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Variation in Air Void Content of Compacted Fill by Considering Variation in Particle Density

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ABSTRACT

Compaction plays a vital role in earthworks to ensure that engineered fill such as embankment is performed at its required capacity. Two main criteria that need to be checked for compacted fill are density and air void content. The air void content is crucial to avoid the possibility of wetting collapse, i.e. failure when water fills the air void. In this study, the effect of different particle densities due to different particle sizes was investigated. The effect of different particle densities on air void content was also investigated. The particle density of soil was determined using two configurations: 1) by combining all sizes and 2) by separating it into five different sizes. The air void content was determined using two different values of particle density. It was found that particle density varies with different size, and it increases as the particle size decreases. This variation results in different air void contents. It was also found that at higher dry density, the air void content might provide a different value that is significant as it differentiates between comply and non-comply. Therefore, this study highlights the importance of considering the effect of variation in particle density in determining the air void content of compacted fill.

Keywords: *air void content; particle density; field density; compaction; fill*

1. INTRODUCTION

In every construction project, earthwork is an important component as it is necessary to ensure that the level of the ground surface reaches the designed height. Earthwork consists of two main parts which are cut and fill. Cut removes excessive earth in order to obtain the desired level, while fill places soil above the existing ground level until it reaches the designed height. Filling works might use soil from cut, or use soil imported from another source.

In order to have a strong base, the fill soil needs to be compacted. This is known as compacted fill. At the site, the fill will be compacted using suitable machineries and equipment, depending on the condition and location of the site. Based on the specification by the Public Works Department (PWD) [1], the soil that had been compacted must satisfy two main requirements: 1) the degree of compaction should achieve 90% (cohesive) or 95% (cohesionless) of maximum dry density and 2) the air void content should be less than 5%.

For the first requirement, the maximum dry density is determined via a laboratory compaction test, which is also known as the Standard Compaction Test and the Modified Compaction Test. There are several differences between these two tests. For the Standard Compaction Test, the

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soil is compacted in a mould that forms three layers, using a 2.5 kg hammer that is dropped at a height of 300 mm. For the Modified Compaction Test, the soil is compacted in a mould that forms five layers, using a 4.5 kg hammer that is dropped at a height of 450 mm.

For the second requirement, the air void content depends on the dry density, water content and specific gravity. Dry density and water content are determined using a field density test whereas specific gravity is determined using a particle density test.

As a result of the different types of materials that constitute soil mass, such as solids that may be moulded into various sizes and shapes, there will be enclosed empty spaces between them that are referred to as voids. When soil is extracted and then filled in to attain the desired elevation of a landform surface, air void is usually created. One way to enhance the characteristics of the soil is by compaction. Rolling, vibration, and tamping are mechanical energy processes used in compaction to rearrange soil particles and fill in air voids. To ascertain whether the applied compaction is successful, a field density test, such as a sand replacement test, is performed. The air void content is determined using Equation 1:

$$A_v = 1 - \frac{\rho_d(1+wG_s)}{G_s\rho_w} \tag{1}$$

A_v is air void content, ρ_d is dry density, w is water content, G_s is specific gravity and ρ_w is density of water.

To determine the G_s value, the sample is carefully transferred into a specific gravity bottle after drying it in the oven for 24 hours. For this test, the G_s value is used as an average, which implies that one tested sample serves as a representative sample for the entire batch.

In order to decrease A_v and increase soil shear strength, compaction is necessary. If compaction is not performed properly, problems such as settlement and liquefaction may occur. The sand replacement test is the most frequently used test to evaluate the effectiveness of compaction. This test provides the dry density and moisture content value, whereas a series of particle density tests yields G_s. The standard particle density test assumes that G_s is constant for the entire soil. The variation in A_v by taking into account the variation inG_s of the soil has not yet been properly evaluated.

This could result in the value of A_v becoming negative. Table 1 shows an excerpt of a report prepared for *Projek: Pembinaan Bangunan Radar, Pejabat dan* 2 Unit Quarters in Kuala Gula Perak [2] which showed the negative result of A_v = -1.971%. Physically, it is not possible for the air void content to become negative. This occurs as a consequence of the value of G_s being taken as an average. Furthermore, the G_s may differ from the other points at the sites where the Sand Replacement Test was conducted.

Table 1: Excerpt from a report indicating a negative value of air void content

Layer	Plot	Dry density [g/cm^3]	Water content [%]	Specific gravity	Air void content [%]
0.8-1.1 m	2	1.783	18.529	2.587	-1.971

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There should be a suitable solution for the issue of negative values. To determine the real value of A_v, a detailed test was conducted, taking into account the various values of G_s for various soil sizes and types. This is accomplished by performing sand replacement tests and then proceeding with the conventional method of oven drying to quantify the moisture content of soil. The proposed method then uses a sieve analysis test to separate the soil into major soil groupings. The soil is separated into five groups based on the types of soil that pass through and are retained on the sieve: fine soil, fine sand, medium sand, coarse sand, and gravel. The G_s value is then determined for each group using the particle density test. Equation 2 is used to determine the G_s value (overall) calculation based on the fraction % of each group of soil type:

$$G_s = (\%\ \text{Gravel} \times G_s\ \text{Gravel}) + (\%\ \text{Coarse Sand} \times G_s\ \text{Coarse Sand}) + (\%\ \text{Medium Sand} \times G_s\ \text{Medium Sand}) + (\%\ \text{Fine Sand} \times G_s\ \text{Fine Sand}) + (\%\ \text{Fine Soil} \times G_s\ \text{Fine Soil}) \quad (2)$$

This study was conducted to determine the variation of specific gravity with respect to the different size distribution of soil and to evaluate the air void content when different values of specific gravity are used for different soil sizes. The output from this study can be used to emphasise the importance of considering the variation of specific gravity in determining air void content.

Several studies have been conducted previously to investigate the effect of different particle sizes. Gaspar et al. [3] investigated the effect of particle size on geochemical elements and found that size is the main factor in geochemical variations. A study by Gu et al. [4] examined the effect of the particle size distribution on the small strain shear stiffness of granular soils. The finding concluded that the small strain shear modulus is influenced by the mean particle size. Li et al. [5] emphasised that particle size is an important physical feature that influences soil nutrients, structure characterisation, and soil hydraulic capabilities, while Darder et al. [6] highlighted that different soil particle sizes (clay, silt, and sand) affect various soil physical, chemical, and biological properties. These studies indicate the need to consider the effect of different particle densities (due to different particle size) on the physical properties of soil, i.e., the air void content.

2. MATERIALS AND METHODS

2.1 Soil Properties

The soil used in this study was taken from Suling Hill, Seberang Perai Tengah, Penang, Malaysia (coordinate: 5°24'27.1"N 100°30'07.7"E). The sample was dried in an oven for 24 hours at 110°C before any test was conducted.

A sieve analysis test was conducted to determine the Particle Size Distribution (PSD) of the soil. The test was conducted in accordance with [7]. The wet sieving method was performed, and based on visual observation, there were fine particles in the soil.

The Atterberg Limit test was not conducted, as it is only necessary if the amount of fine soil (passing 63 μm sieve) is at least 35% [BS5930]. The hydrometer test was also not conducted, as it is only required if at least 10% of soil passes the 63 μm sieve [7].

A particle density test was also conducted to determine the specific gravity (Gs) of the soil, and it was conducted in accordance with [7].

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In determining the maximum dry density and optimum water content, the Standard Proctor Test was conducted, in accordance with [8]. The optimum water content obtained from this test was used for field compaction in the next stage.

2.2 Sample Preparation

For the combined sample, a random sample was taken to conduct the particle density test. For the non-combined sample, to have a variation of particle size, the soil sample was sieved to separate it according to the desired size. There were five variations of sizes under consideration, which included gravel (greater than 2 mm, retained on 2 mm sieve), coarse sand (600 µm to 2 mm, retained on 600 µm sieve), medium sand (200 µm to 600 µm, retained on 212 µm sieve), fine sand (60 µm to 200 µm, retained on 63 µm sieve), and fine soil (lesser than 60 µm, retained on pan). Following the separation of samples according to size, a particle density test was conducted to determine the specific gravity value for each size range. A comparison between the conventional method and the new proposed method is shown in Figure 1 and Figure 2.

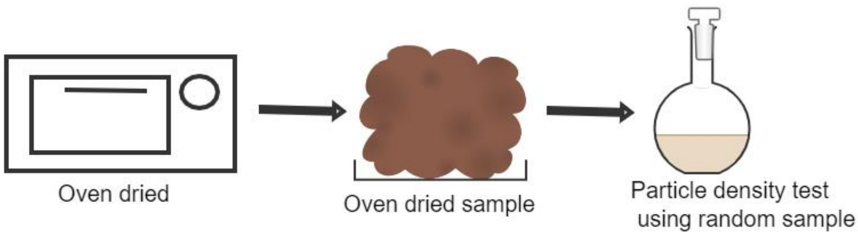

Figure 1: Graphical depiction of the combined sample

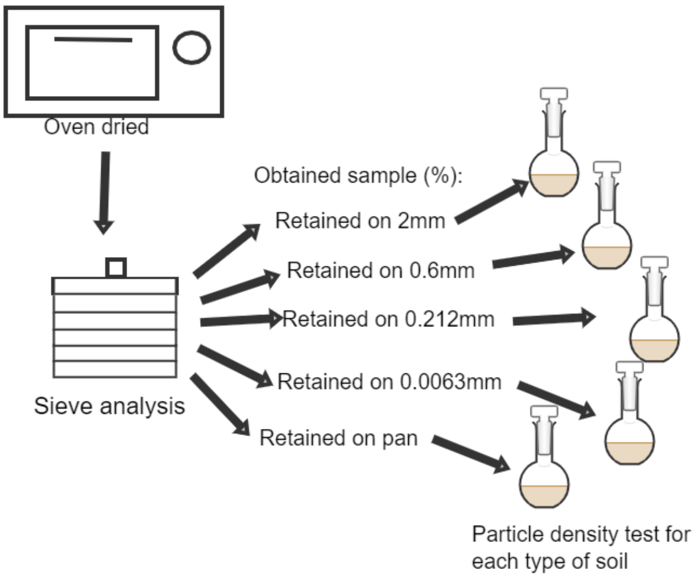

Figure 2: Graphical depiction of the non-combined sample

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In conducting the field density test, the soil sample was compacted in a container and it was performed in the laboratory. It was not performed at the site. The main reason is because at the site, the soil is compacted to maximum density, so there is no or less variation in density. By producing compaction in the laboratory, the compaction effort can be controlled, thus resulting in a variation of density. The sample was compacted in the container using a vibrating hammer, with variation in the duration of compaction. The soil is compacted layer by layer, and the thickness of each layer is approximately equivalent to the thickness of layer in the Modified Compaction Test.

2.3 Field Density and Air Void Content

Sand replacement test was conducted to determine field density, following the procedure outlined in [9]. Prior to testing, calibration was performed for the sand that will be used in the testing. This was done to ensure that the volume of removed soil can be determined by the volume of sand replacing the soil. The bulk and dry densities of soil are determined using Equation 3 and Equation 4, respectively.

$$\rho_b = \left(\frac{m_w}{m_b}\right) \rho_a \quad (3)$$

$$\rho_d = \frac{\rho_b}{1+w} \quad (4)$$

The air void content was determined using Equation 1, and it depends on the dry density, specific gravity, and water content of the soil.

3. RESULTS AND DISCUSSION

3.1 Physical and Mechanical Properties

3.1.1 Particle Size Distribution

The dry sieve analysis test was conducted in accordance to BS 1377. A soil sample must be divided using this process and dried in an oven for 24 hours. After drying in the oven, the sample was allowed to cool for a short while before sieving. Figure 3 shows the percentage of the passing mass that was retained on the sieve and pan. The results were plotted on the BS Sieve Graph. It was found that the soil consisted of 28% gravel, 71% sand, and 1% fine soil. Based on [10], the soil was classified as well-graded very gravelly SAND.

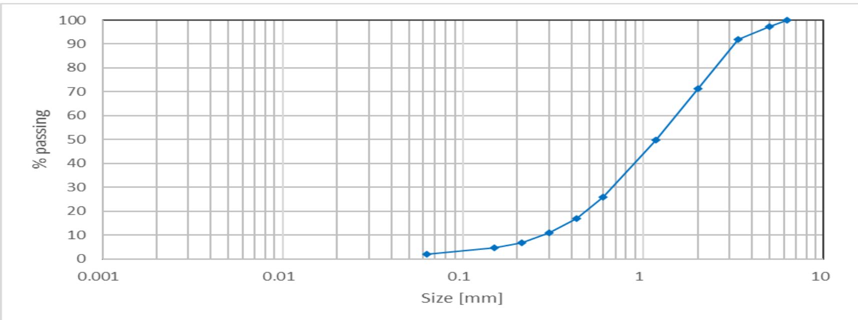

Figure 3: Particle Size Distribution of soil used in this study

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3.1.2 Particle Density

The Particle Density for combined sample (0mm < d < 6.3 mm) is as provided in Table 2.

Table 2: Particle Density of the Combined Sample

Sample Size [mm]	Percentage [%]	Average Particle Density [-]
0 < d < 6.3	100	2.63

3.1.3 Standard Compaction Test

Figure 4 displays the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) values for each distinct percentage of moisture content. The results from compaction test indicate that the maximum dry density and optimum moisture content from the standard compaction test were 1.64 g/cm^3 and 20.5%, respectively.

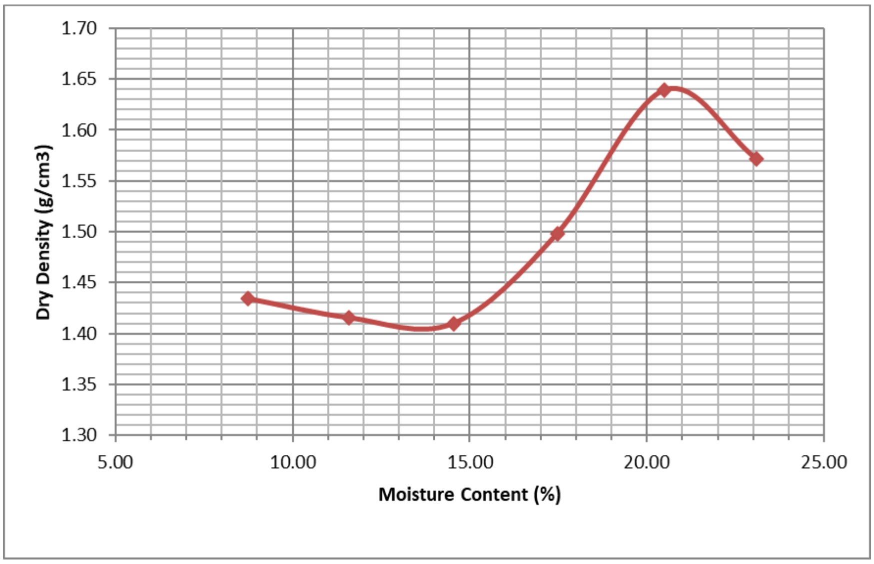

Figure 4: Dry density and moisture content from Standard Compaction Test

The shape of the compaction curve is categorised as Type II (one and one-half peaks) as categorised by [11]. Initially, the moisture content at 14.5% is less than that of OMC; thus, the soil is stiffer in type with more void spaces and porosity. This is the explanation for the reduced dry density achieved, which is 1.41 mg/m^3. When soil particles are moisturised by an increase in moisture content, they become more tightly packed, resulting in greater density that causes the optimum moisture content (OMC) and maximum dry density (MDD) to be 20.5% and 1.64 Mg/m^3 respectively. At the maximum point of the curve, the density of the soil started to drop as more moisture was added to the soil.

Dry soil contains soil particles that are not in contact with one another, and when the soil is compacted too strongly without water or inadequate water, cracks and gaps are formed. When water is added, it produces a thin film over each soil particle, connecting the particles. Compaction compacts the soil, making them denser. At a certain stage, the volume of air in the soil sample reaches a minimum, and the dry density of the soil reaches a maximum. This is

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known as the maximum dry density point, and it is at this point the addition of water should be stopped. Optimum moisture content refers to the moisture content that corresponds to the maximum dry density of the soil.

Laboratory compaction tests act as a foundation for establishing the relative compaction and water content is required to achieve the requisite engineering qualities, as well as for controlling construction to ensure that the required compaction and water content are achieved.

3.2 Field Density

Dry density and soil water content were obtained during the Field Density Test (FDT) using the Sand Replacement Test. Figure 5 shows the variation in dry density with a varied durations of compaction.

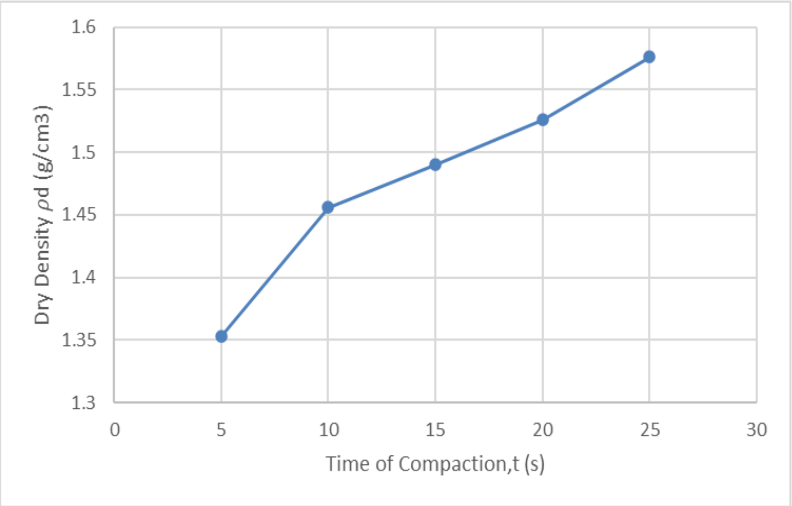

Figure 5: Variation in dry density with respect to the varied time of compaction

From Figure 5, it is obvious that the dry density increased as the time compaction increased. The increase in dry density is related to the time of compaction as the purpose of compaction is to keep soil particles close together, which improves dry soil density with the extra effort of compaction.

Prior to Sand Replacement Test, a calibration procedure was conducted to determine the bulk density of the sand that was used in this test. Table 3 shows the results of the calibration procedure.

Table 3: Data from the calibration procedure of the Sand Replacement apparatus

mass of sand in cone [g]	420
volume calibrating container [cm^3]	1178.1
mass of sand + cylinder before pouring [g]	8695
mass of sand + cylinder after pouring [g]	6750
mass of sand to fill the calibrating container [g]	1525
bulk density of sand [g/cm^3]	1.29

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3.3 Variation of Particle Density

The results of the particle density test for the non-combined sample are as shown in Table 4.

Table 4: Particle Density of the Non-Combined Sample

Sample Size [mm]	Percentage [%]	Average Particle Density [-]
≥ 2	28.78	2.46
$0.6 \leq d < 2$	45.46	2.52
$0.212 \leq d < 0.6$	18.99	2.55
$0.063 \leq d < 0.212$	4.88	2.56
$d < 0.063$	1.90	2.58
Particle Density (using Equation 2)		2.51

In Table 4, it can be seen that as the particle size decreased, the particle density increased. This pattern is consistent with [12], as shown in Table 5.

Table 5: Common value of Particle Density

Type of soil	G_s [-]
Quartz sand	2.64–2.66
Silt	2.67–2.73
Clay	2.70–2.90

3.4 Variation of Air Void Content

The air void content for both the combined and non-combined samples is shown in Figure 6.

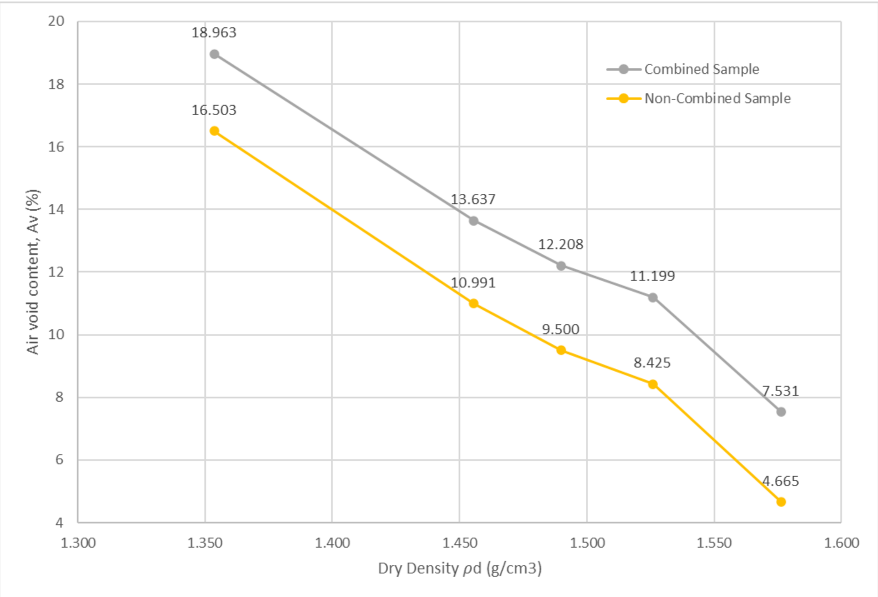

Figure 6: Variation in air void content with dry density

The A_v linearly decreased as the dry density increased. Both A_v lines showed the same trend of change; i.e., decreases as the dry density value increases. The last point of each curve is the most significant point to be observed, as it is the highest density achieved in this study. As stated in [1], it highlighted that the air void content should be less than 5% (to avoid the

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possibility of unsaturated cohesive fill collapsing due to wetting). In the plot, if the analysis is done using the conventional method, it does not fulfil the requirement, whereas if it is analysed using Equation 2, the A_v value is less than 5%, which complies with the requirement of [1].

4. CONCLUSION

This research was conducted to investigate the effect of different particle sizes on the particle density of soil, and the effect of different particle densities on the air void content of soil. This research proves that for different sizes, the value of particle density is different, indicating an inverse trend. As the size of particle increases, the density decreases. The consequence of this difference is that it will provide different values of air void content. The implication from this situation is that the compaction of the fill might not be considered to fulfil the second requirement from the standard specifications of PWD, but it actually fulfils the requirement if the variation in particle density is considered. Furthermore, from a theoretical point of view, it is more accurate to consider the variation as it represents various particle sizes in the soil sample.

For future research recommendation, it is suggested to conduct compaction at the site using in situ compaction machineries. By conducting field compaction, more realistic data that are represented by in situ compaction can be obtained.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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