Received 15 October 2022 | Revised 09 November 2022 | Accepted 10 December 2022
Vol. 03, No. 02, 09 pages

RESEARCH ARTICLE TUJES Tobruk University Journal of Engineering Sciences

Assessment of soil compaction properties: A review

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Abstract. Laboratory determination of the compaction properties of soils is important for use in geotechnical structures. Since compaction properties are normally determined by conducting either standard proctor or modified proctor tests that are laborious and time-consuming, it is useful to review the existing literature where maximum unit weight and optimum moisture content values could be reliably correlated with the indices of soil. This paper reviews literature relating to the soil properties that control the compaction characteristics and introduces some efforts to predict the compaction properties of soils using the index test results. This review was assembled from the existing literature to make an available convenient introduction to this subject, which is of interest to engineers in many diverse fields of civil engineering. From the results of many previous studies, it was proven that, with different and acceptable degrees of confidence levels these properties were proven to be successfully used in estimating of the compaction parameters.

Keywords: Compaction characteristics, prediction, soil compaction, unit weight, moisture content.

1 Introduction

Soil improvement is an essential step in the construction of geotechnical projects such as embankments and roads. Compaction is the artificial improvement of the mechanical characteristics of soils to improve their properties. Therefore, even in ancient times, when road constructors were not aware of soil mechanics, it was known that compaction of soil results in improved roads. Soil compaction is the process whereby soil particles are packed closer together minimizing the air volume, hence preventing the air from entering the pores. Accordingly, an increment in strength and reduction in settlement are obtained [1].

The compaction properties of a soil as attained from a laboratory compaction experiment are maximum dry unit weight (γd max) and optimum moisture content (OMC) where the degree of compaction is measured by its maximum dry unit weight and optimum moisture content. In the construction of many earth structures, it is important to assess the suitability of a soil with regard to the compaction properties. Furthermore, such projects require large quantities of soil, and it may be difficult to attain the desired type of soil from one borrow area. Additionally, to conduct the compaction test in laboratory, it requires considerable time and effort [2]. So, for a preliminary assessment of the suitability of soils needed for the project, it is preferable to use the correlation of compaction properties with soil basic indices such as liquid limit, plasticity index, clay content, sand content and moisture content. This paper presents a review of the most important factors that control the compaction characteristics, effect of compaction on soil's properties and examines which of the index properties correlate well with the compaction characteristics.

2 Historical development of soil compaction

Soil compaction by different means has been practiced for ground improvement in road building in the early 18th century (Roman times). The importance of inter-urban travel was realised, and the need for high standard roads arose resulting in establishing of the School for Bridges and Roads and the Engineering Corps in France during that time [1]. In 1765, Pierre-Marie Tresaguet graduated from this school and followed the Roman work developing the road pavement structures with sub-base layers [3]. Meanwhile, Thomas Telford and John Metcalf applied similar design techniques in Britain. A major issue with these techniques was using large stones in the pavement foundation leading to make the pavement building expensive and slow. Later, John McAdam made an important innovation by suggesting a dense layer of small rocks instead of large stones., these layers of small rocks provide equivalent support to a large stone foundation because of the particle interlocking. Due to manual labour that was the primary form of construction, neither the layers of pavement nor the underlying soil received significant compaction. This resulted in the development of compaction equipment in road construction. Following is the system of symbols and their definitions used in the course of this study.

Table 1. The definitions of symbols used in this study.

Symbol	Definition	Symbol	Definition
$\gamma_{d\ max}$	Maximum dry unit weight	G_s	Specific gravity
OMC	Optimum moisture content	S_r	Degree of saturation
γ	Moist unit weight	D_{10}	Effective size
w_c	Moisture content	D_{50}	Mean grain size
LL	Liquid limit	Cu	Uniformity coefficient
PL	Plastic limit	E	Compactive energy

3 Proctor's compaction curve

Between 1928 and 1929, a study was carried out by California Highway Department reported that the uneven degree of compaction is the main reason for the failure of roads [3]. Accordingly, Proctor compaction test for compaction specification was developed. This test has been applied in the laboratory to acquire the compaction characteristics of a soil with a specific gross energy input. To identify the compaction characteristics of a soil, a moist soil is compacted in 3 layers into a cylindrical mould using a hammer falling from a certain height (30.6 mm). This test devised by Proctor is standardised as the standard test for an energy input of 600 kN-m/m3. The test was modified, to simulate heavier compaction equipment in the field, by imparting higher energy input of 2,703 kN-m/m3 and standardised as the modified Proctor compaction test [4]. The dry unit weight can be calculated as:

$$\gamma_d = \frac{\gamma}{1+\frac{w_c}{100}} \qquad (1)$$

The relationship between the maximum dry unit weight and the corresponding optimum moisture content provides a typical c\zompaction curve with an inverted parabolic shape (Fig. 1). Studies have been performed to explain the inverted parabolic shape of the compaction curve. Proctor [5] stated that water has a dual impact of capillarity and lubrication. The researcher explained that for dry soil, due to high capillarity the dry unit weight is lower and as water is added, the capillarity is decreased, and waFter also lubricates the particle interaction increasing the dry unit weight up to the maximum dry unit weight. However, according to Horn [6], it was showed that the concept of lubrication may not apply for all soils, where some soils show higher friction under wet conditions than under dry conditions. Hogentogler [7] suggested that soils go through four phases of wetting during compaction that include: i. hydration, ii. lubrication, iii. swelling and iv. saturation. This justification was based on the formation of a viscous adsorbed water layer on soil grains and its growth with adding water. However, many studies have shown that the adsorbed layer does not form as proposed for most soils [8, 9]. Furthermore, with increasing moisture content above optimum, soils hardly approach full saturation during compaction, but rather reach it with a continual reduction of dry unit weight.

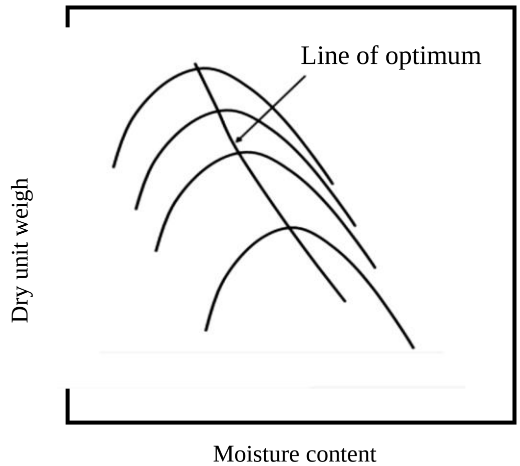

Fig. 1 Compaction curves

4 Principal factors influencing compaction characteristics

4.1 Effect of soil type on compaction behaviour

The soil type in terms of grain-size distribution has a significant impact on the maximum dry unit weight and optimum moisture content. According to Islam [10], unit weight is one of the most important influences on soils containing clay minerals. In the research of Ranjan and Rao [11] sit was reported that the cohesive soil requires more water to reach optimum. In contrast, OMC of sand is obtained either completely dry or saturated condition. However, excessive amount of fines results in reduction in the maximum dry unit weight value of the soil. Das [4] stated that the dry unit weight for sands has a general tendency first to reduce with increasing moisture content, and then to increase to a maximum value with further increase in moisture. The initial reduction in the dry unit weight with increasing of moisture content could be due to the effect of capillary tension. At low moisture contents, the capillary tension in the pore water prevents the soil particles from moving around and being densely compacted.

Doumi, Taiba [12] studied the impact of gradation parameters on compaction of sand-silt mixtures by conducting laboratory experiments. It was concluded that gradation of sand is one of the most important parameters that has an impact on soils during the process of compaction. The results indicated that the maximum dry unit weight of the samples increased with the decrease of effective size (D10) and mean grain size (D50).

4.2 Effect of consistency limits on compaction behaviour

According to Casagrande [13], the engineering behavior of fine-grained soils depends on their plasticity properties rather than on particle size. Consistency limits (liquid limit and plastic limit) are moisture contents at which marked changes occur in the engineering behavior of fine-grained soils. Based on a study conducted by Malizia and Shakoor [14] it was found that an increase in the plasticity of clay caused a decrease in the maximum unit weight and an increase in the optimum moisture content. The authors attributed this behavior to that high plasticity clays have stronger inter-particle bonds and, therefore, require more water to facilitate inter-particle movement to achieve maximum dry unit weight.

4.3 Effect of compaction energy on compaction behavior

Compaction energy is an additional significant parameter that influences the engineering properties of soil. As the compaction energy increases, the maximum dry unit weight increases in a decreasing rate, while the optimum moisture content decreases [15]. The effect of varying compaction effort on shear strength, swelling pressure and permeability of cohesive soil was investigated by Attom [16]. It was observed that with increasing the compaction energy, there was an increase in the shear strength on dry side of optimum moisture content, while there was a slight or no impact on the unconfined compressive strength when the moisture content of the soil is above the optimum. In addition, increasing the compactive energy at the dry side of the optimum reduced the permeability and increased the swelling pressure of the compacted soil. If the compaction energy increases the compaction curve is shifted to the left side and to the top as shown in Figure 1. However, as the moisture content increases the impact of compaction energy on dry unit weight reduces. If the peaks of the compaction curves for different compactive energies are joined the obtained line is called line of optimum.

5 Changes in soil properties due to compaction

Many researchers agree that the densification through soil compaction changes the characteristics of soil such as soil structure, shear strength, swelling pressure and permeability. These properties are modified due to the diminution of the void ratio resulted from soil compaction.

5.1 Effect of compaction on soil structure

Soil compacted at a moisture content less than the optimum moisture content generally have a flocculated structure whereas that compacted at a moisture content more than the optimum moisture content usually have a dispersed structure [17]. On the dry side of the optimum, the moisture content is so low that the attractive forces are more predominant than the repulsive forces resulting in flocculated structure. As the moisture content is increased beyond the optimum, the repulsive forces increase, and the particles get oriented into the dispersed structure. If the compaction effort is increased, there is a corresponding increase in the orientation of the particles and higher dry unit weights are obtained.

5.2 Effect of compaction on shear strength

Generally, the compaction influences the soil strength where the increment in the soil unit weight can lead to strengthen the soil [18, 19]. According to the study performed by Sadek, Chen [20], it was concluded that, the denser soil means the higher shear strength values. The strength of soils compacted at high unit weight decreases with the increase in the moisture content while those compacted at low unit weights increases with the increase in the moisture content to a point and then levels off depending on the clay content, valence of the cations, cation exchange capacity, etc. [21, 22] . The results from Hamidi, Alizadeh [23], Dadkhah, Ghafoori [24], Chenari [25], Farooq, Rogers [26] and Tabibnejad, Heshmati [27] showed that both of friction angle and cohesion increased with the increment of the unit weight. This behaviour, as explained by Alshameri, Madun [28], could be due to the inter-granular void ratio where it explains the relationship between the fine content, coarse content and void ratio. Cho, Dodds [29] emphasized that an increase in unit weight which means reduction in void ratio, will increase friction angle.

5.3 Effect of compaction on swelling pressure

The swelling soils typically contain clay minerals that attract and absorb water. Based on many studies it was found that swelling pressure of swelling soils clearly rises with dry unit weight. In the research of Huang, Wang [30] it was found that the swelling pressure rapidly increased with a low dry unit weight and increased slightly when the dry unit weight was high. According to Sarkar (2015), this behaviour is due to the fact that as the dry unit weight increases which results in a reduction in the interlayer spacing and an increase in the osmotic pressure between the clay platelets, the swelling pressure of the clay increases. Sridharan and Gurtug [31] investigated the compaction behavior of the fine grained soils. The authors noted that the swelling pressure is considerably affected by variation in compaction energy. It was also confirmed that increase in compactive effort significantly improved some engineering properties of soil, but it also revealed an undesirable increase in the swell pressure of soil. A soil compacted dry of optimum moisture content has high water deficiency and more random orientation and hence exert greater swelling pressure and swell to a high moisture content than the soil of the same unit weight that obtained from the wet side [32].

5.4 Effect of compaction on permeability

The effect of compaction is to reduce the permeability. Low permeability is obtained when the soil is compacted at high dry unit weight and a moisture content wet of optimum [33]. The permeability of the soil decreased due to increasing the dry unit weight and better orientation of particles. The reduction is attributed to the larger degree of dispersion in soil structure with higher moisture content [34]. For a given compactive effort, the permeability at wet of optimum moisture content is significantly lower than the permeability at dry of optimum moisture content [35]. Moreover, compaction with higher moulding moisture content results in soil grading that is devoid of macropores (pores being filled with water) which conduct flow [36].

6 Correlation of compaction characteristics with index properties

Compaction parameters can be defined experimentally by Proctor tests or predicted for a preliminary design of a project where there is limited time. Although the compaction properties are very important for construction of many earth structures, few attempts have been made in the past to correlate them with the index properties. Developing engineering correlations between various soil parameters is an issue discussed by many researchers. An early study to predict the compaction properties was made by Johnson and Sallberg [37]. A chart was developed by the authors to determine the approximate optimum water content of a soil using the standard compaction test. It was reported that the chart is a useful in predicting only the optimum water content of the soil from its consistency limits. Another attempt was made by Pandian, Nagaraj [38] to predict the compaction characteristics in terms of the liquid limit. The following two equations were proposed to evaluate the compaction characteristics on the dry side and wet side of optimum.

Dry side of optimum $$\frac{w}{\sqrt{S_r}} = 9.46 + 0.2575\text{LL} \quad (2)$$

Wet side of optimum $$\frac{w}{S_r^2} = 10.61 + 0.3615\text{LL} \quad (3)$$

Pandian's method was proposed for Proctor compaction and for various values of degree of saturation, in the range of 50 % < Sr < 85 % on the dry side of optimum and 85 % < Sr < 95 % on the wet side of optimum. However, this proposed method to predict the compaction properties in terms of the liquid limit alone has some limitations. According to Sridharan and Nagaraj [39], using liquid limit alone in predicting the engineering characteristics of soils is limited where soils having the same liquid but different plasticity properties will behave differently. Sridharan and Nagaraj [39] carried out detailed investigations to find which of the index characteristics correlate well with the compaction properties. From the authors' experimental results, it was found that the compaction characteristics do not correlate well with either the plasticity index or the liquid limit of the soils whereas bear a good correlation with the plastic limit (PL). The following correlation equations are suggested by the authors to predict the compaction characteristics:

$$\text{OMC} = 0.92\text{PL} \quad (4)$$

$$\gamma\text{dmax} = 0.23 * (93.3 - \text{PL}) \quad (5)$$

The findings are consistent with Hasnat, Hasan [40] who found that there are a negative correlation between the maximum dry unit weight and the liquid limit. Furthermore, γdmax values decreased when the PI values increased. This also confirmed by Hussain and Atalar [41] who stated that, the maximum dry unit weight decreases with the increment in the liquid limit. Another study by Günaydın [42] reported that the liquid limit is the most controlling parameter for the estimation of OMC whereas the grain size had more effects on the estimation of γdmax .

In engineering relationships, the correlation coefficient (R) is important to express the degree to which two parameters are varying together. The best correlation is when the coefficient of correlation close to 1. Smith [43] reported that if a proposed model gives a correlation coefficient that is greater than 0.8, a strong correlation would be assumed to exist between measured and predicted values. The study performed by Al-Hamdani, Al-Kasaar [44] showed that some soil properties provided high coefficient of correlation with dry unit weight such as specific gravity and plasticity index while other properties such as liquid limit, plastic limit and moisture content provided low correlation coefficient. The researchers stated that the correlation coefficient is higher when the dry unit weight of soil is correlated with more than one soil properties rather than one property. Additionally, it was concluded that increasing the number of samples used in correlation resulting in higher correlation coefficient. Noor, Chitra [45] incorporated plastic limit (PL), plasticity index (PI) and specific gravity (Gs) to predict the compaction characteristics. The relationships between the dry unit and the geotechnical properties are presented as:

$$\gamma dmax = 27 - PL0.6 - PI0.33 - \frac{G_S}{2.7} \qquad (6)$$

$$OMC = 0.55PL - 0.36PI - \frac{G_S}{2.7} \qquad (7)$$

According to the study of Fondjo and Theron [46] it was found that the maximum dry unit weight decreases by increasing the specific gravity. Based on the justification provided by the authors, the decrement in the maximum dry unit weight could be due to the fact that at the optimum moisture content, the air voids are less and the improvement of the maximum dry unit weight by further addition of water is no longer possible. Based on the compaction results of 22 clayey soils, Blotz, Benson [47] found that the compaction characteristics were best correlated with liquid limit and thus suggesting the following equations:

$$\gamma dmax = (2.27 \log LL - 0.94) \log E - 0.16LL + 17.02 \qquad (8)$$

$$OMC = (12.39 - 12.21\log LL) \log E + 0.67LL + 9.21 \qquad (9)$$

KS, Chew [48] compared the different prediction models and it was concluded that Noor model provides the best model compared to Blotz et al. and Sridharan.

The coefficient of uniformity (Cu) is another influential factor that affects the compaction behaviour and have a significant correlation with the maximum dry unit weight where soil with a value of Cu greater than 4 to 6 is classified as well graded soil whereas that with Cu less than 4, it is classified as poorly graded or uniformly graded soil. A relationship was proposed by Arvelo [15] to correlate the dry unit weight with the uniformity coefficient (Equation 10).

$$\gamma dmax = 87.715 * Cu0.166 \qquad (10)$$

It was observed that this relationship depends on the soil type where for sands with fine content of less than 5 % the increase in the maximum dry unit weight was higher in well-graded sands than in poorly graded sands while for sands having more than 5 % and less than 12 % fine content, the increase was slightly higher in well-graded sands than in poorly graded sands. For soils with fine content of more than 12 %, it was observed that the uniformity coefficient and the maximum dry unit weight of these soils have a maximum value, which tends to reduce by further increase in the fine content. According to the results it was observed that the maximum value was achieved at 20 % fine content for the clayey sands and at 25 % fine content for the silty sands.

These observations are also in accord with those of Fondjo and Theron [46] who found that the maximum dry unit weight value increased when the gravel content increased. The relationship is a linear with correlation coefficient of 0.84. On the other hand, the optimum water content values decreased when the sand content increased. The correlation is a linear function with correlation coefficient of 0.89. As fine-grained content increases, soil particles absorb much more water resulting in increasing the optimum moisture content. On contrast to that, when sand content increases, soil particles absorb less water reducing the optimum moisture content.

Recently, the use of artificial intelligence is receiving an increasing interest in the field of geotechnical engineering. In particular, machine learning algorithms are found very capable to explore nonlinear relationships with high precision [49]. Utilization of Artificial Neural Networks (ANNs) was widely used in several ground studies as an estimation tool, see for instance Das, Samui [50] and Günaydın [42]. Günaydın used 126 experimental results of 9 different soil types and used ANNs method for the prediction of compaction parameters. It was shown that the estimated artificial neural network has powerful correlations (0.84–0.97) between soil classification and compaction parameters.

7 Conclusion

This paper presented a brief review of soil compaction development with special emphasis on the correlations of index characteristics of soils with the optimum moisture content and the maximum dry unit weight. Careful inspection of the technical literature review indicated that the basic properties of soil can successfully be used for estimating the compaction parameters with different degrees of confidence. Strong correlations were achieved by most models. It is recommended that the proposed correlations will be useful for a preliminary design of a project where there is a limited time. According to the aforementioned studies, there is no consensus was reached on which of the index properties correlate well with the compaction characteristics. Therefore, there is a need for a study to address the conflicting opinions. Additionally, the room for development of a predictive model exists which would provide an engineering tool for the prediction of the maximum dry unit weight and optimum moisture content without the need to carry out lengthy experimental programmes. All models from previous research predicted the compaction characteristics with a small number of dataset (less than 250). For future works, more data is required.

Conflict of Interest

This is to certify that the author declares no competing interest.

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