Density-Moisture Relations of Two Trinidad Soils Obtained with a Soil Vibratory Compactor

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Abstract: *Density-moisture relations are required while constructing roads and other structures and during farming operations. The Proctor test is the standard method of determining this relationship but other methods exist including the vibratory hammer or table and the soil vibratory compactor. The design, construction and testing of a soil vibratory compaction machine, which could produce maximum densities that mimic the Proctor test has been described in a previous paper by Leonard et al. (2019). A mechanism was designed and developed that vibrated the soil at a given time, amplitude and frequency and resulted in compacting the soil. It was determined that 17 Hz frequency operating at an amplitude of 1.7 mm for 5 mins were the ideal parameters to operate the compactor. However, it is still unclear whether the soil vibratory compactor could be used to test soils with varying clay contents with different water and organic matter contents. This paper utilises a vibratory compactor working at the pre-determined parameters to test the density-moisture relations of two soils (sandy loam and clay) treated with peat at five different contents (0%, 4%, 8%, 12% and 16%) by mass and compacted at moisture contents which ranged from 5% to 55%. Similar tests were carried out using the standard Proctor test so as to compare the results. Results generally showed that although most bulk density values determined using the soil vibratory compactor were slightly lower (within a range of 0.02 to 0.06 t m^{-3}) than the values from the standard Proctor test, density values from the two methods were perfectly related (r = 0.998). The soil vibratory compactor could then be used to estimate the bulk density values that are obtainable using the Proctor test. The major advantage of the constructed soil vibratory compaction equipment is that it could reduce the tedium involved in the standard Proctor soil compaction test.*

Keywords: *Soil, compaction, vibration, Proctor, test*

1. Introduction

Before structures like buildings, dams, airports or roads are built there is the need to do a compaction test of the soils in the area so as to determine the optimum moisture content for maximum compaction. During compaction, water which acts as a lubricant and allows the soil particles to be aligned and packed properly is added to the soil (Felton and Ali, 1992; Ekwue et. al., 2005). Too much water, however, reduces the density of the soil (Ohu et al., 1985). Thus for a given compaction effort, using compacting forces like ramming, vibration and static rollers, there is an optimum water content at which maximum soil density is achieved. On the other hand, soil compaction is undesirable in agricultural practice since it reduces soil aeration, water availability to plants and imparts high mechanical impedance to root growth (Thompson et al., 1987). There is, therefore, the need for the engineer to know this maximum density as well as the optimum water content for maximum soil compaction, and these are normally obtained by prior laboratory tests. The agriculturist needs the information since it is desirable to limit soil working below the optimum water content, so as to reduce compaction on the soil.

In the literature, the standard Proctor and the modified Proctor tests are the standard methods for determining maximum density and the optimum water content for maximum compaction. The Proctor tests are the most common and involve dropping a 2.5-kg hammer (4.5 kg for the modified test) from a height of 305 mm (450 mm for the modified) onto a sieved soil at a particular water content contained in a cylindrical mould, 0.001 m^3 volume (0.002 m^3 for the modified) in three (five for the modified) layers. This is dropped 25 times (27 for the modified) for each soil layer (ASTM, 2007). The test is continued for increasing water contents until maximum soil density is obtained, and the water content at which this occurs is called the optimum water content for the soil (Ekwue and Stone, 1994). The standard Proctor and modified Proctor tests are very

laborious due to the manual nature of the standard procedure and this has prompted researchers to examine other methods. The vibratory hammer and the vibrating table tests have been devised. The vibration hammer test involves compaction of the soil in a mould similar to the Proctor test using an electrically operated vibrating hammer. The hammer is allowed to vibrate on each of the three layers for about 60 seconds (British Standards Institution, 1990). The vibrating table test, which is the American Standard (ASTM, 2006), is similar to the vibratory hammer test except that the soil in the mould is placed on a table that vibrates and the level of compaction achieved depends on the frequency and amplitude of vibration, as well as the size and shape of the mould in which it is vibrating (Dobry and Whitman, 1973). The density obtained for the soils using the vibrating soil test equipment (such as the vibrating hammer) is comparable to that from the modified Proctor test but is generally greater than that from the standard Proctor test (Prochaska and Drevich, 2005; Waldemar and Lechocka, 2016)

In a previous paper, Leonard et al. (2019) described a soil vibratory compactor which could be utilised to carry out similar tests. These authors examined the various operating parameters of the vibratory compactor and determined that at a frequency of 17 Hz, with an amplitude of 1.17 mm for 5 mins, the maximum densities measured using the vibratory soil compactor were very close to those obtained using the standard Proctor test. It was found that this applied to all soils particularly the sandy soils with low cohesion. Organic matter in form of peat in the presence of water was found to decrease cohesion in sandy soils but to increase it in clay soils (Ekwue et al., 2014). It is not therefore very clear from the previous study whether the soil vibratory compactor could also be used to test soils with a wide variety of properties including different water and organic matter contents. This study tested two soils with five peat contents and utilised the vibratory soil compaction at the ideal operating conditions prescribed by Leonard et al. (2019) and compared the results obtained with those obtained using the standard Proctor test. The aim was to test soils with high organic matter contents and variable water contents using the Proctor and vibratory compactor tests to determine the extent to which the results from both tests were comparable.

2. Description of the Constructed Soil Vibratory Compactor

2.1 Construction and Operation

This soil vibratory compactor (see Figure 1) was fully described by Leonard et al. (2019). The only alteration to this compactor was the replacement of the soil mould with a standard Proctor mould which is split in two pieces and the base of the mould was made separate so as to allow the soil to be easily removed after each test.

The compactor operates on the principle of rotating unbalanced induced vibrations. A shaft is connected to the frame via bearings which are supported by the internal frame. During operation of the soil vibratory compactor, a soil sample is placed in the bottom mould (the same size of the standard Proctor mould) for the first layer of compaction. The motor is then energised. The speed of the motor is set using a variable speed drive and this alters the frequency (determined using accelerometers) of the vibration of the soil compactor. The soil sample in the mould is allowed to vibrate for a given period of time at specific frequencies and amplitudes. Once the first soil layer has been compacted, the procedure is repeated for two other soil layers of equal volume.
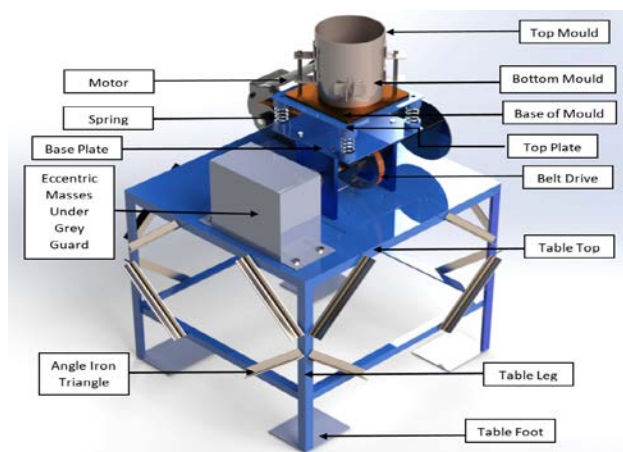

Figure 1. The soil vibratory compactor

3. Testing of the Soils Using the Constructed Vibratory Soil Compactor and the Standard Proctor Equipment

3.1 Purpose of the Tests

The purpose of the tests was to utilise the optimum operating parameters (frequency of 17 Hz, amplitude of 1.7 mm and time of 5 mins) for the vibratory soil compactor and obtain the density of two soils, each with five varying peat contents. The same soils were also tested using the standard Proctor test.

3.2 Procedure of the Testing

For both the standard Proctor test and the test using the constructed soil vibratory compactor, two soil samples common in Trinidad (see Table 1) were utilised: Piarco sandy loam, and Talparo clay. Soil texture was determined by the hydrometer method (ASTM, 2017), while the organic matter contents were determined using the Walkley and Black (1943) method. The soils were first dried, and sieved through 5 mm openings.

Table 1. Classification, organic matter, and the particle size distribution (%) of the soils

Type	Classification*	Organic Matter content (%)	Particle Size and distribution (%)		
			Sand (0.06-0.002 mm)	Silt (0.06-0.002 mm)	Clay (<0.002 mm)
Piarco sandy loam	Typic Kanhaplaquults	1.7**	64.9	17.0	18.1
Talparo clay	Aquentic Eutrudepts	2.7	25.4	28.3	46.3

* Classification according to the Soil Taxonomy System (Source: Ditzler, 2017)
** All values are means of three replicates

Peat was then incorporated at five levels of 0%, 4%, 8%, 12%, and 16%. For the Proctor compaction test, soil was compacted in three even layers at 25 blows each for increasing moisture contents ranging from 5% to 55%. Once the soil had been compacted, the extension of the mould was removed, the excess soil was scraped off and the mould was weighed. The mass of the compacted soil was measured and was then used to determine the dry bulk density.

For the vibratory soil compactor, the initial weight of the empty mould was first obtained. Soils at the same peat and water contents as in the Proctor test were poured into the mould in three equal layers to be compacted for the 5 mins duration each. After the soil had been compacted, the extension was removed, excess soil scraped off and the mould was weighed. This was done to determine the bulk density of the soil and this was compared to that obtained with the standard Proctor test. In both cases, graphs of dry bulk density vs. moisture content were plotted following the examples in previous research (de Kimpe et al., 1982; Felton and Ali, 1992; Ekwue and Stone, 1995; Leonard et al., 2019).

4. Results and Discussion

4.1 Operation of the Soil Vibratory Compactor

During the testing, it was observed that the constructed soil vibratory compactor produced sinusoidal vibration. There was noise generated from the shaking parts though it was bolted to the table and rubber pads were used. The legs of the table that the vibratory compactor rested on were cut and the table was fortified by bracing. Determining maximum dry bulk density using the vibratory soil compactor was not as laborious in nature when compared to the standard Proctor test. However, some effort was required to prepare the samples and remove the mould after each compaction.

4.2 Proctor Test and Soil Vibratory Compactor Test Results

Figure 2 shows the plots of the bulk density-moisture relations of the two soils, each with five varying peat contents using the 25 blows of the standard Proctor method compared with the same plots obtained using the soil vibratory compactor. As expected, for the two soils and methods, the results followed the normal soil behaviour, whereby the density values increased up to maximum values, called the maximum bulk density after which they decreased with further increases in moisture

content. This is typical soil behaviour. The density values obtained for these soils and the moisture contents at which they occurred were similar to those obtained for the same soils using the Proctor test in previous studies by Stone and Ekwue (1993), Ekwue and Stone (1994), Ekwue and Stone (1995) and Leonard et al. (2019).
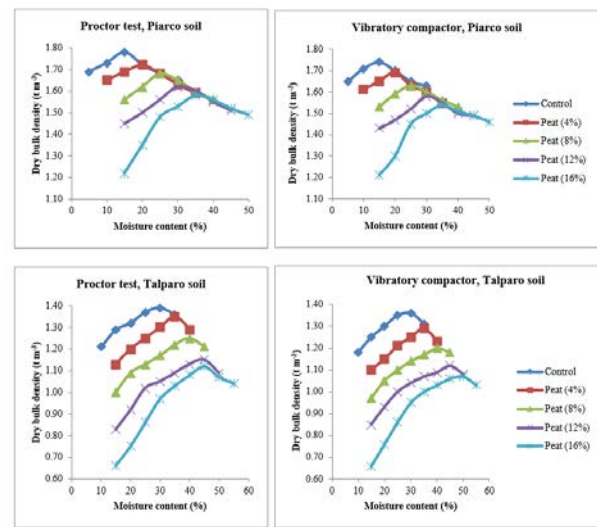

Figure 2. Density-water relations of the Piarco sandy loam and Talparo clay soils using the standard Proctor test and the soil vibratory compactor

Also as expected, the bulk density values for Piarco sandy soil were generally greater than those for the Talparo soil. Sandy soils are more compactable than clay soils (Ekwue and Stone, 1995; Suryakanta, 2014). This is because they contain less air voids and have little cohesion between the soil particles. In each case, as expected, the bulk density values decreased with increasing peat contents as peat is known to be less dense and therefore reduces soil bulk density (Ohu et al., 1985; Ekwue and Stone, 1994).

Most values of the bulk densities obtained with the soil vibratory compactor were lower than the Proctor ones by 0.02 to 0.06 t m^{-3} with a mean difference of 0.03 t m^{-3} (see Figure 2). The 95% confidence interval for the mean differences is (-0.04, -0.03). Since this confidence interval does not include zero, the difference between the means were significant at 5% level. This was confirmed by using a paired t-test which showed a significant (P = 0.05) t-value of – 14.83 between the two means.

Table 2. Maximum bulk densities using the soil vibratory compactor and the standard Proctor test

Soil type	Compaction Method	Peat content (%)				
		0	4	8	12	16
Piarco sandy loam soil	Vibratory soil compactor	1.74 (98%)*	1.69 (98%)	1.63 (97%)	1.58 (98%)	1.54 (97%)
	Standard Proctor test	1.78	1.72	1.68	1.62	1.58
Talparo clay soil	Vibratory soil compactor	1.36 (98%)	1.29 (96%)	1.20 (96%)	1.12 (97%)	1.07 (96%)
	Standard Proctor test	1.39	1.35	1.25	1.15	1.12

*Proportion of the value from the standard Proctor test

In general, maximum bulk densities obtained using the soil vibratory compactor were within 96% to 98% of corresponding values obtained using the Proctor test (see Table 2) and were lower by 0.02 to 0.06 with a mean of difference of -0.04 t m^{-3}. The 95% confidence interval is -0.05, -0.03. Since this interval does not contain zero, this also means that the differences between the mean values were significantly different at 5% level. This again was confirmed by a paired t-test value of -12.86, which is significant at 5%. The mean differences between the two soil compaction methods in both cases were well less than 0.1 t m^{-3} and are well within the error expected in soil measurements, bearing in mind that soils by their nature are very variable and complex. This is similar to the results obtained by Leonard et al. (2019).

As showed in Figure 3, the values for the bulk densities obtained using the two methods are highly correlated, although the 1:1 line drawn through the points demonstrated that most of the soil vibratory compactor values were slightly lower than the standard Proctor ones as already mentioned.
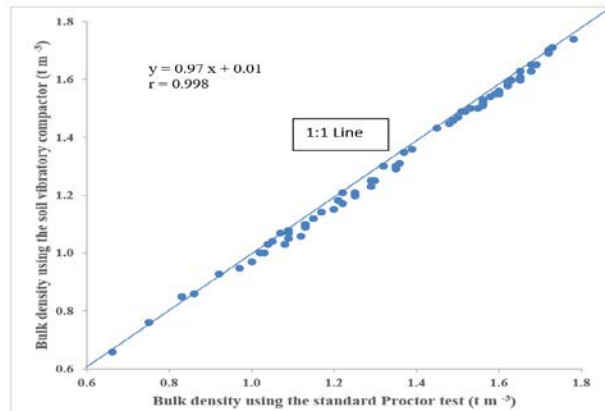
Figure 3. Comparison of bulk density using the two soil compaction methods

As explained in the materials and methods section, the soils were incorporated with the same levels of peat and compared at the same water contents. Results show that the values obtained with the soil vibratory compactor are lower but very close to the ones that obtained using the standard Proctor test. The new compactor is gives mostly reliable results. The present study has demonstrated in particular that the optimum operating parameters for the soil vibratory compactor developed in the previous study by Leonard et al. (2019) applies equally to the soils with different levels of organic matter content. This finding was not evident before the present study since organic matter in form of peat affects the soil cohesion, which influences the efficiency of the operation of the soil vibratory compactor.

4.3 Factors Affecting the Values of Bulk Densities in the Proctor Test and the Soil Vibratory Compactor

Table 3 summarises the mean values of dry bulk densities for the different experimental factors. The two soils with the peat contents were compared at the common four moisture contents of 15%, 20%, 25% and 30%. The mean values followed the same trend in Figures 2 and 3. It shows that there is little or no difference between the bulk densities (1.34 and 1.31 t m^{-3}) obtained with the two compaction methods. The mean value of bulk density was greater for Piarco sandy soil (1.57 t m^{-3}) than the Talparo clay (1.07 t m^{-3}). This is not surprising since it is known that sandy soils which are less cohesive have higher bulk density than the clay soils which are more cohesive and more aggregated (Ekwue et al., 2014; Suryakanta, 2014).

Table 3. Mean* bulk densities for the experimental factors

Factor	Dry bulk density (t m^{-3})
Method of compaction	
Standard Proctor test	1.34
Soil vibratory compactor	1.31
Soil type:	
Piarco sandy loam	1.57
Talparo clay	1.07
Peat content (%):	
0	1.51
4	1.43
8	1.34
12	1.24
16	1.09
Moisture content (%):	
15	1.25
20	1.31
25	1.36
30	1.38

* - Mean values for each factor were computed by averaging values over the levels of the other three experimental factors. Number of experimental points is 160 representing a factorial experiment with 2 methods of soil compaction, 2 soil types, 5 peat contents and 4 common moisture contents with two replications.

Table 4. Analysis of variance for dry bulk density

Source	DF	SS	MS	F	P
Method of compaction	1	0.027	0.027	34.23	0.00
Soil type	1	9.890	9.890	13000	0.00
Peat content	4	3.442	0.861	1089.51	0.00
Moisture content	3	0.393	0.131	165.68	0.00
Method *soil	1	0.001	0.001	1.53	0.22
Method* peat content	4	0.005	0.001	1.52	0.20
Method * Moisture content	3	0.0003	0.0001	0.13	0.94
Soil * peat content	4	0.229	0.057	72.35	0.00
Soil * Moisture content	3	0.075	0.025	31.66	0.00
Peat * Moisture content	12	0.267	0.022	28.16	0.00
Error	123	0.097	0.00079		
Total	159	14.426			

Moreover, bulk density values decreased with increasing peat content as has been found in previous studies by Ohu et al. (1985), Ekwue and Stone (1994) and Ekwue and Stone (1995). As expected, values of mean density increased with increasing moisture contents up the range of 15% to 30% moisture contents compared. The analysis of variance (see Table 4) carried out on the results showed that the effects of the main experimental factors of soil type, peat content, and moisture content of the soil were all significant in that order at 1% level. The F value for method of compaction was significant at the same level confirming that that the density values obtained with the soil vibratory compactor were significantly lower than those obtained from the standard Proctor test, although the values were close.

In addition, the most significant interactions that affected soil density are those between soil type and peat content, soil type and moisture content, as well as peat content and moisture content. These are considered below.

The interaction between soil type and peat content (see Figure 4a), showed that although bulk density decreased with peat content for the two soils, the decrease was more dramatic for Talparo soil than the Piarco sandy loam soil as the peat content increased. Ekwue et al. (2014) found that peat reduces the cohesion in sandy soils and therefore makes them more compactible. They also found that peat increases the cohesion in clay soils and make them less compactible. The incorporation of peat to decrease soil compactibility (as measured with bulk density) will therefore be more beneficial in clay rather than sandy soils. The interaction between soil type and peat content (see Figure 4b) and that between peat content and moisture content (see Figure 4c) showed that increase in bulk density with increasing moisture contents was greater in Talparo soils and also in soils with greater peat content more than those in Piarco sandy soil and soils with lower peat contents. In these latter plots, it can be seen that although bulk density was lower for Talparo clay and soils with high peat contents, as the moisture content in the soils increased, the values of bulk density converged. The effect of clay or peat content in decreasing the bulk

density during soil compaction was higher at lower moisture contents and declined as the moisture content of the soils increased. A major reason for this is that at the range of moisture contents compared for the two soils (15% to 30%), the moisture contents of Talparo clay soil with different peat contents were still below the optimum and therefore the bulk densities were still rising (Figure 2), while those for the Piarco sandy loam were between the rising or falling limbs of the curves.
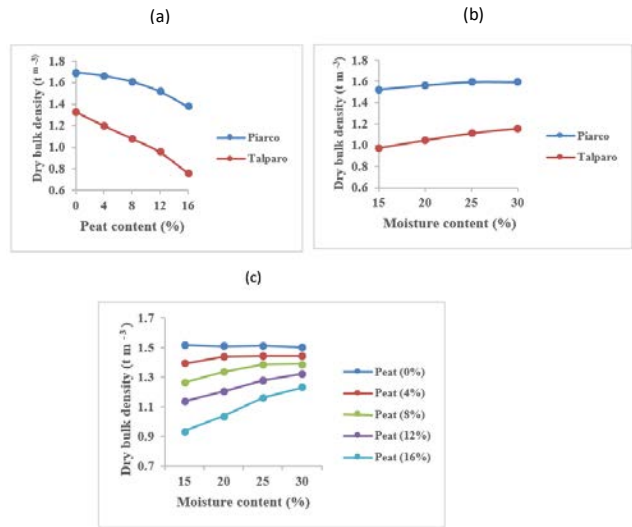
Figure 4. Interaction effects between (a) soil type and peat content (b) soil type and moisture content and (c) peat content and moisture content on dry bulk density

4.4 Relationships between Dry Bulk Density and the Experimental Factors

For each method of compaction, values of dry bulk density for the two soils with the five peat contents at the soil moisture contents were used to generate a multiple regression linear equation that could be used to predict bulk density. The two Equations (1) and (2) are:

For Proctor Test:

$$\rho_b = 1.95 - 0.0170 \, CL \, (\%) - 0.025 \, Pt \, (\%) + 0.006 \, MC \, (\%),$$
$$R^2 = 0.935, N = 68 \tag{1}$$

Student 't'   66.21   -27.15   -14.65   6.99

For Vibratory Compactor:

ρ_b = 1.91 - 0.0167 CL (%) - 0.024 Pt (%) + 0.005 MC (%),

R^2 = 0.945, N = 68   (2)

Student 't'   73.2   -30.02   -15.69   7.15

where: ρ_b = dry bulk density (t m^{-3});

        CL = clay content (%)

        Pt = peat content; MC = moisture content;

        R^2 = coefficient of determination;

        N = number of observations

The signs of the experimental factors in the equations above confirm how the factors affected the soil dry bulk density. The multiple coefficients of determination (R^2) for the two equations were significant at 1% level. The Student 't' values for all the experimental factors were significant at 1% level. The relative 't' values in Equations (1) and (2) for all the factors also confirmed that the most important factor that affected soil densities in the Proctor test soil vibratory compactor tests were soil type, peat content, and soil moisture content for testing the soil in that order.

5. Conclusion

The study involved comparing density values from a soil vibratory compactor to those obtained using the standard Proctor test. Soil samples from two Trinidad soils incorporated with peat at five levels were tested with varying moisture contents using the standard Proctor method and with the soil vibratory compactor. It was found that the density and the maximum density values of soils obtained with the soil vibratory compactor were lower but within 0.02 to 0.06 t m^{-3} of those obtained using the Proctor test. The objectives of the study have been met. The following can be concluded from the study:

1. During testing, it was discovered that the constructed soil vibratory compactor is user friendly and easy to operate.
2. The constructed soil vibratory compactor is suited for laboratory testing of maximum density for most soils with different properties like peat and moisture contents, and
3. Density and maximum density values produced for the test soils were consistent and are very close to those obtained with the standard Proctor test.

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