Control of dispersivity of soil using lime and cement

T.S. Umesha, S.V.Dinesh, and P.V. Sivapullaiah
siva@civil.iisc.ernet.in

Abstract**—** Dispersion of a sodic soil occurs when it is wetted and the clay particles are forced apart. Thus dispersive soils erode under small seepage velocity leading to problems of stability of earth and earth retaining structures. The extent of dispersion depends on mineralogy and clay chemistry as well as the dissolved salts of the pore fluid. Soil dispersivity is mainly due to the presence of exchangeable sodium present in the structure. The attractive forces are less than the repulsive forces under saturated conditions and this will help the particle to segregate and to move in suspension. The use of lime and cement to bind the soil clay particles and reduce the dispersivity and improve the strength of soil has been studied. The relative performace of them depends on the type of soil and the pore fluid chemistry. It has been shown that 3 percent lime or 3 percent cement can improve the strength of the soil. The rate of improvement of strength is rapid for the first three days and gradual with further curing up to 14 days. The Young's modulus of the soil also increases with the addition of lime and with curing. There is good correspondence between the unconfined compressive strength and Young's modulus for stabilized soils. For the soil under study it was shown that lime is a better additive than cement.

Keywords**—** Cement, Disperive soil, Lime, Unconfined compressive strength, Young's modulus.

I. Introduction

In the past, when soils with good engineering properties such as low plasticity, high bearing capacity, low settlements etc were not available for the construction of embankments, highways, airport runways, dams and other earthen infrastructure, the ease of construction and ease in procuring the materials were the factors that governed the choice of site rather than economic factors. But at present, due to increased land use pattern there is more concern about the economy. In practice, soils with low bearing capacity, low stability, high settlements, excessive swelling or shrink properties are usually encountered. It has become necessary to make such soils suitable for construction by increasing the strength, reducing compressibility, swelling or shrinkage and increasing the durability of soils by altering the properties. In this direction, soil stabilization is very promising and in particular lime and cement stabilization is generally adopted in the field of highways and construction of earthen infrastructure due to its cost advantage and several beneficial changes in the engineering properties of soil such as improvement in plasticity and strength, decrease in shrink swell potential and erosion. The strength of the clayey soil increases with increase in lime content up to certain limit, called optimum lime content which depends on clay content and reactive silica. It is observed that the lime treatment reduces the settlement and improves the strength and is useful in problematic soil. Broms and Boman [1] used lime columns to stabilize clays. Okumara and Terashi [2] have used lime column method to stabilize thick soft marine clay deposits in a Japanese harbor area. Balasubramaniam et al [3] have adopted quicklime for the stabilization of soft Bangkok clays. They observed that unconfined compressive strength increased nearly ten times by the addition of 5 percent lime. Imran et al [4] reported that the unconfined compressive strength of stabilized soils increased with addition of cement with respect to curing days. Sadek Deboucha et al [5] reported that the results show the influence of curing period on the unconfined compressive strength of the cement stabilized soil samples. Higher strength was obtained from samples that had been cured for 14 days compared with 7 days cured samples. Tan et al [6] reported that the properties of Singapore marine clays improved by cement mixing. It was observed from experimental results that there is increase in strength and stiffness with time for cement stabilized clay. Saiosseiri and Muhunthan [7] have reported that there is also considerable improvement in the unconfined compressive strength and modulus of elasticity of cement treated soil. Yin et al [8] have reported that peak strength and the stiffness have increased with increase in the cement/soil ratio. Fang et al [9] have studied the engineering properties of soil cement stabilized with deep mixing method by fabricating soil cement columns from construction site of liquefied natural gas station. Chew et al [10] have conducted studies on the physicochemical and engineering behavior of cement treated clays and they observed that there are changes in the properties and behavior of cement treated marine clay due to the interaction of microstructural mechanisms. Miura et al [11] have studied the engineering behavior of cement stabilized clay at high water content and they concluded that clay water/cement ratio plays a major role in the strength and deformation behavior of cement stabilized clay at high water content.

II. MECHANISM OF LIME STABILIZATION

Stabilization of soil by lime is achieved through cation exchange, flocculation, agglomeration, lime carbonation and pozzolanic reaction. Cation exchange, flocculation and agglomeration reactions takes place rapidly and bring immediate changes in soil properties such as strength, plasticity and workability[12], whereas, pozzolanic reactions are time dependent. These pozzolanic reactions involve interactions between soil silica and/or alumina and lime to form various types of cementatious products thus enhancing the strength.

The chemical interaction plays an important role in the lime stabilization of soils. The following four basic reactions take place when lime is added to soil:

(1) Cation exchange

$$Ca^{++} + Clay \rightarrow Ca^{++}Clay + (Na^{+}, K^{+}) \quad (1)$$

(2) Flocculation/Agglomaration

(3) Carbonation

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (2)$$

(4) Pozzolanic reactions

$$Ca^{++} + 2(OH)^{-} + SiO_2 \rightarrow CSH \quad (3)$$

$$Ca^{++} + 2(OH)^{-} + Al_2O_3 \rightarrow CAH \quad (4)$$

The cation exchange starts to take place between the metallic ions associated with the surface of the clay particles and that are surrounded by a diffuse hydrous double layer, which is modified by the ion exchange of calcium, because of which there is alteration in the density of the electrical charge around the clay particles, that leads to the flocculation of particles. This process is mainly responsible for the modification of the engineering properties of clay soils treated with lime [13].

The carbonation reactions are generally undesirable because it gives weak cementing agents. The pozzolanic reaction is time dependent and it is mainly responsible for improvement in soil properties. The long term physico-chemical changes are due to pozzolanic reactions. The pozzolanic reactions are facilitated by the lime creating highly alkaline soil pore chemistry. This promotes dissolution of silicon and aluminium from the clay. The dissolved components react with the calcium ions present in the pore water forming calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). These compounds crystallize with time that results in changes in clay plasticity, increase in shear strength and reduction in permeability [14].

III. MECHANISM OF CEMENT STABILIZATION

When cement is mixed with soil, generally there will be reduction in liquid limit, plastic limit and the potential for volume change of soils. But there will be increase in the shrinkage limit and shear strength. The increase in strength of cement treated soil is by primary and secondary cementitious reactions in the soil cement matrix. The primary cementation is due to hydration products of Portland cement. A variety of compounds and gels are formed by hydration reaction. The Portland cement is a heterogeneous substance containing tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetra calcium alumino-ferrite (C_4AF). The compounds in the Portland cement are transformed on addition of water and the reactions are shown in equations (5 to 9).

$$2(3CaO.SiO_2) + 6H_2O \rightarrow 3CaO.2SiO_2.3H_2O + 3Ca(OH)_2 \quad (5)$$

$$2(2CaO.SiO_2) + 4H_2O \rightarrow 3CaO.2SiO_2.3H_2O + Ca(OH)_2 \quad (6)$$

$$4CaO\ Al_2O_3\ Fe_2O_3 + 10H_2O + 2Ca(OH)_2 \rightarrow 6CaO.Al_2O_3.Fe_2O_3.12H_2O \quad (7)$$

$$3CaO.Al_2O_3 + 12H_2O + Ca(OH)_2 \rightarrow 3CaO.Al_2O_3.Ca(OH)_2.12H_2O \quad (8)$$

$$3CaO.Al_2O_3 + 10H_2O + CaSO_4.2H_2O \rightarrow 3CaO.Al_2O_3.CaSO_4.12H_2O \quad (9)$$

Hydration of cement occurs and major hydration products are formed when the pore water of the soil comes in contact with cement. The products are hydrated calcium silicates, hydrated calcium aluminates and hydrated lime. The first two of the hydrated products are the main cementitious products and the hydrated lime is deposited as a separate phase. A hardened skeleton matrix is formed when these cement particles bind the adjacent cement grains together and encloses the unaltered particles. The silicate and aluminate phases are internally mixed and may not completely crystalline. The hydration products induce cementation between the soil particles when cement content is sufficiently high. Part of calcium hydroxide may also be mixed with other hydrated phase. In addition to primary reaction process there is also secondary phase between the liberated calcium hydroxide and alumina and silica of soil clay that leads to the formation of additional calcium silicate hydrates and calcium aluminate hydrates. The pozzolanic reaction increases the pH of pore water due to the dissolution of the hydrated lime and the strong base dissolves soil silica and alumina from clay minerals. The hydrous silica and alumina slowly react with calcium ions liberated from hydrolysis of cement to form insoluble compounds that harden on curing to stabilize the soil.

IV. DISPERSIVE SOILS

Soils that are dislodged easily and rapidly in flowing water of low salt concentration are called dispersive soils. Earlier, clays were considered to be non erosive but it is now clear that erosive clay soils do exist. A number of earth dams, hydraulic structures, and road way embamkments have failed due to erosion problems. In each case, the soil containing readily dispersive clay particles went easily into suspension in flowing water. The tendency of clays to disperse or deflocculate depends on clay type and soil chemistry. Problems associated with dispersive soils are reported from many parts of the world. Most failures have occurred in embankments, dams and slopes composed of clays with low-to-medium plasticity (CL and CL-CH). Dispersive piping in dams has occurred either on the first reservoir filling or, less frequently, after raising the reservoir to highest level. Tunneling failures commence at the upstream face when the reservoir is filled for the first time, the settlement may accompany saturation of the soil, particularly if the soil was placed dry of optimum and not well compacted. Settlement below the phreatic surface and arching above can result in crack formation. In the present paper, a locally available dispersive soil in which many failures have occurred has been stabilized with lime and cement and the results have been reported.

V. MATERIALS AND EXPERIMENTAL METHODS

The study deals with stabilization of soil called Suddha soil that is present in Southern parts of Karnataka, India. It is wide spread below a depth of 1.5 m from the ground level and extends to depths greater than 10 m. It possesses good strength in dry condition and upon increase in moisture content looses strength. Many failures have been observed along canal slopes, road bases and foundations at sites where this soil is present. For the present study Suddha soil (silty sand) was collected from Hemavathi canal zone, near Tumkur, from locations where canal side slopes had failed. The properties are shown in Table I. It has sand as the major constituent followed by silt and clay with the group symbol SM. It has liquid limit of 41 and plasticity index of 17.

Chemically pure lime obtained from standard manufacturers is used as stabilizing agent. The concentrations of lime used are 1, 2 and 3 percent by dry weight. Commercially available Birla 53 grade ordinary portland cement was used. The concentrations of cement used are 1, 2, 3 and 5 percent by dry weight of soil. The experiments were conducted to determine the Atterberg's limits, compaction characteristics and unconfined compressive strength. The tests were carried out as per relevant IS codes of practice and standards.

Table I

Geotechnical properties of Suddha soil

Sl. No.	Properties	Value
1	Particle size analysis	
	Gravel (%)	4
	Sand (%)	57
	Silt (%)	26
	Clay (%)	13
2	Liquid limit (%)	41
3	Plastic limit (%)	24
4	Plasticity index	17
5	Shrinkage limit (%)	22
6	Specific gravity	2.6
7	Compaction Characteristics	
	Optimum Moisture Content (%)	14
	Maximum dry unit weight (kN/m^3)	17.8
8	Soil Classification	SM

VI. DOUBLE HYDROMETER TEST FOR THE DETERMINATION OF DISPERSION

The Soil Conservation Service laboratory dispersion test, also known as the double hydrometer test is one of the first methods developed to assess dispersion of clay soils [15]. The particle size distribution is first determined using the standard hydrometer test in which the soil specimen is dispersed in distilled water with a chemical dispersant namely sodium hexa metaphosphate. A parallel hydrometer test is then made on an identical soil specimen, but without chemical dispersant. The percent dispersion is the ratio of the dry mass of particles smaller than 0.005 mm diameter in a test without dispersing agent to the mass of particles smaller than 0.005 mm in a test with dispersing agent expressed as a percentage. Procedures for performing the test are outlined in USBR 5405, Determining dispersibility of clayey soils by the Double Hydrometer Test Method [16]. The criteria for evaluating degree of dispersion using results from the double hydrometer test are shown in Table II. Test results indicate that a high percentage of soils with dispersive characteristics, exhibited 30 percent or more dispersion when tested by this method [17].

Table II

Degree of dispersion using results from double hydrometer test

Percent dispersion	Degree of dispersion
<30	Non-dispersive
30 to 50	Intermediate
>50	Dispersive

VII. SAMPLE PREPARATION

The soil collected from the site was pulverized with a wooden mallet to break lumps and then air-dried. It was then sieved through 2.00 mm IS sieve and then dried in an oven at 105^0 C for 24 hours. The required quantity of lime and cement in powder form were added to soil and mixed thoroughly to ensure uniform mixing.

The soil specimens for the determination of unconfined compressive strength were prepared by compacting soil-lime and soil-cement mixtures at their respective optimum moisture contents and maximum dry densities. The soil specimens were cured for 1, 3, 7 and 14 days in a desiccator at 100 percent relative humidity. Specimens cured for 1 day were soaked for 1 hour and specimens cured for 3, 7 and 14 days were soaked for 1 day. All specimens were soaked by immersing them in a sand bath filled with water such that the specimens were saturated from the bottom such that the head causing flow is equal to the height of specimen. The soaked specimens were kept in air for drying for about 30 minutes then the specimens were subjected to unconfined compressive strength test. Three identical specimens were cast and tested in each case. The results are the average of the three tests.

VIII. EXPERIMENTAL PROGRAMME

The experimental programme is shown in Table III. Atterberg's limits and compaction tests were carried out for all the soil-lime and soil-cement mixtures. Unconfined compression tests were conducted for all the soil-lime and soil-cement mixtures under unsoaked and soaked conditions.

Table III

Experimental Programme

Name of additive added	Additive dosage (%)	Parameters	Conditions for Unconfined Compression Tests	
			Curing Period in days	Satu--ration condition
Lime	0 1 2 3	Atterberg's limits, Compaction parameters Unconfined compressive strength	-	Un soaked
	1	do	1,3,7 & 14	Soaked
	2	do	1,3,7 & 14	Soaked
	3	do	1,3,7 & 14	Soaked
Cement	0 1 2 3	Atterberg's limits, Compaction parameters Unconfined compressive strength	-	Un soaked
	1	do	1,3,7 & 14	Soaked
	2	do	1,3,7 & 14	Soaked
	3	do	1,3,7 & 14	Soaked
	5	do	1,3,7 & 14	Soaked

IX.RESULTS AND DISCUSSIONS

Fig. 1 shows the results of percentage fines versus particle size in double hydrometer test conducted on Suddha soil. Grain size curves of Suddha soil with and without dispersing agent are plotted. The percentage fines at any given time in a suspension is more when dispersing agent is used and therefore grain size curve with dispersing agent locates above that of the grain size curve without dispersing agent. The difference in percentage fines of these two curves at 0.005 mm is an indicator of dispersivity. In the present case the percentage of dispersion is 35 percent and it corresponds to intermediate dispersion as per [17].

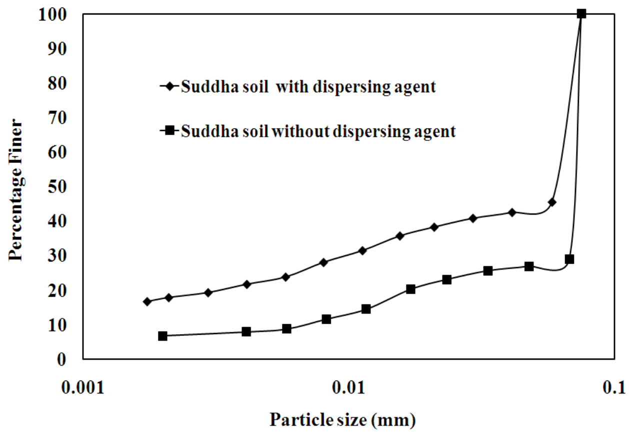

Fig. 1 Double hydrometer test for Suddha soil

Fig. 2 shows the effect of addition of lime on Atterberg's limits. It is observed that there is a slight increase in both liquid limit and plastic limit at 1 percent lime and thereafter both limits remain fairly constant. The initial increase in liquid limit indicates flocculation of soil particles due to addition of lime. The effect of cation exchange of soil particles with calcium ion which decreases liquid limit due to suppression of diffuse double layer is negligible for Suddha soil with very low cat ion exchange capacity. The effect of flocculation which increases the water holding capacity within flocculated structure is maximum at 1 percent lime and does not seem to increase further with increase in lime content. The same is the case with plastic limit of soil. The decrease in the plasticity index of soil till 1% lime content shows that the increase in plastic limit is more than the increase in liquid limit there by a net reduction in plasticity index.

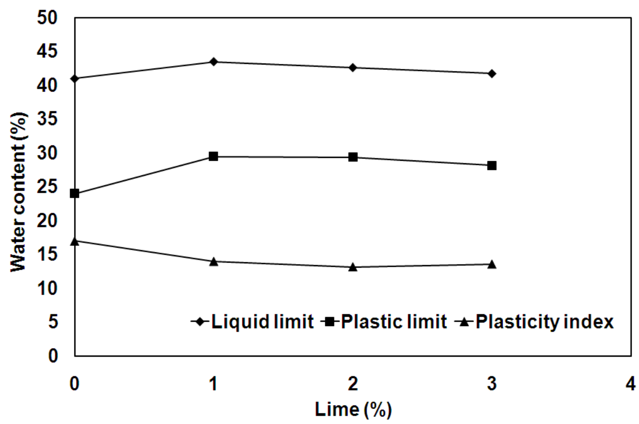

Fig. 2 Effect of lime on Atterberg's limits

Fig. 3 shows the effect of cement on Atterberg's limits and it is observed that there is no variation in Atterberg's limits till 2 percent cement content and there is slight increase in liquid and plastic limits beyond 2 percent and in general the variation is negligible.

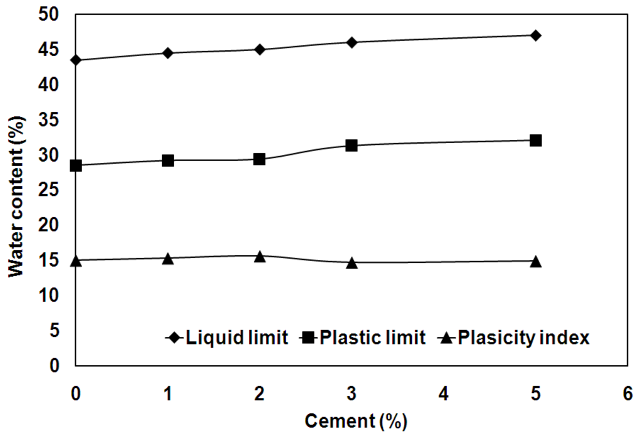

Fig. 3 Effect of cement on Atterberg's limits

Fig. 4 shows compaction curves for various soil lime mixtures. It can be observed from the graph that for all the three percentages of lime the value of optimum moisture content is less than the optimum moisture content of Suddha soil without the addition of lime. But the optimum moisture content has decreased when 1 percent lime is added to soil, but thereafter for the addition of 2 and 3 percent lime, optimum moisture content has increased. Thus the highest maximum dry density and lowest optimum moisture content has been obtained for soil with 1 percent lime. Actually flocculation of soil particles which has been indicated by Atterberg's limit should have decreased the maximum dry density and increased optimum moisture content. At one percentage of lime though the soil particles are flocculated there is no sufficient lime to bind the flocculated particles. Thus during compaction the flocculated particles might have collapsed leading to higher density due to increased void ratio and lower moisture content. As the lime content increases the soil particles are slowly cemented increasing the particle resistance to compactive effort and reduction in the density and increase in the water content. But in general addition of lime has the effect of increased compactive effort.

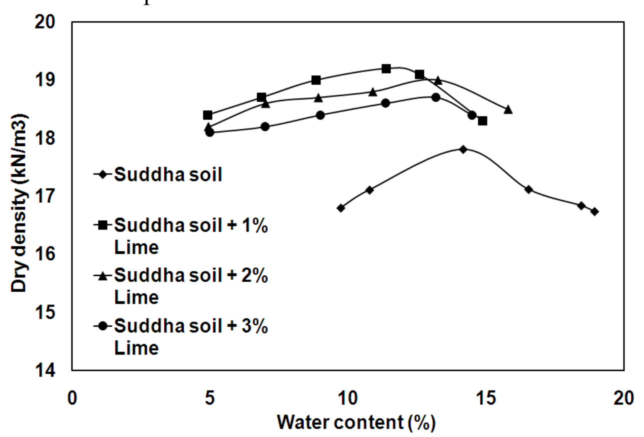

Fig. 4 Compaction curve of Suddha soil with lime

Fig. 5 shows the compaction curves for soil cement mixtures. It can be seen from the graph that for all the four percentages of cement the value of optimum moisture content is less than the optimum moisture content of suddha soil without the addition of cement and maximum dry density is more than the maximum dry density of suddha soil without the addition of cement. The optimum moisture content has decreased and there is slight increase in maximum dry density with addition of cement.

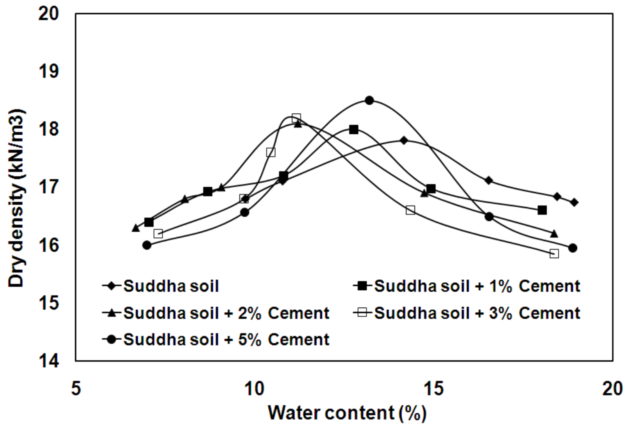

Fig. 5 Compaction curve of Suddha soil with cement

Unconfined compressive strength tests were carried out on Suddha soil using lime and cement as additives under unsoaked condition without curing. It is observed from table IV that there is improvement in unconfined compressive strength of Suddha soil with addition of lime and cement.

Table IV Unconfined compressive strength of Suddha soil with Lime and Cement (unsoaked)

Sl. No.	**Soil+ Additive**	**Unconfined compressive strength with Cement (kN/m^2)**	**Unconfined compressive strength with Lime (kN/m^2)**
1	Suddha soil	171	171
2	Suddha soil + 1 % additive	208	218
3	Suddha soil + 2 % additive	228	246
4	Suddha soil + 3 % additive	262	288

Fig. 6 shows unconfined compressive strength of soil with different lime contents after curing for 1, 3, 7 and 14 days under soaked conditions. Suddha soil when soaked does not possess any strength and specimen was unstable. This kind of collapse was also observed along the slopes of canals. The strength of soil does not improve with 1 percent lime even after curing for 14 days because of the formation of flocculated structures as explained earlier. The strength of soil increases with higher percentages of lime with lime content and curing period. It was earlier observed that the density of soil is highest with 1 percent lime. Thus the effect of pozzolanic reaction which proceeds well with higher percentage of lime masks the effect of density. With increase in lime content the rate of increase in strength increases with curing period. The effect of curing period is seen more clearly from Fig. 7 which presents the results of unconfined compressive strength with curing periods. At any given curing period, the strength gain is more with increase in lime content. In the present case minimum lime content shall be 3 percent with curing period not less than 3 days under soaked condition.

When excess lime (more than optimum) is added, it acts as a filler material resulting in lower strength. The optimum lime content depends on the clay content of the soil and the reactive silica. The soluble silica increases as the fineness of clay increases and more lime is required to completely react with this silica. Water content is essential for pozzolanic reaction to produce gelatinous compounds. Effective formation of pozzolanic compounds does not take place when sufficient quantity of water is not available for soil lime reaction. On the other hand when water is more than required, the distance between soil particles increases which leads to lowering of strength because of ineffective binding by pozzolanic reaction compounds. Hence type of clay and water quantity present in the system influence the optimum lime content. Thus at optimum moisture content, optimum lime content required for effective stabilization of soil is found to be between 3 to 6 percent [18].

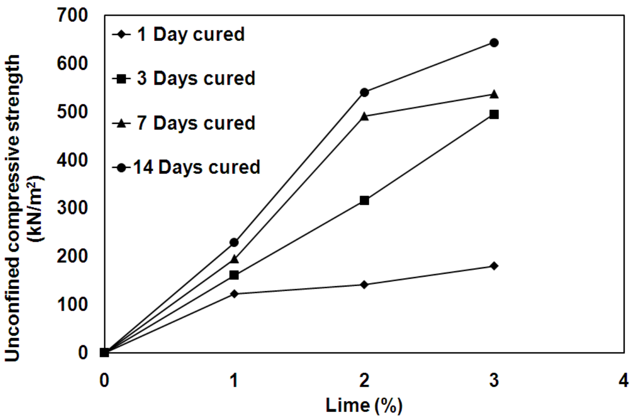

Fig. 6 Unconfined compressive strength of Suddha soil with lime

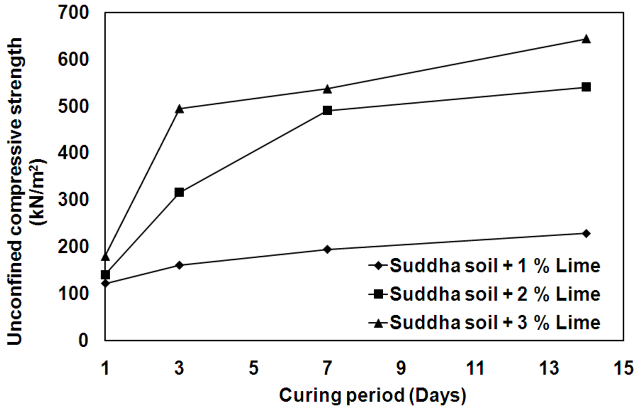

Fig. 7 Effect of curing period on unconfined compressive strength with lime

Fig. 8 shows unconfined compressive strength with cement content for 1, 3, 7 and 14 days under soaked conditions. The strength of soil does not improve with 1 percent even after curing for 14 days. The strength of soil increases with higher percentages of cement both with cement content and curing period. With increase in cement content the rate of increase in strength increases with curing period. The effect of curing period is seen more clearly from Fig. 9 which presents the results of unconfined compressive strength with curing periods. At any given curing period, the strength gain is more with increase in cement percent.

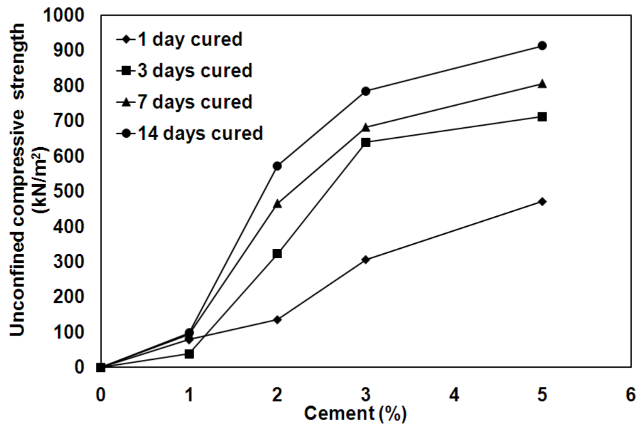

Fig. 8 Unconfined compressive strength of Suddha soil with cement

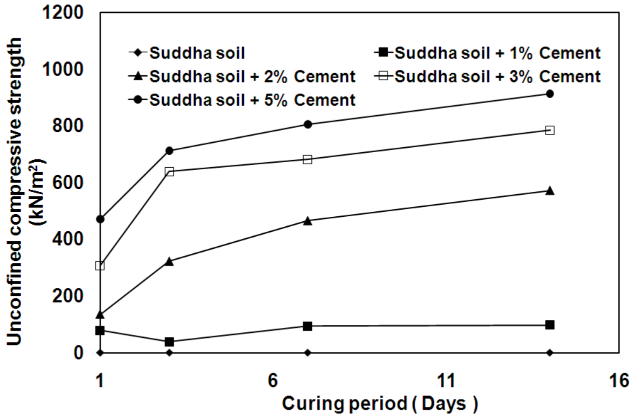

Fig. 9 Effect of curing period on unconfined compressive strength with cement

Fig. 10 shows Young's modulus for lime treated Suddha soil. At any given percentage of lime content young's modulus is higher. There is a steep increase in the Young's modulus up to 2 percent of lime and there after there is a gradual increase with increase in lime content. Fig. 11 shows Young's modulus for lime treated soil with curing period. The increase in Young's modulus is rapid up to 3 days and gradual subsequently.

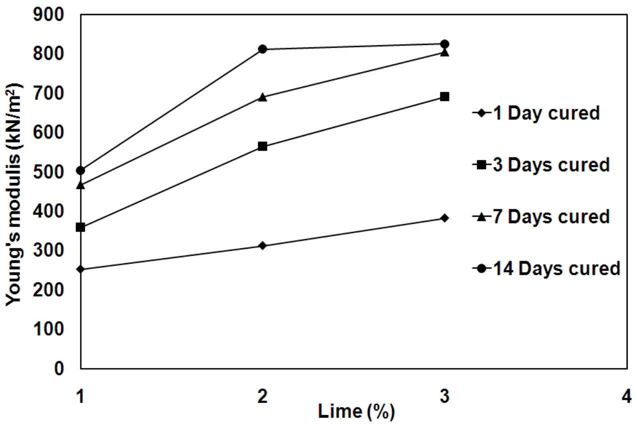

Fig. 10 Young's modulus versus lime

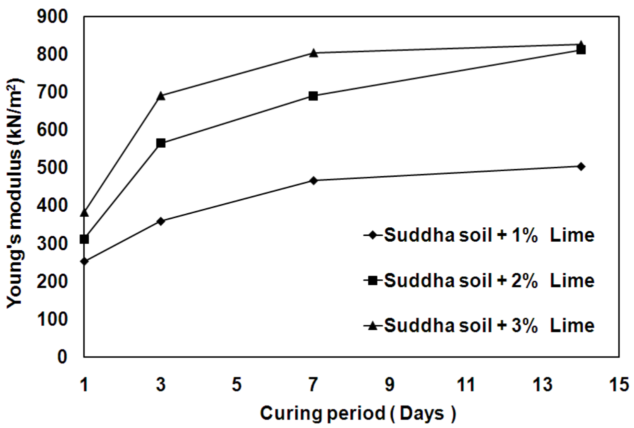

Fig. 11 Effect of curing period on Young's modulus

Fig. 12 shows Young's modulus for cement treated Suddha soil. At any given percentage of cement content young's modulus is higher than untreated soil. There is a steep increase in the Young's modulus up to 3 percent of cement and gradual after 3 percent of cement content. Fig. 13 shows Young's modulus for cement treated Suddha soil with curing period. The increase in Young's modulus is very significant up to 3 days and gradual subsequently.

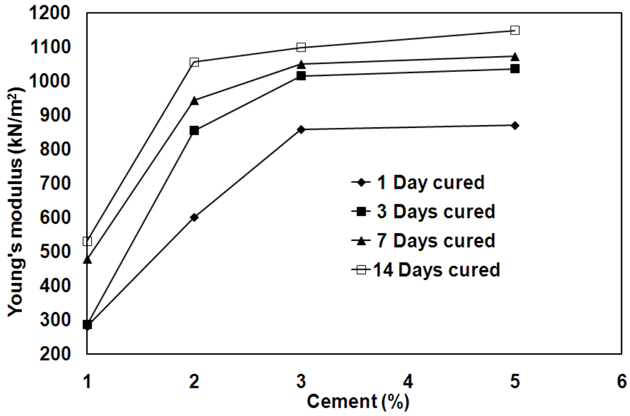

Fig. 12 Young's modulus versus cement

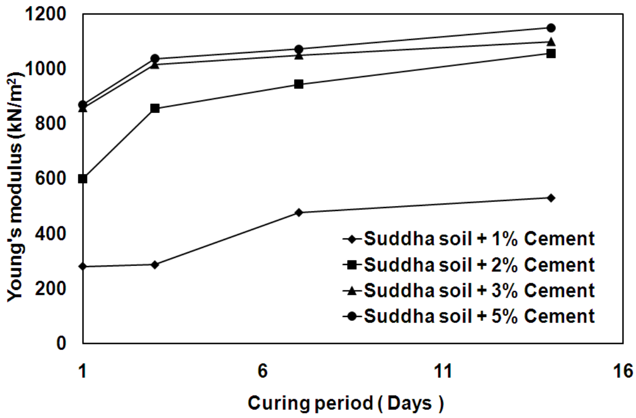

Fig. 13 Effect of curing period on Young's modulus

Fig. 14 shows the effect of lime and cement on unconfined compressive strength under soaked condition for a curing period of 14 days. The gain in strength is more with 3 percent under soaked condition. The gain in strength is slightly more with cement than with lime at 3 percent.

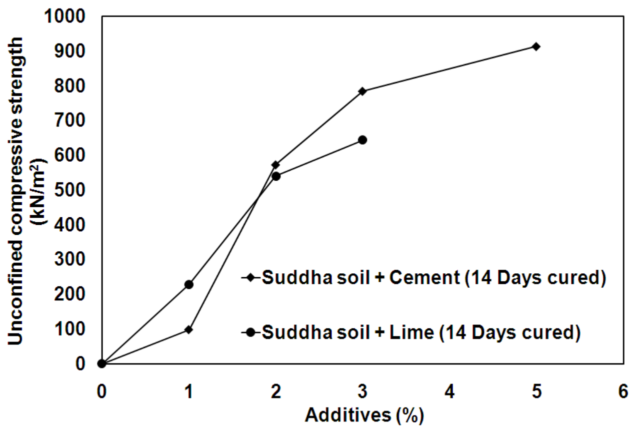

Fig. 14 Comparison of unconfined compressive strength of lime and cement treated Suddha soil

It is thus clear that the Young's modulus of the soil is increasing with lime and cement content and also with curing period. Fig. 15 shows variation of Young's modulus with unconfined compressive strength for both lime and cement treated Suddha soil. It is noted that there exists a good correlation between young's modulus and unconfined compressive strength for lime and cement treated soil. The relationship between Young's modulus of the treated soil and with a correlation of 85 percent unconfined compressive strength is given by equation 10.

$$E_s = 0.9q_c + 330 \quad (10)$$

Where, Es = Young's modulus (kN/m^2)

q_c = Unconfined compressive strength (kN/m^2)

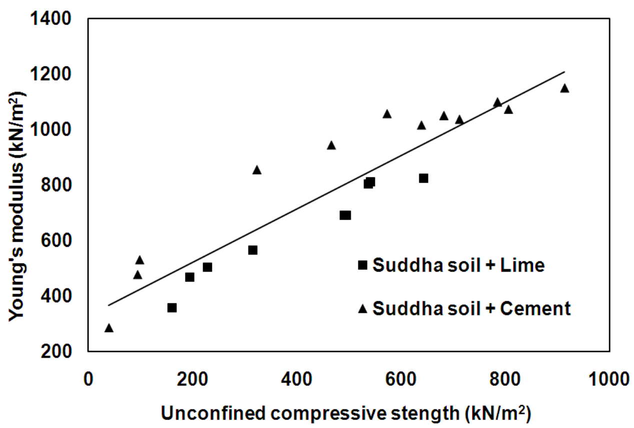

Fig. 15 Young's modulus versus unconfined compressive strength for lime and cement treated Suddha soil

X. CONCLUSIONS

The paper brings out that compacted dispersive soils respond well to lime and cement stabilization and improve unconfined compressive strength significantly. The improved strength is also sustained in soaked condition. Optimum lime and cement content is 3 percent. The rate of increase in strength is higher for first three days and but is sustained for relatively long time. Young's modulus and unconfined compression strength correlates well for stabilized soils and equation (10) can be used for predicting the Young's modulus.

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T S Umesha: He is working as Assistant Professor in the Dept. of Civil Engg at Siddaganga Institute of Technology, Tumkur. He is pursuing Ph.D in the field of Environmental Geotechniques. He has teaching experience of more than 25 years. He is the Life member of Indian Geotechnical society.

S V Dinesh: He is working as Professor in the Dept. of Civil Engg at Siddaganga Institute of Technology, Tumkur. He obtained his Ph.D degree from Indian Institute of Science, Bangalore in 2003. He is working in the area of Constitutive behavior of granular material, Numerical modeling of Geomaterials using DEM, Liquefaction potential and Dynamic properties of soils and Behaviour of contaminated soils. He has more than 20 years of teaching experience. He is the recipient of NPEEE fellowship from MHRD, Govt. of India for International Research training. He has more than 40 publications in various journals and conferences.
He is life member for Indian Geotechnical society (IGS), Indian Society of Earthquake Technology (ISET), Indian Road Congress (IRC), Associate member American Society of Civil Engineers (ASCE).

P V Sivapullaiah: He is working as Professor in the Dept. of Civil Engg at Indian Institute of science, Bangalore. He obtained his Ph.D degree from Indian Institute of Science, Bangalore in 1977. He is working in the area of Geoenvironmental Engineering, Stabilisation of Soils at High Water Content - Influence of Pozzolanic Material, Simplified Methods of Evaluation of Diffused Double Layer Parameters. He has 180 publications in various journals and conferences. He has guided number of Ph.D and M.Sc (Engg) students. He has involved in many sponsored research projects.

He is life fellow of Indian Geotechnical Society, Member of International Society of Soil Mechanics and Geotechnical Engineering, Clay Mineral Society of India, Instrument Society of India, Indian Society for Analytical Scientists