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The Effect of Compaction Effort on Shear Strength Parameters of Low/High Plasticity Clay Soils

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ABSTRACT: This paper investigates the effect of compaction effort on shear strength parameters of clay. Four clayey soils, two with high plasticity and two with low plasticity were used in this study. The initial physical properties of the clay such as gradation, optimum moisture content, maximum dry density, and Atterberg limits were determined in accordance with American Standard for Testing and Materials (ASTM) standard procedures. All soil specimens were remolded at five different compaction levels at three different water contents: dry, optimum and wet conditions. Empirical formulae were suggested to obtain optimum moisture content and maximum dry unit weight at an energy level utilizing the results obtained from the standard Proctor test. The shear strength parameters of the prepared specimens were determined using direct shear test. Another set of empirical formulae were also suggested to obtain the cohesion and friction angle at an energy level utilizing the cohesion and friction angle obtained from direct shear test at maximum dry unit weight and optimum moisture content from standard Proctor test.

KEYWORDS: Compaction energy, Cohesion, Angle of internal friction, Shear strength.

1. INTRODUCTION

Compaction of soil is a common engineering practice in many projects such as earth fill dams, landfills, embankments and contaminant facilities (Fener and Yesiller, 2013). Compaction is defined as densification of soils by the use of mechanical energy (Hotlz et al., 2010). This procedure will move the soil particles closer together reducing the volume of the air and voids in soil fabric. The compaction will also tend to change the soil structure arrangement from flocculated to disperse when the water content increases from the dry side to wet side of the optimum moisture content for the same compaction effort (Lambe and Whitman, 1979). This rearrangement of soil microstructure and macrostructure results in decreasing its compressibility, hydraulic conductivity, and increasing its shear strength (Craig, 1987; Sridharan and Gurtug, 2004).

The impact of compaction on the clay behaviour and its physical properties has been well recognized (Mitchell, 1956; Lambe, 1958; Seed and Chan, 1959). Many investigators studied different physical properties of compacted clay such as compressibility, drained and undrained shear strength, swelling, anisotropy, stiffness and permeability under different initial conditions. Ghosh (2013) studied the effect of soil moisture content on the undrained shear strength of compacted clay and showed that shear strength of clay decreases exponentially with the increase of the water content. Cokca and Tilgen (2010) developed a function between moisture content and suction curve to study the relation between soil suction and shear strength of compacted Ankara clay at different moisture contents. Cokca and Tilgen (2010) concluded that increase in soil suction will increase the shear strength of compacted clay. Another research conducted by Fredlund and Rahardjo (1993) showed that the shear strength of unsaturated compacted clay is affected by the soil suction. Vanapalli et al. (1996) used a modified direct shear apparatus to determine the shear strength of compacted glacial till at three different levels of initial water content. It has been found that the different levels of compaction changes the soil structure and the same soil at different water content and densities should be considered as different soil even if they have same mineralogy, plasticity and texture. Rahardjo et al. (2011) simulated the Young's moduli of saturated and unsaturated compacted soil. It was revealed that the Young's modulus of the compacted soil increased by increasing the normal stress and the matric suctions.

Other investigations on shear strength of dynamically and statically compacted specimens of clay and sand showed that the appropriate displacement should be selected for each test condition (Escario and Saez, 1986; Gan and Fredlund, 1992). Shear anisotropy of compacted clay were also investigated by many researchers. Hartge and Bachmann (2004) and Bachmann et al. (2006) investigated the anisotropic behaviour of mechanical properties in relation to consolidation condition of the clay soil. Attom and Al-Akras (2008) conducted a comprehensive study on the anisotropy in the shear strength of clay soils. The study was based on fifteen different types of clayey soils extracted from different depths varies from 1 to 5 m below the ground surface. These samples were extracted in three different directions; horizontally, vertically and diagonally (45 degree to the horizontal). It was found that both unconfined compressive strength and failure strain in the vertical direction are larger than in the horizontal direction. It was also found that anisotropy increased with increasing the depth and over-consolidated ratio. Rowshanzamir and Askari (2010) conducted an investigation on the shear anisotropy of compacted clay. Their investigation was conducted on samples prepared in a large cube and were extracted in two different directions from the cube parallel and perpendicular to the direction of compaction. The anisotropy was observed in all tested samples. They revealed in their investigation that unconfined shear strength in the compacting direction is greater than in perpendicular to the compaction direction and it may reach as high as to 1.23. Fazekas & Horn (2005) indicated that the pre-compression stress in laterally confined earth fill platy structure is greater than in horizontally sampled soils. Other properties of compacted clay have also been studied. The investigation on the effect of wetting-drying cycle on hydro-mechanical behaviour of unsaturated compacted clay was conducted by Chen and Ng (2013). According to their study a smaller pre-consolidation stress value was observed due to wetting-drying cycle. It was clear that the clayey soil can be affected by many mechanical factors that influence significantly its physical properties.

The main objective of this research is to investigate the shear strength behaviour of compacted clay at different initial water content and compaction levels. The study is based on four types of clayey soils (S1, S2, S3 and S4) with different clay contents and consistency limits. The shear strength parameters of the tested soils such as angle of internal friction and the cohesion were determined at different compaction levels. All tests were conducted on remoulded samples using Direct Shear test in accordance with ASTM D3080.

2. LABORATORY TESTING PROGRAM

2.1 Soil Physical Properties

To achieve the objectives of this research, four types of clayey soils were selected. The selection was based on the clay fraction and consistency limit to ensure using clay with different properties. The initial physical properties such as consistency limits, grain size distribution, specific gravity and maximum dry density and optimum moisture content were determined in accordance with ASTM standard procedures. The soils were then classified according to Unified Soil Classification System (USCS). The shear strength parameters such as angle of internal friction and cohesion have been determined using direct shear test. The samples used in the test were remoulded at 95% relative compaction and optimum moisture content from the Standard Proctored test values. Table 1 shows the physical properties of the soils used in this research. The compaction parameters were determined according to the standard procedures of Standard Proctor density test.

Table 1 Physical properties of different clays used in the study

Description	Soil 1	Soil 2	Soil 3	Soil 4
Consistency limits				
Liquid limit (%)	71	61	37	25
Plastic limit (%)	25	25	18	15
Plastic Index (%)	46	36	19	10
Activity	0.74	0.61	0.40	0.26
Grain Size Distribution				
Clay (<2 µm) (%)	62	59	48	39
Silt (75 µm - 2 µm) (%)	27	35	33	32
Sand (2 mm - 75 µm) (%)	15	6	19	29
Specific gravity of solid, G_s	2.67	2.65	2.67	2.67
Soil Classification	CH	CH	CL	CL

2.2 Sample preparation

The standard proctor density test mould was used to prepare the specimens. Specimens from each type of soil were prepared at five different compaction levels by applying five different energy levels on the soil in the compaction mould. The first level of compaction was obtained by compacting the soil in 3 layers with 15 blows on each layer with a hammer mass equal to 2.49 kg falls from 30.48 cm. The second compaction set is similar to first set but with 25 blows instead of 15 blows. For the third compaction set, the soil was compacted at 5 layers at 25 blows and hammer weight equal to 2.49 kg falling from 30.48 cm. The fourth set was compacted in 3 layers with 25 blows on each layer with hammer drop height equal to 45.72 cm and hammer weight equal to 4.53 kg. The fifth and final set was prepared similar to fourth set but at 5 layers instead of 3 layers. This variation in the number of layers, hammer weight and drop height deliver different compaction effort to the prepared specimens. The energy levels applied to the various soils equal to E1 = 355.6 kN-m/m^3, E2 = 592.7 kN-m/m^3, E3 = 987.8 kN-m/m^3, E4 = 1629.1 kN-m/m^3 and E5 = 2693.8 kN-m/m^3 respectively. Table 2 summarizes the different energy levels applied to four clayey soil samples. The energy level, E was obtained using Eq. (1).

$$E = (W \times N1 \times N2 \times H)/V \tag{1}$$

where,

W = Weight of the hammer
N1 = Number of layers
N2 = Number of blows
H = height of the drop and
V = Volume of the mould.

Table 2 Different compaction energies applied on tested samples

Sample No	Hammer mass (kg)	Height of drop (cm)	No. of blows	No. of layers	Volume of mold (cm^3)	Energy applied (kN-m/m^3)
E1	2.4947	30.48	15	3	934.45	355.6
E2	2.4947	30.48	25	3	934.45	592.7
E3	2.4947	30.48	25	5	934.45	987.8
E4	4.5359	45.72	25	3	934.45	1629.1
E5	4.5359	45.72	25	5	934.45	2693.8

Figure 1 shows the compaction tests results for the four soils at the various applied energy levels. The typical compaction curves were obtained as shown in the Figure 1. The maximum dry unit weight increases as the applied energy level increases. However, the optimum moisture content decreases as the applied energy level increases. The optimum moisture contents for the high plasticity soils (S1 and S2) were higher than those obtained for low plasticity soils (S3 and S4). The maximum dry unit weights for low plasticity soils were higher than those obtained for the high plasticity soils.

Tables 3 and 4 summarize the water contents on dry side of optimum, optimum and wet side of optimum considered in preparing the samples for determination of shear strength parameters (cohesion and friction angle). The water contents at dry and wet conditions were obtained at 95% of the maximum dry unit weight. At the end of proctor's compaction test, complete sample was extruded from the mould using mechanical sample extruder. Thereafter, it was very carefully cut into a shape with size 1-2 mm more than direct shear test mould in all directions and then gently pushed into it. Standard direct shear tests were performed and three identical samples were prepared for each direct shear test. Samples were sheared under three different normal stresses of 27.5 kPa, 55 kPa and 110 kPa respectively. The shearing stresses under different normal stresses were obtained. The angle of internal friction and the cohesion of the soil were obtained from the shearing stress versus the normal stress plots. It shall be noted that all shear parameters plotted in various figures as part used as part of this research are in peak state.

3. DISCUSSION OF RESULTS

3.1 The Effect of Compaction Effort on the Optimum Moisture Content

Figure 2 shows the normalized moisture contents for the four soils at the various applied energy levels. A curve was fitted to allow determining the optimum moisture content at a specific applied energy level other than the energy level used for the standard Proctor test. The equation is as follows,

$$\omega_{opt} = 2.6 \times \omega_{opt}^{*} \times E^{-0.15} \tag{2}$$

where,

ω_{opt} = Optimum moisture content at applied energy level E
ω^{*}_{opt} = Optimum moisture content obtained from standard Proctor test (E = 600 kN-m/m^3)
E = applied energy level in kN-m/m^3

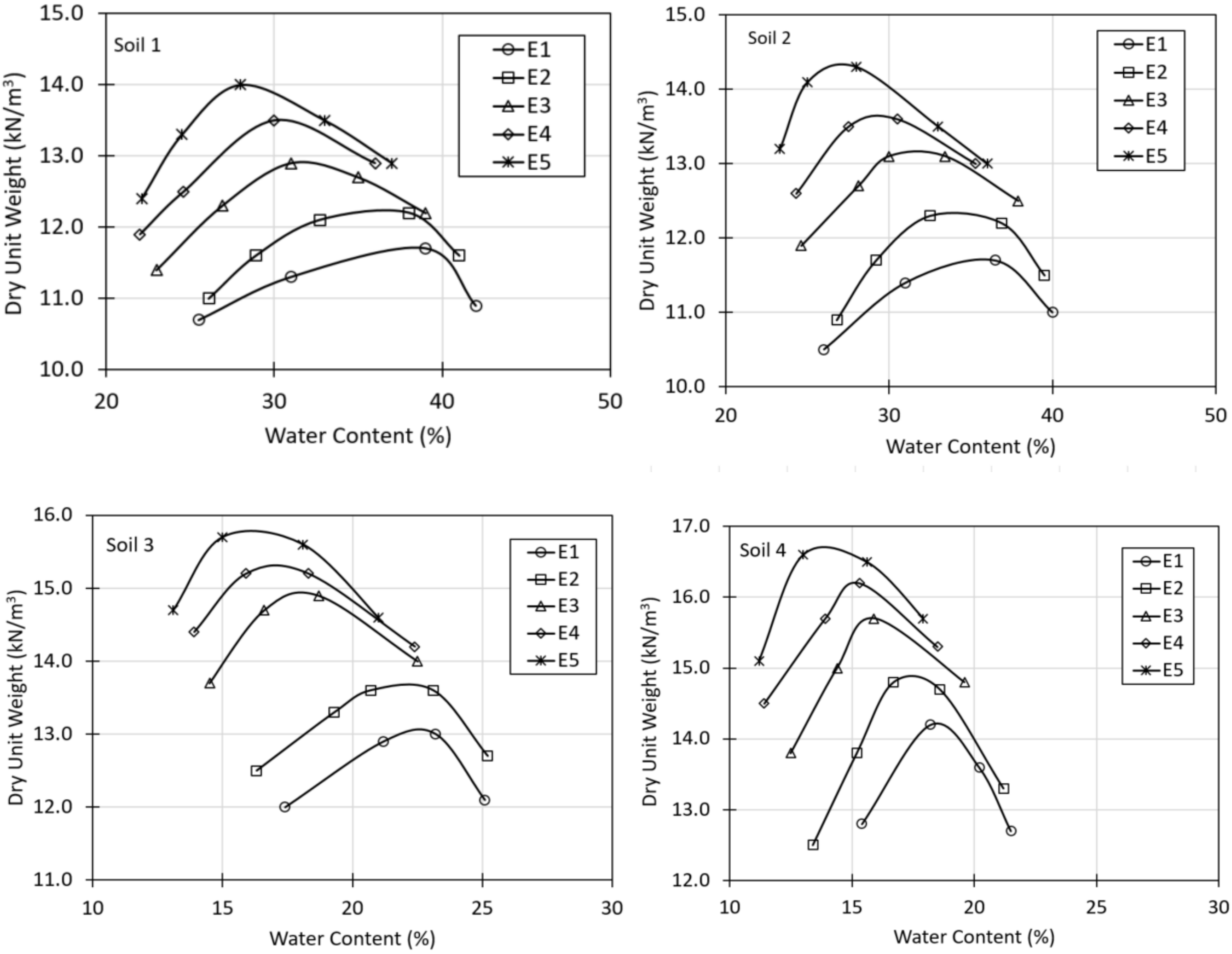

Figure 1 Compaction test results for four soils (S1, S2, S3 and S4) at the five different energy levels (E1, E2, E3, E4, and E5)

Table 3 Dry, optimum, wet moisture contents and maximum dry unit weights at the various energy levels for high plasticity soils (S1 and S2)

Energy Level	**Soil 1**				**Soil 2**			
	$\gamma_{dry-max}$ (kN/m^3)	**ω_{dry} (%)**	**$\omega_{opt.}$ (%)**	**ω_{wet} (%)**	**$\gamma_{dry-max}$ (kN/m^3)**	**ω_{dry} (%)**	**$\omega_{opt.}$ (%)**	**ω_{wet} (%)**
E1	11.7	29.0	38.7	40.9	11.7	29.3	35.7	39.4
E2	12.2	28.9	37.0	41.4	12.4	29.3	34.0	38.8
E3	12.9	26.5	31.7	38.7	13.2	27.3	31.7	37.8
E4	13.5	26.0	30.3	36.0	13.7	25.6	29.3	35.3
E5	14.0	24.5	28.2	34.4	14.4	24.0	27.0	32.3

Table 4 Dry, optimum, wet moisture contents and maximum dry unit weights at the various energy levels for low plasticity soils (S3 and S4)

Energy Level	**Soil 3**				**Soil 4**			
	$\gamma_{dry-max}$ (kN/m^3)	**ω_{dry} (%)**	**$\omega_{opt.}$ (%)**	**ω_{wet} (%)**	**$\gamma_{dry-max}$ (kN/m^3)**	**ω_{dry} (%)**	**$\omega_{opt.}$ (%)**	**ω_{wet} (%)**
E1	13.1	19.1	22.6	24.5	14.2	16.7	18.5	20.4
E2	13.7	18.1	22.1	24.6	14.9	15.7	17.5	19.7
E3	15.0	15.5	18.0	21.7	15.7	14.3	15.9	19.2
E4	15.3	14.3	17.0	21.0	16.2	13.3	15.1	17.3
E5	15.8	13.6	16.1	20.0	16.7	12.0	13.9	17.4

This trend of decreasing the optimum moisture content with increasing the compaction level can be explained as the energy level increased more soil solids will be placed in the same volume and therefore it will replace the water in the mould. In other words, these soils particles will enter the voids and reduce the volume of voids that will be filled with water.

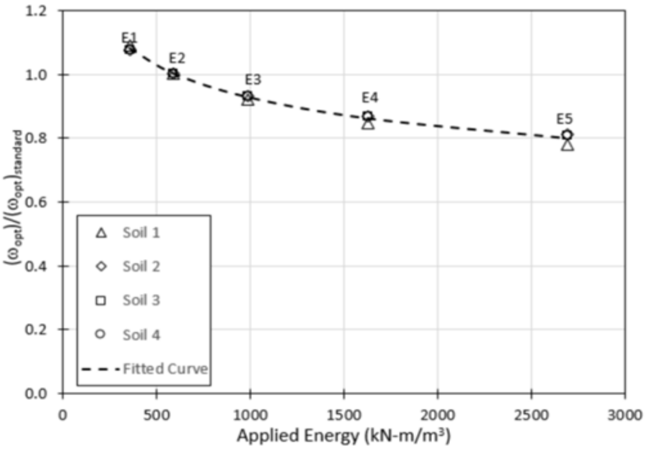

Figure 2 Normalized optimum moisture contents versus applied energy

3.2 The Effect of Compaction Effort on the Maximum Dry Density

Figure 3 shows the relationship between the normalized maximum dry unit weights and the applied energy levels. From the figure, a curve was fitted to allow determining the maximum dry unit weight at any energy level from the maximum dry unit weight obtained from the standard Proctor test. The maximum dry unit weight at any energy level is obtained using Eq. (3).

$$\gamma_{d-max} = 0.56 \times \gamma^*_{d-max} \times E^{0.092} \tag{3}$$

where,

$\gamma_{d\text{-}max}$ = Maximum dry unit weight at a specific energy level (E)
$\gamma^*_{d\text{-}max}$ = Maximum dry unit weight obtained from standard Proctor test (E = 600 kN-m/m^3)
E = applied energy level in kN-m/m^3

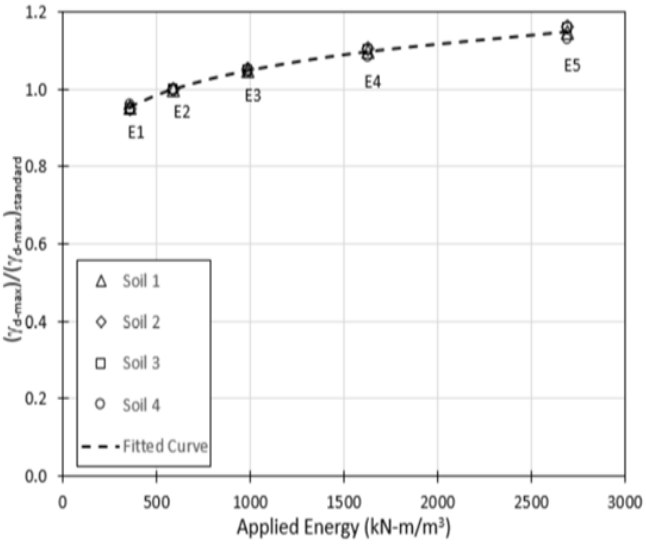

Figure 3 Normalized maximum dry unit weights versus applied energy

As it can been noticed that the increase in the compaction level will increase the maximum dry density contrasting of what has been noticed in the optimum moisture content behaviour. The trend supports the explanation in the section 3.1. This is due to the fact that more soil will be placed in the same volume that filled the voids resulting in increasing the weight of the soil and furthermore increase the maximum dry density.

3.3 The Effect of Compaction Effort on the Angle of Internal Friction Compacted Soils

Figure 4 shows the friction angles of soils obtained from the direct shear test at the dry, optimum and wet moisture contents. In general, the soil friction angles for low plasticity soils were higher than the high plasticity soils. The friction angles at wet conditions were not changing considerably (almost constant) for different applied energy levels. However, soil friction angles were increasing as the applied energy level increases when compacted at or dry side of the optimum. Overall, soil friction angles at the optimum moisture contents were highest compared to those obtained from samples compacted on wet and dry side of the optimum. This increase in angle of internal friction on the dry side can be explained as a result of clay behaviour at the micro-scale level. The clay particles in the dry side of the optimum are in the flocculated condition and increasing the energy level tends to bring the soil particles closer and denser. The flocculated conditions of the clay particles will resist the movement and need more shearing forces for the shear parameter to mobilize. This will lead to a higher friction angle at the dry side due to the increase in the compaction level.

The relationship between the normalized friction angles and the applied energy levels on wet and dry side of optimum is shown in Figure 5. A curve was fitted to the dry condition and the friction angle at energy level can be obtained from the friction angle obtained at optimum moisture content and maximum dry unit weight from the standard Proctor test using Eq. (4). For the wet condition, the friction angle at any energy level is same friction angle obtained using optimum moisture content and maximum dry unit weight from standard Proctor test. However, the friction angle at the optimum condition at any energy level can be obtained using Eq. (5) based on the normalized relationship shown in Figure 6.

$$\left(\frac{\emptyset}{\emptyset^*}\right) = \left(\frac{E}{600}\right)^{0.3} \tag{4}$$

$$\left(\frac{\emptyset}{\emptyset^*}\right) = \left(\frac{E}{600}\right)^{\beta} \tag{5}$$

where,

$\emptyset$ = Soil friction angle at a specific energy level (E)
$\emptyset^*$ = Soil friction angle obtained from direct shear test at dry Eq. (4) and optimum Eq. (5)
β is obtained from Figure 7 using either the plasticity index (PI%) or activity (A)

3.4 The Effect of Compaction Effort on the Cohesion of the Soil

Figure 8 shows the relationship between the soil cohesion at dry, optimum and wet conditions for the four soils at the five energy levels. In general, the cohesion was higher for high plasticity soils than the low plasticity soils. For all soils, the cohesion at the wet condition was decreasing as the energy level decreases. However, the cohesions at the dry and optimum conditions were increasing for all soils as the energy level increases. Overall, the cohesions at the optimum for all soils were the highest compared to those at the wet and dry conditions.

The relationship between the normalized cohesions at dry, optimum and wet conditions with the energy levels is shown in Figure 9, wherein three curves were fitted for obtaining the cohesion at any energy level from the cohesion obtained at standard Proctor results. The cohesion at any energy level is obtained using Eq. (6).

$$\left(\frac{Cohesion}{Cohesion^{*}}\right) = \left(\frac{E}{600}\right)^{\alpha} \qquad (6)$$

where,

Cohesion = is the cohesion at a specific energy level (E)
$Cohesion^*$ = is the cohesion obtained from direct shear test at dry, optimum and wet moisture contents based on standard Proctor test.
α = 0.255 for dry, 0.235 for optimum and -0.08 for wet

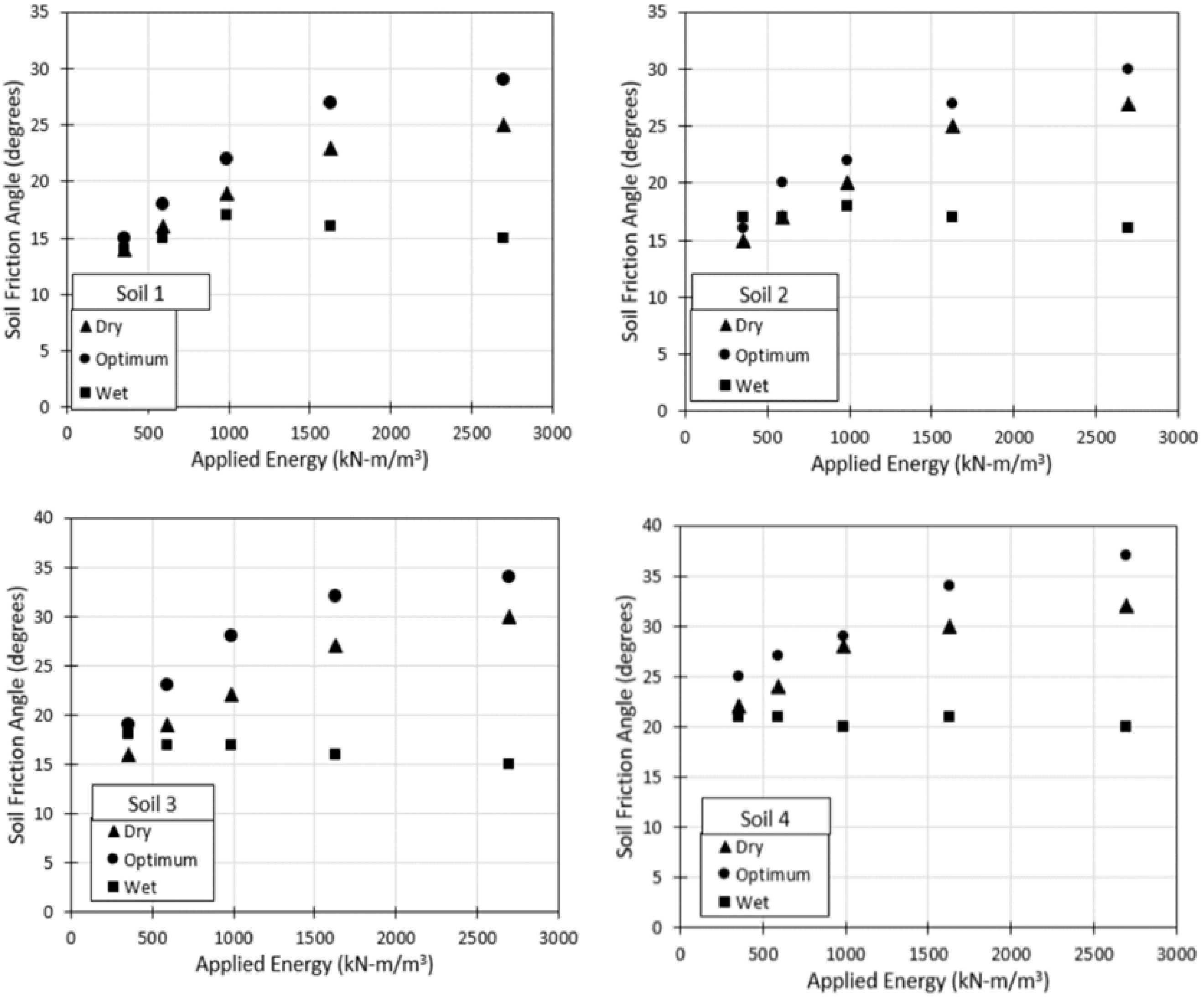

Figure 4 Soil friction angle at dry, optimum and wet moisture contents versus applied energy

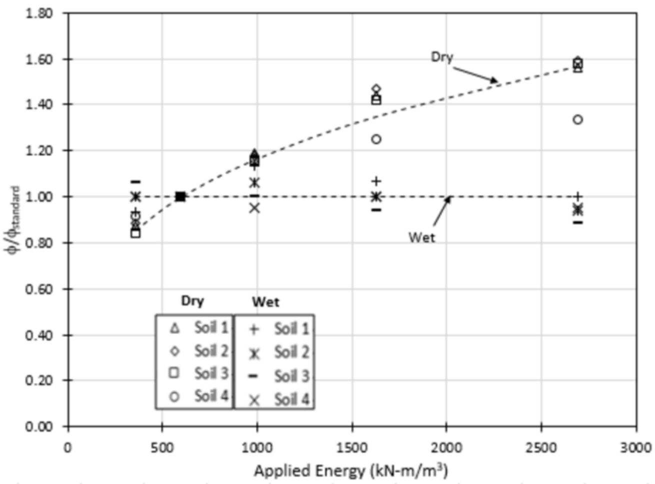

Figure 5 Normalized soil friction angle at dry and wet conditions versus applied energy

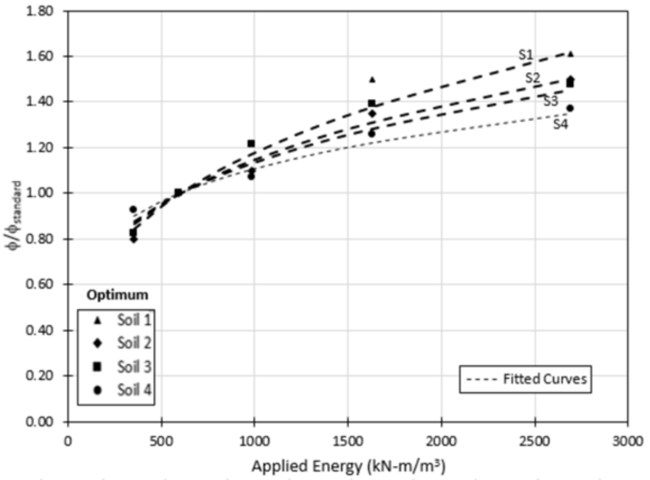

Figure 6 Normalized soil friction angle at the optimum condition versus applied energy

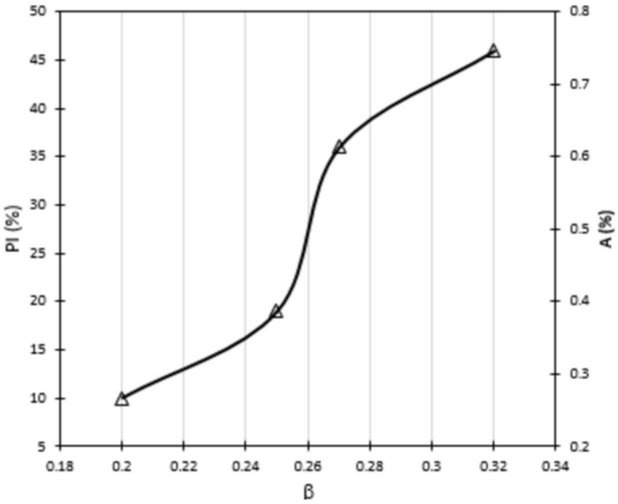

Figure 7 Relationship between the plasticity index, soil activity and β

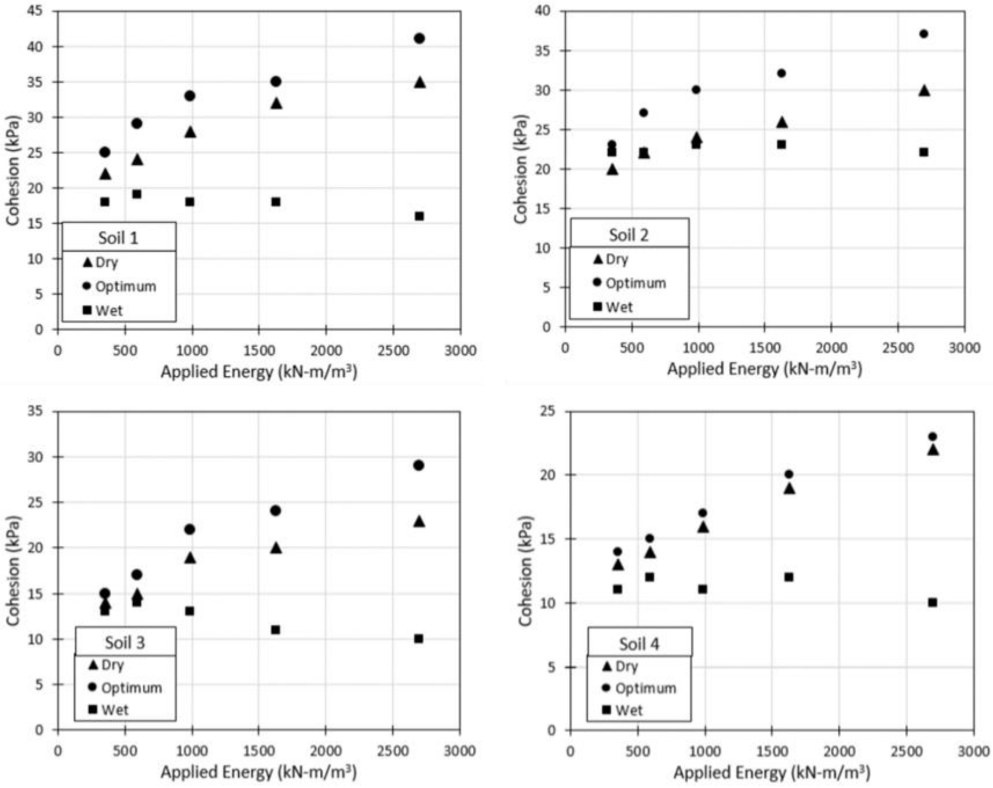

Figure 8 Soil cohesion at dry, optimum and wet moisture conditions versus applied energy

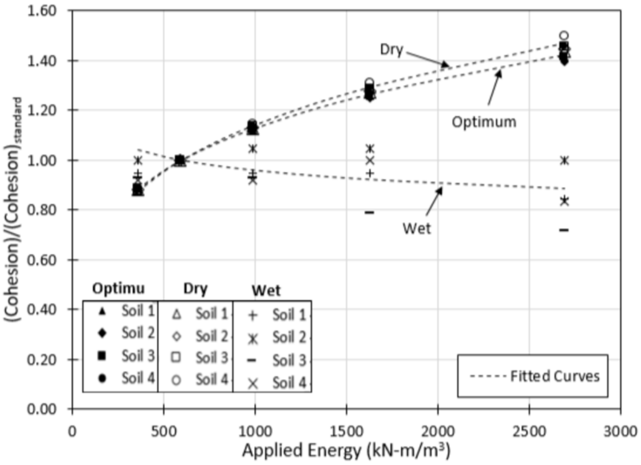

Figure 9 Normalized soil cohesions at dry, optimum and wet conditions versus applied energy

3.5 The Effect of Compaction on the Strength of the Soil

The shear strength of the soil is mainly a function of cohesion and angle of internal. Mohr–Coulomb theory states that the shear strength of the soil can be calculated by Eq. (7).

$$\tau_f = c + \sigma \tan\phi \qquad (7)$$

where c is the cohesion, σ is the normal stress and ϕ is the angle of internal friction

As shown before, the compaction effort significantly improved the angle of internal friction and the cohesion of the soil if the soil initial water content is at the dry side or at the optimum moisture content. This obviously increases shear strength of the all four types of clays. To verify this, shear strength for all four clays were determined at various normal stress levels and found that shear strength increases with increase in applied energy at optimum moisture content and dry side of it, whereas it decreases on wet side of optimum moisture content. This is due to the fact that cohesion and angle of internal friction are directly proportional to shear strength of the soil (Eq. 7). However such improvement in shear strength of the soil is expected only if the soil water content is on dry side or at the optimum moisture content. To depict this, a sample graph (Figure 10) assuming the density of soil as 18 kN/m^3 throughout the ground strata that develops a stress of 18 kPa at 1.0 m depth was plotted. However, in practice, normal stress at any depth can be calculated using density and thickness of various layers and shear strength can be calculated using the cohesion and friction angle. The reduction in shear strength parameters or shear strength itself above optimum moisture content could be attributed to change in structure of soil to dispersed state in which the soil particles will lose its interlocking property and shears easily.

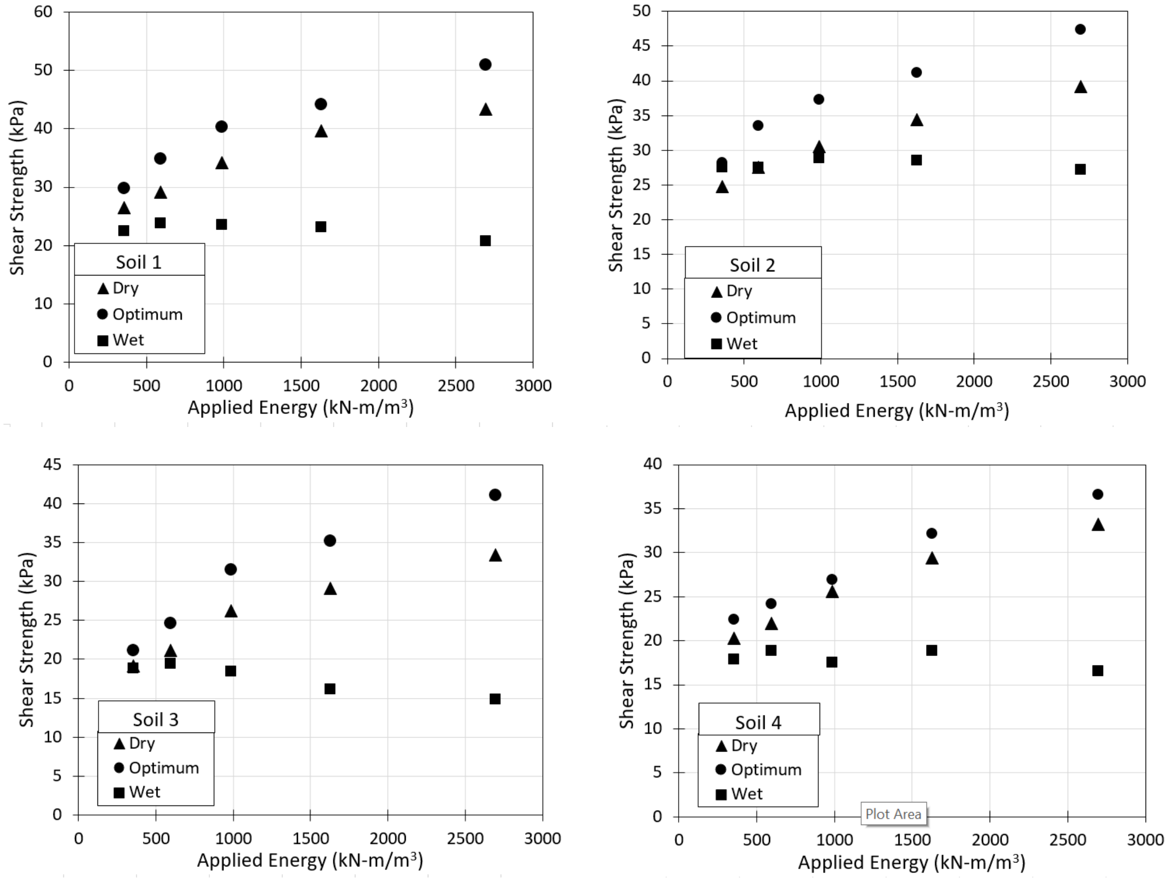

Figure 10 Soil shear strength at dry, optimum and wet moisture conditions versus applied energy

4. CONCLUSIONS

Based on the direct shear test results on four types of clays in evaluating shear strength parameters of compacted clay prepared at different initial water content and compaction efforts, the following conclusions were drawn:

1) The shear strength parameters of the compacted clayey are significantly affected by the initial water content and the compaction effort.
2) Increase the compaction effort will increase the angle of internal friction and cohesion of soils if the water content at below or at the optimum moisture content. This has been noticed in all clays tested in this research work.
3) The compaction effort has no effect or may decrease the angle of internal friction and cohesion if the water content of the soil is above the optimum moisture content.
4) Increase in shear strength of the clay increases with increase the compaction effort if the water content level is below or at optimum water content. However, this behaviour is limited to water content at or below optimum level.
5) Empirical formulae were developed to predict the shear strength parameters of clays at any desired compaction levels.

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