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| RESEARCH ARTICLE

Comparison of the Number of Compactor Passes and the Constrained Modulus of a Compacted Volcanic Soil

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| ABSTRACT

Volcanic soil is often used as fill material in road embankment construction in Java island-Indonesia. An understanding of the engineering properties of compacted volcanic soils is needed, especially during the preliminary design phase and during the detailed design phase of the road embankment. Carrying out a field compaction trial test will significantly assist in the design of the compaction process of the road embankment construction. Selecting the correct number of passes from the compactor and the engineering properties of compacted volcanic soils can be obtained from field compaction trial tests. Constrained modulus is one of the engineering properties that can indicate the stiffness of the fill material used in a road embankment. This study aims to determine the constrained modulus of compacted volcanic soil and compare it to the number of passes of a compactor from the field compaction trial test. The volcanic soil used in this study is classified as pumiceous tuff, which is derived from older volcanic rocks. The highest value of the oedometer modulus of compacted volcanic soils is 10.38 MPa which comes from eight (8) times passes of smooth drum roller conducted on field compaction trial test.

| KEYWORDS

Compacted volcanic soils, constrained modulus, oedometer test, field compaction trial test.

| ARTICLE INFORMATION

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1. Introduction

In road embankment construction, it is often encountered where the parameters and engineering properties of the subgrade soil at the construction site or the soil to be used as fill material do not meet the technical specifications as required in the design. One way to overcome this problem is to mechanically stabilize the soil. Mechanical stabilization is also known as compaction. In Java island-Indonesia, volcanic soil is often used as fill material or subgrade soils in road embankment construction because the alignment of highway projects often passes through areas around volcanoes [Indonesia Highway Corp, 2017]. Volcanic soil is soil that originates from volcanic eruptions and is classified as residual soil [Wesley et al. (2010), Shoji et al. (1993), and Neall (2006)].

Understanding the special characteristics of residual soil and how it is compacted is crucial. This could reduce costs and maximize compaction effort [Blight and Leong, 2012]. The preparation stage for road embankment construction requires information about the most appropriate number of passes from a compactor in the field to achieve the highest dry density and stiffness of the fill material. One of the stiffness parameters is the constrained or oedometer modulus value (E_{oed}).

Wesley (2001, 2009) investigated the result of an oedometer test on undisturbed soil samples from Indonesia and New Zealand. Sampling was done either using thin-walled sample tubes or by taking block samples. For settlement analysis based on an oedometer test of overconsolidated soils, which lack a distinct preconsolidation pressure (σ_p'), the linear parameter E_{oed} and m_v (coefficient of compressibility) may well be more appropriate rather than compression index (C_c) obtained from semi logarithmic curve between void ratio (e) and applied pressure (σ_v').

Ali (2014) studied the compaction and strength characteristics of granular volcanic ash from Sana'a city, Yemen. The result showed that the maximum dry density for mixtures of different fine contents increases linearly with cement content. The California Bearing Ratio (CBR) increases linearly with cement content for various fine contents.

Angelim et al. (2016) studied the large-scale earth embankment constructed in the city of Goiania in the Midwest Region of Brazil. Highly weather tropical soil is used for the construction of the embankment. Consolidated drained triaxial test and oedometer test in the laboratory were performed on a sample from undisturbed soil blocks at their natural water content. Young's modulus was derived from the laboratory test compared with the elastic modulus measured from the Menard pressuremeter test in the construction of the earth embankment.

Hernandez et al. (2018) evaluated the behaviour of volcanic soil using a mineralogical characterisation test, thermogravimetric analysis, compressibility, direct shear, water retention curves, and distribution of pores in the structure. The result of the research showed the high irreversibility of the characteristics of the soil depending on the changes in water content that the soil undergoes before compaction.

This study aims to determine the constrained modulus value of compacted volcanic soil and compare it to the number of passes of smooth drum roller from the field compaction trial test. The constrained modulus (E_{oed}) value was obtained from the oedometer test in the laboratory. The compacted volcanic soil sample used for the oedometer test was taken from block samples at their natural water content from the field compaction trial test.

2. Material and Methods

2.1 Volcanic Soil

The volcanic soil (namely, SOIL-B) used as fill material came from a borrow pit adjacent to the field compaction trial test location, as shown in Figure 1. The volcanoes adjacent to the study site are Mount Salak and Mount Gede-Pangrango. Volcanic soil is classified as pumiceous tuff, which is derived from older volcanic rocks as described on the geological map [Effendi et al., 1988]. The color of volcanic soil is brownish yellow [Munsell, 1975]. Soil tests to determine moisture content, specific gravity, Atterberg limits, sieve analysis, and hydrometer tests for volcanic soils are carried out in the laboratory. To obtain compounds and minerals from the soil, X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) tests will be performed.

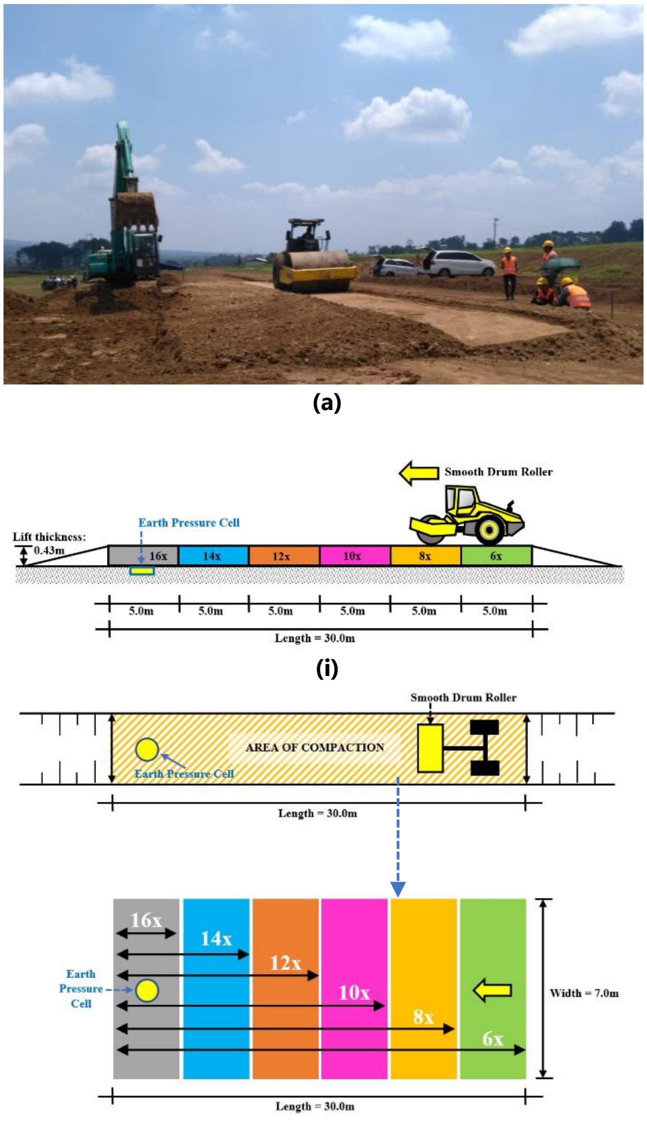
Fig. 1 Volcanic Soil

2.2 Method of Field Compaction Test

The field compaction trial test location is located ± 17 km south of the city of Bogor-West Java, Indonesia. The schematic of the field compaction trial test is shown in Figure 2. As a compactor, a smooth drum roller with static linear pressure = 27.2kN/m is used [Sakai, 2019]. The static linear is obtained from the ratio between load on the front axle (58kN) and compaction width (2.13m).

During the compaction process in the field, the compactor is operated at its slowest speed (1.3 km/hour). Vibration from the drum is not used during compaction. The smooth drum roller moves in two directions (forward and backward = one time (1x) pass).

Area for field compaction test = 30.0m x 7.0m, which is divided into 5 segments, where the length of each segment is 5.0m. Lift thickness for volcanic soil as fill material = 0.43m. The number of passes of compactor used for this field compaction trial test is: 6 times (6x), 8 times (8x), 10 times (10x), 12 times (12x), 14 times (14x), and 16 times (16x).



(a)

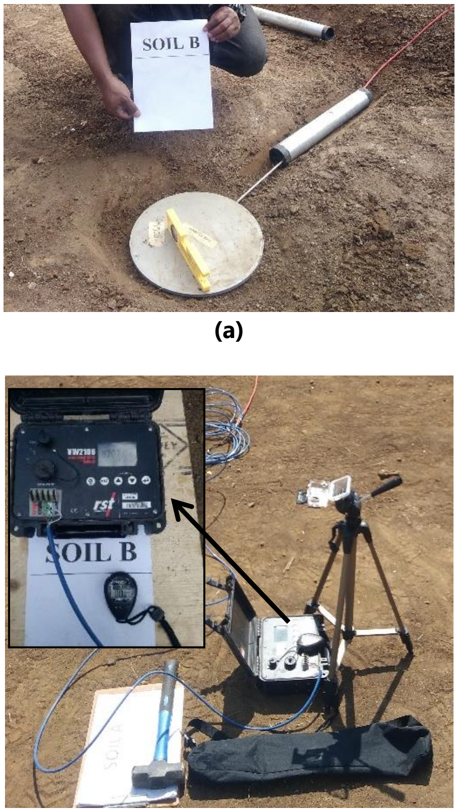
(i)

(ii)

(b)

Fig. 2 (a) Field Compaction Trial Test of Volcanic Soil with Smooth Drum Roller (b) Schematic of Field Compaction Test (Not Scale) (i) Side View (ii) Top View

The earth pressure cell, data logger, stopwatch, and digital camera shown in Figure 3 were used to record the amount of pressure generated by the compactor and elapsed time while compacting the soil in the field.



(a)

(b)

Fig. 3 (a) Earth Pressure Cell (b) Data Logger

As a quality control for the end of the product of the compaction process in the field, the Dynamic Cone Penetrometer (DCP) test, which refers to ASTM D-6951, is performed for each segment of the field compaction trial. Based on the DCP test, the value of the California Bearing Ratio in the field (CBR_{field}) will be obtained.

Fig. 4 Block Sample from the Field Compaction Test

Figure 4 shows an example of a block sample (compacted volcanic soils) taken from a field compaction trial test which will be used for laboratory tests. On compacted soil samples originating from block samples for each segment of the field compaction trial test, tests will be carried out in the laboratory to obtain dry density referring to ASTM D-7263.

2.3 Method of Oedometer Test

As shown in Figure 5, compacted volcanic soils from the block sample will be tested with an oedometer apparatus in the laboratory. The oedometer test refers to ASTM D-2435. The applied pressures used in the odometer tests are: 25, 50, 100, 200, 400, and 800 kPa for loading stages, and the applied pressures for unloading stages are: 200 kPa and 50 kPa for samples from 6x passes; 100 kPa and 25 kPa for samples from 8x passes and 16x passes.

(a)

(b)

Fig. 5 (a) Result of Compacted Volcanic Soils Sampling from Block Sample for Oedometer Test (b) Oedometer Test Apparatus in Laboratory

Constrained modulus calculated by equations [Holtz and Kovacs, 1981] as follows:

$$E_{oed} = \frac{\Delta\sigma_v{}'}{\Delta\varepsilon_v} \quad (1)$$

or

$$E_{oed} = \frac{1}{m_v} \quad (2)$$

where:

$\Delta\sigma_v{}'$ = difference of applied pressure

$\Delta\varepsilon_v$ = difference of vertical strain

m_v = coefficient of volume change or coefficient of compressibility [Murthy, 2003]

3. Results and Discussion

3.1 Result of Soil Properties Test

Table 1 shows the references and results of laboratory tests for water content, specific gravity, Atterberg limits, and particle size tests for soil.

Table 1. Index Properties, Atterberg Limits and Particle Size of Soil

Properties	Units	Value	Reference
Water Content, w	(%)	42	ASTM D 2216
Specific Gravity, G_s		2.77	XP CEN ISO/TS 17892-3
Liquid Limit, LL	(%)	52	ASTM D 4318
Plastic Limit, PL	(%)	38	
Index Plasticity, IP	(%)	14	
Percentage of Gravel	(%)	0	ASTM C 136
Percentage of Sand	(%)	33	
Percentage of Silt	(%)	27	ASTM D 422
Percentage of Clay	(%)	40	

Table 1 shows that the soil consists of 67% fines (the percentage of silt and clay) and 33% sand. According to Shoji et al. (1983), the main mineral composition of volcanic ash soils falls into the light mineral category if the specific gravity value is lower than 2.8. The water content of the soil is close to the plastic limit, and for this condition, Wesley (2010) states that the soil will show a steady increase in strength with an increase in compaction effort.

3.2 Result of XRD and XRF Tests

The analysis for the XRD test on volcanic soils is divided into two parts: quantitative analysis results and qualitative analysis results. Table 2 shows the weight ratio of the quantitative analysis of the XRD test results. Figure 6 shows the results of the qualitative analysis of the XRD test.

Table 2. Weight Ratio from Quantitative Analysis Result of XRD Test

Phase name	Content (%)
Andesine	72
Quartz	18
Muscovite	4.4

According to the results of the two analyses, there are two dominant volcanic minerals from the soil: Andesine (72%) and Quartz (18%). The slopes of Mount Salak and Mount Gede volcanoes consist of intermediary volcanic tuff (andesite) [Buurman, 1980]. This shows the suitability between the minerals obtained from the XRD test results and the area where the soil was taken and used as material in the field compaction trial test.

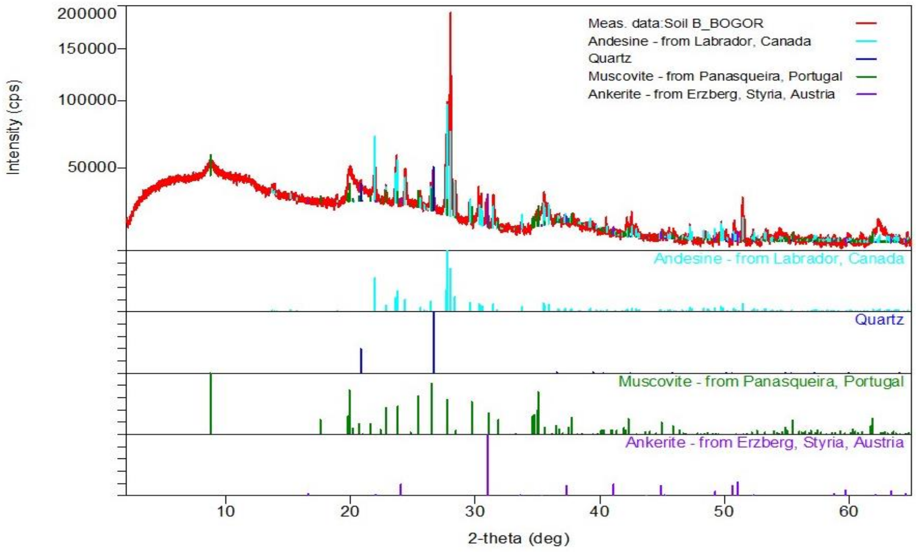


Fig. 6 Qualitative Analysis Result of XRD Test

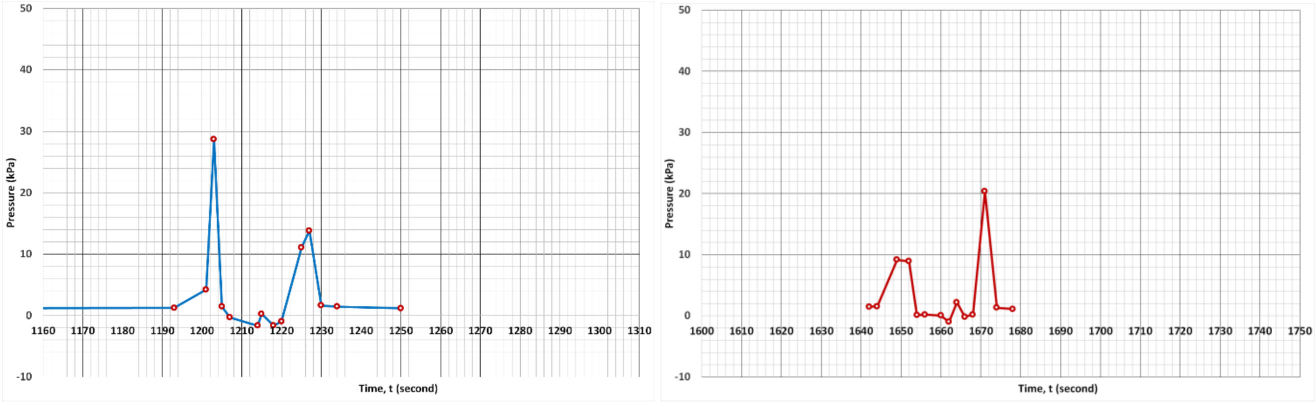
Table 3. Result of XRF Test

No.	Component	Result	Unit	Det. limit	El. line	Intensity	w/o normal
1	**Na_2O**	0,584	mass%	0,02638	Na-KA	0,0732	0,4078
2	**MgO**	0,297	mass%	0,02325	Mg-KA	0,0950	0,2071
3	**Al_2O_3**	35,5	mass%	0,03141	Al-KA	44,3575	24,7522
4	**SiO_2**	49,8	mass%	0,05696	Si-KA	34,5354	34,7734
5	**P_2O_5**	0,244	mass%	0,01024	P -KA	0,1432	0,1701
6	**SO_3**	0,441	mass%	0,00989	S -KA	0,4367	0,3080
7	**Cl**	0,622	mass%	0,00259	Cl-KA	2,3005	0,4341
8	**K_2O**	0,538	mass%	0,01040	K -KA	0,7794	0,3753
9	**CaO**	3,20	mass%	0,01041	Ca-KA	6,4097	2,2345
10	**TiO_2**	0,781	mass%	0,02397	Ti-KA	0,3672	0,5448
11	**MnO**	0,190	mass%	0,00591	Mn-KA	0,4272	0,1329
12	**Fe_2O_3**	7,69	mass%	0,00988	Fe-KA	25,0774	5,3643
13	**ZnO**	0,0133	mass%	0,00306	Zn-KA	0,1263	0,0093
14	**SrO**	0,0499	mass%	0,00263	Sr-KA	1,5033	0,0348
15	**ZrO_2**	0,0515	mass%	0,01414	Zr-KB1	0,3661	0,0359

The result from the XRF test of volcanic soil is listed in Table 3. XRF test results show that there are two dominant compounds, namely SiO_2 (silica or silicon dioxide or quartz) at 49.8% and Al_2O_3 (aluminum oxide) at 35.5%. As stated in Section 2.1, the color of the volcanic soil used in this study is brownish yellow. The colors (red or yellow) of tropical soils come from the presence of dominant Al_2O_3 and Fe_2O_3 compounds.

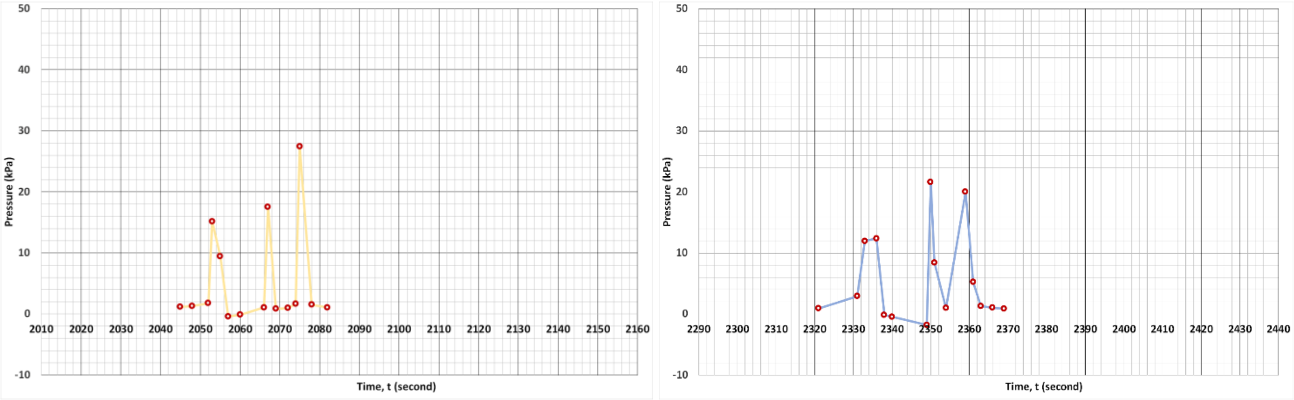
3.3 Result of Field Compaction Trial Test

Pressure from the compactor in the field subjected to compacted soils for each number of passes recorded by the earth pressure cell and data logger, as shown in Figure 3. The curve between the pressure from the smooth drum roller (compactor) and the time for each number of passes are shown in Figure 7, Figure 8, and Figure 9. The maximum pressures that occur during the compaction process in the field are respectively as follows; 28 kPa for 6x passes, 20 kPa for 8x passes, 28 kPa for 10x passes, 22 kPa for 12x passes, 38 kPa for 14x passes, and 42 kPa for 16x passes. Based on these data, there are similarities in the maximum pressure generated by the compactor during the field compaction test between segment 6x passes, and segment 10x passes, between segment 8x passes and segment 12x passes, and between segment 14x passes, and segment 16x passes.



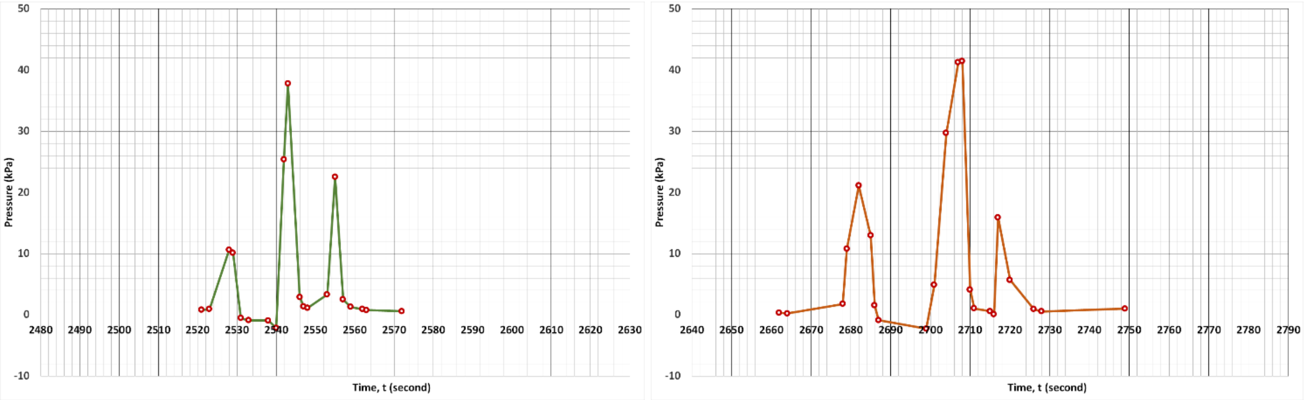
(a) **(b)**

Fig. 7 Data Recorded from Earth Pressure Cell for Each Smooth Drum Roller Passes (a) 6x passes (b) 8x passes



(a) **(b)**

Fig. 8 Data Recorded from Earth Pressure Cell for Each Smooth Drum Roller Passes (a) 10x passes (b) 12x passes



(a) **(b)**

Fig. 9 Data Recorded from Earth Pressure Cell for Each Smooth Drum Roller Passes (a) 14x passes (b) 16x passes

Table 4 shows the CBR$_{field}$ values based on the DCP test in the field and dry density values based on laboratory tests for compacted volcanic soil. Increasing the number of passes from the smooth drum roller from 6x passes to 8x passes will increase the CBR$_{field}$ value by 0.8%, while the CBR$_{field}$ value will decrease by 1.6% for the increasing number of passes from 8x passes to 16x passes. As in the CBR$_{field}$ value, increasing the number of passes from the smooth drum roller from 6x passes to 8x passes will increase the γ_{dry} value by 0.19kN/m^3, while the γ_{dry} value will decrease by 0.16kN/m^3 for the increasing number of passes from 8x passes to 16x passes ("over-compaction" condition [Wesley, 2010]).

Table 4. CBR$_{field}$ and Dry Density for Each Number of Passes of Compactor

Number of Passes of Compactor	CBR$_{field}$ (%)	Dry Density γ_{dry} (kN/m^3)
6x	2.7	1.08
8x	3.5	1.27
16x	1.9	1.11

According to the CBR$_{field}$ value and dry density value, the number of passes from the smooth drum roller that can produce the maximum value of dry density and highest soil strength of compacted volcanic soils in the field is 8x passes.

3.4 Result of Oedometer Tests

According to similarities of maximum pressure developed from field compaction test as mentioned in Section 3.3, only samples from compacted volcanic soils with 6x, 8x, and 16x roller passes will be conducted oedometer tests. The oedometer test results for compacted volcanic soils are expressed in the form of a curve between applied pressure and vertical strain (σ_v' - ε_v), as shown in Figure 10. There are two linear trends in the curve of applied pressure – vertical stress. The first trend occurs in the range of applied pressure, 0 – 100 kPa and then the second trend occurs in the range of applied pressure, 200 – 800 kPa.

The σ_v' - ε_v curve for 6x passes is the lowest when compared to the other curves. At the time of the range of applied pressure; 0 – 200 kPa, the σ_v' - ε_v curve for the 16x passes is above the 8x passes, but within the range of applied pressure; 200 – 400 kPa, the opposite occurs where the curve σ_v' - ε_v for 8x passes is above the 16x passes. This shows that compacted volcanic soil with 6x passes tends to have the lowest compressibility.

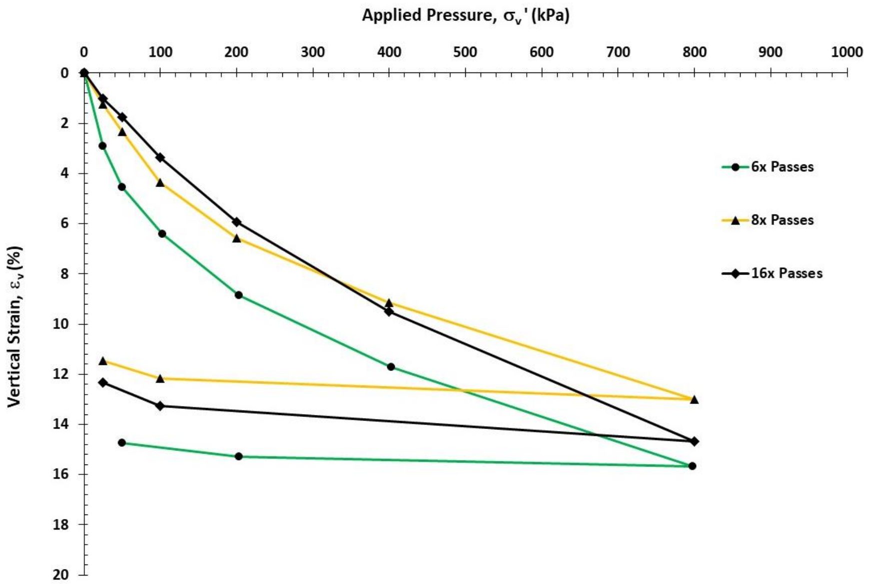
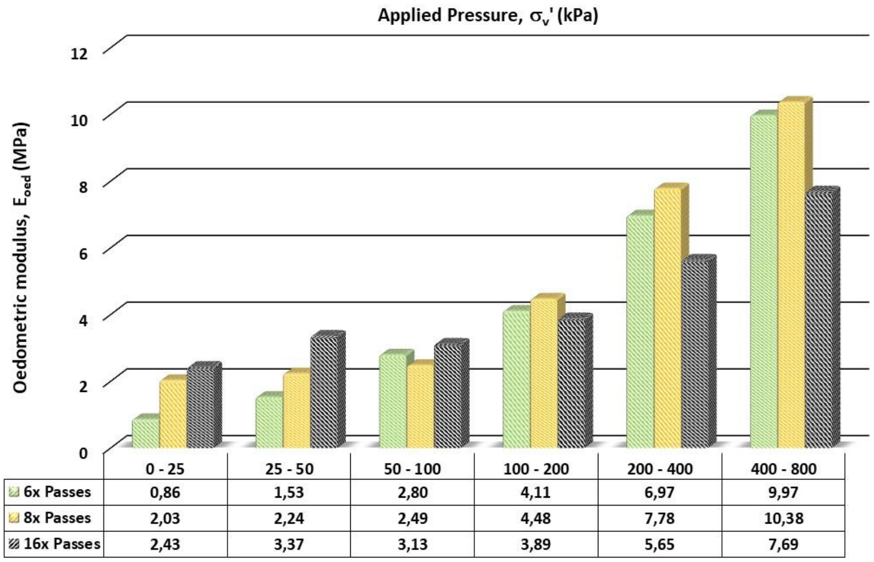


Fig. 10 Curve of Applied Pressure – Vertical Strain



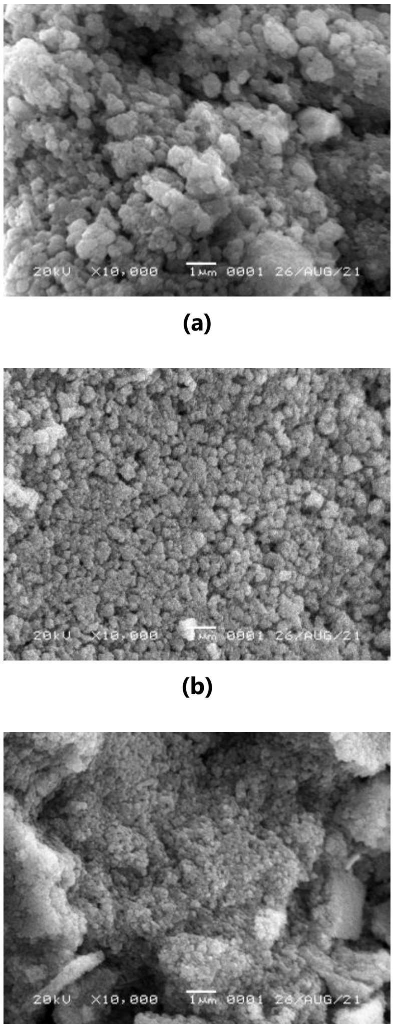
	0 - 25	25 - 50	50 - 100	100 - 200	200 - 400	400 - 800
6x Passes	0,86	1,53	2,80	4,11	6,97	9,97
8x Passes	2,03	2,24	2,49	4,48	7,78	10,38
16x Passes	2,43	3,37	3,13	3,89	5,65	7,69

Fig. 11 Oedometric Modulus for Each Range of Applied Pressure

It was found that there was a tendency to change the slope of the curve linearly for all the σ_v' - ε_v curves when the vertical strain was more significant than 6%. The vertical strain that occurs when the applied pressure is 800 kPa, respectively are; 14.69% for 16x passes, 13.02% for 8x passes, and 15.67% for 6x passes. It appears that the segment 6x passes has the largest vertical strain when a pressure of 800 kPa is applied to the oedometer test in the laboratory. This also happens when the applied pressure is; 25, 50, 100, 200, and 400 kPa, where compacted volcanic soil with 6x passes has the highest vertical strain value when compared to the 8x passes and 16x passes. Based on Figure 11, E_{oed} steadily increases with increasing stress. However, the change in modulus with the number of passes (compaction effort or compaction energy) is not consistent. At low stress levels (0 - 50 kPa), the modulus increases with the number of passes, while at high stress levels (50 - 800 kPa), the constrained modulus is greatest at 8x passes (10.38 MPa) and then drops at 16x passes. It clearly shows that when the 16x passes, the condition of "over-compaction" occurs for volcanic soils.

3.5 Result of Scanning Electron Microscope (SEM) Tests

Result of the SEM test for compacted volcanic soils with 6x passes, 8x passes, and 16x passes shown in Figure 12.



(a)

(b)

(c)

Fig. 12 SEM test result of compacted volcanic soil (a) 6x passes (b) 8x passes (c) 16x passes

Figure 12 showing sub-rounded kaolinite for compacted volcanic soils. Mohsen and El-maghraby (2010) also found sub-rounded kaolinite in red clay soil. According to Figure 12, the structure of compacted volcanic soil with 8x passes is denser than that of compacted volcanic soil with 6x passes. During the 16x passes of the number of compacted passes, the soil structure is destroyed. The SEM test results confirmed that the volcanic soil was "over-compaction" during the 16x passes of the compactor in the field.

4. Conclusion

The conclusions from this study are as follows:

1. The volcanic soil used in this study is classified as pumiceous tuff, which is derived from older volcanic rocks.
2. 8 times passes of smooth drum roller for the compaction process of volcanic soils in the field can produce the maximum value of dry density (γ_{dry} = 1.27 kN/m^3) and highest soil strength of compacted volcanic soils (CBR$_{field}$ = 3.5%).

3. The highest value of the constrained modulus of compacted volcanic soils is 10.38 MPa which comes from 8 times passes of smooth drum roller.
4. The constrained modulus depends on the pressure or stress subjected to compacted volcanic soils. The higher of range of stress, the higher the constrained modulus of compacted volcanic soils.
5. The condition of "over-compaction" occurs in volcanic soil when the number of passes of the smooth drum roller in the field reaches 16 times passes.

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