Short Communication

Maximum dry density of sand–kaolin mixtures predicted by using fine content and specific gravity

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Abstract
Numerous studies have covered the comparison of maximum dry density (MDD) toward the combination of soil properties and compaction parameters. These combinations are dominated by Atterberg limits, moisture content, and compaction effort. Nevertheless, minimal efforts have been expended in predicting the MDD using two simple soil properties, i.e., fine content (FC) and specific gravity (G_s). Sand–kaolin mixtures were compacted and then used to examine the correlation between MDD, FC, and G_s through different moisture content, and FC ranged from 20 to 70%. The results showed the importance of considering both G_s and FC in the correlation estimation in order to reduce the uncertainty of using only FC as a single parameter. A linear relationship was obtained with an excellent correlation coefficient ($R^2 = 0.99$) between MDD and the ratio of FC/$G_s{}^2$. The empirical correlation equation was justified using data from 163 measured MDD obtained from previous studies. All predicted MDD were within the confidence interval of ± 10, which confirmed a low error range of the predicted MDD. The application of the equation was limited to FC and FC/G_s less than 77% and 0.302, respectively. It should, however, be noted that the presence of a high amount of gravel in the soil mixture will not be applicable for this correlation.

Keywords Empirical correlation equation · Soil parameters · Compaction parameter · Maximum dry density · Fine content · Specific gravity

1 Introduction

Compaction is a mechanism to rearrange the positions of particles in order to achieve a higher density by determining the maximum dry density (MDD) and optimum moisture content (OMC) [1]. The compaction process is virtually paramount in projects involving road, dam, earthworks, and so on; however, implementation of the laboratory compaction is a time- and effort-consuming process. Therefore, several studies have been conducted to reduce the required time and effort in order to provide the desirable MDD and OMC vis-a-vis, predicting the MDD and OMC using empirical correlation equations. Several studies have correlated MDD with numerous index soil properties and compaction parameters. For example, the MDD was correlated to: (1) A combination of six parameters in Gunaydın [2] using liquid limit, plastic limit, specific gravity, fine content, gravel content, and sand content; (2) A group of five parameters in Bera and Ghosh [3] using compaction energy, specific gravity, liquid limit, plastic limit, and grain size; (3) A combination of four parameters in Karimpour-Fard et al. [4] using optimum moisture content, saturation degree, specific gravity, and unit weight of water also in Di Matteo et al. [5] using optimum moisture content, plastic limit, liquid limit, and specific gravity; (4) A group of three parameters in Omar et al. [6] using specific gravity, fine content, and liquid limit, Farooq et al. [7] using liquid limit, plasticity index, and compaction effort;

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(5) A mix of two parameters in Khalid [8] using plastic and liquid limits; (6) As a single parameter in Sivrikaya [9] and Emmanuel [10] using individual correlations of optimum moisture content, plastic limit, and liquid limit.

In general, using a single parameter in the empirical equation will significantly reduce the cost and time of MDD prediction, but the uncertainty will rise. Emmanuel [10] created an equation to predict MDD using a single parameter; however, the equation showed a scatter in the MDD values (i.e., MDD ranging from 1.56 to 1.22 Mg/m^3) for almost the same OMC value (OMC ≈ 22%). The same was found in a study by Sivrikaya [9], where the same value of liquid limit (LL = 67) produced a similar range of MDD values from 11.5 to 16.5 kN/m^3. On the other hand, combining more parameters will reduce the uncertainty of the empirical equations, as shown in Omar et al. [6], where the error range between the measured and predicated MDD was within 5%. According to Omar et al. [6], among the three parameters (specific gravity, fine content, and liquid limit) that have been used in the correlation, the specific gravity has a greater influence on MDD. The significant effect of the specific gravity was confirmed in the study carried out by Di Matteo et al. [5], Karimpour-Fard et al. [4], and Bera and Ghosh [3] using 4, 4, and 5 soil parameters, respectively, on the MDD predictions.

Moreover, using a combination of only two simple index parameters such as fine content and specific gravity without considering the Atterberg limits to predict MDD produced less effort, as shown in previous studies. Therefore, the presented study examined the implementation of an empirical correlation between the MDD, the fine content, and the specific gravity. The use of simple index properties such as fine content and specific gravity in predicting the maximum dry density can minimize the required effort and time needed to implement a laboratory compaction investigation in comparison with using other soil properties.

2 Compaction materials and test procedures

Sand–kaolin mixtures of 31 samples were compacted under different moisture content ranging from 8 to 24% using fine content (Kaolin) of 70, 60, 50, 40, 30, and 20%. The coarse material was sand with a maximum particle size of 3.35 mm, and grain size distribution of sand, as shown in Fig. 1. The Kaolin was provided by Associated Kaolin Industries SDN BHD in Malaysia with brightness (ISO 24 70) of 76% minimum, particle size (< 2 µm) of 40% minimum, 325 mesh residues (45 µm) of 0.05% maximum and packed in FIBC/Paper Bag. The specific gravity (G_s) of each mixture was measured according to the specifications of ASTM D854 (2010). The measured specific gravity of the mixtures FC = 70, 60, 50, 40, 30, and 20% were G_s = 2.553, 2.563, 2.576, 2.585, 2.597, and 2.61, respectively. Table 1 shows the properties of the mixtures. The void ratio in Table 1 was calculated corresponding to the specific gravity, water density in g/cm^3, and dry density in g/cm^3.

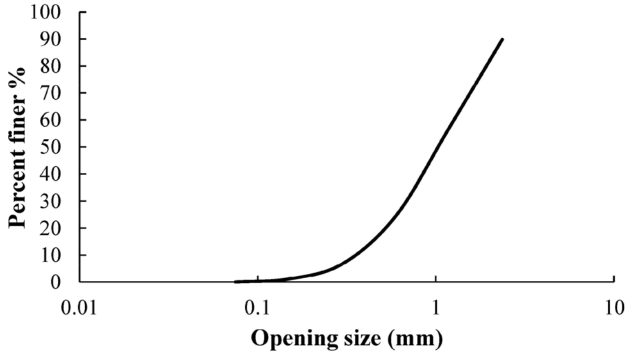


Fig. 1 Particle size distribution curve of sand

The preparation of samples and the procedure for laboratory compaction were in accordance with the standard compaction effort of ASTM D698 [1] using the method B and 6″ mold in the following steps: (1) The coarse material was extracted from the retaining of 0.075 mm sieve and passed 3.35 mm. (2) A dry mixing (of minimum 5 kg for each mixture) was applied for sand–kaolin using a blinder. (3) The desirable water content was added by hand with an interval of 2%. (4) The first layer on 152.4 mm compaction mold was compacted using 56 blows manually. The process was repeated for the second and third layers, respectively. (5) The reused compacted sample was avoided. (6) The compacted sample was extracted and weighed. Then three samples were taken to measure the water content through oven drying. (7) The moist density was evaluated, and the dry density was calculated using Eq. 1:

$$\rho_{\text{dry}} = \frac{\rho_{\text{wet}}}{\left[1 + \left(\frac{w}{100}\right)\right]}, \tag{1}$$

where ρ_{wet} is the bulk density, ρ_{dry} is the dry density of the compaction point, and w is the water content of the compaction point. The result of the compaction curve for each mixture in Fig. 2 showed a decrease in the maximum dry density with an increase in both the fine content and moisture content [2, 11–13]. Increasing the water content lubricates the sliding surface between the sand particles, causing a reduction of particle friction, thereby facilitating the rearrangement of the sand particles closely, while reducing the voids and increasing the density [14]. The presence of the fine content (Kaolin) reduced the interparticle friction surface and facilitated the sand rearrangement [14]. Also, with an increment of the Kaolin content (FC), the voids between the sand particles were filled by

Table 1 Properties of the soil mixtures

Sand (%)	Kaolin (%)	Maximum–minimum dry density (g/cm^3)	Maximum–minimum moisture content (%)	OMC (%)	MDD (g/cm^3)	The specific gravity of sand	The specific gravity of kaolin	The specific gravity of the mixture	Void ratio corresponding to MDD ($e = \frac{\gamma_w G_s}{\text{MDD}} - 1$)
80	20	1.93–1.79	16–8	12	1.93	2.62	2.5	2.61	0.35
70	30	1.89–1.76	16–8	12	1.89	2.62	2.5	2.597	0.38
60	40	1.81–1.72	16–8	12	1.79	2.62	2.5	2.585	0.43
50	50	1.71–1.63	20–10	16	1.72	2.62	2.5	2.576	0.50
40	60	1.64–1.59	22–14	18	1.65	2.62	2.5	2.563	0.57
30	70	1.58–1.52	24–16	20	1.57	2.62	2.5	2.553	0.66

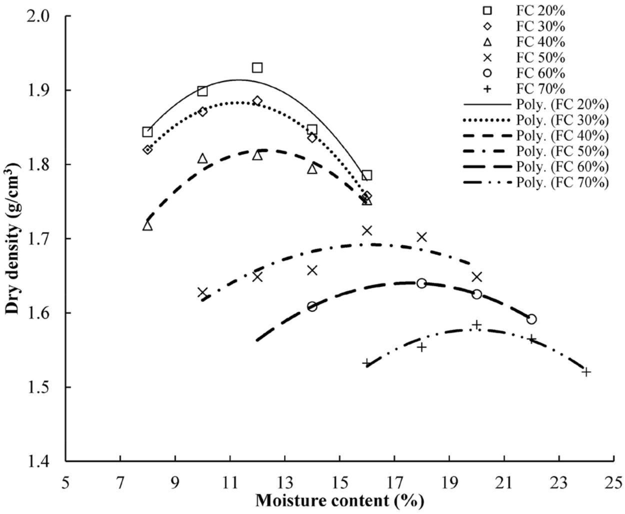


Fig. 2 Compaction curves for the different fine content mixtures

the Kaolin, consequently increasing the density. However, increasing the water content in parallel to the FC developed cohesion forces in the Kaolin [14], which caused a restriction in the movement of both Kaolin and sand particles, thereby accelerating the achievement of the MDD at the same OMC for different FC (FC = 20, 30, and 40%). This behavior is explained by the inter-granular void ratio, which represented the interface between the voids, G_s of fine content, G_s of soil mixture, and fine content toward the physical soil properties [11, 13]. A further increase in the FC and water content (FC ≥ 50% and w% ≥ 16%) using the same coarse material (sand) which has the same specific gravity, the voids will be almost filled, and the effect of the inter-granular void ratio on the physical soil properties and the density will be limited [15]. At this stage, increasing both the water content and FC parallel to decreasing G_s will lead to a decrease in the MDD and an increase in the OMC. This is clearly indicated by the presence of the flattened compaction curves at FC ≥ 50% (see Fig. 2). The optimum moisture content and maximum dry density were both determined, as seen in Fig. 2. The maximum dry density ranged from 1.93 to 1.58 g/cm^3, while the optimum moisture content ranged from 12 to 20%.

3 Predict maximum dry density using fine content and specific gravity correlations

Maximum dry density values selected from the compaction curves in Fig. 2 were used in the correlation. The compaction curves in Fig. 2 indicated that the range of FC was between 20 and 40% and showed the same value of OMC but with different MDD values. This can be explained using the inter-granular void ratio (i.e., the interface between voids, G_s of fine content, G_s of soil mixture, and fine content). Therefore, the direct correlation between the fine content and the MDD in the range of FC 20–40% without considering the void ratio can lead to confusion or uncertainty using the correlation between OMC and MDD, as asserted by Emmanuel [10]. Consequently, the need for adding a parameter that is connected to the void ratio and inter-granular void ratio (i.e., specific gravity) becomes increasingly critical. This will reduce or eliminate the uncertainty in the correlation [3–5, 11–13]. Due to the significant influence of the specific gravity on the compaction parameters [6], the specific gravity was considered in the correlation between the fine content and the maximum dry density [6]. The ratio of fine content to the power of two of the specific gravity (FC/G_s^2) was plotted against the maximum dry density for each mixture in Fig. 3. The results showed a linear relationship between MDD and FC/G_s^2. The highest value of MDD = 1.93 g/cm^3 was located at FC = 20% and G_s = 2.61, whereas the lowest value of MDD = 1.58 g/cm^3 was also located at FC = 70% and G_s = 2.553, while the range of the ratio FC/G_s was between 0.274 and 0.77. The correlation in Fig. 3 provided an empirical equation (i.e., Eq. 2) between the maximum dry density, fine content, and specific gravity, with a high value of correlation coefficient R^2 = 0.99, indicating a strong correlation between the maximum dry density, fine content, and

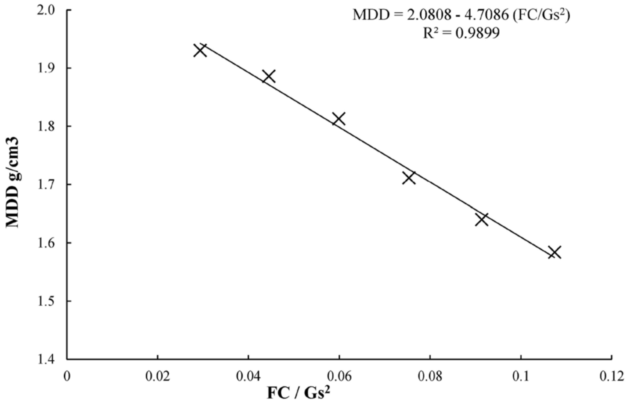


Fig. 3 Maximum dry density toward the ratio of fine content and specific gravity

specific gravity. The results are consistent with the outcomes reported in Karimpour-Fard et al.[4] and Omar et al. [6] using various types of soil.

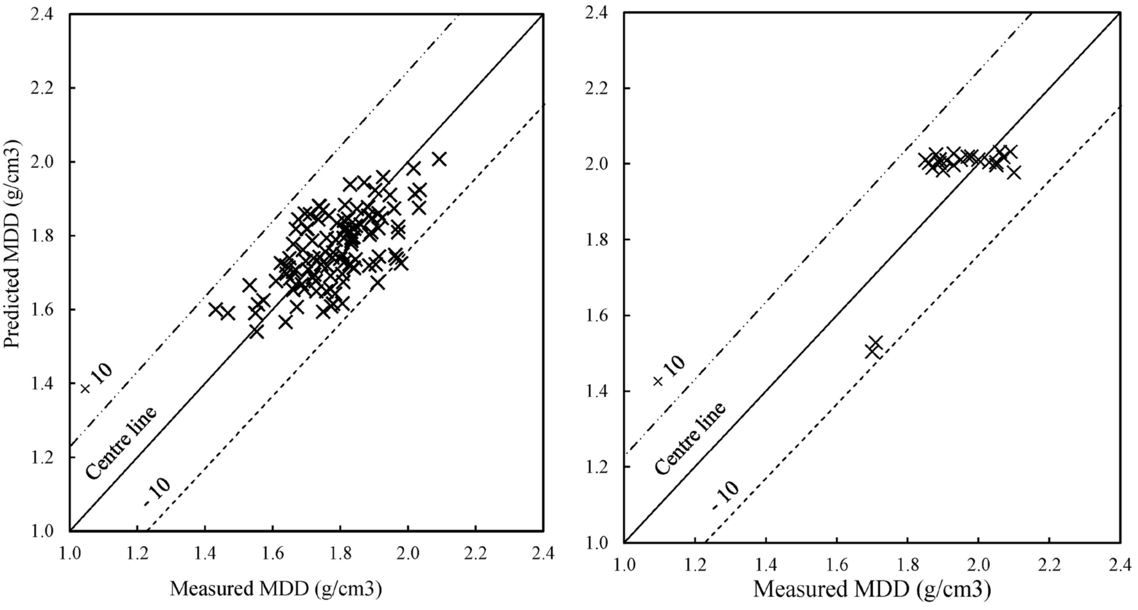
$$\mathrm{MDD} = 2.0808 - 4.7086\frac{\mathrm{FC}}{G_s^2} \quad \left(R^2 = 0.9899\right), \tag{2}$$

where MDD is the maximum dry density in g/cm^3, FC is the fine content in %, and G_s is the specific gravity.

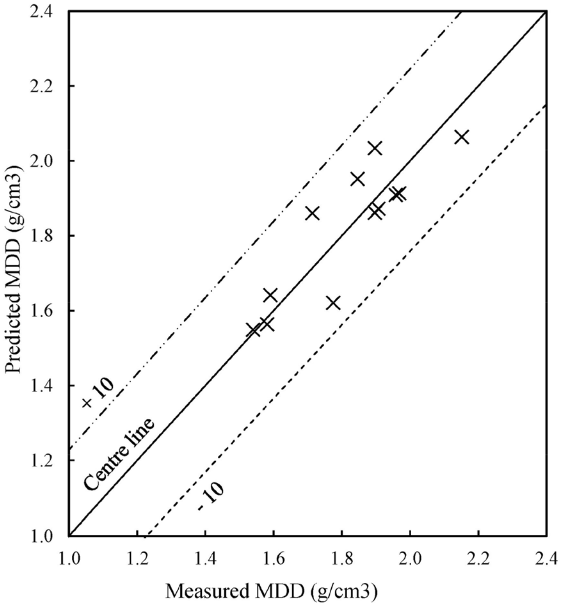
Data were obtained from the studies of Gunaydın [2] using 126 measured MDD in Nigde, Turkey; Maduka et al. [16] using 25 measured MDD on Nsukka-Adoru-Idah highway, Southeastern Nigeria, and Karimpour-Fard et al. [4] using 12 measured MDD from a summary of 728 compaction tests were used to verify the application of Eq. 2 in Fig. 4a–c, respectively. The prediction accuracy of the MDD was within the confidence interval of ± 10, which indicated a low error range of the predicted MDD [4]. On the other hand, applying Eq. 2 in the condition of fine content which is larger than 77% and the ratio of FC/G_s greater than 0.302 (i.e., larger than + 10% of the maximum values of fine content and FC/G_s in the present study) resulted in an underestimated predicted MDD as shown in Fig. 5. In Fig. 5b, the variation of the predicted maximum dry density for samples with a specific gravity higher than 2.53 corresponded to FC higher than 77%, while samples with FC higher than 77% recorded specific gravity less than 2.53, all within the confidence interval of ± 10. This indicated a significant effect of specific gravity on the predicted maximum dry density [3–6]. It can be said that an oversized specific gravity has the major effect of underestimating the predicted MDD compared with a minor impact on the fine content [17]. Meanwhile, applying Eq. 2 on the mixture with a high percentage of the gravel will produce critical miscalculation due to the absence of the effect of the gravel in Eq. 2. This empirical finding was confirmed by applying Eq. 2 on the data from Oluwafemi et al. [18] using mixtures of gravel, sand, silt, clay, and coconut shell powder.

4 Conclusion

Sand–kaolin mixtures of 31 samples were compacted and used to examine the correlation between the maximum dry density (MDD), fine content (FC), and specific gravity (G_s) using moisture content ranging from 8 to 24% and FC ranging from 20 to 70%. The linear relationship showed an excellent correlation coefficient value ($R^2 = 0.99$), exemplifying the magnitude of the correlation between MDD and the ratio of FC/$G_s{}^2$. The empirical correlation equation was justified using a total of 163 measured MDD samples from previous researchers. All predicted MDD were within the confidence interval of ± 10, which indicated a low error range of the predicted MDD. The results indicated the significant influence of specific gravity on the predicted maximum dry density in comparison with the effect of the fine content. The change in behavior of the compaction curves when FC ≥ 50% indicated a reduction in the inter-granular void ratio effect (due to filled voids) on the MDD; hence, only the FC and G_s effect remained. Consequently, combining both FC and specific gravity reduced the uncertainty in the correlation between the MDD toward both FC and G_s at a wider range of FC. It is hence concluded that using Eq. 2 can lead to an underestimation of the predicated MDD in the cases where the FC and the ratio of FC/G_s are larger than 77% and 0.302, respectively. Thus, Eq. 2 is not applicable in the presence of a high amount of gravel.

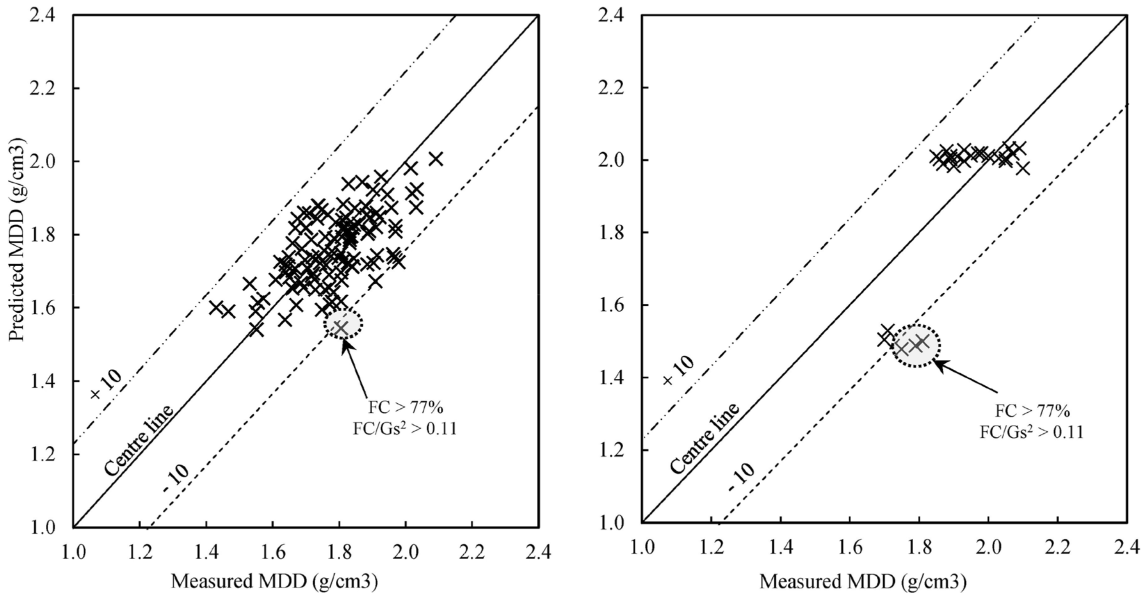


(a) Gunaydın [2] **(b)** Maduka et al. [16]



(c) Karimpour-Fard et al. [4]

Fig. 4 The application of Eq. 2 on the previous works



(a) Gunaydın [2]

(b) Maduka et al. [16]

Fig. 5 Limitations of Eq. 2

Compliance with ethical standards

Conflict of interest The author declares that there is no conflict of interest regarding the publication of this article.

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