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ORIGINAL PAPER

Improved dataset for establishing novel relationships between compaction characteristics and physical properties of soils

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Abstract
In the past, several studies were performed for assessment of compaction properties of different types of soils. A comprehensive evaluation of compaction parameters is essential for engineers working in practice. The main goals of compaction in landfills including highways and railways can be listed as reducing permeability and developing strength as well as enhancing the stability of soils. Literature includes various correlations proposed for establishing the link between the compaction properties of soils and Atterberg limits. Besides, many researchers performed laboratory studies to obtain correlations among soil index, strength, compression, and compaction characteristics of soils. In this study, in addition to authors' own data composed of compaction, strength, index, and consistency identifiers of sand-clay mixtures from three different types of sands (S1, S2, Q) and two types of clays (kaolinite and bentonite), a vast amount of data from past studies including tests on different types of soils around the world were also compiled. The global database was evaluated to propose novel correlative relationships among compaction characteristics, grain size distribution properties, and Atterberg limits. Proposed equations and relationships for estimation of compaction characteristics seem to be viable to use in practice.

Keywords Compaction curve · Maximum dry density (MDD) · Optimum water content (OWC) · Optimum degree of saturation (ODS) · Physical properties · Atterberg limits

Highlights
- Results of compaction tests on a wide range of soil types were presented.
- Effect of fines content on compaction parameters are evaluated.
- Dependency of degree of saturation on consistency and water content was questioned.
- Effect of soil consistency on degree of compaction was discussed.
- Effect of compactive effort on compaction identifiers was assessed.

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Abbreviation and notation list

α	Dimensionless parameter $\left(\frac{MDD_{MP}}{MDD_{SP}}\right)$
β	Dimensionless parameter $\left(\frac{OWC_{MP}}{OWC_{SP}}\right)$
C_u	Uniformity coefficient
CE	Compaction energy (kJ/m^3)
CEL	Compaction energy level
D_c	Degree of compaction (ρ_d/ρ_{dmax})
F_c	Fines content (< 75µm)
γ_{dmax}	Maximum dry unit weight (kN/m^3)
MDD	Maximum dry density (g cm^{-3})
MP	Modified Proctor compaction tests
LL	Liquid limit (%)
OCL	Optimum compaction line
OWC	Optimum water content (%)
ODS	Optimum degree of saturation (%)
PL	Plastic limit (%)
PI	Plasticity index (%)
ρ_d	Dry density (g cm^{-3})
ρ_s	Soil grain density (g cm^{-3})
ρ_w	Water density (1.0 g cm^{-3})
R_p	Plasticity ratio (*PL/LL*)
R^2	Coefficient of determination

R	Coefficient of correlation
S_r	Degree of saturation (%)
SP	Standard Proctor compaction tests
$S^{\#}$	Normalized degree of saturation (S_r/S_{opt})
v_a	Air porosity (%)
w	Water content (%)
$w^{\#}$	Normalized water content (w/w_{opt})
ZAV	Zero air voids ($v_a = 0\%$

Introduction

Compaction of soil is one of the most common soil improvement techniques in geotechnical engineering, particularly in infrastructure projects. Compaction is defined as densification of soil by application of dynamic or static action, which causes a reduction in the volume of air voids—air is expelled through the interstices of the soil mass. Millions of tons of soil mass are compacted every day in geotechnical engineering applications, which include the construction of roads, retaining structures, and many land reclamations works. Although there are many alternatives available for soil improvement, compaction is preferred due to its cost-effectiveness as well as improvement in strength, compressibility, and permeability properties. Field compaction control is achieved by the application of Proctor tests in the laboratory, which is also referred to as a dynamic compression test.

The main purpose of compaction of landfills, earth dams, highway, and railway embankments is to obtain a soil mass that possesses a higher shear strength accompanied by a low amount of settlement. Many other geostructures such as highway and railway subgrade soils and airfield base/subbase materials also need to be compacted properly. Apart from its utilization in transportation structures, after compaction, the bearing capacity of the foundation soils, which is a function of shear strength, also increases. Selection of appropriate compaction equipment, energy, and parameters lead to enhanced engineering properties, including improved slope stability. Thanks to decreased permeability, this method is also known as a viable tool in wastewater collection zones, enhancing leachate characteristics. Compaction is also an alternative method that can be preferred to reduce the risk of groundwater pollution. For this reason, this old but not outdated method is frequently used in geotechnical engineering applications to achieve desired strength, compressibility, and permeability properties of soils (Sridharan and Nagaraj 2005a, b).

Empirical correlations are widely used in geotechnical engineering applications to estimate the engineering properties of both fine-grained soils and sand-clay mixtures (Cabalar and Hasan 2013; Karakan and Demir 2018; 2020; Cabalar and Demir 2019; Miftah et al. 2020). In the past, concerning cohesive soils, many interrelationships among engineering properties were proposed (Dolinar and Trauner 2004, 2005; Dolinar and Škrabl 2013; Quintela et al. 2014; Sivakumar et al. 2015; Shimobe 2000, 2010, 2012; Ng et al. 2017; Wang et al. 2017; Nagaraj et al. 2018; O'Kelly et al. 2018; Vardanega et al. 2018; Rehman et al. 2018; Shimobe and Spagnoli 2019; Spagnoli et al. 2019). Thereby, index, compression, and strength properties available as well as correlations can be used as viable tools for validation of results of laboratory tests—in the preliminary design of geotechnical structures. The correlations existing in literature are focused on the basic properties and compaction characteristics of soils. Limited information is available for the prediction of compaction characteristics of soil mixtures, with the help of index properties (Shimobe and Spagnoli 2020; Spagnoli and Shimobe 2020). For instance, Sridharan and Nagaraj (2005a, b) showed that the plastic limit value was a better selection than the liquid limit or plasticity index in the estimation of maximum dry density (*MDD*) and optimum water content (*OWC*) of fine-grained soils under the standard Proctor compaction test (SP). Noor et al. (2011) showed that not only the Atterberg limit values but also the specific gravity is effective for the prediction of compaction characteristics of fine-grained soils based on the SP test. On the other hand, Omar et al. (2003) carried out the modified Proctor compaction tests (MP) of 311 coarse-grained soils and developed the predictive equations for compaction parameters (i.e., *MDD* and *OWC*). Mujtaba et al. (2013) developed the correlations among compaction parameters, gradational parameter (uniformity coefficient, C_u), and compaction energy levels (SP and MP tests) for 110 coarse-grained soils. Recently, Verma and Kumar (2020) explores the existing prediction models in the literature which seek out to improve the database of compaction parameters for fine- and coarse-grained soils.

In essence, compaction is not a key identifier of soil behavior alone. Mineralogical properties of soils, grain shape, grain size distribution, classification, permeability, and water absorption capacity, as well as the type and density of compaction, are also influencing parameters (Sivappulaiah et al. 2000; Cabalar and Hasan 2013; Karakan and Demir 2018; 2020). Accordingly, a detailed laboratory study was carried out to characterize the behavior of *MDD*-*OWC* and *MDD*-optimum degree of saturation (*ODS*), degree of compaction (D_c)-normalized water content ($w^{\#} = w/OWC$), D_c-normalized degree of saturation ($S^{\#} = S_r/ODS$). An intensive experimental framework is also including Atterberg tests (liquid limit with fall cone device, liquid limit with Casagrande method, plastic limit) and standard Proctor tests. Assessment of test results led to a rational approach for estimating the engineering parameters needed in the design and construction of compacted soil structures.

Within the scope of this study, under varying compactive efforts, the relationships among maximum dry density (*MDD*), optimum water content (*OWC*), degree of saturation (S_r), optimum degree of saturation (*ODS*), liquid limit (*LL*), plastic limit (*PL*), plasticity index (*PI*), and plasticity ratio (R_p) were established, by use of data collected from previous studies and authors' own research. Considering the research background mentioned above, this study is intensively focused on the evaluation of soil compaction parameters with index properties based on the comprehensive viewpoint.

Experimental study and compilation of database

Compaction quality control is made by comparison of field dry density measurements with those obtained in laboratory. As known, the recommended procedure for obtaining the water content-dry density relationship is the use of Proctor tests under varying compactive efforts. The test consists of compacting soil into a mold of known standard dimensions. After compaction, optimum water content and maximum dry density of the soil are determined. The efforts are repeated at varying water contents to obtain a compaction curve. The dry density of a soil obtained by a given compactive effort depends on the amount of mixture water. For a certain soil and a given compactive effort, there is one water content—the optimum water content that will result in a maximum dry density of the soil, and the water contents lower and higher than this optimum value (the dry and wet side of optimum, respectively) will result in dry densities lower than the maximum dry density (ASTM D698).

In this study, authors' own data consists of a total of 66 standard Proctor tests on mixtures incorporating two different types of clay (kaolinite and bentonite), 3 different types of sands (S1, S2, and Q) (Karakan and Demir 2018; 2020), and 60 different compaction test results on 5 different types of clean sands (Sezer 2008). Compaction test results performed on 66 types of sand-clay mixtures and 60 types of clean sands were compiled within the scope of the study. Besides, a comprehensive literature review was made to collect compaction and related data (more than 3000 points) from past studies, for soils ranging from coarse- to fine-grained soils. A map including information about the origins of data is given in Fig. 1. It should be noted that the test data is composed of results including systematic and measurement errors. Thus, uncertainties due to errors in applied energy, determination of water content, grain size distribution characteristics, and water adsorption capacity are probable. Since the data includes past test results on many types of soils from different regions, these uncertainties may cause misinterpretation of results. For instance, during compaction testing, high water contents in soils of high plasticity may be responsible for the transfer of lower energy from compaction hammer to soil. Aggregation is also possible during compaction of soils of LL values higher than 100%; therefore, the formation of lumped masses may cause misinterpretation of OWC and MDD. Besides, material retaining above ¾ inches sieve size is unacceptable in compaction testing. Several tests in our database provided ODS values greater than 100%; this is also an unacceptable value. This was attributed to misinterpretation of specific gravity test results in the laboratory. The OWC and MDD of volcanic soils are also extraordinary; the compaction characteristics of these soils are significantly different from the rest of the compaction results (MDD values are found to be less than 1 g/cm^3). Some of authors' own data consists of compaction tests on clean granular materials. Since the behavior of these types of soils is relatively hydrophobic,

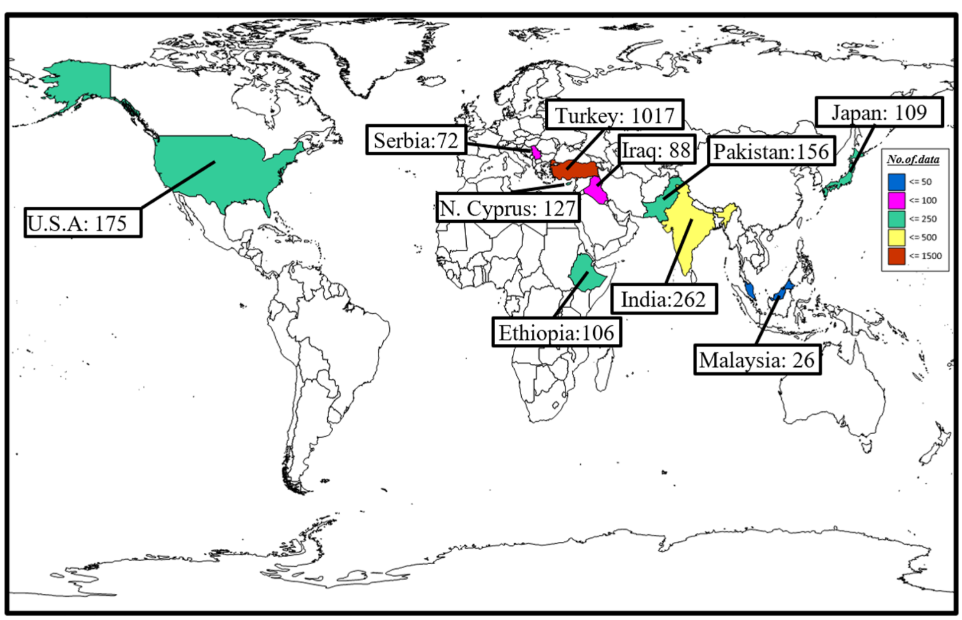


Fig. 1 Information about the origins of database with reference to countries

parts of compaction curves at higher water contents can be questionable; however, the MDD and OMC of these types of soils are remarkably different from those including fines. It was aimed to include test data of soils from a wide range of grain size distributions, for the generalization ability of the results discussed. This may cause compaction curves showing bell-shaped, double-peaked, one and a half peaked, and odd-shaped behaviors. Therefore, misinterpretation of behaviors different from bell-shaped curves may affect the quality of the database in this study. In this manner, during selecting data from past studies, great care was given to obtain consistent data, taking the soil type, grain size distribution, mineralogical characteristics, and regionality into consideration.

Results and discussions

Compaction, index, and strength identifiers were compiled from previously published papers, and unified with authors' own data. In this section, it was aimed to establish the relationships among different identifiers of compaction and index properties of soils.

Compaction curves (coarse- and fine-grained and mixed soils)

The relationships between water content and dry density are used to evaluate the compaction data. Furthermore, it is known that the proximity of data points to zero air voids (*ZAV*) curve is a descriptor of a better compaction. In this regard, Fig. 2 shows a family of compaction curves obtained under standard Proctor effort (Karakan and Demir 2018, 2020; Sezer 2008). In the study conducted by Karakan and Demir (2018, 2020), the compaction data are obtained by testing sand-clay mixtures with different plasticities. In addition, Sezer (2008) presented the results of Proctor tests under different compactive efforts performed on poor and well-graded clean sands with different origins. Figure 2 also shows the zero air voids (*ZAV*) and the constant degree of saturation (S_r) lines ($S_r = 30$, 50, 70, 90, and 100%). The experimental results depicted in the figure reveal that, at lower water contents, the dry density (ρ_d) values dominantly range between 1.5 and 2.0 g/cm^3. Increasing the water content values beyond 40%, dry density values tend to decrease, and the ρ_d-w plots accumulate in the vicinity of $S_r = 90\%$ curve. It is understood that increasing water contents results in higher saturation levels.

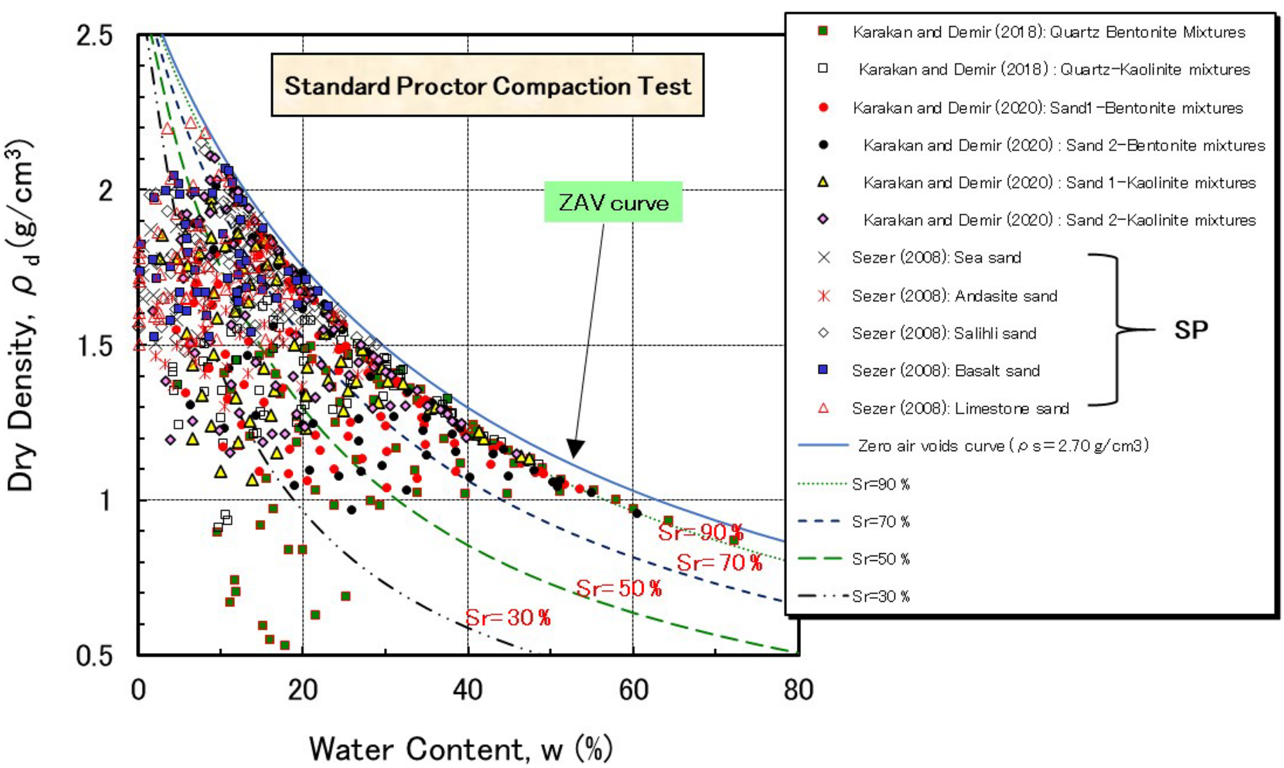


Fig. 2 Typical compaction curves and the constant degree of saturation S_r lines

In this paper, as the compaction characteristics of coarse- and fine-grained soils including soil mixtures are discussed from basic physical properties, among their index properties first of all we take up the effect of fines content F_c (< 75μm) on the compaction parameters (i.e., *MDD*, *OWC*, and *ODS*). Figure 3a–c) shows the *MDD*-, *OWC*-, and *ODS*-F_c relationships of soils obtained by both authors' own and literature data. As a result, it is seen from Fig. 2 that a notable behavior change in *MDD*-F_c and *OWC*-F_c relations under standard Proctor compaction (SP) after a F_c of 10% exists, which is in accordance with the data given in literature (e.g., Isik and Ozden 2013). Besides, Isik and Ozden (2013) carried out the SP compaction tests on 200 soil mixtures prepared by blending gravel, sand, and clay and suggested the transition fine content 12% constant value against both of *MDD*-F_c and *OWC*-F_c relationships. On the other hand, no clear and meaningful relationships between *ODS* and F_c including the modified Proctor compaction test (MP) etc. were recognized. The evidence (outcome) for *ODS*-F_c relations has not been encountered in literature so far. But even so, the fines content is a more important factor among the compaction parameters of soils.

The relationships between water content (w) and degree of saturation (S_r) for predicting the entire compaction curve were previously discussed in terms of liquid limit (*LL*) and/or compaction energy (*CE*) (Pandian et al. 1997; Nagaraj et al. 2006). Pandian et al. (1997) and Nagaraj et al. (2006) have suggested a phenomenological model and an ideal pore model for fine-grained soils, respectively. According to their models, the two-state parameters $w/S_r^{0.5}$ and w/S_r^{2} were separately proposed for the dry and the wet sides of optimum, respectively as follows:

Pandian et al. (1997):

$$\frac{w}{\sqrt{S_r}} = a + b \cdot LL\ w < OWC \text{ in SP test} \quad (1)$$

$$\frac{w}{s_r^2} = c + d \cdot LLw \geq OWC \text{ in SP test} \quad (2)$$

Nagara et al. (2006):

$$\frac{w}{\sqrt[LL]{S_r}} = 1.24 - 0.18\log_{10} CEw < OWC \quad (3)$$

$$\frac{w}{LLS_r^2} = 1.70 - 0.28\log_{10} CEw \geq OWC \quad (4)$$

where w and *LL* are expressed as the percentages, and S_r and *CE* as the decimal fraction and kJ/m^3, respectively. The constants a, b, c, and d in Eqs. 1 and 2 are also presented 9.48, 0.258, 10.61, and 0.362 (Pandian et al. 1997). We tried to verify the prediction accuracy in the S_r-w relationship as per Pandian et al. (1997)'s approach. Here, the accuracy of their *OWC* prediction was verified. Figure 4 shows the verification results based on the author's data and literature. As a result, it was observed that the majority of $OWC_{pred.}$ is within the range $0.95 \times OWC_{meas.}$ to $1.05 \times OWC_{meas}$. On the other hand, Horpibulsuk et al. (2008) also proposed an approach for the assessment of compaction curves of fine-grained soils at various energies using a one-point test (so-called the utilization of modified Ohio's curves considering the compaction energy levels *CELs*).

Figure 5 shows the water content and degree of saturation variations of both Sand2-Kaolin and Sand2-Bentonite mixtures. Besides, Sand 2 represents well-graded sand (SW). From Fig. 5, for sand-clay mixtures, it is understood that S_r-w relationship is not unique for clays of different origins and contents. It should be noted that the proposed equations, for both kaolin-sand (Eq. 5: kaolin 100%) and bentonite–sand (Eq. 6: bentonite 100%) mixtures, are the second-order equations with a higher coefficient of determination R^2(0.99) established by the use of the least squares method, based on data from Karakan and Demir (2020) (Fig. 5).

$$S_r = -0.063w^2 + 6.014w - 40.498 \quad (5)$$

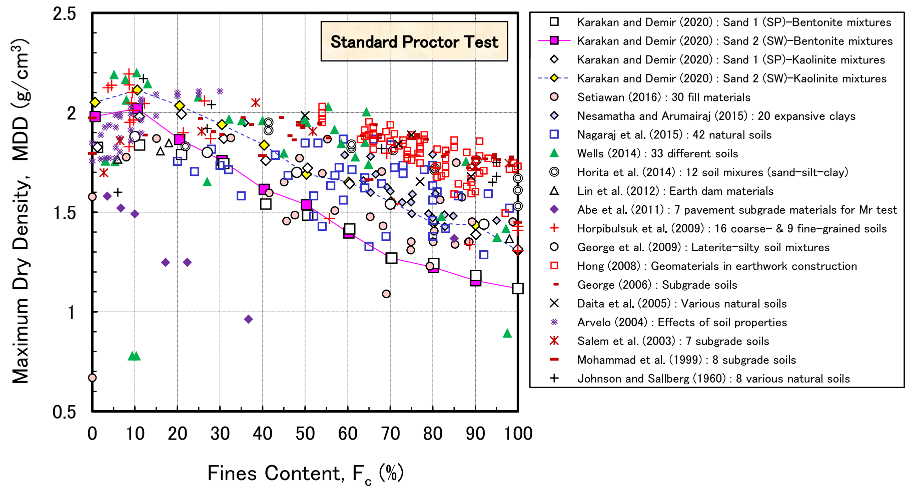
$$S_r = -0.054w^2 + 6.307w - 86.633 \quad (6)$$

The degree of saturation level corresponding to 30% of water content is on the order of 50% and 80% for sand-bentonite and sand-kaolinite mixtures, respectively. This is a bare evidence of the effect of clay mineralogy or geological origin on saturation level. In addition, these behaviors change by the mixed proportion and/or the increasing sand content; the lower the water content, the higher degree of saturation becomes at the same water content. Moreover, the S_r-w relationships estimated by the quadratic curves at their maximum curvatures approximately correspond to the optimum compaction points (*OWC, ODS*).

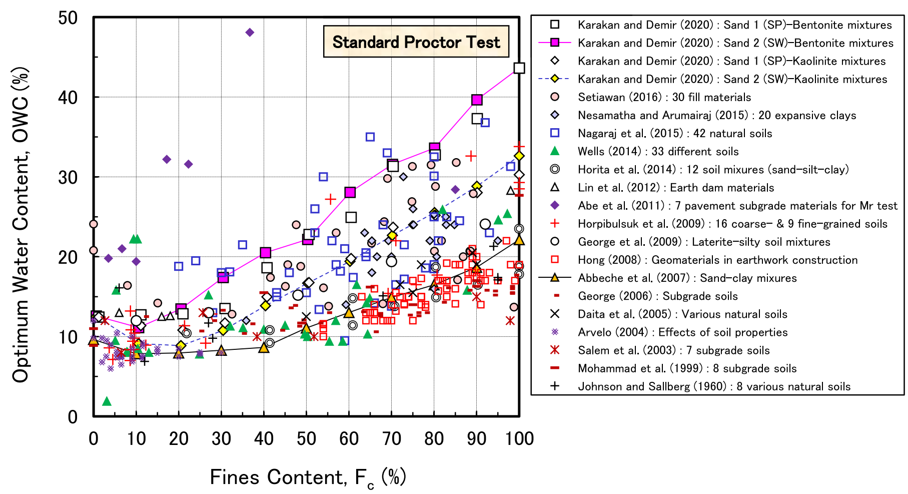
Correlations between MDD, OWC, and ODS vs LL

In the literature, various correlations between *MDD* and liquid limits of fine-grained soils or soils including fines were proposed, based on data from standard Proctor tests (Al-Khafaji 1993; Blotz et al. 1998; Sridharan and Nagaraj 2005a, b; Ng et al. 2015; Farooq et al. 2016; Saikia et al. 2017) and modified Proctor tests (Sivrikaya et al. 2013). More than 900 data from over many publications have been collected and analyzed (Table 1). Regarding Table 1, the relationships among maximum dry density (MDD) and liquid (LL) and plastic limits (PL) and optimum water content (OWC) with liquid (LL) and plastic limits (PL) are summarized. Figure 6 shows the test results from past studies and authors' past research in terms of the

Fig. 3 Effect of fines content on the compaction parameters **a** *MDD*, **b** *OWC*, and **c** *ODS*



(a)



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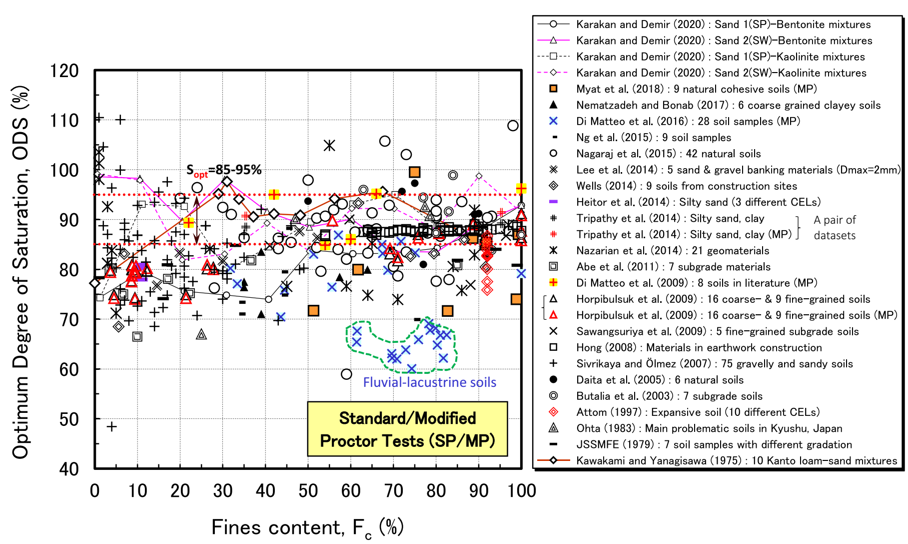

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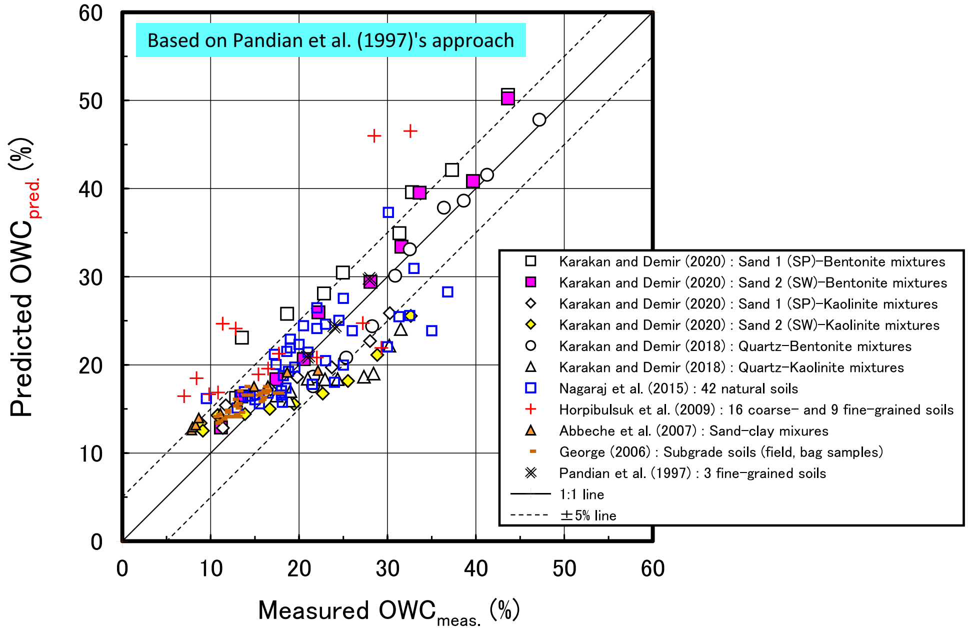


Fig. 4 Comparison between measured and predicted *OWCs*

MDD-LL relationship. It was observed that the approximate curve in the *MDD-LL* relationship (see Seq. 7 in Table 1 and black solid line in Fig. 6) proposed by Gurtug et al. (2018) roughly explained the experimental trend above at the *LL* values between 20 and 150%. However, especially the volcanic cohesive soils (Kanto loam, Japan; e.g., Hatsumi 1971) have the geotechnical peculiarity due to the effect of Allophane (amorphous clay mineral) and those soils highlighted in pink dotted closed line are greatly the outliers in the figure. Moreover, the trend is as well as the cases of *OWC-LL*; *MDD*, *OWC-PL*; *MDD-PI* and *MDD-*R_p relationships presented hereinafter, respectively (see also Figs. 7, 8, 9, 10a, and 11a).

Figure 7 shows the relationships between the *OWC* and *LL*, which is established using the results of standard and modified Proctor tests obtained from the literature, along with test results of sand (quartz)-clay mixtures from authors' own database. Analyzing above listed past studies, it is clear that all the equations proposed are linear. Similarly, using the database above, Eqs. 7 and 8 are obtained for quartz-kaolin and quartz-bentonite mixtures, respectively:

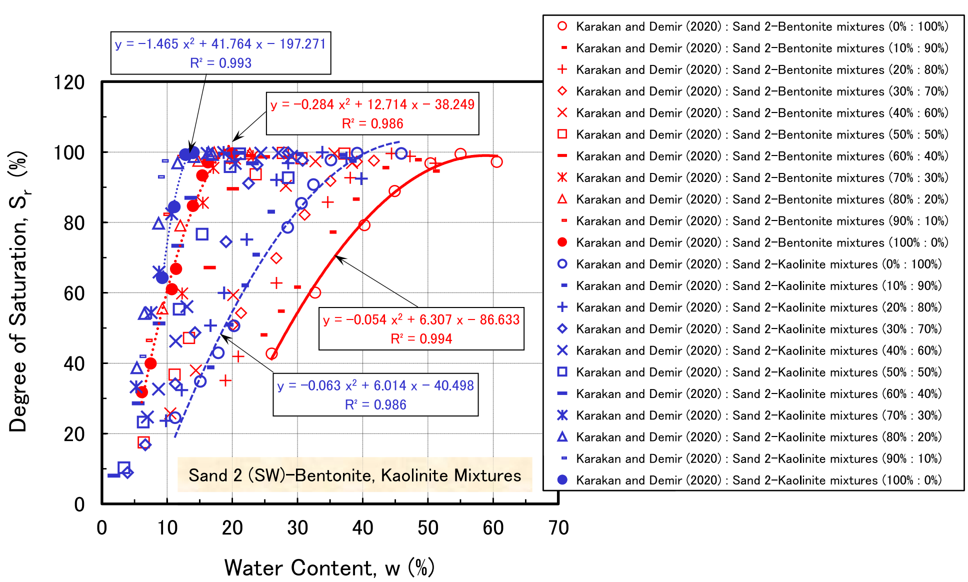


Fig. 5 Correlations between degree of saturation and water content relationship for sand-clay mixtures. Percentages in parentheses stand for sand and clay (bentonite or kaolinite) contents, respectively

Table 1 Relationships between maximum dry density (MDD)/optimum water content (OWC) and liquid limit (LL) with plastic limit (PL)

Seq	Authors	Proposed equations	Remarks
1	Al-Khafaji (1993)	$MDD = 2.44 - 0.02PL - 0.008LL\left(\frac{g}{cm^3}\right)$	88 types of soil samples collected from Iraq
2	Al-Khafaji (1993)	$MDD = 2.27 - 0.019PL - 0.003LL\left(\frac{g}{cm^3}\right)$	88 types of soil samples collected from USA
3	Blotz et al. (1998)	${}_{dmax} = 17.02 - 0.16LL + (2.27\log LL - 0.94)\ \log\ CE(\frac{kN}{m^3})$	22 types of clay to find a plausible relationship between maximum dry unit weight (γ_{dmax}) and *LL* considering compaction energy *CE* (kJ/m^3):
4	Sridharan and Nagaraj (2005a, b)	${}_{dmax} = 0.09(218 - LL) = 19.62 - 0.09LL\left(\frac{kN}{m^3}\right)$	By use of test results on 64 fine-grained soils:
5	Ng et al. (2015)	$MDD = 2.669 - 0.023LL\left(\frac{Mg}{m^3}\right)$	Based on test data on soils from various sites in Malaysia:
6	Saikia et al. (2017)	${}_{dmax} = 20.97 - 0.127LL\left(\frac{kN}{m^3}\right)$	Test results on 40 different natural fine-grained soils in India
7	Gurtug et al. (2018)	${}_{dmax} = 41.97LL^{-0.127}\left(\frac{kN}{m^3}\right)$	106 fine-grained soils in Turkey, established a correlation between maximum dry unit weight and *LL*
8	Firomsa and Quezon (2019)	$MDD = 1.861 - 0.006LL\left(\frac{g}{cm^3}\right)$	Test results on 50 different fine-grained soils from Ethiopia
9	Karakan and Demir 2018	$MDD = 1.664e^{-0.003LL}\left(\frac{g}{cm^3}\right)$	44 samples, Sand-clay mixtures from Turkey
10	Al-Khafaji (1993)	$OWC = 0.24LL + 0.63PL - 3.13$	Analyzing the studies in the last 20 years
11	Blotz et al. (1998)	$OWC = 9.21 + 0.67LL + (12.39 - 12.21\log LL)\ \log\ CE$	*OWC*, *LL*, and compaction energy (*CE*) by performing tests on 22 types of clays—within a ± 2% error margin
12	Sridharan and Nagaraj (2005a, b)	$OWC = 0.37LL + 4.61$	*OWC* and *LL*, based on a series of tests on 64 fine-grained soils from India:
13	Đoković et al. (2013)	$OWC = 0.239LL + 7.757$	Tests performed on 72 samples from clay core of dams in Serbia:
14	Sivrikaya et al. (2013)	$OWC = 0.4422LL$	Tests on 86 soil samples of different fines contents obtained from Turkey, and found out a relationship between *OWC* and *LL* with a correlation coefficient *R* of 0.98 and standard error of ± 2.71%, respectively
15	Gurtug et al. (2018)	$OWC = 0.50LL$	Tests on 106 types of fine-grained soils (*R* = 0.89)
16	Firomsa and Quezon (2019)	$OWC = 0.312LL + 7.601$	Tests on 50 types of fine-grained soils from Ethiopia

$$OWC = 0.437LL + 6.907\left(R^2 = 0.79\right) \quad (7)$$

$$OWC = 0.197LL + 14.701\left(R^2 = 0.98\right) \quad (8)$$

While the *LL* corresponding to an *OWC* of 31% is 60% for quartz-kaolin mixtures, in sand-bentonite mixtures, the *LL* corresponding to 47% of *OWC* is greater than 140%. The mineralogical properties of clay control the overall behavior of the mixture. Furthermore, in order to evaluate the compaction energy level (*CEL*), variations of *OWC* and *LL* obtained from standard and modified Proctor tests are shown in Fig. 7. The results reveal that, for the same *LL* value, *OWC* values obtained by the modified Proctor test are frankly lower than those obtained by standard Proctor tests. For instance, for a clay of *LL* = 80%, *OWC* values corresponding to modified and standard Proctor tests are 23% and 40%, respectively. Therefore, not only the geological origins of clay, but the compaction energy significantly affects the relationship between *LL* and *OWC*. Besides, the volcanic cohesive soils such as Kanto loam with high water content and high plasticity (highlighted in pink dotted closed line) are greatly the outliers also in the case of *OWC-LL* relationships as well as the *MDD-LL* relationships in Fig. 6.

Figure 12 shows the relationships among optimum saturation level (*ODS*) and *LL* based on results of a total of 700 tests under standard and modified Proctor compaction energy. It should be emphasized that tests were performed on a wide range of soils: gravels, sands, natural clays, artificial sand-clay mixtures, volcanic soils, and expansive soils. Regarding *ODS-LL* relationship, the figure also presents 85% and 95% optimum degree of saturation (*ODS*) lines

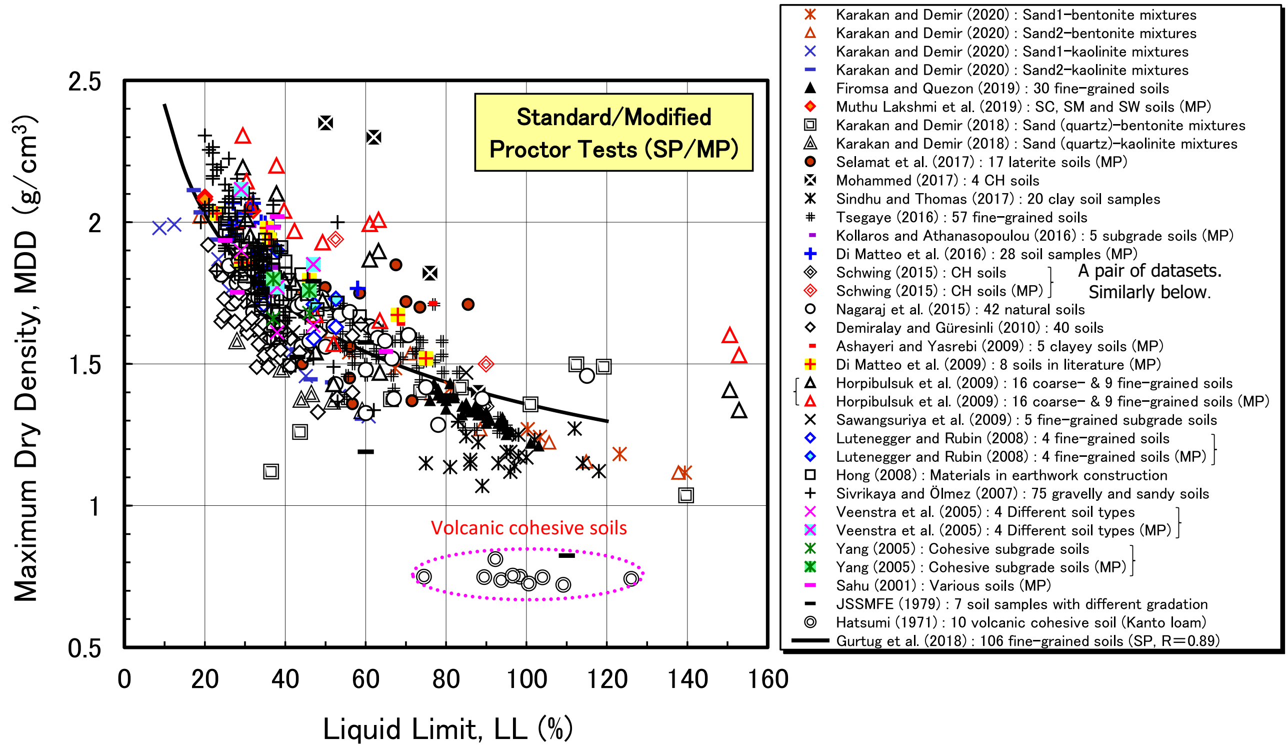


Fig. 6 Correlations between *MDD* and *LL* (data from standard/modified Proctor tests)

corresponding to the whole *LL* range. It is to be underlined that the optimum degree of saturation levels ranging between 85 and 95% can be used for control of both standard and modified Proctor test results. For soils of varying plasticity, this band is a descriptor of a better degree of compaction. According to Shimobe and Spagnoli (2020) and Spagnoli and Shimobe (2020), it is known that the *ODS* values for most soils generally range from 85 to 95% (in terms of the air porosity (v_a) at the ODS values, those correspond to v_a = 2–10%), almost irrespective of the compaction energy levels. Moreover, it is interesting that the volcanic cohesive soils (Kanto loam) analyzed in the *ODS-LL* relationships is not subject to the effect of geotechnical peculiarity and the experimental evidence (*ODS*≈95% constant) is helpful for the effective utilization of *ODS* to soil compaction control (as well as the cases of other different plasticity parameters in *ODS-PL*, *ODS-PI*, and *ODS*-R_p relationships respectively; see also Figs. 13, 10c, and 11c). Namely, it means that the problematic soils as Kanto loam may be easy to cope with the soil compaction control using the *ODS* values.

Correlations between MDD, OWC, and ODS vs PL

In the scope of the current study, apart from studies investigating the relationship between *MDD* and *LL*, relationships between *MDD* and *PL* are also presented. In this scope,Fig. 9 shows the variations of *MDD* and *PL* for soils with different characteristics. The data is collected from studies beyond 2000 to the present day. In addition, data by authors are added to Fig. 9. As can be seen in the figure, excluding the data on volcanic cohesive soils, as the *PL* increases, *MDD* decreases from about 2.5 to 1.2 g/cm^3. In Table 2, correlations between *PL* and *MDD* from studies published in the last 20 years are presented in chronological order. The correlations tabulated in Table 1 approve the findings above: *PL* is inversely proportional with *MDD*. Equations obtained are shaped as $MDD = A - B \cdot PL$. In this regard, Eqs. 9 and 10 are obtained for quartz-kaolinite and quartz-bentonite mixtures from authors' own data, respectively:

$$MDD = 1.977 - 0.018PL\left(R^2 = 0.795\right) \tag{9}$$

$$MDD = 1.7679 - 0.0095PL\left(R^2 = 0.794\right) \tag{10}$$

Figure 9 shows the relevance between *OWC* and *PL*. The plot was prepared by use of more than 600 previously published data obtained from standard/modified Proctor test results. Studies excluding Hatsumi (1971) and JSSMFE (1979) are conducted in the last two decades, among them *OWC* = 0.92*PL* (from standard Proctor test results) and

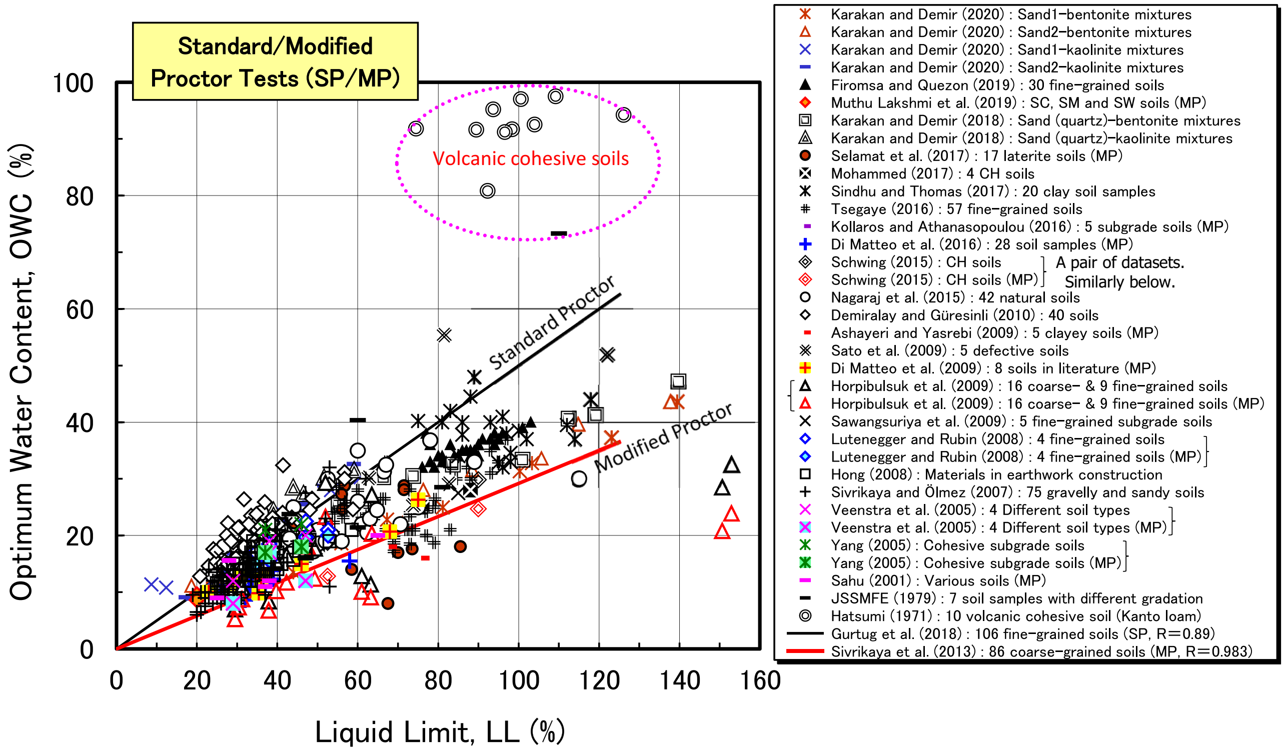


Fig. 7 Correlations between optimum water content and liquid limit for standard/modified Proctor compaction tests

$OWC = 0.69PL$ (from modified Proctor test results) relationships from studies of Sivrikaya and Soycan (2009) and Sivrikaya et al. (2008) were also included, respectively. Mathematical *OWC-PL* relationships for authors' quartz-kaolinite and quartz-bentonite are also obtained as (Karakan and Demir 2018):

$$OWC = 0.772PL + 3.003\left(R^2 = 0.784\right) \quad (11)$$

$$OWC = 0.5458PL + 7.216\left(R^2 = 0.930\right) \quad (12)$$

In Table 3, *OWC-PL* relationships proposed for fine-grained soils are given in chronological order. All the equations are first-order linear equations. Figure 9 and Eqs. 11 and 12 show that both the clay fraction and the compaction energy level strongly influence the *OWC-PL* relationship. For instance, for a *PL* of 40%, *OWC*s of soils compacted under standard and modified energies are on the order of 37% and 27.6%, respectively. *OWC*s of volcanic cohesive soils are between 80 and 100%, whereas their *PL*s are greater than 60%, they are observed to be the outliers to the above-mentioned relationships.

In Fig. 13, *ODS-PL* relationships are given for data from both standard and modified Proctor tests. Data obtained from literature was presented along with that obtained from authors' research. From the figure, it is inferred that the *PL* of scattered data is accumulated between 20 and 40%. Constant and horizontal ODS lines are between 85 and 95%, which is again an indicator of a better densification level. But even so, the consistency parameter *PL* is a more important factor as well as the gradational one F_c among the compaction parameters (*MDD* and *OWC* except for *ODS*) of soils. Recently, although Wang and Yin (2020) recommend highly the proposed equations of Nagaraj et al. (2015) as the prediction models for *MDD* and *OWC* in the literature (see Seqs. 4 and 10 in Tables 2 and 3, respectively), judging from the results of this study with an extended range of index properties in Figs. 8 and 9, their conclusions are not necessarily appropriate. Apart from the previous models, they developed a new prediction model for the soil compaction parameters using multi-expression programming (*MEP*) for a large number of soils with high accuracy. According to their high-performance prediction model, it is highlighted that the *PL* and the F_c have more significant influences on the prediction results. This evidence is in agreement with the important results in the present study mentioned above.

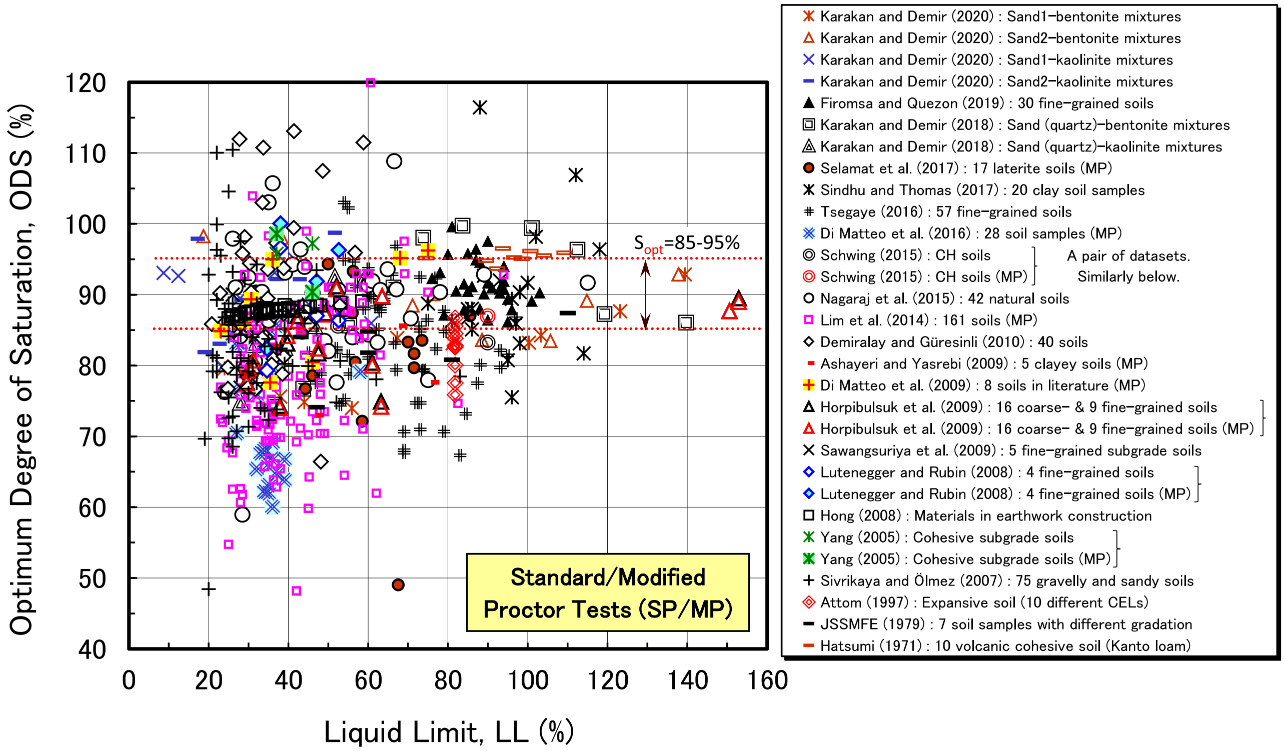


Fig. 8 Correlations between *ODS* and *LL* for standard/modified Proctor tests

Correlations between MDD, OWC, and ODS vs PI

Figure 10 presents the variations of *MDD*, *OWC,* and *ODS* by *PI* in terms of applied compactive effort. Figure 10a–c also include past studies concerning the *MDD-PI* relationship, along with both proposed equations of Khalid and Rehman (2018), composed of standard/modified Proctor test results on 126 types of soils (see the black and red solid line, respectively). Analyzing those figures, it is understood that *MDD* is inversely proportional with *PI* (Fig. 10a). For the same plasticity index value, *MDD* values obtained from modified Proctor tests are greater than those obtained from standard Proctor tests, as expected. Besides, the *MDD-PI* relationship of Koyama et al. (2014) obtained from standard Proctor tests on 66 types of soils with different grain size distributions was also shown together (see the black dotted line in Fig. 10a). A relationship between *OWC* and *PI* similarly suggested by them is given in Fig. 10b (black dotted line). Contrary to *MDD*, *OWC* values decrease with increasing *CEL*. Analyzing the trendlines demonstrating a certain relationship between *OWC* and *PI*, it was observed that the slope of expression proposed by Koyama et al. (2014) was remarkably greater than that of Khalid and Rehman (2018). In this manner, *PI* increases by increasing the *OWC* value. A semi-logarithmic plot between *ODS* and *PI* obtained from results of standard and modified Proctor tests is given in Fig. 10c. Analysis of the figure revealed that the *PI* values were clustered within 10 to 50% and corresponding *ODS* values range between 85 and 95%.

Table 4 lists the past correlations among *MDD*, *OWC,* and *PI* in chronological order. Glancing at the table, it is seen that linear relationships exist between the above-mentioned parameters. Nevertheless, an increase in *MDD* and a decrease in *OWC* are observed by increasing *PI* (data of laterite soils by Selamat et al. 2017).

Correlations between MDD, OWC, and ODS vs R_p (PL/LL)

Figure 11 demonstrates the relationships among *MDD*-plasticity ratio (R_p), *OWC*-R_p vs *ODS*-R_p by use of standard and modified Proctor test results. It is noticed that the figure includes data from testing soils of a broad grain size distribution range and distinct soil classes (GW, SW, SP, SM, SC, ML, MH, CL, CH, and so on). For reference, as an average trend for the relationship between *MDD* and R_p, the following linear equation using modified Proctor test results by Selamat et al. (2017) is obtained (see the dark brown solid line in Fig. 13a):

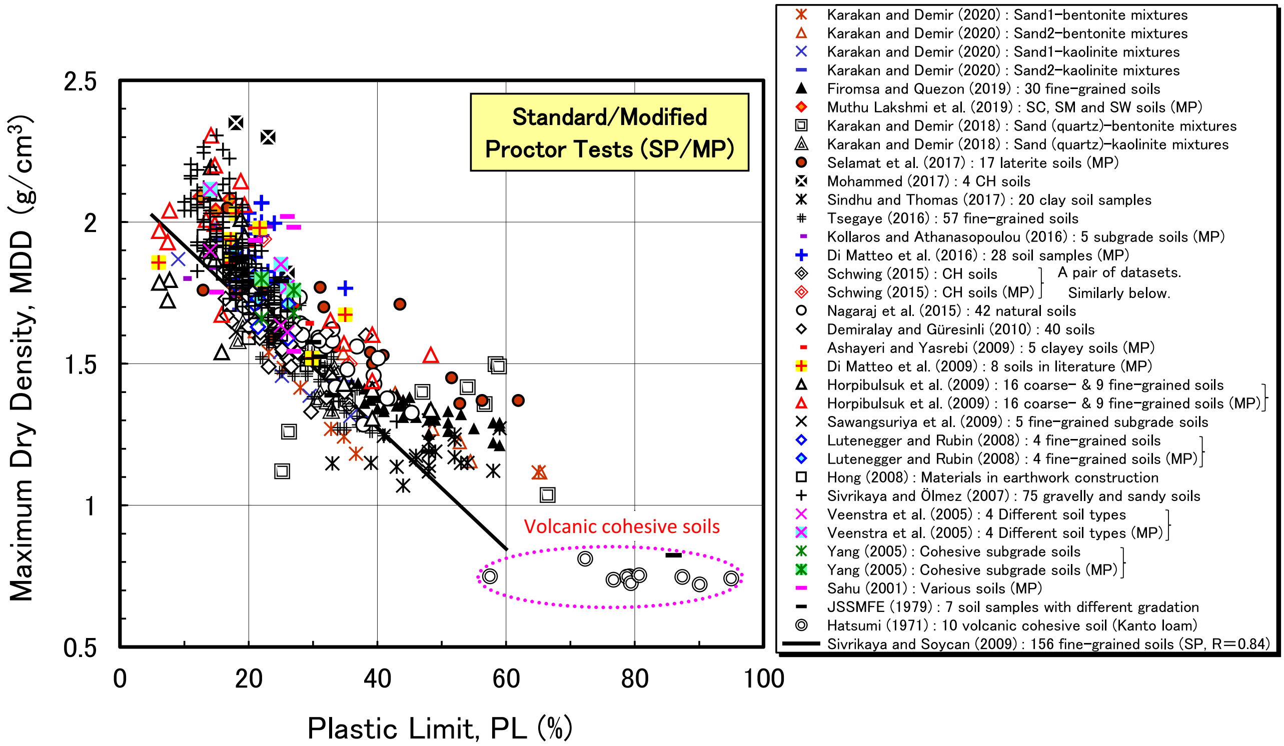


Fig. 9 Correlations between *MDD* and *PL* for standard/modified Proctor tests

$$MDD = -0.652R_p + 2.043\left(R^2 = 0.620\right) \tag{13}$$

It is clearly seen that *MDD*s increase with decreasing R_p values. However, analyzing Fig. 13a, it is observed that data obtained from results of standard Proctor tests on fine-grained soils (e.g., Tsegaye 2016; Sindhu and Thomas 2017; Karakan and Demir 2018; Firomsa and Quezon 2019) are not in harmony with trend offered by Eq. 13. On the other hand, the trend of the *OWC*-R_p relationship is nearly inverse of that of the *MDD*-R_p relationship. In this regard, as a measure for the average trend the following expression using modified Proctor test results of Selamat et al. (2017) is suggested (see the dark brown solid line in Fig. 13b):

$$OWC = 22.663R_p + 5.532\left(R^2 = 0.683\right) \tag{14}$$

This time, the *OWC*-R_p relationship from standard Proctor tests on fine-grained soils (e.g., Tsegaye 2016; Sindhu and Thomas 2017; Karakan and Demir 2018; Firomsa and Quezon 2019) is well above the relationship offered by Eq. 14 (Fig. 13b). For clayey soils of a certain plasticity ratio range (0.4 ~ 0.6), the determination for Eqs. 13 and 14 can be updated so that lower *MDD* and higher *OWC* values can be obtained. Besides, the *ODS*-R_p relationship looks like no correlation (Fig. 13c). As a result, for Fig. 13a–c, R_p values are mostly clustered between 0.4 and 0.8, which can be deemed as a characteristic of ordinary compactible soils, as the volcanic cohesive soils are not in agreement with the rest of the test data.

Effect of compaction energy levels

A relationship between *MDD* and *OWC* based on applied energy is a good option to use in practical applications. Using standard Proctor effort, 66 sand-clay mixtures and 60 types of clean sands were used to obtain a correlation between *MDD* and *OWC* (Fig. 14). The zero air voids (*ZAV*) curve also can be drawn for S_r = 100%. The *ZAV* curve is normally used as a guide to generate a suitable compaction curve for a region of higher water content (Ishibashi and Hazarika 2011). In the past, correlative equations for *MDD* and *OWC* under standard and modified Proctor efforts were proposed by many researchers (Uno et al. 2002; Pandian 2004; Sridharan and Nagaraj 2005a, b; Di Matteo et al. 2009; Gurtug and Sridharan 2015). In addition, many studies in the past suggest correlations among compaction test results and index properties of different types of soils (Sivrikaya and Ölmez 2007; Koyama et al. 2014). Thus, in order to evaluate the *MDD-OWC* relationship of soils, all the test results including the effect of *CEL*s are presented in Fig. 14. The dataset of clean sands corresponding to less than 10% of

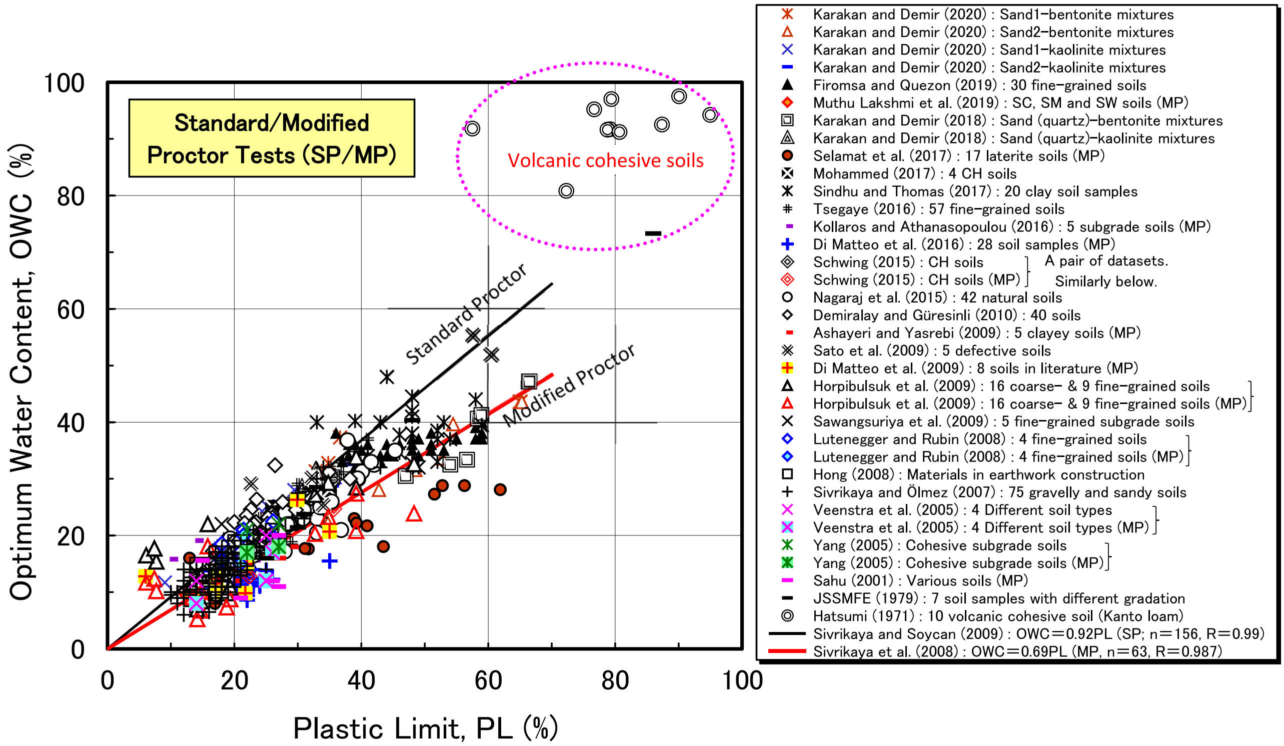


Fig. 10 Correlations between *OWC* and *PL* for standard/modified Proctor tests

OWC was not in agreement with Mori's (1962) equation, but confirms to empirical equation suggested by Ekwue and Stone (1997). The data of sand-clay mixtures obtained from Karakan and Demir (2018, 2020) study were found to be in harmony with the universal *MDD-OWC* curve proposed by Mori (1962). Besides, the Mori (1962) equation at SP compaction energy is presented as follows:

$$MDD = \frac{1}{A \cdot OWC + B} = \frac{1}{0.0107OWC + 0.403} \tag{15}$$

where A and B represent the experimental constants. Ohta (1983) carried out the SP tests for typical problematic soils (weathered granite soil and volcanic coarse- and fine-grained soils) in Kyushu, Japan, and presented $A = 0.0111$ and $B = 0.4306$ in the same linear form as Eq. 15 (correlation coefficient, $R = 0.989$). Moroto (1989) also presented $A = 0.0117$ and $B = 0.376$ ($R = 0.93$) for the volcanic cohesive soils in Aomori Prefecture, Japan. These results are a strong supporting evidence for the Mori (1962) equation, e.g., as well as Ohio's compaction curves (Joslin 1959) in the USA and the *MDD-OWC* relationships in Turkey by Sivrikaya and Ölmez (2007).

Rewriting the equation of Mori (1962) to obtain *ODS*, it is obtained that:

$$ODS = \frac{\frac{\frac{1}{MDD} - 0.4}{0.0107}\rho_s}{\frac{\rho_s}{MDD} - 1}\rho_w \tag{16}$$

where the density of soil particle ρ_s and density of water ρ_w are 2.65 g/cm^3 and 1.0 g/cm^3, respectively. The dry density-degree of saturation relationship corresponding to the optimum compaction point is important for compaction control in geostructures. The *MDD-ODS* relationship can be obtained using Eq. 16 (Shimobe and Spagnoli 2020):

$$MDD = \frac{\rho_s}{\frac{\rho_s OWC}{ODS \rho_w} + 1} \tag{17}$$

Using the *OWC* and *ODS* values, the *MDD* value can be obtained from Eq. 17. In Fig. 15, Mori's (1962) equation is applied to obtain *ODS*. Figure 15 shows the dependence of *MDD* on *ODS* using authors' own improved data, based on a novel definition of optimum compaction line (*OCL*: red solid line). It is evident that most of the data remain in an empirical approximate interval of *OCL* (air porosity $v_a = 2\%$ to 10%) irrespective of *CEL*s. However, it was observed that if the optimum degree of saturation was less than 40%, the data remains outside the band of *OCL*. Also, most of the

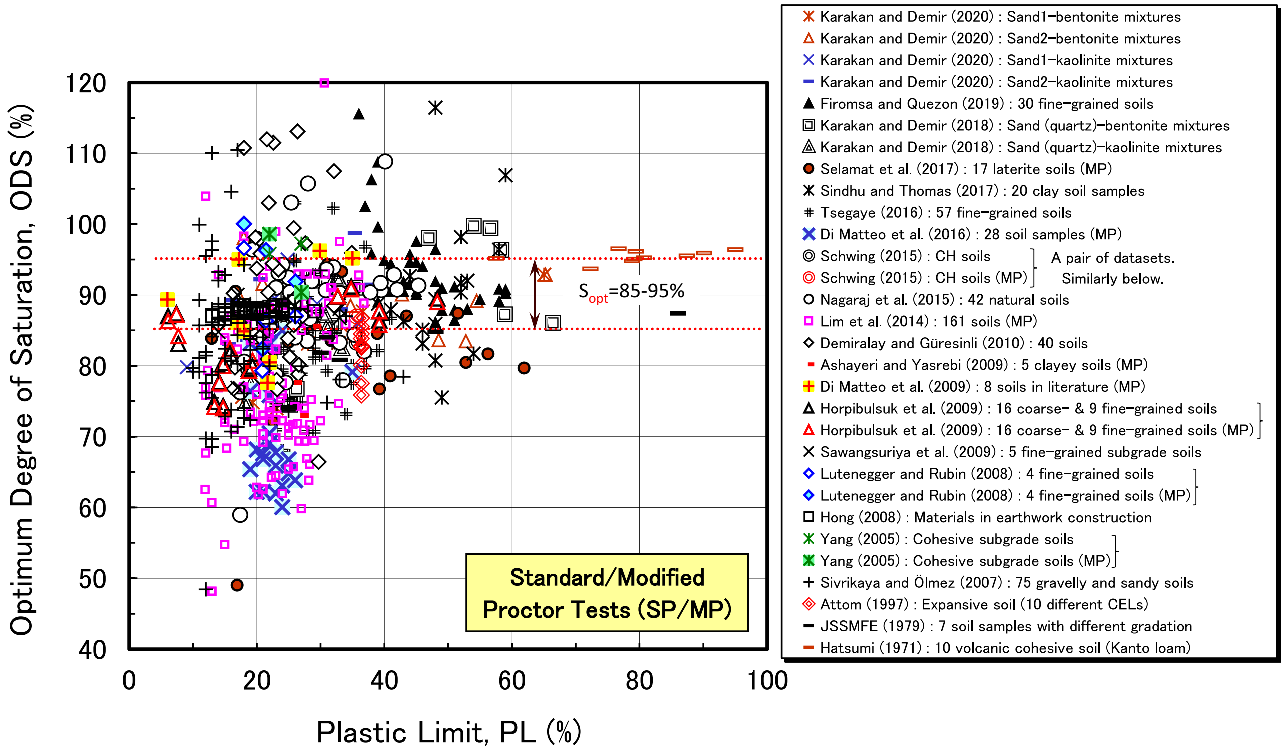


Fig. 11 Correlations between *ODS* and *PL* from standard/modified Proctor tests

clean sands (free of fines content) plotted on the left-hand side of the optimum compaction line (*OCL*) had significantly lower *ODS* values, as expected.

Figure 16 shows the verification of the validity of the *OCL* mentioned above from a large number of works of literature. Besides, for comparison, the transformation of Khalid and Rehman's Eq. (2018) to *ODS* (black dotted line) and Ohio's curves (Joslin 1959; orange double-broken line) are also depicted together in this figure. As a result, although the general trend is almost unchanged compared to the results in Fig. 15, the scatters of data are greatly extended and suggest the re-examination of these experimental pieces of evidence strongly. In spite of such results, the significance of *OCL* (corresponding to air porosity line $v_a \approx 7\%$) for compaction quality control in field remains still.

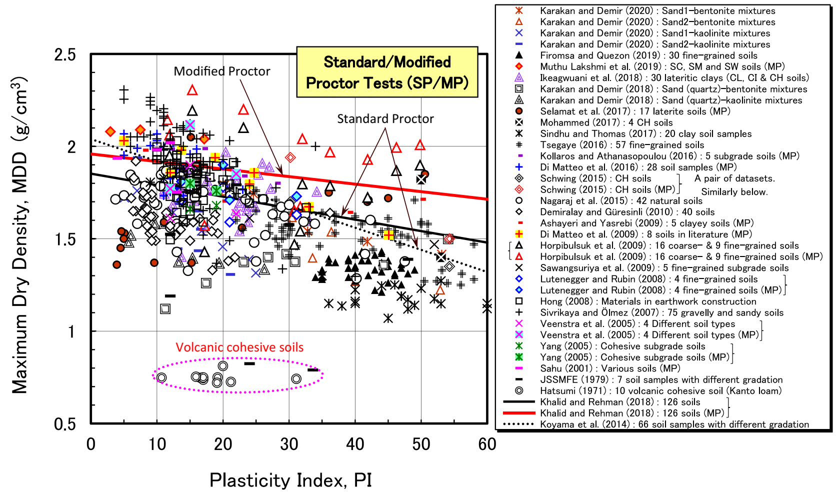
Data from the literature were used (including authors' own) to obtain the S_r-w relationships (see also Fig. 5) over a wide range of water content from standard Proctor (Furukawa et al. 1992; Hatakeyama et al. 1992; Sezer 2008; Horpibulsuk et al. 2008; Sivakugan and Das 2009; Bello 2013; Mir and Sridhan 2013; O'Kelly 2016; Karakan and Demir 2020), modified Proctor (Sezer 2008; Sivakugan and Das 2009; Bello 2013; O'Kelly 2016), miniature compactor (Thakur et al. 2005) and Harvard miniature compactor tests (Shimobe 2000). Here, the suggested equations (Eqs. 18 and 19), i.e., the third-order linear regression ones based on data from Sezer (2008) and Hatakeyama (1992) and the two average trend lines combined with other several test data are depicted in terms of semi-log plot in Fig. 17, respectively. Furthermore, for comparison with the previously suggested curves in S_r-w relationship, the typical plot (red double solid line) by Daita et al. (2005) and the Enhanced Integrated Climatic Model (EICM; pink solid line) of Zapata et al. (2007) are also presented together.

$$S_r = -0.002\left(\log_{10}w\right)^3 - 0.096\left(\log_{10}w\right)^2 + 7.431\log_{10}w - 4.154\left(R^2 = 0.83\right) \tag{18}$$

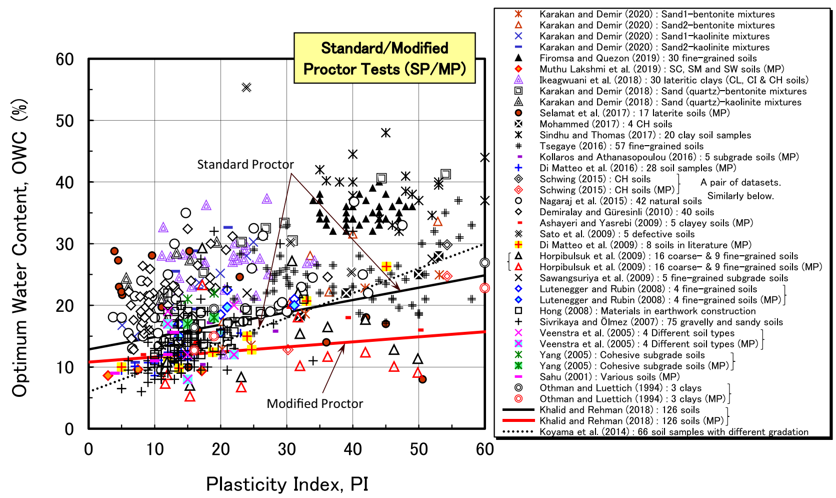
$$S_r = -0.006\left(\log_{10}w\right)^3 + 0.294\left(\log_{10}w\right)^2 - 0.747\log_{10}w + 11.371\left(R^2 = 0.87\right) \tag{19}$$

From Fig. 17, it is seen that the S_r-w relationships maintain the similar form of third-order function in spite of different soil types over a wide range of water content (i.e., including higher *LL* values > 50%) and also are insensitive against the effect of *CEL*s. These results are useful in assessing the entire compaction curves. In addition, Figs. 18 and 19 establish the relationships between *MDD* and *OWC* values determined using standard and modified Proctor compaction effort (where MP and SP subscripts stand for modified and

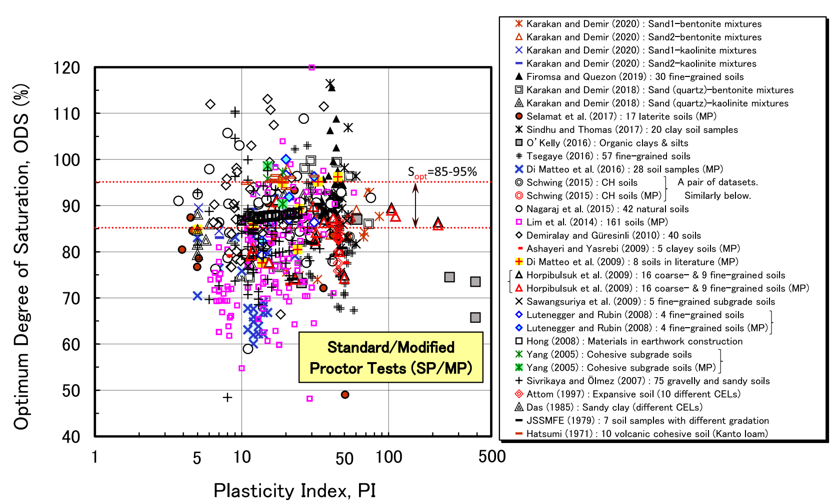
Fig. 12 Correlations between **a** *MDD* and *PI*, **b** *OWC* and *PI*, **c** *ODS* and *PI* for standard/modified Proctor compaction tests



(a)



(b)



(c)

Fig. 13 Correlations between **a** *MDD* and R_p, **b** *OWC* and R_p, **c** *ODS* and R_p, for standard/modified Proctor compaction tests

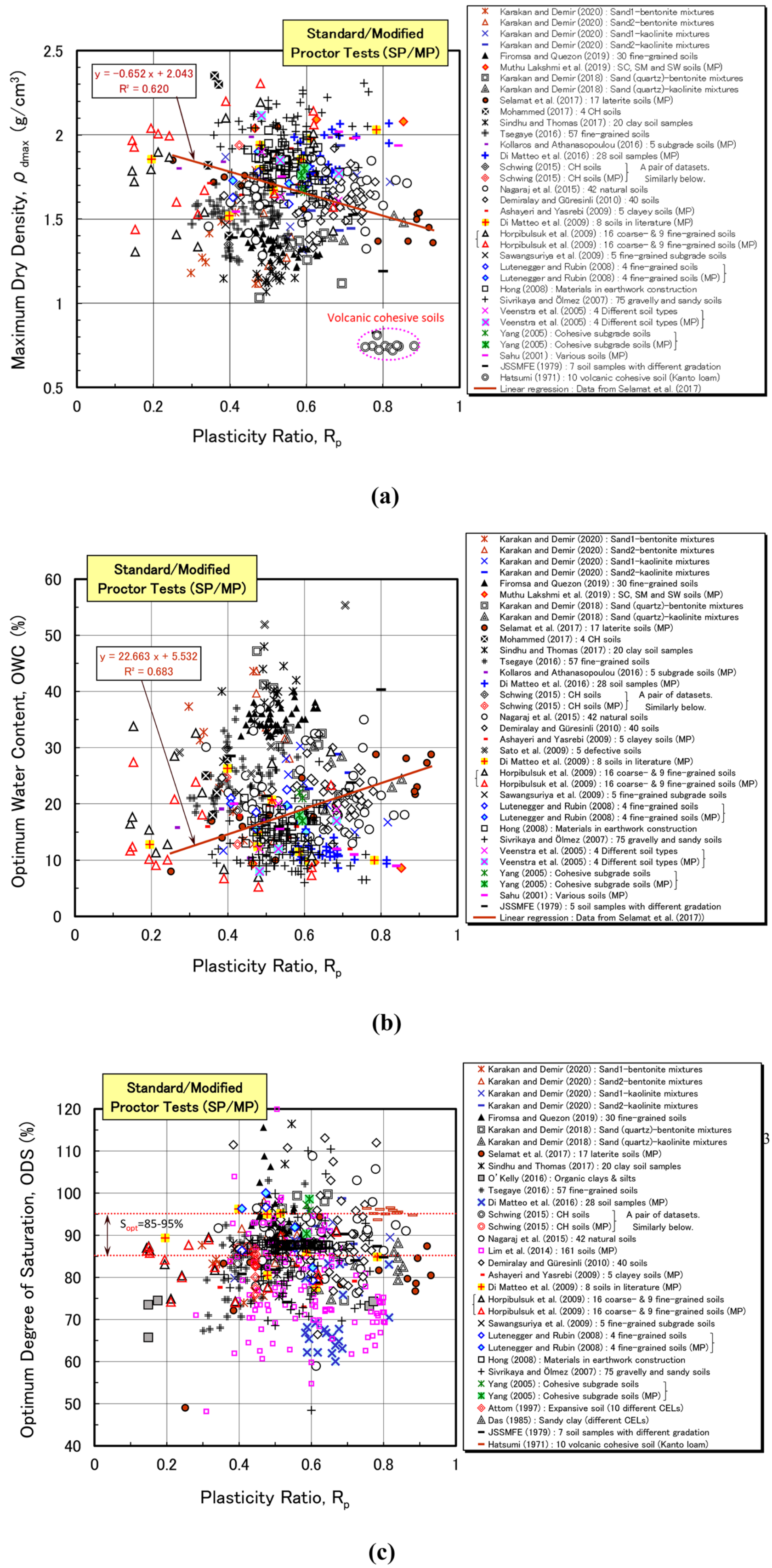


Table 2 Correlations between *MDD* and *PL* obtained by use of standard (SP) and modified (MP) Proctor compaction test results

Seq	Author(s)	Soil type and number of samples	Compaction type	Correlation
1	Sridharan and Nagaraj (2005a, b)	64 fine-grained soils	*SP*	$\gamma_{dmax} = 21.46 - 0.23PL$
2	Sivrikaya and Soycan (2009)	156 fine-grained soils	*SP*	$\gamma_{dmax} = 20.90 - 0.21PL$ (black solid line in Fig.9)
3	Ören (2014)	9 clayey soils	*SP*	$\gamma_{dmax} = 19.2 - 0.168PL$
4	Nagaraj et al. (2015)	57 natural sandy and clayey soils	*SP*	$\gamma_{dmax} = 20.82 - 0.17PL$ [Wang and Yin (2020) recommend highly as the prediction model for MDD in the literature]
5	Selamat et al. (2017)	17 lateritic soils	*MP*	$\gamma_{dmax} = 20.94 - 0.215PL$
6	Firomsa and Quezon (2019)	50 fine-grained soils	*SP*	$_{dmax} = 1.683 - 0.007PL$

standard Proctor, respectively). Besides, those figures were updated and revised based on data provided by Spagnoli and Shimobe (2020).

Comparing the MDD_{SP} and MDD_{MP} values along with those in literature (Humdani 1987; Al-Badran and Schanz 2014; Khalid and Rehman 2018 and including the relations combined after Fleureau et al. 2002; Sivrikaya et al. 2008), it was observed that the whole data was scattered around the line of equality. This behavior is compatible with the trend presented by linear equation from data of Horpibulsuk et al. (2009). In this regard, the use of the following relationship is possible and plausible:

$$1.0MDD_{SP} < MDD_{MP} \leq 1.30MDD_{SP} \tag{20}$$

The *MDD* values obtained by application of standard Proctor tests are much lower. However, a reverse behavior was observed in comparison of OWC_{SP} and OWC_{MP} with those in literature. All the experimental results are well below the line of equality. In this case, extrapolating the equation suggested using data from Horpibulsuk et al. (2009), OWC_{SP} values are computed to be considerably higher.

Normalization of compaction curves

The degree of compaction ($D_c = \rho_d / MDD$) is an important parameter for clarification of the compaction behavior and practical use. Using the experimental results obtained by

Table 3 Correlations between *OWC* and *PL* from standard *(SP)* and modified Proctor *(MP)* test data

Seq	Author(s)	Soil type and number of samples	Compaction type	Correlation
1	So (1999)	43 volcanic cohesive soil	SP	$OWC = 0.9735PL + 14.20$
2	Gurtug and Sridharan (2002)	86 fine-grained soils	SP	$OWC = 0.92PL$
3	Gurtug and Sridharan (2004)	181 compaction data	SP	$OWC = (1.95 - 0.38\log CE)PL$
4	Sridharan and Nagaraj (2005a, b)	64 fine-grained soils	SP	$OWC = 0.92PL$
5	Sivrikaya (2008)	156 fine-grained soils	SP	$OWC = 0.94PL$
6	Sivrikaya et al. (2008)	130 fine-grained soils 63 fine-grained soils	SP MP	$OWC = 0.94PL$(SP) $OWC = 0.69PL$ (MP) (red solid line in Fig. 10)
7	Sivrikaya and Soycan (2009)	156 fine-grained soils	SP	$OWC = 0.92PL$ (black solid line in Fig. 10)
8	Ören (2014)	9 clayey soils	SP	$OWC = 0.596PL + 8.57$
9	Ng et al. (2015)	9 soil samples from various sites	SP	$OWC = 1.204PL + 16.98$
10	Nagaraj et al. (2015)	57 natural sandy and clayey soils	SP	$OWC = 0.76PL$ [Wang and Yin (2020) recommend highly as the prediction model for OWC in the literature]
11	Saikia et al. (2017)	40 natural fine-grained soils	SP	$OWC = 0.742PL + 6.64$
12	Gurtug et al. (2018)	127 fine-grained soils	SP	$OWC = 0.943PL$
13	Firomsa and Quezon (2019)	50 fine-grained soils	SP	$OWC = 0.372PL + 17.243$

Table 4 Correlations among *MDD*, *OWC*, and *PI* from results of standard and modified Proctor tests

Seq	Author(s)	Soil type and number of samples	Compaction type	Correlation
1	Zapata et al. (2007)	43 road materials	SP	$OWC = 1.3(F_cPI)^{0.73} + 11$
2	Noor et al. (2011)	106 fine-grained soils	SP	$\gamma_{dmax} = 27 - PL^{0.6} - PI^{0.33} - \frac{Gs}{2.7}$
3	Koyama et al. (2014)	66 soil samples with different gradations	SP	$MDD = 2.04 - 0.012PI$(SP) (dotted line in Fig. 12a)
4	Koyama et al. (2014)	66 soil samples with different gradations	SP	$OWC = 0.40PI + 5.97$(SP) (dotted line in Fig. 12b)
5	Ng et al. (2015)	9 soil samples from various sites	SP	$MDD = 2.845 - 0.073PI$
6	Ng et al. (2015)	9 soil samples from various sites	SP	$OWC = 2.726PI - 27.19$
7	Tsegaye et al. (2017)	56 natural fine-grained soils	SP	$\gamma_{dmax} = 21.182 - 0.18PL - 0.027PI$
8	Tsegaye et al. (2017)	56 natural fine-grained soils	SP	$OWC = 0.916PL - 0.03PI - 0.875$
9	Khalid and Rehman (2018)	156 fine-grained soils	SP MP	$\gamma_{dmax} = 18.17 - 0.061PI$(SP) $\gamma_{dmax} = 19.22 - 0.40PI$ (MP) (black and red solid line in Fig. 12a, respectively)
10	Khalid and Rehman (2018)	156 fine-grained soils	SP MP	$OWC = 0.20PI + 12.85$(SP) $OWC = 0.082PI + 10.80$ (MP) (black and red solid line in Fig. 12b, respectively)

authors and data published in the literature, the normalized water content ($w^{\#} = w/OWC$) and degree of compaction in Fig. 20a and normalized degree of saturation ($S^{\#} = S_r/ODS$) with the degree of compaction in Fig. 20b were obtained. In addition, $D_c = 0.95MDD$ line was also added in Fig. 20a, b (Nowak and Gilbert 2015). This line ($D_c = 0.95MDD$) was added to ensure compaction quality control of the soils. The degree of compaction can be expressed as shown in Eq. 21 (Shimobe and Spagnoli 2020):

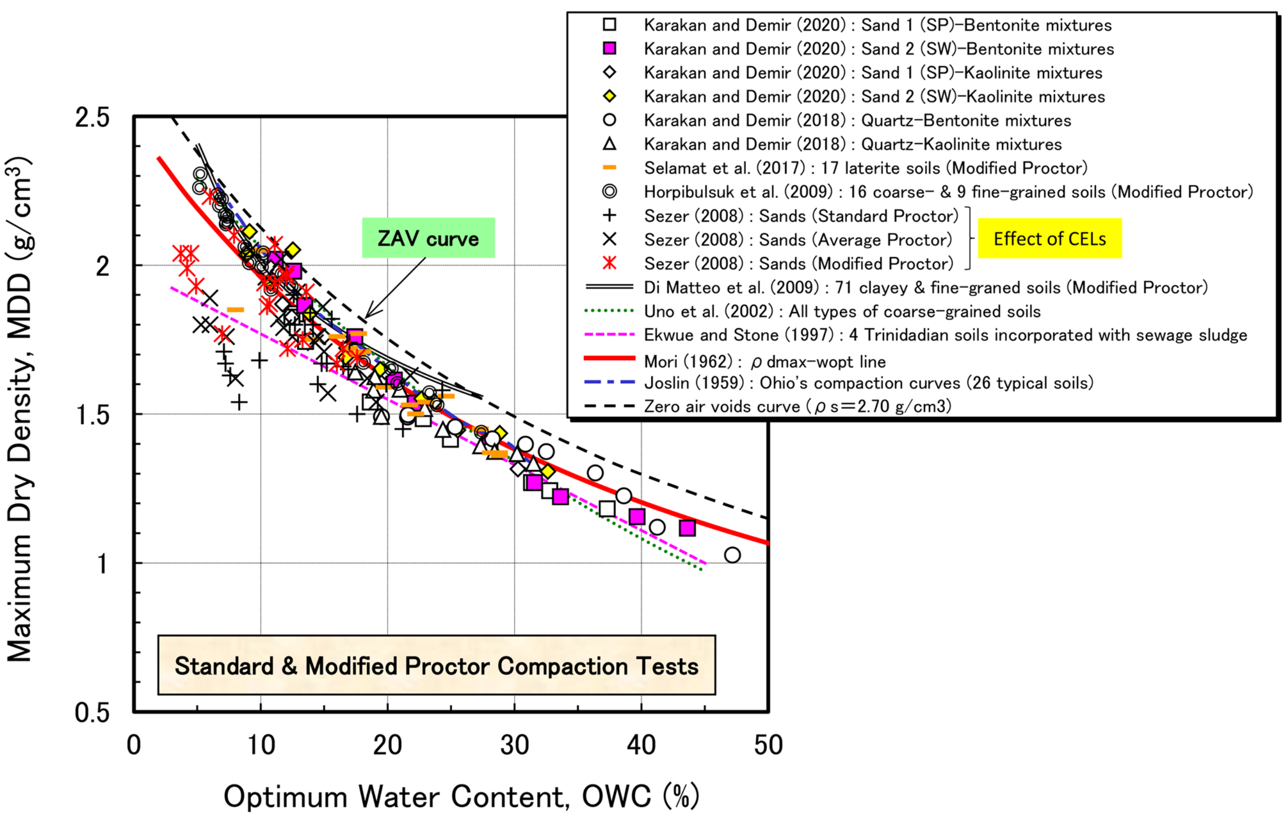


Fig. 14 Correlations between *MDD* and *OWC* for standard/modified Proctor compaction tests

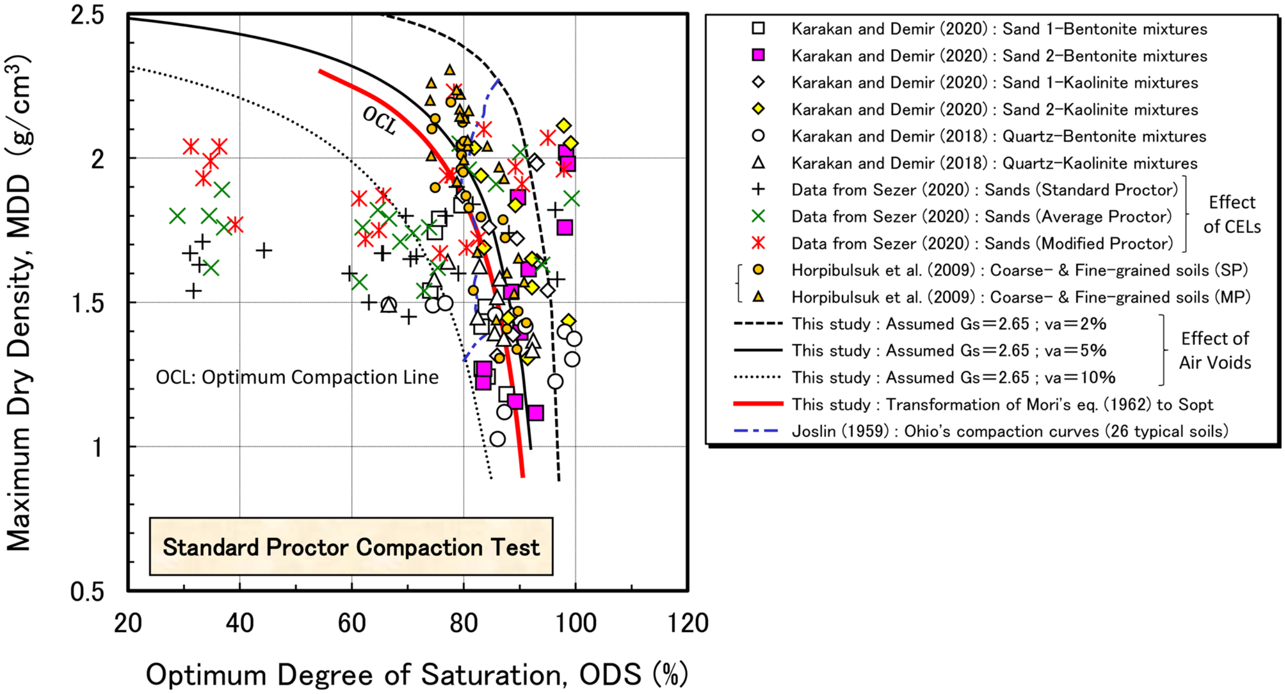


Fig. 15 Correlations between maximum dry density (*MDD*) and optimum degree of saturation (*ODS*)

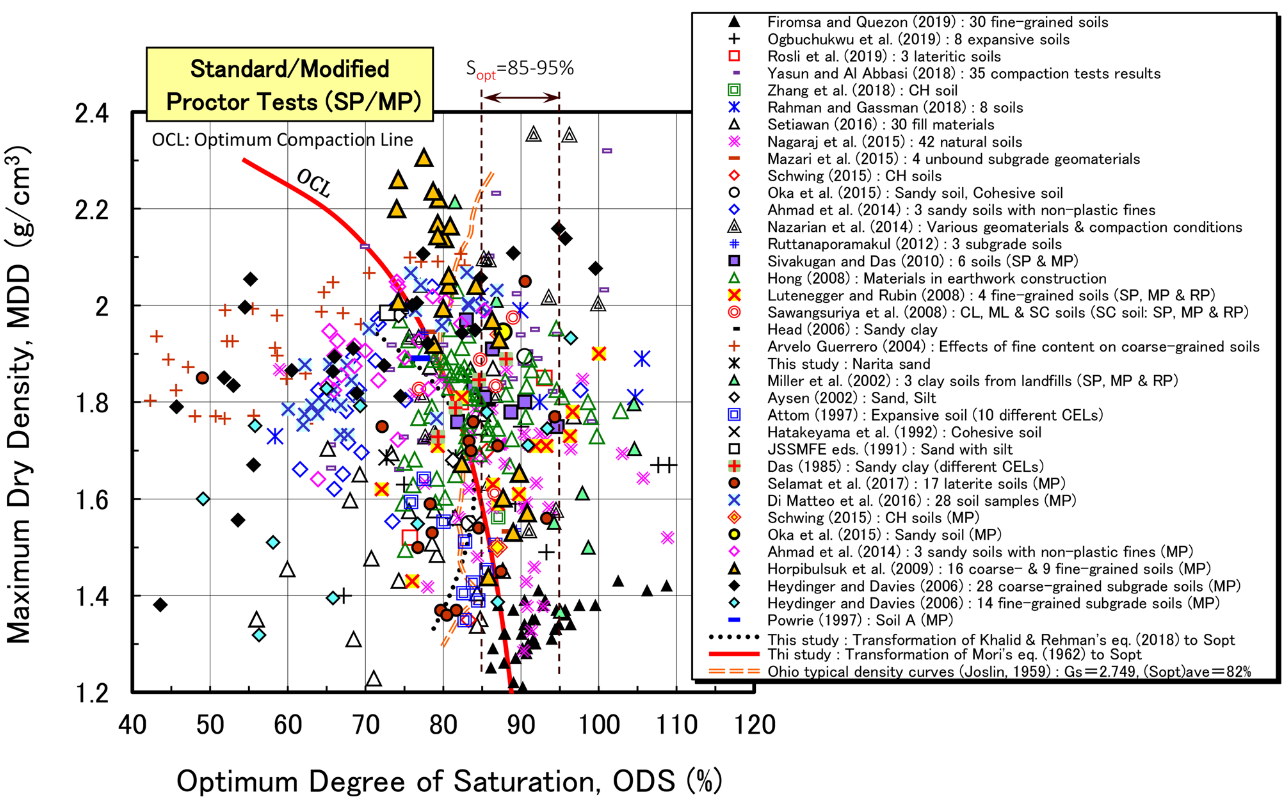


Fig. 16 Various correlations between *MDD* and *ODS* from a large number of works of literature

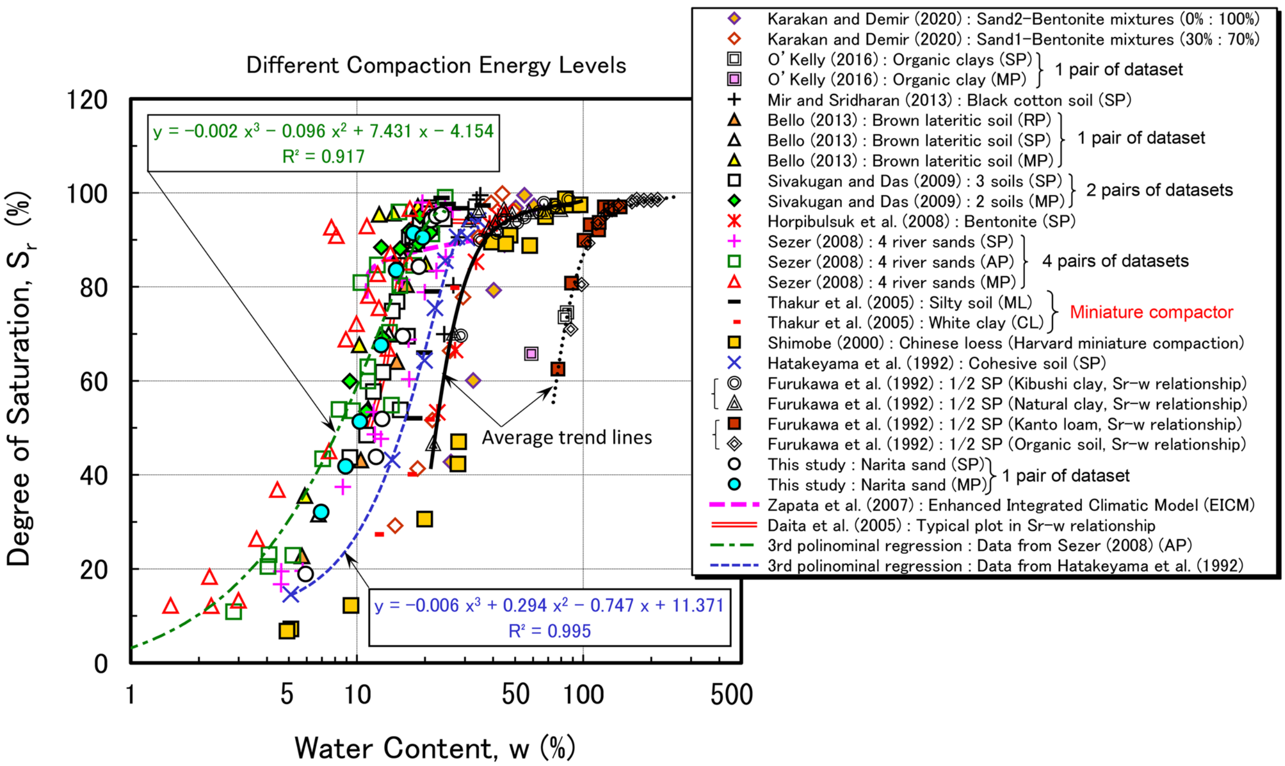


Fig. 17 Degree of saturation S_r—water content w relationships

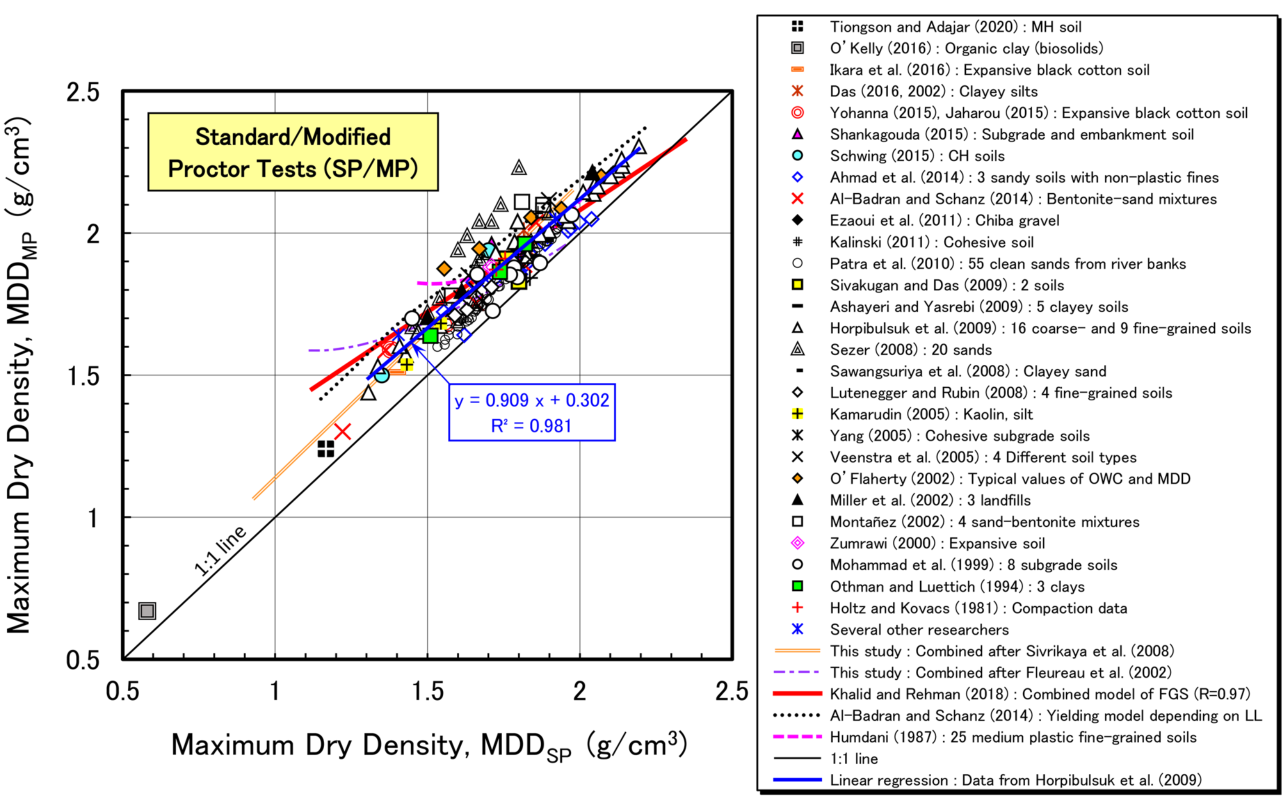


Fig. 18 Comparison of *MDD* values from standard and modified Proctor tests

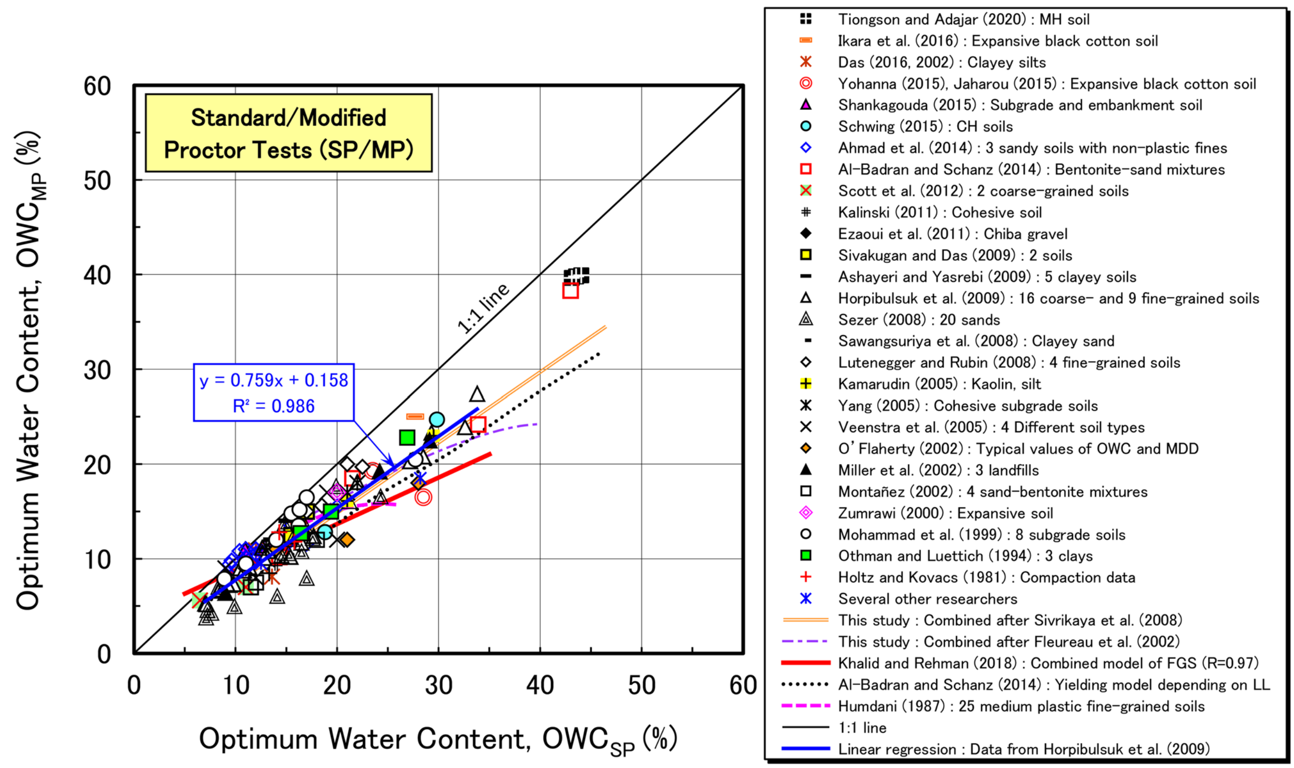


Fig. 19 Comparison of optimum water content in standard and modified Proctor compaction tests

$$D_c = \frac{\rho_d}{MDD} = \frac{1 + \frac{S^\#}{w^\#} * e}{1 + e} \tag{21}$$

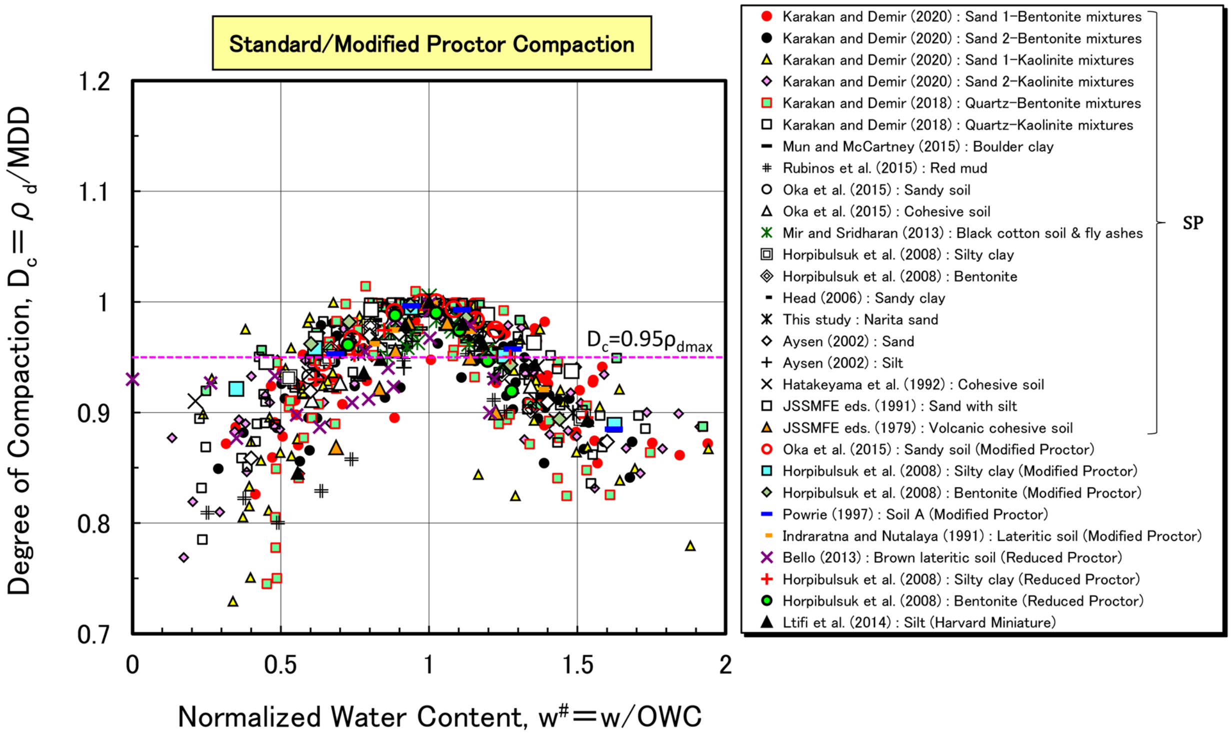
According to Eq. 21, the degree of compaction (D_c) varies depending on the void ratio (e), normalized degree of saturation ($S^\#$), and normalized water content ($w^\#$). D_c-$w^\#$ relationship shown in Fig. 20a replicates the behavior of an ordinary *MDD-OWC* relationship, which seems like a family of compaction curves. On the other hand, D_c-$S^\#$ relationship shown in Fig. 20b is shaped like a boomerang, showing a more scattered behavior, including more outliers. In the D_c-$w^\#$ relationship obtained in Fig. 20a, the normalized water content varied between 0 and 2, while the normalized degree of saturation varied between 0 and 1.5 in the D_c-$S^\#$ relationship obtained in Fig. 20b. This shows that the D_c-$w^\#$ relationship is much more affected not only by the soil type but also by the compaction energy level. This trend varies at the outside of the range between 90 and 110% of the optimum water content (*OWC*), while at the normalized degree of saturation ($S^\#$), it is at the outside of the range between 85 and 95% of the optimum degree of saturation (*ODS*). In this case, an increase in water content or degree of saturation means that the peak dry density cannot be achieved unless the normalized water content or normalized degree of saturation takes values between 0.85 and 0.95. These experimental results are also consistent with the results obtained in the literature by Drnevich et al. (2007), Shimobe and Spagnoli (2020), and Spagnoli and Shimobe (2020).

By the way, we tried to interpret the D_c-$S^\#$ relationship shown in Fig. 20b with the help of previous research results phenomenologically. Horpibulsuk et al. (2008) proposed that on the dry and wet sides of optimum, the more general relationships between the water content (w) and the degree of saturation (S_r) at a specific compaction energy were expressed by the power function as follows:

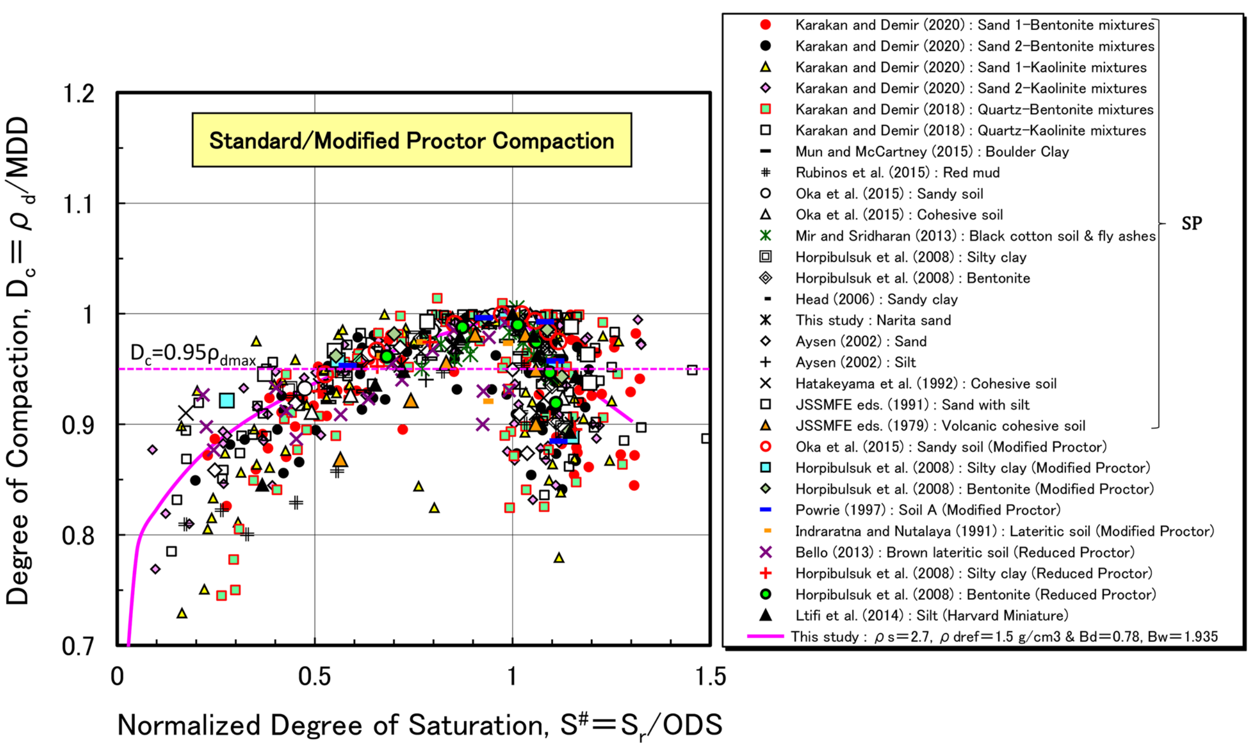
$$w = A_d S_r^{B_d} \text{ for the dry side of optimum } (w < OWC) S_r < ODS \tag{22}$$

$$w = A_w S_r^{B_w} \text{ for the wet side of optimum } (w > OWC) S_r > ODS \tag{23}$$

where A_{d}, B_{d}, A_{w}, and B_{w} are the experimental constants. The w and S_{r} are represented in percentage and decimal, respectively. According to them, the constants A_{d} and A_{w} control the *MDD,* and also the *MDD* increases (the *OWC* decreases) with decreasing A_{d} and A_{w} values. On the other hand, the constants B_{d} and B_{w} are dependent on soil type and irrespective of *CEL*s.



(a)



(b)

Fig. 20 Correlations between degree of compaction and **a** normalized water content and **b** normalized degree of saturation

Pay attention to the ratio of the normalized parameter ($S^{\#}/w^{\#}$) in Eq. 21, the ratio can be rewritten using Eqs. 22 and 23 as follows:

$$\frac{s^{\#}}{w^{\#}} = (S^{\#})^{1-B_d} \text{ for the dry side of optimum} \tag{24}$$

$$\frac{s^{\#}}{w^{\#}} = (S^{\#})^{1-B_w} \text{ for the wet side of optimum} \tag{25}$$

Re-examining the experimental data presented by Horpibulsuk et al. (2008) in detail, since the constants B_d and B_w were insensitive to soil type unexpectedly, we used 0.78 and 1.935 as those average values in the SP and MP compaction energy levels, respectively. Thereby, the degree of compaction D_c is governed by two influence factors (i.e., void ratio e and normalized degree of saturation $S^{\#}$) as:

$$D_c = f\left(e, S^{\#}\right) \tag{26}$$

Moreover, rewriting Eq. 26 by dry density $\rho_d\left(e = \rho_s/\rho_d - 1\right)$

$$D_c = \frac{\rho_d + \left(\rho_s - \rho_d\right) \cdot (s^{\#})^{0.22}}{\rho_s} \text{ for the dry side of optimum} \tag{27}$$

$$D_c = \frac{\rho_d + \left(\rho_s - \rho_d\right) \cdot (s^{\#})^{-0.935}}{\rho_s} \text{ for the wet side of optimum} \tag{28}$$

If the soil particle density is assumed $\rho_s = 2.70 g/cm^3$ and any dry density is given as reference value (e.g., $\rho_{dref} = 1.0, 1.5 \text{and} 2.0 g/cm^3$), the trend lines for D_c-$S^{\#}$ relationships are obtained using Eqs. 27 and 28. Figure 21 shows the typical example for several soils and for a wide range of soils; the proposed model is also shown in Fig. 20b with an average reference value of $\rho_{dref} = 1.5 g/cm^3$. From these figures, this model will be useful in interpreting the D_c-$S^{\#}$ relationships phenomenologically.

Additionally, the plots of ODS_{MP} against ODS_{SP} values obtained from standard and modified Proctor tests are given in Fig. 22. Nagaraj et al. (2006) yielded the same *ODS* value for different fine-grained soils compacted under the same energy and indicated that the *ODS* increased with *CEL*s (e.g., *ODS* = 81.6, 83.3% for SP and MP compaction energies, respectively). However, from this figure, it is evident that the *ODS* values are dependent on soil types, and also most of the ODS_{MP}—ODS_{SP} plot data falls within a range of ± 10% of the line of equality. This evidence is in agreement with the results of Horpibulsuk et al. (2008, 2009) for coarse- and fine-grained soils.

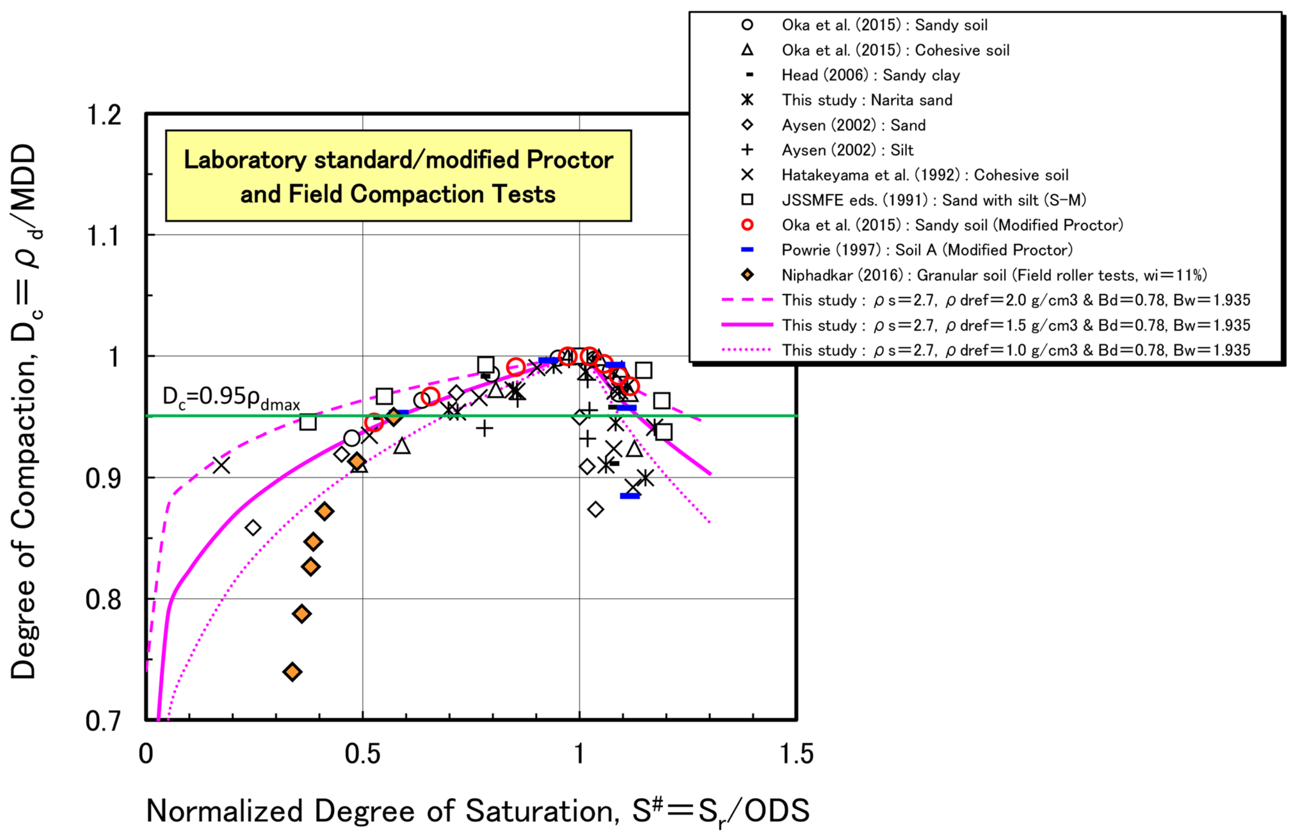


Fig. 21 Correlations between degree of compaction and normalized degree of saturation (proposed phenomenological model)

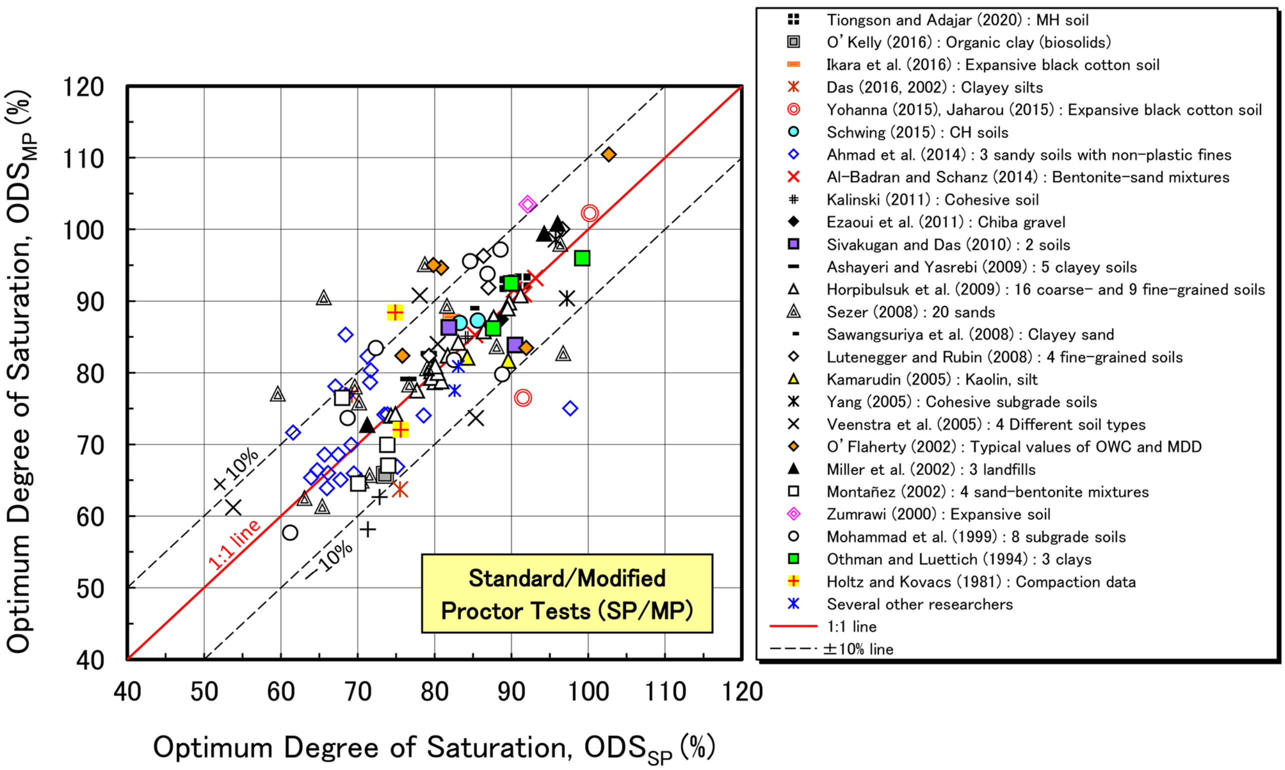


Fig. 22 Correlation for optimum degree of saturation from standard and modified Proctor tests

Lastly, the ratio of MDD_{MP} over MDD_{SP} is defined by (e.g., Rabaiotti et al. 2010; Mujtaba et al. 2014):

$$\alpha = \frac{MDD_{MP}}{MDD_{SP}} \tag{29}$$

where α is a dimensionless parameter. Figure 23 presents the variation of α with MDD_{SP}. Analyzing the overall data, it is understood that α values substantially decrease with increasing MDD_{SP}, and the values of α seem to be ranging from 1.3 to 1.0. The database also includes sands free of fines (Sezer 2008), which may behave differently from the rest of the data due to the effects of fines. Similar comments can be made for cement-admixed gravel data by Ezaoui et al. (2011). It is hard to generalize the overall behavior with the limited number of data from pure granular soils. For different coarse-grained soils, Rabaiotti et al. (2010) proposed $\alpha = 1.075$–1.031, Mujtaba et al. (2014) also suggested $\alpha = 1.072$–0.785 for 120 sandy samples. For 105 fine-grained soils, Farooq et al. (2016) presented $\alpha = 1.08$–1.07. On the other hand, the ratio of OWC_{MP} to OWC_{SP} is defined by the parameter β (Mujtaba et al. 2014):

$$\beta = \frac{OWC_{MP}}{OWC_{SP}} \tag{30}$$

Figure 24 shows the dependence of dimensionless parameter β on OWC_{SP}. It should be stressed that β ranges between 1.1 and 0.6, and decreases exponentially by increasing OWC_{SP}. According to Mujtaba et al. (2014), they indicated the values of β ranging from 1.054 to 0.787 for 120 sandy samples. Farooq et al. (2016) presented $\beta = 0.83$–0.80 for 105 fine-grained soils. Besides, for reference, the trend lines for these dimensionless parameters α and β combined based on the previous several research results (Humdani 1987; Fleureau et al. 2002; Gurtug and Sridharan 2004; Sivrikaya et al. 2008; Al-Badran and Schanz 2014; Khalid and Rehman 2018) are also depicted together in Figs. 23 and 24. From these figures, the general trend of these correlations seems that the combined lines (in red solid lines) based on the results of Khalid and Rehman (2018) is roughly fitted to the entire data.

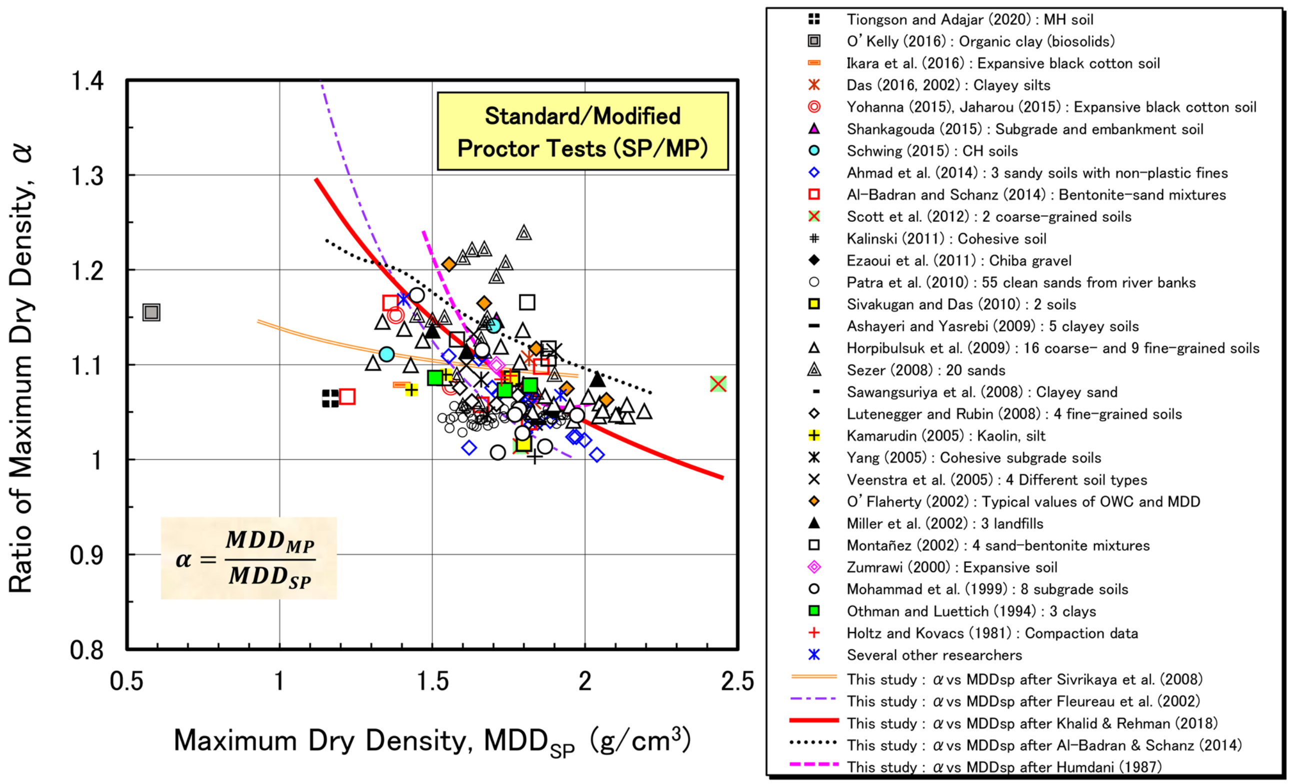


Fig. 23 Variation of parameter α with MDD_{SP}

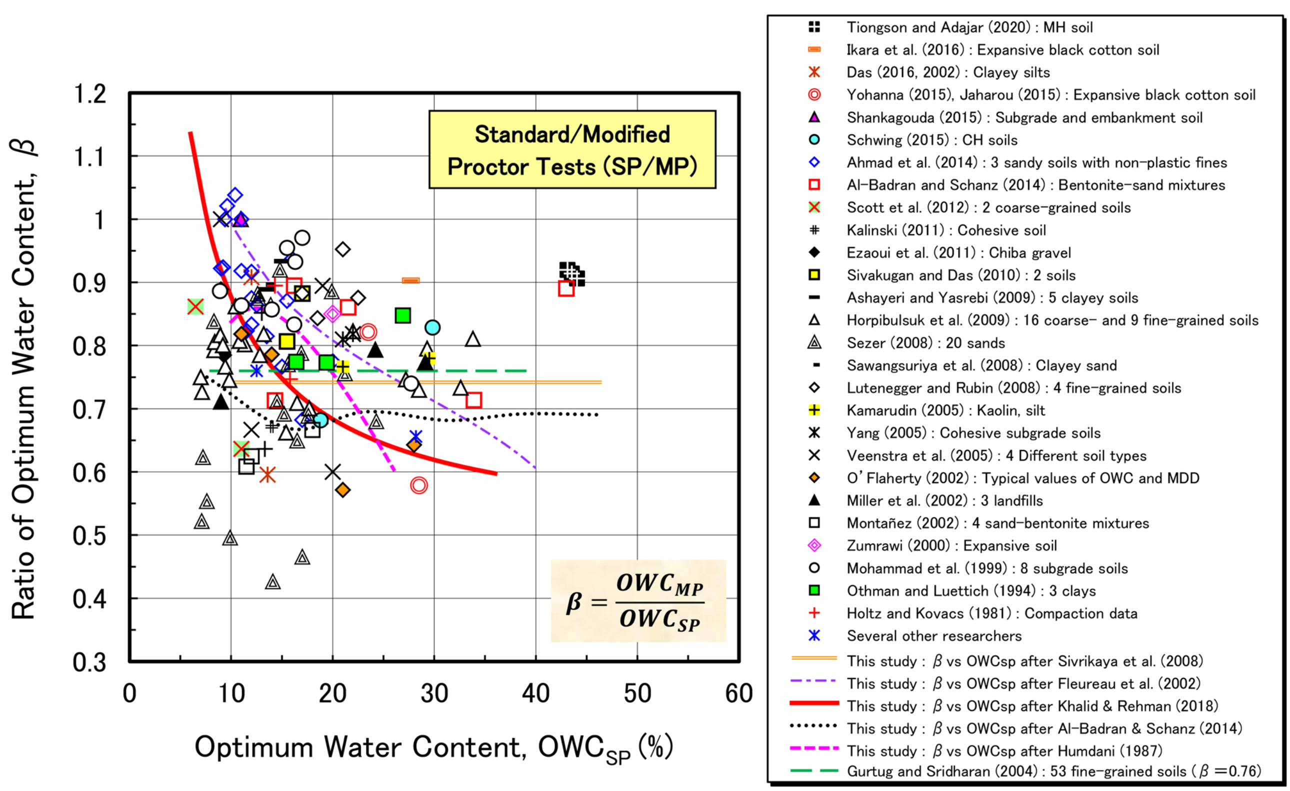


Fig. 24 Change of parameter β with OWC_{SP}

Conclusions

In this study, a vast amount of data was used to obtain practical relationships among compaction and index identifiers. The following conclusions can be drawn from the analysis of results:

1. Analyzing Figs. 14 and 15, although they may include significant amounts of fine sands, it is evident that data from pure granular materials seem to change the trend obtained from other studies. Besides, Figs. 6, 7, 8, 9, and 10a include data from volcanic soils with geotechnical peculiarity, which are outliers to trends obtained from the rest of the data. Therefore, great care was taken to evaluate the data as a whole, and a data from a certain source which is inconsistent with the rest of the data in hand was not permitted to the effect on the overall behavior.
2. The degree of compaction can mostly be expressed by three parameters: void ratio, normalized water content, and normalized degree of saturation. Experimental results show that the effect of normalized degree of saturation on the degree of compaction is greater than that of normalized water content. Finally, according to the proposed phenomenological model, the degree of compaction is governed by the two-state parameters (void ratio or dry density, normalized degree of saturation).
3. Data composed of roughly 300 points were used to determine relationships among *MDD*–F_c and *OWC*-F_c. In this regard, a vast amount of data covering results of tests on many types of soils including sand-clay mixtures, expansive clays, natural soils, and silt-sand-clay mixtures were compiled. The results reveal that the threshold fines content corresponding to *MDD-OWC* of soil is 10%. As expected, *MDD* increases up to this threshold level and later shows a decreasing trend by increasing fines content.
4. Second-order polynomial relationships between saturation level (S_r) and water content were obtained for sand-clay mixtures, including clays of different plasticity values (kaolin and bentonite). For sand2-bentonite mixtures, at a S_r value of 100%, while water content corresponding to 10% of bentonite content is in the vicinity of 20%, it increases up to 60% by increasing bentonite content to 100%. A similar trend is observed in sand2-kaolin mixtures, for a S_r value of 100%, while water content of mixtures composed of 10% kaolin and 90% sand2 is 15%, keeping the S_r value constant, water content goes up to 45% by increases in kaolin content up to 100%.
5. An exponential relationship is obtained between the maximum dry density (*MDD*) and liquid limit (*LL*) of soils. While *MDD* value is decreased from 2.5 to 1.4 g/cm^3, *LL* is increased from 10 to 100%. On the other hand, the relationship between *OWC* and *LL* is linear and these values are directly proportional. Herein, the *LL* corresponding to an optimum water content (*OWC*) of 31% in quartz-kaolinite mixtures is 60%. For quartz-bentonite mixtures, a *LL* of 150% is recorded for a 47% *OWC* value. This is a proof of the dependence of behaviors of sand-clay mixtures on clay mineralogy. Moreover, the variation of *OWC* by applied compactive effort is also proved. It is clear that, for a constant compaction energy level, *OWC*s from standard Proctor tests are greater than those obtained from modified Proctor tests.
6. An inverse linear relationship was observed between *MDD* and *PL*. As *PL* increases, *MDD* value linearly decreases. It was observed that, when *PL* is less than 20%, *MDD* is ranged between 1.5 and 2.3 g/cm^3. Increase in plastic limit roughly decreases *MDD* to half of these values. The variation of *OWC* with *PL* is similar to the one between *OWC* and *LL*. For a constant *PL* value, *OWC*s from standard Proctor tests are greater than those obtained from modified Proctor tests. Besides, for plastic limits ranging between 10 and 30%, the *OWC-PL* relationship is concentrated within a very narrow range, regardless of the compaction energy. As *PL* is increased, the difference among *OWC*s of standard and modified Proctor tests is increased.
7. The degree of saturation (S_r) is dependent on water content and applied compaction energy. For higher S_r values (> 80%), the water content values range between 10 and 200%, plotting the data in hand along with four relationships from literature, it is understood that a single relationship is far from explaining the dependence of S_r on *w*.
8. In addition to the analyses above, relationships among *MDD-PI* and *OWC-PI* obtained from standard and modified Proctor test results were also investigated. While *MDD* values decreased from 2.0 to 1.6 g/cm^3 for an increase of *PI* from 0 to 60 under standard Proctor compactive effort, *MDD* values decreased from 1.8 to 1.3 g/cm^3 under modified Proctor compactive effort.
9. Most of the plasticity ratio (R_p) values are concentrated between 0.4 and 0.8, and *MDD* values are clustered in a range from a very low value of 1.03 to 2.36 g/cm^3. In essence, these *MDD* values are scattered in a very broad range. Although there seem to be linear relationships among *MDD*, *OWC,* and *ODS* vs. R_p, the expressions and corresponding values are from past studies, and the strength of the relationships proposed is far from describing the overall behavior. Analyzing the relationship between *OWC* and R_p, it is evident that

the *OWC* values change abruptly with the change in soil class, which also provides a wide scattered data between these parameters. Similar comments can be made for *ODS* and R_p; *ODS* values are accumulated between 48 and 120%, which is far from providing an exact relationship, when plotted against R_p. It should be noted that the range of *ODS* between 85 to 95% comprises the majority of the data in hand.

10. Experimental results reveal that *MDD*s from modified Proctor tests are greater than those obtained from standard Proctor tests. While the plot of MDD_{MP} against MDD_{SP} values is scattered above the line of equality, an opposite behavior is observed for corresponding *OWC* values where the plots retain well below the line of equality.
11. For a certain compaction energy, excluding clean sands, *MDD* values drastically decrease after a *ODS* value of 80%. When fines content exceeds 10%, *ODS* values roughly range between 80 and 100%. *ODS* values obtained from SP and MP tests are scattered in the vicinity of the line of equality, and the ODS_{SP} and ODS_{MP} plots rarely fall beyond a range of ± 10% of the line of equality.
12. Dimensionless parameters α and β, which are the ratios of MDD_{MP} over MDD_{SP} and OWC_{MP} over OWC_{SP}, respectively, are defined. With the increase in MDD_{SP}, α exponentially decreases from 1.3 to 1.0. While OWC_{SP} increases from 5 to 35%, β also exponentially decreases from 1.1 to 0.6.
13. The main factors' influence on the compaction characteristics of soils are not only the Atterberg limits (consistency characteristics), but also the gradational characteristics. Especially, the former is the plastic limit (*PL*) and the latter is the fines content (F_c), respectively, which seem to have more significant influences on the test results.

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