Optimum Water Content and Maximum Dry Unit Weight of Clayey Gravels at Different Compactive Efforts

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ABSTRACT

Compaction is one of the efficient ways to improve the strength and stiffness properties of soils, such as elasticity modulus and shear modulus. Moreover, compaction decreases soil settlement, improves bearing capacity and the stability of sloped embankments. An optimum water content is required to provide the best path to enter energy into soil and compact it. A constant value of energy applied to a particular type of soil, at optimum water content, leads to a maximum dry unit weight. The aforementioned parameters (γ_{dmax} , w_{opt}) are not unique for various types of soils and vary with the type of soils and the compaction energy. At the present study, an empirical method is presented to estimate the maximum dry unit weight, and the optimum water content of clayey gravel at different compaction energy levels. The study is performed at four different compaction energy levels. Based on the results, it is observed that γ_{dmax} and w_{opt} hold a linear relationship with log E. The two quantities, i.e. γ_{dmax} and w_{opt} are function of the fine grain (clay) content. Finally, the mathematical models are developed to determine γ_{dmax} , w_{opt} of the studied soils regarding two variables, i.e. energy levels and the clay percentage and the spatial surface is presented. A comparison performed on the empirical and predicted values of γ_{dmax} and w_{opt} shows high and acceptable accuracy of the equations. Since the clayey gravels(GC) are one of the very common used soils in construction projects, for instance, as priority in the crust or core of embankment dams, using the equations and the figures at the present study, a correct estimation can be made for γ_{dmax} and w_{opt} of such soils.

KEYWORDS: Compactive effort- Maximum dry density - Optimum water content –Fine grained soils – Coarse grained soils- Clayey gravel

INTRODUCTION

Soil compaction is a method which improves physical and mechanical soil properties.On the other hand, estimation of laboratory dry unit weight is one of the main parts to identify the state of embankments and to draw a conclusion about their quality[1]. Regarding the vast varieties of particle size distribution and mechanical properties of soils, most researchers have tried to study on the properties of a special grain-size distribution. Several researchers [e.g., Jumikis (1958), Hilf (1956), Ring et al. (1962), Ramiah et al. (1970), and Wang and Huang (1984)] have described some methods to estimate the optimum water content and/or maximum dry unit weight of clayey soils. In most of these methods, consistency indexes are used to estimate the maximum dry unit weight and optimum water content at a given compactive effort [2, 3, 4, 5].

Boutwell (1961) reported that a linear relationship exists between maximum dry unit weight and the common logarithm of compaction energy (log E).His tests was based on the observed behaviour of well graded micaceous silty sand. By investigation of recorded data from several tests conducted on clayey soils, it was found that there is a linear relationship between optimum water content and maximum dry unit weight with common logarithm of compaction energy(Fig.1)[6]. Blotz, Benson and Boutwell (1998) have described a simple empirical method for estimation of maximum dry unit weight (γ_{dmax}) and optimum water content (w_{opt}) of clayey soils at different compactive efforts using the liquid limit (LL) or LL with a compaction curve. The method is based on the linear relationship between γ_{dmax} and the common logarithm of compaction energy (log E), and the linear relationship between ω_{opt} and log E as determined in laboratory testing. These linear relationships correlate well with the liquid limit[7]. Most of the researches related the mechanical soil properties to the soil nature, Atterberg limits and the compaction condition of the soils under consideration. The coarse grained gravel with considerable clay such as GC has been studied. These types of soils are used in homogeneous embankment dams as the first priority at the crust and at the non-homogeneous embankment dams as the first priority at the core. These types of soils due to the high content of gravel, hold high modulus of elasticity and holding clay makes them less permeable. Regarding the importance of GC and it's great application, the focus of the present study is on the influence of the weight percentage of fine grained soils on γ_{dmax} and ω_{opt} at different compaction energy levels.

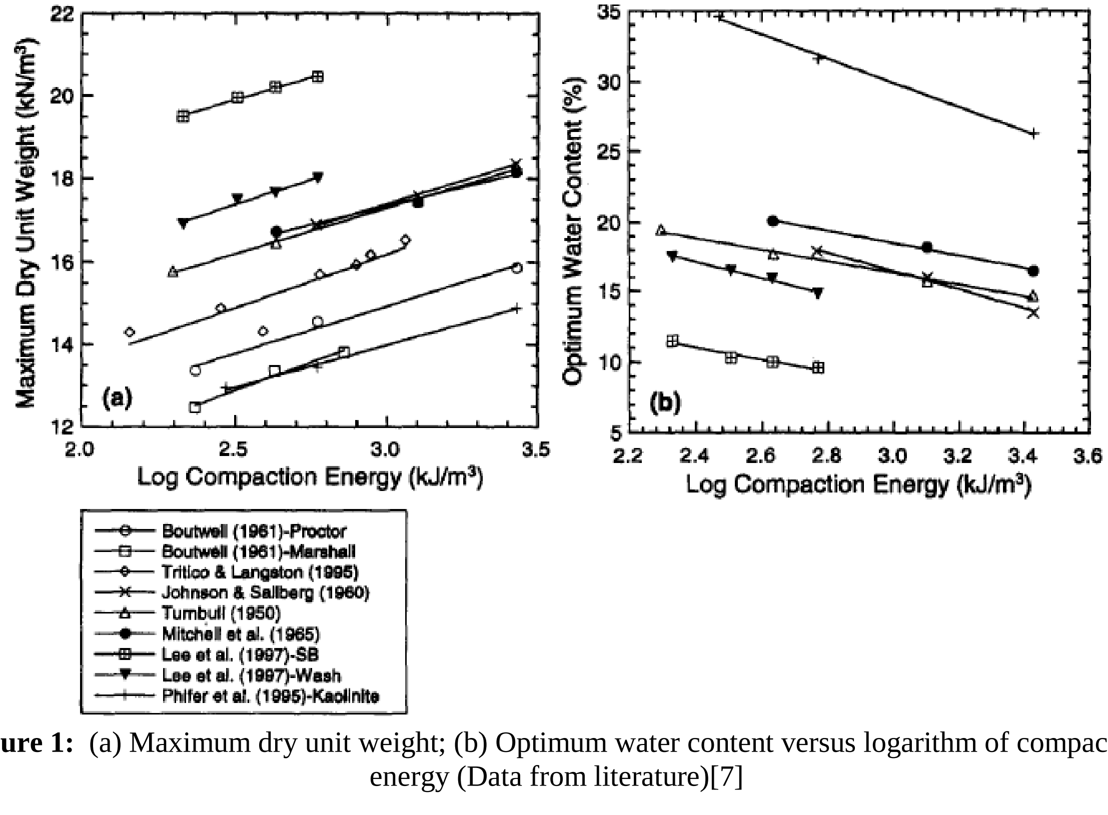

Figure 1: (a) Maximum dry unit weight; (b) Optimum water content versus logarithm of compaction energy (Data from literature)[7]

Materials and methods

The soil used in this study was coarse gravel. Different percentages of fine- grained soils (clay) were added to the samples to provide plastic and sealing conditions[8]. Table 1 shows the properties of the samples. All the tests were based on the ASTM standard code of practice. A constant percentage of sand was utilized in all samples to reassure well- grained and non gap- grained mixtures which results in better compaction (Table 2 and Fig. 2).

Table 1: Mechanical properties and consistency of soils

	Liquid limit	Plastic limit	Plasticity Index	Specific Gravity	Absorption
Clay	22.8	14.78	8.02	2.74	--
Gravel	--	--	--	2.53	1.19

Table 2: Properties of particle size distribution

	%particle passing from Sieve (mm)					%particle passing from Sieve no.			
Soil	25	19	12.5	9.5	4.75	8	20	40	200
A	100	80.75	61.5	42.25	23	16	9	3	3
B	100	82.00	64.00	46.00	28	21	14	8	8
C	100	83.75	67.5	51.25	35	28	21	15	15
D	100	86.25	72.5	58.75	45	38	31	25	25
E	100	88.75	77.5	66.25	55	48	41	35	35
F	100	91.25	82.5	73.75	65	58	51	45	45

All soils were compacted using two compactive effort including standard Proctor (ASTM D698-91) and modified Proctor (ASTM D1557-91). Based on the grain size distribution,all compaction tests were in accordance with procedure C of ASTM D 698-91[9]. In order to investigate the effect of compaction energy on γ_{dmax} and ω_{opt} more accurately,another two compaction energies including “reduced standard” Proctor (RP) and “Reduced modified” Proctor (RMP)were tested on the samples. The properties of compaction tests are summarized in Table 3.

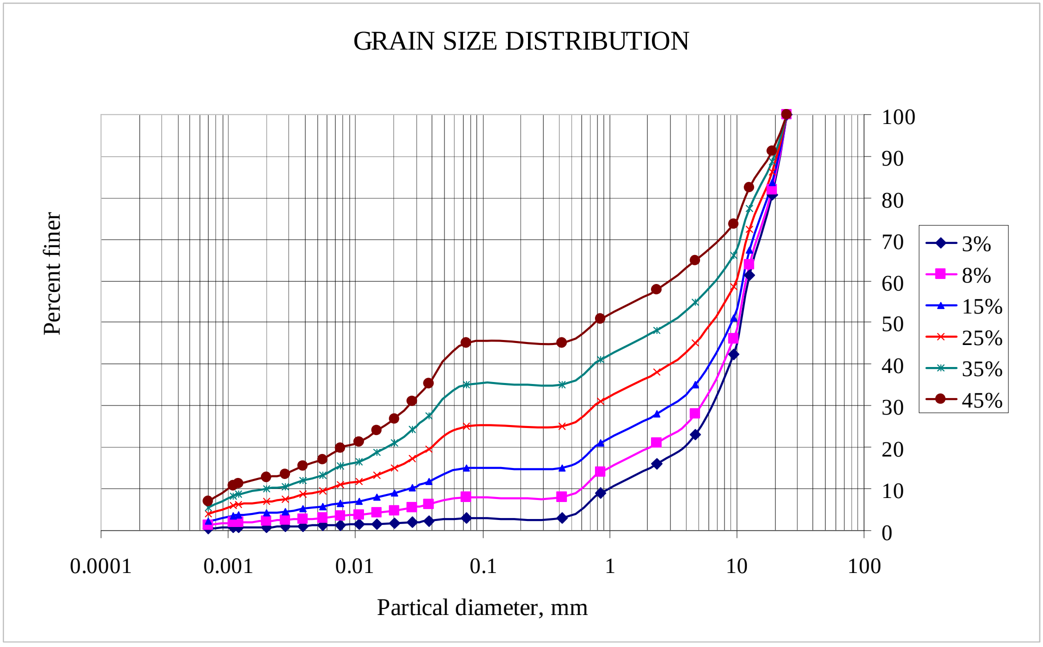

Figure 2: Grain size curve

Table 3: Properties of compaction tests

Type of Compaction	Soils Layers	Blows per Layer	Compaction Energy (KN-m/m3)
Reduced Proctor (RP)	3	35	370
Standard Proctor (SP)	3	56	590
Reduced Modified Proctor (RMP)	5	25	1200
Modified Proctor (MP)	5	56	2680

RESULTS

In this part, effect of different parameters on maximum dry unit weight and optimum water content will be discussed.

Effect of compactive effort on maximum dry unit weight and optimum water content

Figs. 3 and 4 show the variation of γ_{dmax} and ω_{opt} versus common logarithm of compaction energy (loge E)on semi logarithmic scale. As shown in Fig. 3, it may be concluded that with an increase in compaction energy, the maximum dry unit weight increases likewise. At lower percentages of clay content (3% and 8%), the increase in maximum dry unit weight with increasing energy keeps a steeper trend. This observation is due to the fact that the high compaction energy fractures the coarse grains of gravel in the samples and the fractured particles fill the pores between the gravels and hence the maximum dry unit weighs increases considerably. The fitted line offered for ω_{opt} in logarithmic scale shows the variations of ω_{opt} at different compaction energies (Fig. 4).Slope of fitted lines are almost equal and negative. As shown in Fig. 4, with increasing clay content optimum water content increases, and with increasing compaction energy, optimum water content decreases[10].

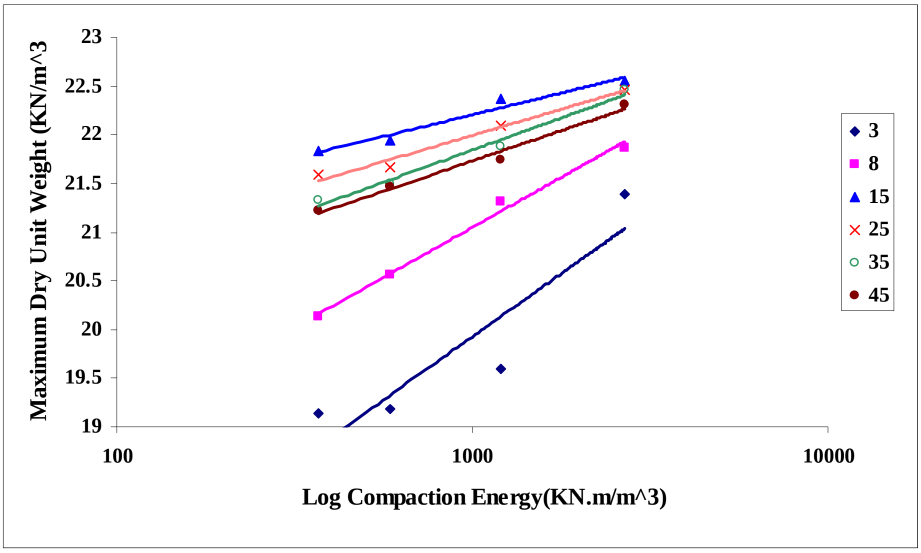

Figure 3: Maximum dry unit weight versus logarithm of compaction energy

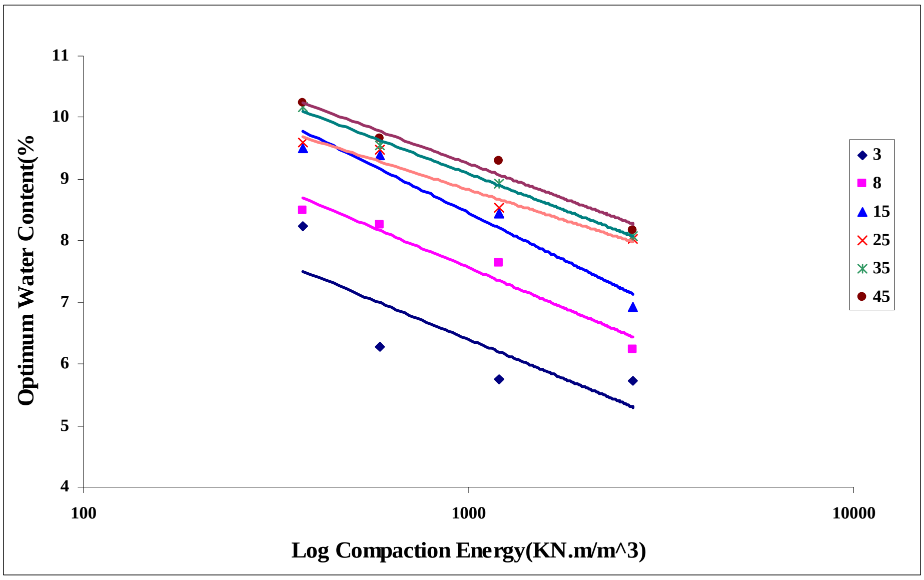

Figure 4: Optimum water content versus logarithm of compaction energy

The effect of clay on maximum dry unit weight and optimum water content

Figs. 5 and 6 display the variation of γ_{dmax} and ω_{opt} versus the clay content with various compaction energy levels.

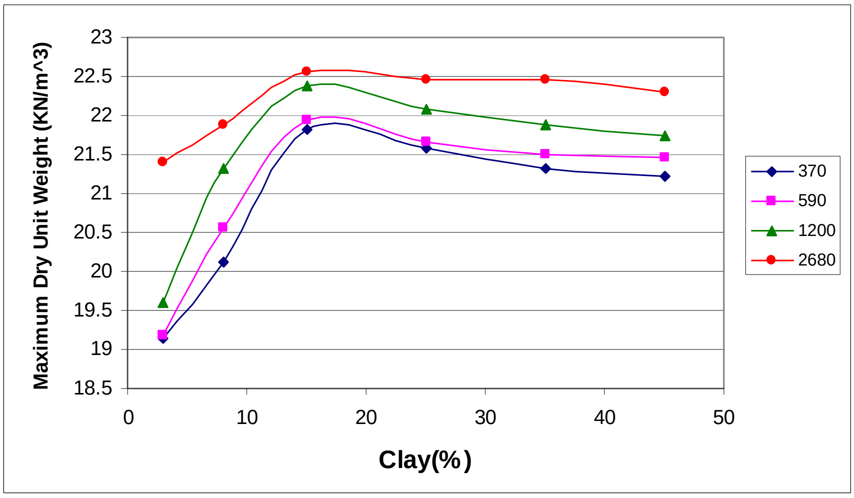

Figure 5: Maximum dry unit weight versus clay percentage

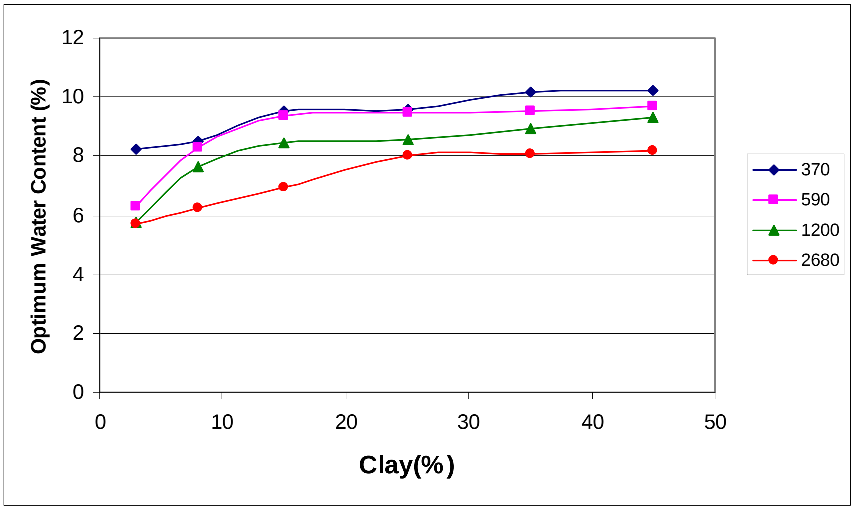

Figure 6: Optimum water content versus clay percentage

Study of the γ_{dmax} vs. clay(%) curve shows that at all four compaction energy levels, the curve ascends with a steep slope to the clay percentage of 15-20 and passing this range the curve descends to hold a mild slope.On the other hand,there is an optimum percentage of clay between 15-20 for different energy levels at which γ_{dmax} is obtained. At low energy levels as those less than the standard (370 kN-m/m3) the effect of optimum clay value is more outstanding, but at high energy levels, which may be encountered at most construction projects, this effect is less considerable. At low energy levels, the present clay content of the mixture, fills out the pores between the coarse particles and thus at the outset increasing the clay content results in increasing γ_{dmax} . Passing over an optimum clay content, the repulsive effect between the layers of clay prevents optimum compaction. More increase in fine grains causes the coarse grains to be away from each other and this changes the soil state from semi-buoyant to buoyant and as a result, γ_{dmax} decreases. At high energy levels, the effect of this optimum clay content is less considerable. It seems that the high compaction energies have a more important effect on obtaining higher maximum dry unit weight[10].Fig. 6 shows that from mixture one (A) to mixture six (F), the optimum water content keeps a rising trend which is due to the increase in clay content of the mixtures, since generally for obtaining maximum dry unit weight by increasing clay content, larger optimum water content is needed.

Mathematical equations

A wide variety of statistical models have been employed to investigate the governing relationship between $\gamma_{dm} - w_{opt}$ and the effective parameters which most of them, as mentioned previously, express that there is a linear relationship between $\gamma_{dm} - w_{opt}$ and LogE. In this study, mathematical equations were obtained by mathematical and statistical analyses based on the assumption that there is such relationship.

Maximum dry unit weight with respect to compactive effort and clay content

The following equation expresses a linear relationship between γ_{dmax} and log E:

$$\gamma_{d\max} = a_1 \log E + b_1 \qquad (1)$$

Where
a_1 = slope of the line
b_1 = intercept
E = energy (kN.m/m^3)
γ_{dmax} = maximum dry unit weight (kN/m^3)

It should be noted that based on the present study, for any constant percentage of clay, the relation between γ_{dmax} and Log E would be obtained accurately (Table 4), and this means that the parameters a_1 and b_1 can be found accurately as functions of each clay content. In order to to obtain these functions, the variation of these coefficients versus the clay content is plotted based on the available points (Figs.7 and 8) and then the equations are presented . So that γ_{dmax} is expressed as a two-variable function of compaction energy and clay content:

$$a_1 = -1.23og(clay\%) + 3 \qquad (2)$$

$$b_1 = 5.27 \log(clay\%) + 10.59 \qquad (3)$$

By Combining Eqs. (1) and (2) and (3), the following equation is obtained which determines maximum dry unit weight:

$$\gamma_{d\max}(kN/m^3) = [3 - 1.23 \log(clay\%)] \log(E) + 5.27 \log(clay\%) + 10.59 \qquad (4)$$

This equation is a two- variable function of clay content and compaction energy that can be used for estimating maximum dry unit weight.

Fig. 9 shows three axial figure of γ_{dmax} variation versus Log E and clay content. It can be seen that with increasing compaction energy and clay content, maximum dry unit weight increases[10].

Table 4: Properties of soils used to develop method

				compactive effort (kN.m/m^3)								Eq.(1)			Eq.(5)		
				370		590		1200		2680							
soil	clay (%)	sand (%)	gravel (%)	w_{opt} (%)	γ_{dmax} (kN/m^3)	w_{opt} (%)	γ_{dmax} (kN/m^3)	w_{opt} (%)	γ_{dmax} (kN/m^3)	w_{opt} (%)	γ_{dmax} (kN/m^3)	A	B	R^2	β	δ	R^2
A	3	20	77	8.23	19.14	6.28	19.18	5.75	19.6	5.73	21.39	1.13	12.15	0.84	-1.12	14.11	0.67
B	8	20	72	8.5	20.13	8.27	20.56	7.64	21.32	6.24	21.87	0.89	14.88	0.99	-1.14	15.45	0.94
C	15	20	65	9.51	21.83	9.39	21.94	8.45	22.37	6.93	22.55	0.39	19.52	0.96	-1.34	17.72	0.95
D	25	20	55	9.6	21.59	9.47	21.66	8.53	22.09	8.02	22.47	0.47	18.76	0.98	-0.86	14.78	0.96
E	35	20	45	10.17	21.33	9.54	21.5	8.92	21.88	8.08	22.46	0.57	17.87	0.98	-1.03	16.20	0.99
F	45	20	35	10.23	21.22	9.67	21.46	9.3	21.75	8.16	22.31	0.54	18.01	0.99	-1.00	16.13	0.97

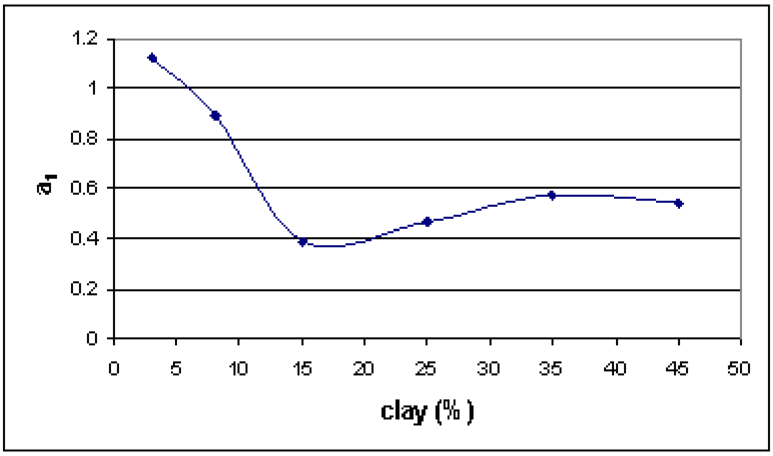

Figure 7: Parameter a_1 versus clay percentage

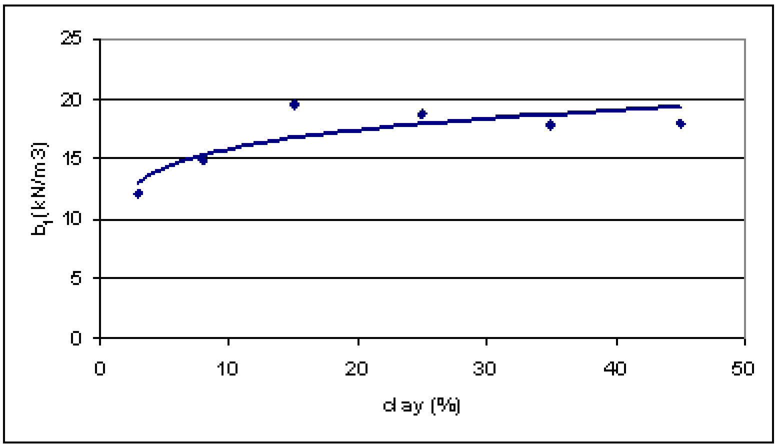

Figure 8: Parameter b_1 versus clay percentage

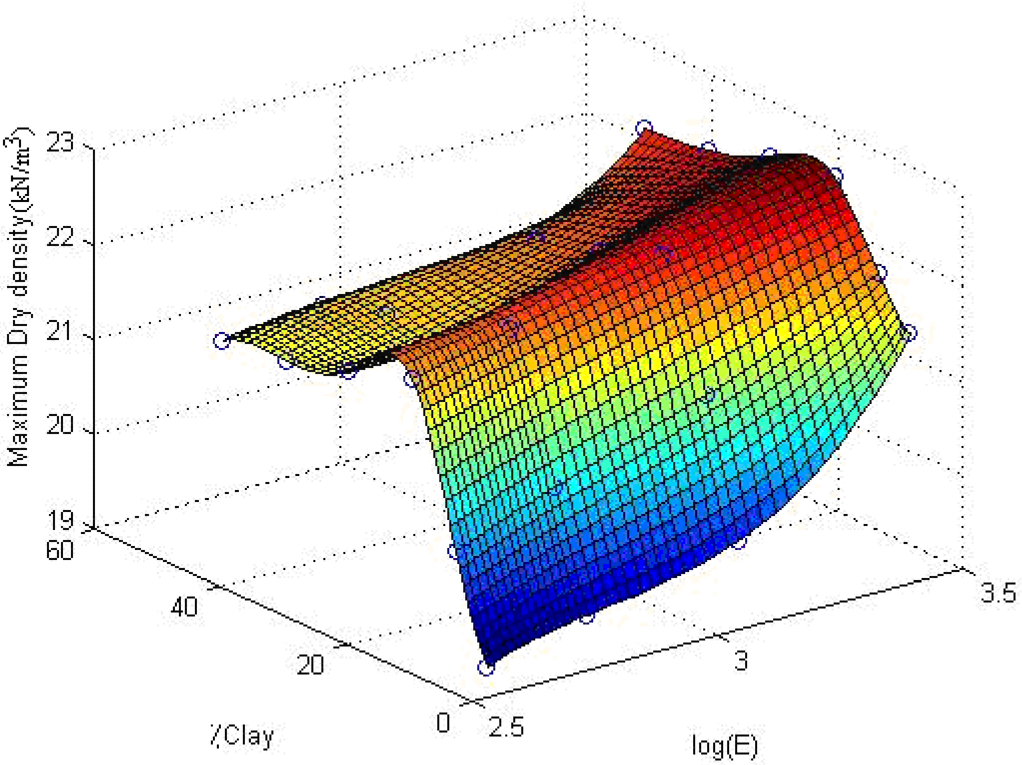

Figure 9: Spatial surface for variation of maximum dry unit weight versus clay% and log E

Optimum water content with respect to compactive effort and clay content

Similarly,the relationship between ω_{opt} and log E can also be expressed as a two-variable function in which the data presented in Table 4 are used:

$$\omega_{opt}\% = a_2 \log E + b_2 \qquad (5)$$

Where
a_2: slope of the line
b_2: intercept
E = energy(kN.m/m^3)
γ_{dmax} = maximum dry unit weight(kN/m^3)

The coefficients in Eq. (5) (a_2, b_2) are depend on clay content of the mixture. Their variation with clay percentage are shown in Figs. 10 and 11. Based on the mathematical analyses the following equations are presented to obtain a2 and b2 in terms of clay percentage:

$$a_2 = 0.35 \log(clay\%) - 2.91 \qquad (6)$$

$$b_2 = 1.40 \log(clay\%) + 14.07 \qquad (7)$$

By combining Eqs. 5 - 7, the following equation is obtained which determines optimum water content:

$$\omega_{opt}\% = [0.35\log(clay\%) - 2.91]\log(E) + 1.40\log(clay\%) + 14.07 \qquad (8)$$

This equation is a two- variable function of clay content and compaction energy that can be used for estimating optimum water content. Investigation of experimental results and data obtained from Eq. (8) shows that optimum water content decreases with increasing compaction energy and increases with increasing clay content. As observed, the data obtained using Eq. (8) agrees well with the laboratory data and with increasing compaction energy and clay content, they become closer to each other.

Fig. 12 shows spatial surface of optimum water content variation versus Log E and clay percentage[10].

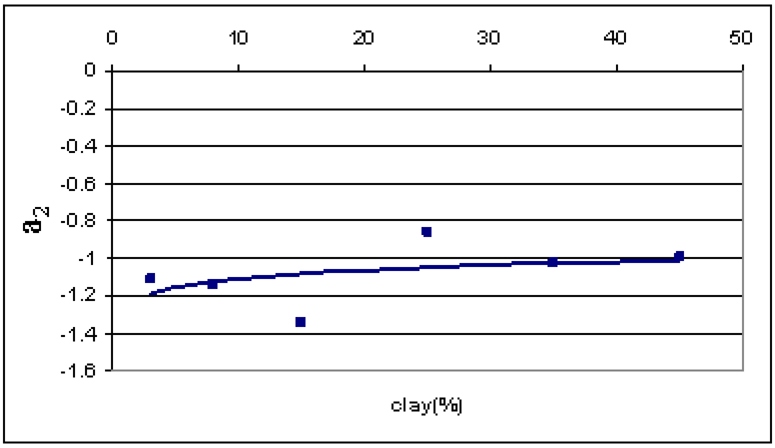

Figure 10: Parameter a_2 versus clay percentage

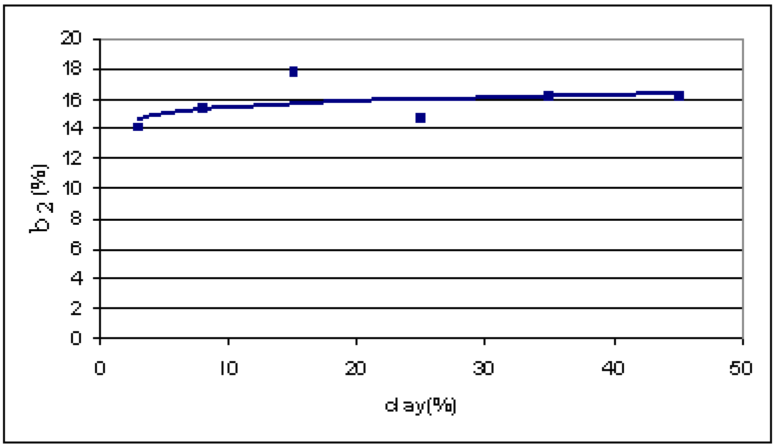

Figure 11: Parameter b_2 versus clay percentage

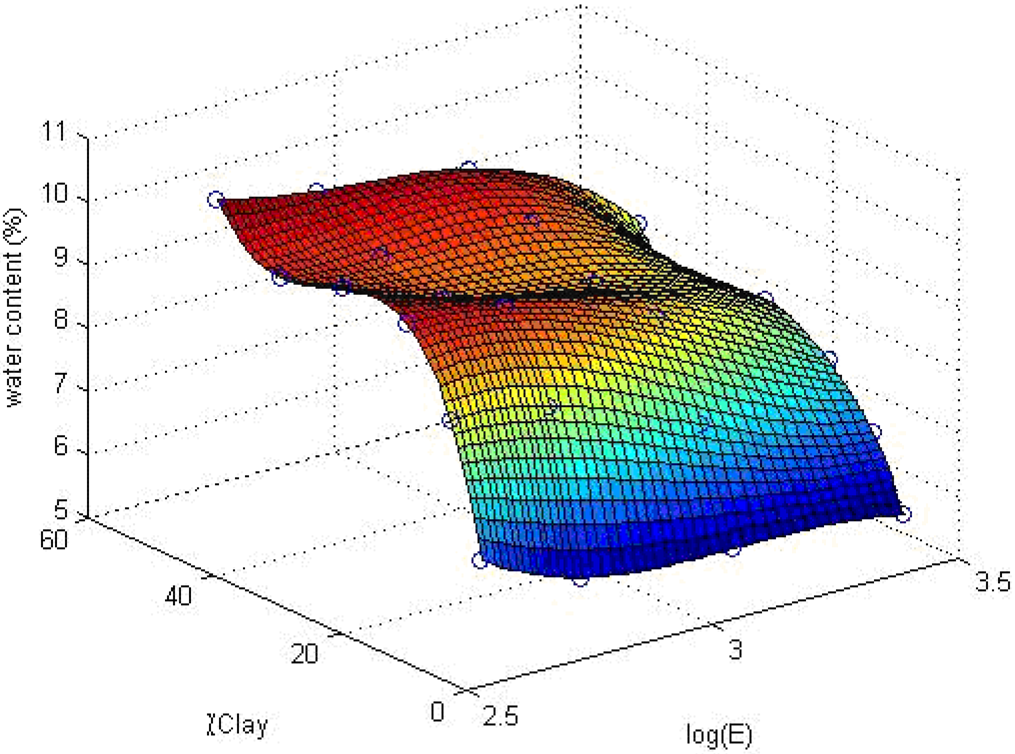

Figure 12: Spatial surface of variation of optimum water content versus clay% and log E

Data validation

A comparison is performed on the results of Eqs. 4 and 8 and the laboratory results to evaluate the reliability of the estimated data. For this reason γ_{dmax} and ω_{opt} of the mixtures listed in Table 1 are estimated by Eqs. 4 and 8. Then,a comparison is performed on the predicted and the laboratory results. The outcome of this comparison is presented in Table 5. It is observed that the data are highly accurate and acceptable, except for mixture type A in which the difference between measured and predicted values is considerable. The main cause of this deviation is the effect of other factors such as the effect of shape and strength of grains on the compaction of such mixtures.

Table 5: Comparison between measured and predicted values of γ_{dmax} and w_{opt} at different compaction energy

	calculated from clay Eq.(2,3)		calculated from clay Eq.(6,7)		Compactive effort (kN-m/m^3)							
					370				590			
					Predicated		Actual – predicated (Error)		Predicated		Actual – predicated (Error)	
soil	a_1	b_1	α_2	β_2	ω_{opt}	γ_{dmax}	ω_{opt}	γ_{dmax}	ω_{opt}	γ_{dmax}	ω_{opt}	γ_{dmax}
A	1.05	13.06	-1.19	14.73	7.69	19.3	0.54	-0.16	7.13	19.79	-0.85	-0.61
B	0.82	15.33	-1.13	15.33	8.67	20.19	-0.17	-0.06	8.15	20.57	0.12	-0.01
C	0.67	16.78	-1.08	15.71	9.3	20.76	0.21	1.07	8.79	21.08	0.6	0.86
D	0.55	17.96	-1.05	16.02	9.81	21.23	-0.21	0.36	9.32	21.49	0.15	0.17
E	0.48	18.73	-1.03	16.22	10.15	21.54	0.02	-0.21	9.67	21.76	-0.13	-0.26
F	0.42	19.31	-1.01	16.37	10.4	21.77	-0.17	-0.55	9.93	21.96	-0.26	-0.5

Table 5: (Cont.)

	calculated from clay Eq.(2,3)		calculated from clay Eq.(6,7)		Compactive effort (kN-m/m^3)							
					1200				2680			
					Predicated		Actual – predicated (Error)		Predicated		Actual – predicated (Error)	
soil	a_1	b_1	α_2	β_2	w_{opt}	γ_{dmax}	w_{opt}	γ_{dmax}	w_{opt}	γ_{dmax}	w_{opt}	γ_{dmax}
A	1.05	13.06	-1.19	14.73	6.29	20.53	-0.54	-0.93	5.33	21.37	0.4	0.02
B	0.82	15.33	-1.13	15.33	7.35	21.16	0.29	0.16	6.44	21.81	-0.2	0.06
C	0.67	16.78	-1.08	15.71	8.03	21.56	0.42	0.81	7.15	22.1	-0.22	0.45
D	0.55	17.96	-1.05	16.02	8.58	21.88	-0.05	0.21	7.73	22.33	0.29	0.14
E	0.48	18.73	-1.03	16.22	8.94	22.1	-0.02	-0.22	8.11	22.48	-0.03	-0.02
F	0.42	19.31	-1.01	16.37	9.21	22.26	0.09	-0.51	8.4	22.59	-0.24	-0.28

The comparison of actual and predicted values listed in Table 5 shows that the maximum deviation is +1.07 kN/m^3 for mixture C at 370 kN.m/m^3 compaction energy. In reality, prediction of maximum dry unit weight in such mixtures is made conservatively and with increasing compaction energy,the difference between actual and predicted values of maximum dry unit weight decreases. It is also observed that minimum difference between actual and predicted values of maximum dry unit weight is 0.01 kN/m^3 and appears at 590 kN.m/m^3 compaction energy. Standard deviation of studied quantities for different compaction energies are listed in Table 6. Figs. 13 and 14 show the variation of standard deviation corresponding to maximum dry unit weight and optimum water content versus different compaction energies. As can be seen, minimum standard deviation is for maximum dry unit weight and optimum water content at compactive effort of modified Proctor test.

Table 6: Results of data analysis in Table 5.

Compactive effort (kN-m/m^3)								Error
2680		1200		590		370		
w_{opt} (%)	γ_{dmax} (kN/m^3)	w_{opt} (%)	γ_{dmax} (kN/m^3)	w_{opt} (%)	γ_{dmax} (kN/m^3)	w_{opt} (%)	γ_{dmax} (kN/m^3)	
0	0.06	0.03	-0.08	-0.06	-0.06	0.04	0.07	Average
0.28	0.24	0.33	0.61	0.49	0.54	0.3	0.57	standard deviation

CONCLUSIONS

Based on the results of this investigation., there is a linear relationship between maximum dry unit weight and optimum water content with log E.

At low percentages of clay in mixtures (3% and 8%), the rising trend of maximum dry unit weight versus rising log E holds a steeper slope and passing this range the curve descends to hold a mild slope. At all compaction energy levels the maximum dry unit weight is obtained at certain range of clay percentage(15-20).At low compaction energy levels like those lower than the standard energy, the effect of clay content is more conspicuous. But at high energy levels, which are encountered at many practical projects, this effect is less considerable. As the clay content of mixtures increases, the optimum water content increases. The error with defined functions for w_{opt} and γ_{dmax} becomes minimum for mixtures B and E, respectively. Maximum difference in predicting maximum dry unit weight is 1.07 kN/m^3 for mixture C at 370 kN.m/m^3 compaction energy. Minimum difference between actual and predicted maximum dry unit weight values is 0.01 kN/m^3 for mixture B at 590 kN.m/m^3 compaction energy. Maximum difference in predicting optimum water content is 0.85% for mixture A at 590 kN.m/m^3 compaction energy. Minimum difference in predicting optimum water content is 0.02% at 370 and 1200 kN.m/m^3 compaction energies. Generally, with increasing compaction energy, the general trend in amount of mathematical equations errors with respect to actual values obtained in laboratory is almost descending. Minimum standard deviation for maximum dry unit weight and optimum water content is observed at compactive effort of modified Proctor test(0.24 and 0.28,respectively).

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