

A Study of the Immediate and Long Term Strength of a Cement Modified Cohesive Soil

by

R. Kapur*

Introduction

INCREASING demand for and decreasing availability of suitable base and sub-base materials for modern highway and airfield constructions, as also for earthfills, has led to a search for an economic method of converting locally available natural soils to suitable construction materials by the use of admixtures. Portland cement is one of the most common soil stabilizers being very successfully used these days.

In a soil-cement, soil forms a major portion (nearly 90 per cent) of the mixture. Hence, it is essential that the shear strength characteristics of compacted clays under different environmental conditions be properly understood. Clays, in general, have a major portion of particles that are smaller than 2 microns. These fall in the colloidal range. It has been proved by colloidal chemists that clay particles carry a net negative charge on their surface and a positive charge at the edges. The negative charge is balanced by exchangeable cations. When the clay is dry, the cations cluster at the surfaces to neutralize the charges and when a clay particle comes into contact with water, the cations (plus a small number of anions) swarm or diffuse around the colloid. The swarm of counter ions is called a 'double layer' and the colloid plus the double layer is termed as 'Micelle'.

Due to the presence of opposite electric charges on the surfaces and edges of the clay particles and also due to the presence of the double layer, which by itself is an electric field, electrical forces act between the adjacent particles. These electrical forces, both attractive and repulsive, control the structure of clay. The structure of clay, in turn, controls the shear strength, which may be attributed to a combination of physical and physico-chemical factors. Important physical factor is the externally applied effective pressure which controls the friction and interlocking between particles. The physico-chemical factors, formulated on the basis of colloidal chemistry, are the electrolyte concentration, cation exchange of high and low valencies, dielectric constant, *pH* value, size of hydrated ion, and temperature of the pore fluid⁽¹⁾. The Gouy-Chapman theory states that a tendency towards flocculation is usually caused by increasing electrolyte concentration, ion valence, and temperature, and

*Scientist, Central Building Research Institute, Roorkee, (Formerly Post-Graduate Student, Civil and Hydraulic Engineering Department, Indian Institute of Science, Bangalore-12).

This paper was received on 3 September 1970. It is open for discussion up to December 1971.

by decreasing dielectric constant, size of hydrated ion, pH value and anion adsorption. It has been shown by Lambe⁽²⁾ and Seed and Chan⁽³⁾ that at lower strains a flocculated structure gives a higher strength than a dispersed structure.

Soil-cement Reactions

Most fine-grained soils contain a large quantity of crystalline silica and alumina, the colloidal clay minerals. These are essentially acidic in nature, and a small but important fraction of silica and alumina present on the particle surface is in a highly reactive hydrous state.

In a neat cement paste, the major hydration products are :

- (a) Basic calcium silicate hydrate $C_2 SH_x$ or $C_3 S_2 H_x$ or both ;
- (b) Calcium aluminate hydrate, $C_3 AH_x$, and
- (c) Hydrated lime.

(The notations for chemical composition of cementing products are $C-CaO$; $S-SiO_2$; $A-Al_2O_3$; $H-H_2O$).

Strength increase in a clayey soil due to the addition of cement is attributed to two changes—physico-chemical and chemical. Immediate increase in the strength is attributed to ion exchange and flocculation of clay particles, which occur very rapidly due to the presence of lime in cement. In addition to the fresh lime available in a fresh cement paste, highly reactive lime is generated during the chemical reaction between cement and clay minerals. This increases the electrolyte concentration of the pore water. Also heat of hydration of cement increases the temperature of the system. Lime also reduces the pH value of the pore fluid. In addition, calcium ions present in lime bind the soil particles closer together and reduce the potential energy, thereby particles approach each other, so as to form a flocculated structure.

In Portland cement calcium silicate hydrate and calcium aluminate hydrate constitute the major cementitious components, whereas lime is deposited as a separate crystalline phase. Consider an intimate mixture of soil-silica and cement with sufficient water to make almost saturated system after compaction. As the Tricalcium* from the cement begins to diffuse, first place at which this compound appears is at cement-silica points. As hydration and hydrolysis occur, forming lime and gelatinous silicate, lime reacts with soil silica with a consequent drop in the pH value and formation of hydrous calcium silicate on the silica particle surface. This secondary silicate is also cementitious and contributes to interparticle bonding. So, a sizeable amount of cementitious material formed is by soil itself. Hence, the quantity of cementitious material available for bonding in soil-cement is much more than that in a neat cement paste.

Increase in the strength of a cohesive soil due to physico-chemical mechanisms is almost immediate, whereas, increase due to chemical reaction is a progressive one. Purpose of the present experimental investigation is to evaluate quantitatively the immediate and long-term

*Tricalcium silicate is chosen for discussion because it is the major and most important constituent of Portland cement.

(after initial set) increase in the shear strength parameters due to the addition of cement. Apart from the effect of cement, influence of initial soil structure is also studied.

The soil used is black cotton clay, a tropical clay, available in the Western and Central regions of India. This clay, even though of immense value to agriculturists, is regarded by practising engineers as a treacherous foundation medium because of its swelling and shrinkage characteristics. Even though best stabilizer for this clay is lime, cement was used in this investigation, because the object is to study the effect of cement on a cohesive soil and not to find a suitable stabilizer for black cotton clay.

Experimental Work and Test Results

SOIL PROPERTIES

Physical properties of the black cotton clay selected for study are given in Table I.

TABLE I

Properties of black cotton clay.

Liquid limit	74.0%	
Plastic limit	35.0%	
Plasticity Index (PI)	39.0%	
Shrinkage limit	13.2%	
Silt and clay fraction	80.0%	
Clay fraction (<2 μ)	36.0%	
Max. dry density	87.8% lb/cu ft	} Standard Proctor.
Optimum moisture content	30.8%	

Figure 1 shows the grain-size distribution curve of the soil. The soil is classified as 'CH' according to Casagrande's A-line. Figure 2 shows the moisture-density relation of the soil obtained from standard Proctor test.

PROPERTIES OF CEMENT

Cement used for the investigation was Portland cement, physical properties of which are given below :

Normal consistency = 38 per cent

Initial setting time = 45 mts.

Initial setting time of cement was retarded by mixing different percentages of gypsum. Effect of different percentages of gypsum on the initial setting time of Portland cement is shown in Table II.

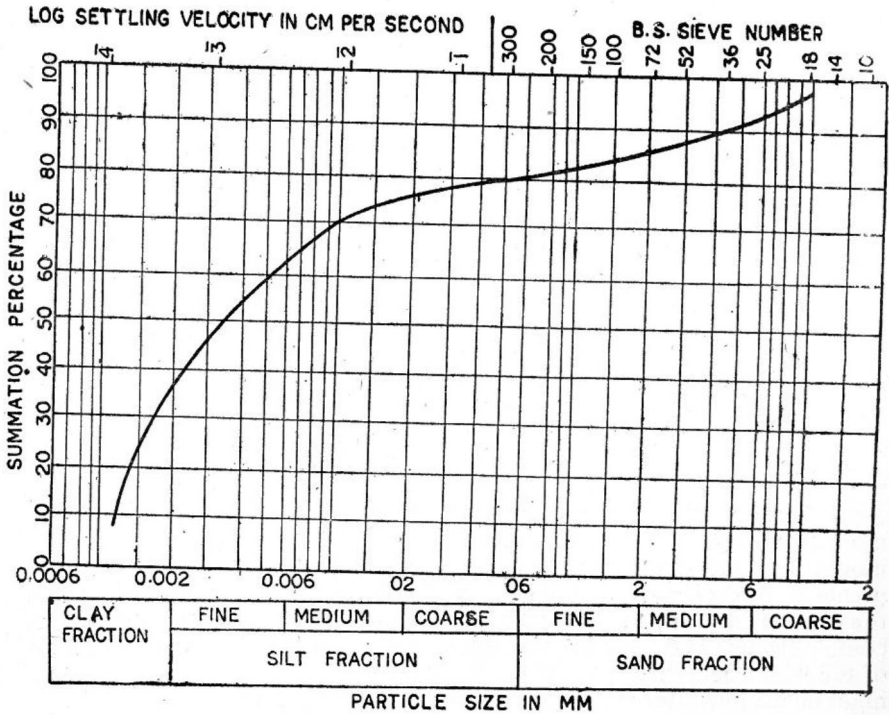


FIGURE 1 : Grain-size distribution curve.

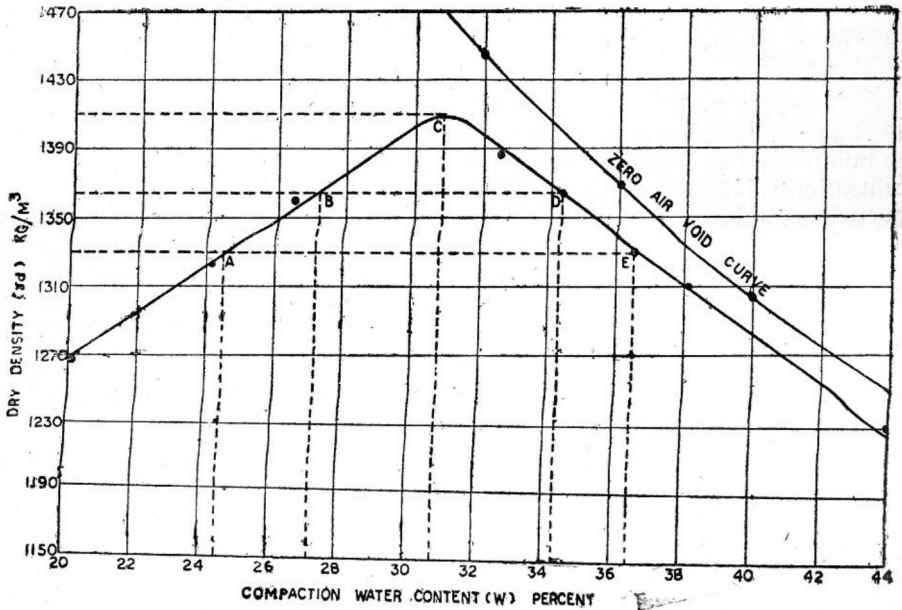


FIGURE 2 : Dry density/Compaction water content relationship.

TABLE II

Effect of Gypsum on the initial setting time of cement.

Percentage of gypsum added to cement	Initial setting time (minutes)
0	45
3	120
4	150
5	210

Quantity of gypsum mixed with cement was 5 percent as it gave an initial setting time of $3\frac{1}{2}$ hours, which was quite sufficient to mix soil, prepare sample and test it.

CONTROL OF INITIAL SOIL STRUCTURE

The initial soil structure is governed mainly by moulding moisture content^(1, 3) all other factors like mineral composition, mode of compaction, and the dry density remaining constant. Five points *A, B, C, D* and *E* were selected on the curve in Figure 2 to study the effect of initial soil structure. At point *A* the moulding moisture content (*w*) is 24.5 percent and dry density (γ_d) is 1330 kg/m³. Because of the water deficiency condition the electrolytic concentration is very high, hence low interparticle repulsion results. Consequently, this results in a flocculent, structure^(1, 3) whereas, at point *E*, moisture content is higher (36.5 percent) but dry density is the same as that at point *A*. This increase in water content causes considerable decrease in electrolyte concentration, resulting in expansion of the double layer and hence an increase in interparticle repulsion. This results in highly dispersed soil structure^(1, 3).

At point *B*, the moulding moisture content is 27.4 percent and γ_d is 1364 kg/m³. Even though the moisture content is more when compared to point *A*, water deficiency condition still exists and the electrolyte concentration is high, though not as high as at point *A*, hence low interparticle repulsion, results. Consequently, the soil at point *B* is little less flocculent than that at point *A*^(5, 6). At point *D*, even though the dry density is the same as at point *B*, moisture content is higher (34.5 percent), although when compared to point *E* it is somewhat lower. This results in a soil structure that is slightly less dispersed than the structure at point *E*^(3, 6).

At point *C*, dry density is 1410 kg/m³ and moisture content is 30.8 percent. This is the optimum point of the Proctor's curve and the soil structure is neither fully flocculent nor fully dispersed, but is somewhere in between^(1, 3).

PREPARATION OF SOIL SAMPLES

Oven dry soil passing through B.S. Sieve No. 7 was used throughout the investigation. Known percentage of water was added within a variation of ± 0.5 percent and mixed thoroughly for 5 minutes. A time interval of 15 minutes was given for moisture to distribute evenly before

the soil samples were prepared. Since similar samples could not be procured from soil compacted in the Proctor mould, a remoulding device designed by Nagaraj⁽⁵⁾ was used. This device is shown in Figure 3. It is so designed that uniform samples of 3.8 cm ($1\frac{1}{2}$ in.) diameter by 7.6 cm (3 in.) height can be procured. Variation of dry density of samples compacted in this device was ± 0.5 percent, which is negligible.

PREPARATION OF SAMPLES OF SOIL MIXED WITH CEMENT AND CEMENT-GYPSUM

Desired percentage of cement or cement-gypsum was added to the oven dry soil and mixed thoroughly so as to get a uniform distribution of the additive particles. Then, the known percentage of water corresponding to the point on the Proctor's curve (+2.5 percent extra to compensate for moisture loss during hydration) was added to the mix and mixed thoroughly. A time interval of 15 minutes was allowed before the samples were prepared using the above remoulding device. Only one sample was prepared at a time and stored in a desiccator (without any calcium chloride) to prevent moisture loss.

Test Procedure and Results

First, four soil samples corresponding to each of the five points on the Proctor's curve, were subjected to unconsolidated undrained triaxial test, with ambient pressure of 0.705, 1.41 and 2.11 kg/cm². A uniform time interval of 5 minutes was maintained in each case to build up the pore pressure due to corresponding ambient pressure. Then the samples were subjected to deviator stress. A constant rate of strain of 1 percent per minute was used.

For each percentage of additive at least four samples were also subjected to unconsolidated undrained triaxial test with the same range

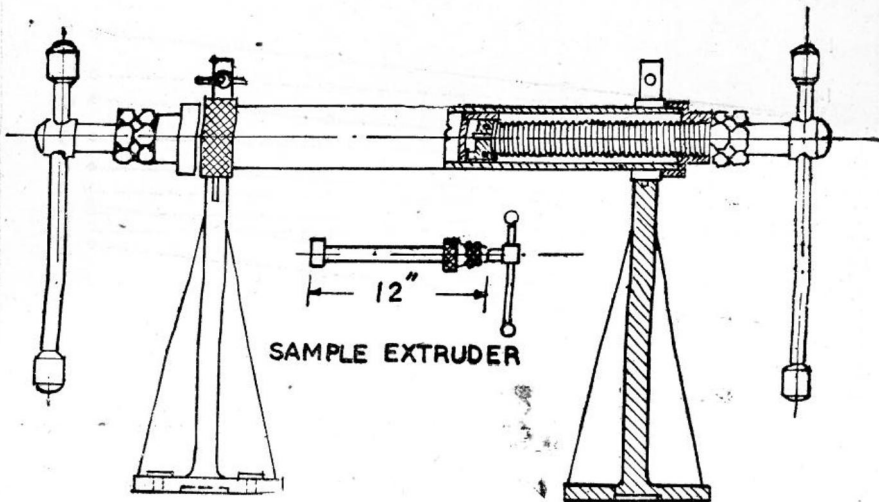


FIGURE 3 : Remoulding device for soil samples with sample extruder (After Nagaraj, 1963).

of ambient pressures as for the untreated soil samples. Same time interval of 5 minutes was allowed before stress was applied at a strain rate of 1 percent per minute. Percentage of additive was varied from 1 to 3 with an equal interval of 1 percent. Samples prepared from soil mixed with cement-gypsum were tested immediately so as not to allow the initial set to commence. Samples prepared from soil with cement only were tested after the initial set had taken place.

Figure 4 shows the variation of the shear parameters cohesion, c_u and angle of internal friction, ϕ_u with increase in percentage of additive. In Figure 5 is plotted the percentage increase in the value of c_u and ϕ_u over the values for untreated soil against increase in percentage of additive. Figure 6 shows the moisture content *versus* density of soil and

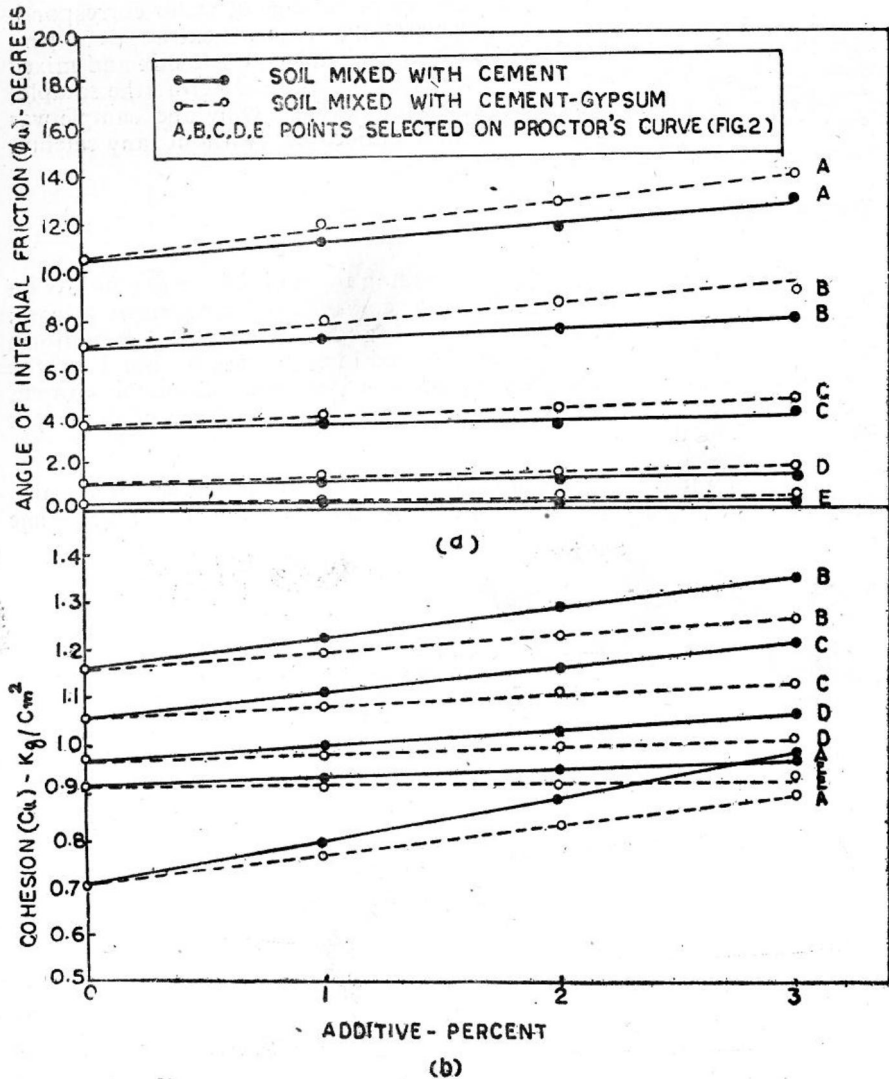


FIGURE 4 : c_u and ϕ_u for different percentage of additive.

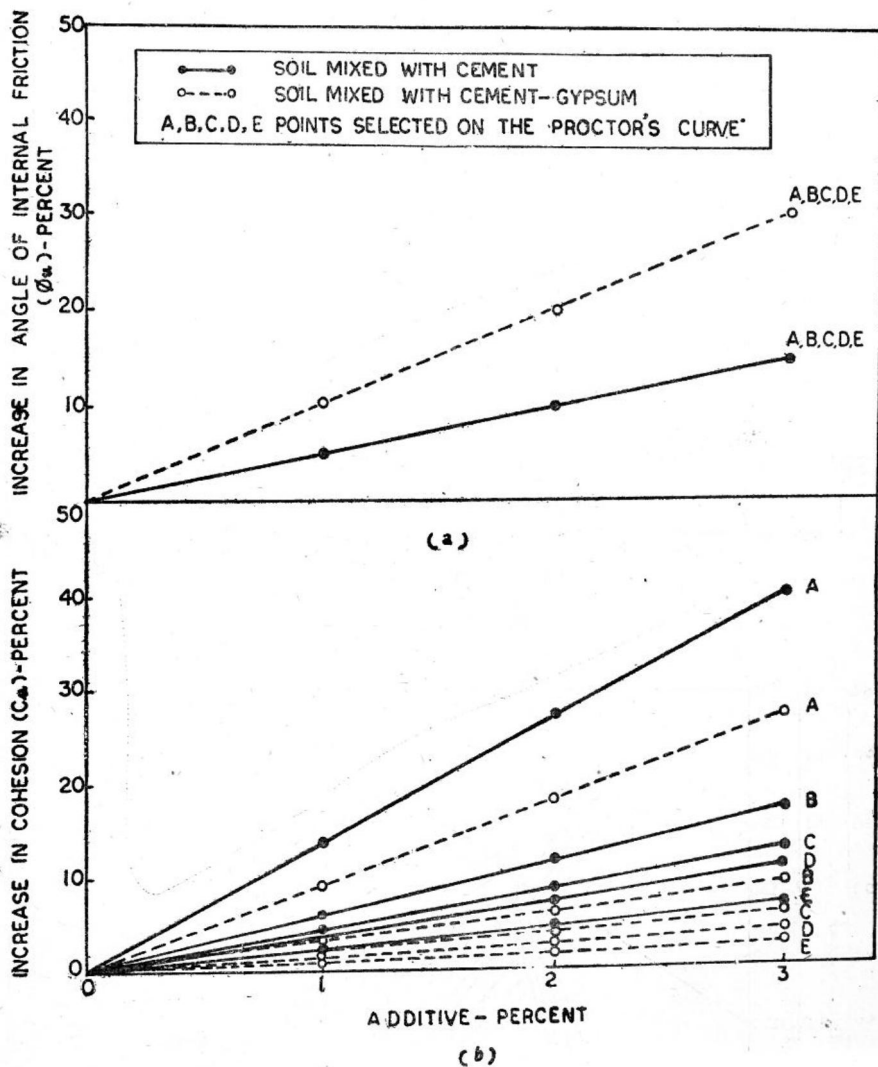


FIGURE 5: Percentage increase in ϕ_u and c_u for different percentage of additive.

moisture content *versus* c_u and ϕ_u relationship for soil treated with cement only. Figure 7 shows the moisture content *versus* density of soil and moisture content *versus* c_u and ϕ_u relationship for soil mixed with cement-gypsum. Figure 8 shows the relation between maximum deviator stress and percentage of additive.

Discussion of Test Results

Shearing strength of cohesive soils was originally divided by Coulomb into two parts—frictional resistance and cohesion. Even at this stage these two components of shear strength occupy the same important

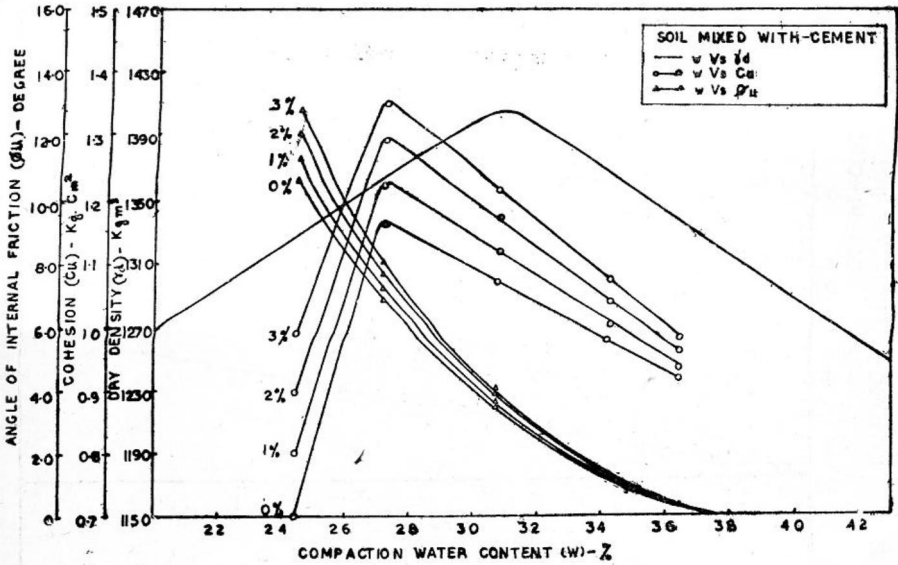


FIGURE 6.

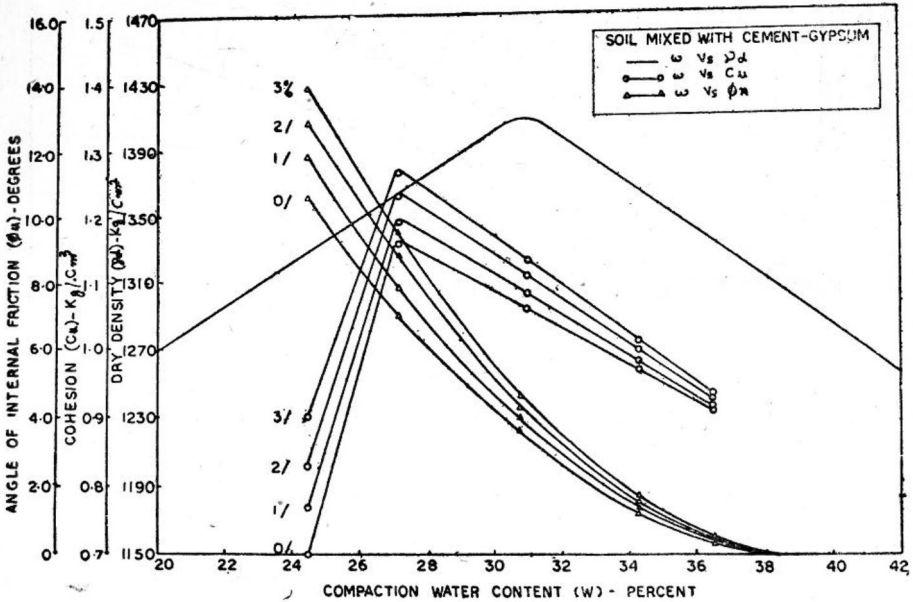


FIGURE 7.

place. Shear strength can be increased by changing environment. One of the methods is the addition of a stabilizer to the soil. Cement was used in the present investigation. Apart from the influence of cement on c_u and ϕ_u , effect of initial soil structure was also studied.

Effect of addition of cement and cement + 5 percent gypsum on c_u and ϕ_u is shown in Figure 4 for five different types of initial soil structures corresponding to points *A*, *B*, *C*, *D* and *E* on the Proctor's curve (Figure 2). The curves in dotted lines are for black cotton clay mixed with cement plus 5 percent gypsum and for samples tested before the initial set has taken place while the curves in full lines are for black cotton clay mixed with cement only. It can be readily noticed that for soil mixed with cement plus gypsum, the value of ϕ_u is greater than that for soil mixed with cement only. This may be due to the reason that gypsum, which is calcium sulphate, contains a certain amount of exchangeable divalent calcium (c_a^{++}) cations which cause a further increase in the degree of flocculation in addition to the increase caused by the calcium cations present in the cement. Figure 4(a) shows the variation in the value of ϕ_u with an increase in the percentage of additive. Figure 5(a) shows the percentage increase in the value of ϕ_u over that for untreated soil against the percentage of additive. It may be observed that for point *A* ($\gamma_d=1330 \text{ kg/m}^3$, $w=24.5$ percent) ϕ_u increases rapidly with an increase in the percentage of cement or cement-gypsum. As we go to point *B* ($\gamma_d=1364 \text{ kg/m}^3$, $w=27.4$ percent) on the Proctor's curve, the percentage increase in the value of ϕ_u with an increase in the percentage of additive becomes smaller. This rate reduces further as we reach the optimum point *C* ($\gamma_d=1410 \text{ kg/m}^3$, $w=30.8$ percent) and ϕ_u becomes very small (1.1° at point *D*, 0.3° at point *E*) for samples compacted on the wetter side of optimum moisture content, *i.e.*, at points *D* ($\gamma_d=1364 \text{ kg/m}^3$, $w=34.3$ percent) and *E* ($\gamma_d=1330 \text{ kg/m}^3$, $w=36.5$ percent). At point '*A*', the small amount of water present results in a high electrolyte concentration which prevents the diffused double layer from developing fully. This results in a low interparticle repulsion, leading to tendency towards flocculation of the particles and a consequent low degree of particle orientation. If the water content is increased to point '*B*' the electrolyte concentration is reduced, resulting in an expansion of the double layer and an increased degree of particle orientation. So, an equal amount of divalent calcium ions added to samples compacted at points '*A*' and '*B*' will be able to make the structure more flocculated in the former case rather than in the latter. Hence the difference in the rate of increase of ϕ_u with increase in the percentage of additive in the two cases [Figure 5(a)]. At point '*C*' the particle orientation would have increased further, hence the observed smaller rate [Figure 5(a)]. At points '*D*' and '*E*', the high moulding water content gives a lower electrolyte concentration which results in a relatively thick double layer, resulting in increased interparticle repulsion and hence, a dispersed structure. Since the percentage of cement or cement-gypsum added is very small, it is possible that the small amount of exchangeable divalent calcium cations present are not sufficient to affect any substantial decrease in the interparticle repulsion. Hence, ϕ_u remains very small even after addition of cement or cement-gypsum.

It is readily observed in Figures 4(b) and 5(b) and that c_u is greater for soil mixed with cement and tested after initial set has taken place than for soil mixed with cement plus a retarder (5 percent gypsum). The increase in the value of c_u after initial set may be attributed to the increase in the bonding by means of cementitious products formed by the reaction between cement and clay mineral. It can be noticed that even for the soil mixed with cement-gypsum and tested before initial set has taken

place the value of c_u increases with an increase in the percentage of additive, though at a smaller rate than that of soil mixed with cement only. Probably, the pozzolanic action begins as soon as or a little after cement is added and progresses even after the final set has taken place.

From Figures 6 and 7 it is observed that the value of c_u increases rapidly as the moulding water content is increased, starting from point 'A', till a maximum is reached at point 'B', after which further increase in the moulding water content results in a decrease in the cohesion component, c_u . On the other hand, the value of ϕ_u decreases from its peak at a point 'A' to a very small value (0.3°) at point after which it becomes asymptotic to the abscissa. It is possible that the peak may lie a little to the left of point 'A' or ϕ_u may decrease at lower dry densities and

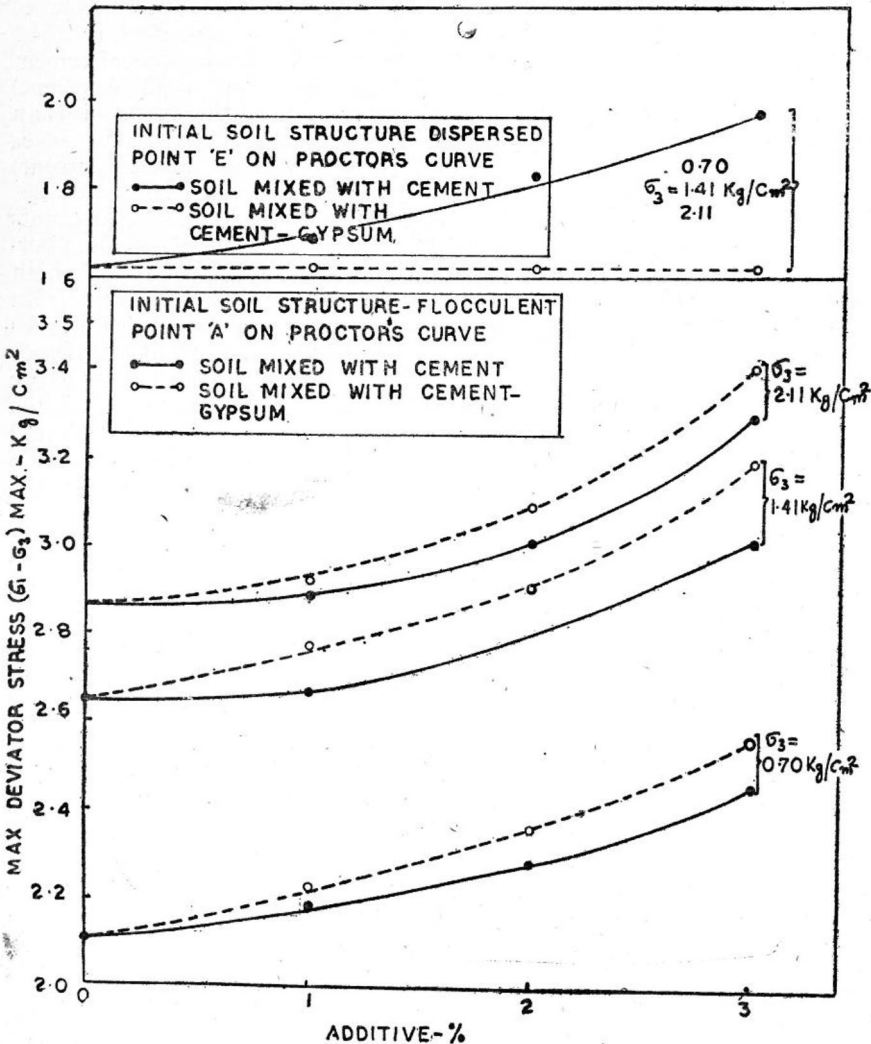


FIGURE 8 : Maximum deviator stress for different percentage of additive.

lower moisture content than that at 'A'. It is clear that samples compacted very much on the dry side of optimum (e.g., point 'A') show considerably lower values of cohesion for marked value of angle of internal friction. Because of higher void ratio, the interparticle cohesion due to adhesive Van-der-Waals forces is of a lower magnitude.

It is clear from Figures 8 that for the same moisture content and dry density, on the dry side of optimum deviator stress at failure is greater for samples of soil mixed with cement-gypsum than for the soil mixed with cement only. This can be attributed to the increased flocculation due to the greater number of calcium cations (because of gypsum) in the former case. On the contrary, on the wet side of optimum the maximum deviator stress for a sample of soil mixed with cement-gypsum is lower than that for soil mixed with cement only. This may be due to the reason that the available calcium cations were not sufficient to decrease the high interparticle repulsion, and hence the degree of particle orientation. The increase in resistance to external load is only due to cohesive bonds formed by chemical products. It is also clear from the same figure that as the percentage of additive increases, the maximum deviator stress also increases.

Conclusions

Following conclusions can be drawn from the above investigation :—

- (1) Addition of cement to a fine grained plastic cohesive soil with initial soil structure as flocculent, results in an almost immediate increase in the value of angle of internal friction whereas the cohesion component of shear strength increases progressively and has an appreciable value after the initial set has taken place. It increases further with time of curing of soil-cement. The resulting soil structure builds up high resistance to external loads, hence, an appreciable increase in the bearing capacity.
- (2) In the case of cement stabilization with initial soil structure dispersed, there is no appreciable increase in the value of angle of internal friction, but, the cohesion increases substantially.
- (3) *Initial soil structure has a great influence on the load-carrying capacity of soil-cement mixtures. For samples compacted at the same dry density but at different moisture contents so as to give two different structures—flocculent and dispersed, it can be concluded that the former can take a higher load before it fails when compared with that taken by the latter. Hence, a strict control of initial soil structure of soil used for stabilization with cement in the field is very essential.*

Acknowledgements

This study was conducted at the Indian Institute of Science, Bangalore and formed a part of the requirements for the degree of Master of Engineering. The study was conducted under the able guidance of Dr. T S. Nagaraj, Lecturer (Soil Mechanics), to whom the author is deeply indebted. The author wishes to thank Dr. B.V. Ranganatham, Dr. A.

Siva Reddy and Dr. M.R. Madhav for their helpful suggestions and for the encouragement extended during the investigation.

The paper is published with the permission of the Director, Central Building Research Institute, Roorkee.

References

- (1) LAMBE, T.W. (1955). The Structure of Compacted Clays. *Jnl. S.M.&F. Div., Proc. A.S.C.E.*, Vol. 84, No. 2, Paper No. 1654.
- (2) LAMBE, T.W. (1960). A Mechanistic Picture of Shear Strength in Clays. *Proc. A.S.C.E., Res. Conf. on Shear Strength of Cohesive Soils*. Colorado, pp. 555-580.
- (3) SEED, H.B. & CHAN, C.K. (1961). Structure and Strength Characteristics. *Trans. A.S.C.E.*, Vol. 126, Part 1, pp. 1344-1385.
- (4) SEED, H.B. MITCHELL, J.K. and CHAN, C.K. (1960). The Strength of Compacted Cohesive Soils. *Proc. A.S.C.E., Res. Conf. on Shear Strength of Cohesive Soils*, Colorado, pp. 877-964.
- (5) NAGARAJ, T.S. (1963). A Remoulding Device for Soil Samples. *Jnl. Irrigation & Power C.B.I.P.*, Vol. 20, No. 2.
- (6) PACEY, J.G. (1956). The Structure of Compacted Clays. *M.Sc. Thesis*, Massachusetts Inst. of Tech. Cambridge.