteristics of fine-grained soils are tiring and time-consuming, the researchers are tended to develop prediction models to calculate the mentioned parameters based on simple tests that are easy to measure. In order to utilize from this perspective, a test set that was performed to define the characteristic properties of a school site in Boyalık localization in Arnavutköy was utilized. The current study provides to presents an acceptable model to determine the compaction parameters of fine-grained soils utilized by the mentioned dataset. For this purpose, in this research, univariate regression capability for the prediction of compaction (MDD and OMC) of cohesive soils has been investigated. For the performance evaluation of the regression analyses, the software Microsoft Excel was used and the R^2 value has been used as the measure to control the correlation strengths of the mathematical expressions achieved. The results indicated that representative univariate two-dimensional regression analyses models can be developed depending on the site-specific analysis. The researchers and designers can apply the suggested relations at preliminary assessments of the projects constructed adjacent to the European side of Istanbul Province nearest the studied localization because the models developed herein have sufficient predictability.

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