Bearing Capacity Improvement of Loose Sandy Foundation Soils through Grouting

Santhosh Kumar. T.G[1]; Benny Mathews Abraham[2]; A.Sridharan[3] and Babu. T. Jose[4]
1Lecturer in Civil Engineering, Govt. Polytechnic College, Chelad .P.O. Kothamangalam, Ernakulam 686 681, India
2Professor & Head , Dept. of Civil Engineering, School of Engineering, Cochin University of Science and Technology, Cochin-682 022
3Former Deputy Director & Professor of Civil Engineering, Indian Institute of Science, Bangalore 560 012.
4Emeritus Professor, Cochin University of Science & technology ,Cochin -682 022

ABSTRACT
The constructional activities in the coastal areas often demand deep foundations because of the poor engineering properties and the related problems arising from weak soil at shallow depths. The very low bearing capacity of the foundation bed causes shear failure and excessive settlements. Further, the high water table and limited depth of the top sandy layer in these areas restrict the depth of foundation thereby further reducing the safe bearing capacity. This paper discusses grouting as one of the possible solutions to the foundation problems of coastal areas by improving the properties of soil at shallow depths..

Keywords - Grouting; sand; cement; shear strength; bearing capacity; settlement.

1. INTRODUCTION
The construction of structures on weak ground often requires the soil to be improved in order to ensure the safety and the stability of surrounding buildings. Ground improvement in granular soils can be achieved by different methods such as vibro-flotation, compaction piles, compaction with explosives, excavation and replacement, well point system, reinforced earth, grouting etc. The selection of the most suitable method depends on a variety of factors, such as: soil conditions, required degree of the compaction, type of structures to be supported, maximum depth of compaction, as well as site-specific considerations such as sensitivity of adjacent structures or installations, available time for completion of the project, competence of the contractor, availability of equipments and materials etc. Soil compaction can offer effective solutions for many foundation problems, and is especially useful for reducing total settlements in sands.

However, efficient use of soil compaction methods requires that the geotechnical engineer understands all factors that influence the compaction process. The poor quality soils, especially their low bearing capacity, make it necessary to improve their properties by stabilization.

The compaction of soils is intrinsically dependent upon the vertical effective stress, the type and gradation of soil,etc. Broadly, a well-graded soil compacts more than a uniform soil and moisture content is a significant parameter [1]. Dynamic compaction can only be used to a maximum depth of 10m to 20m and will not yield good results when the water table is at shallow depths [2].

A question has been raised as how to increase the relative density of loose sands located within shallow depths. It is an inevitable problem in dynamic soil improvement methods that vibration induced on the ground surface tends to loosen the cohesionless soils. Hence alternative methods for developing the density and strength of loose sand at shallow depths are required.

Soil stabilization, with cement grouts injected under pressure, has come into widespread use in construction. At present the method of grouting is highly prevalent in a number of branches of structural engineering; and in foundation engineering for the reinforcement of existing foundations beneath buildings and structures as well for strengthening the soils in their beds. The penetrability of soils, which can be characterized by the permeability and the dispersivity of the cement - water suspension, which can be characterized by its grain size distribution; serve as criteria for defining the possibility of the impregnation of a soil by cement grout . Moreover, the method is sufficiently economic, and does not require complex equipment, and is also ecologically safe for the environment [3].

Pressure grouting substantially alters the strength, modulus, failure strain, and mode of failure of sand. It would be both practical and useful to estimate the properties of the grouted sand from the constituent properties that will lead to proper selection of grouts. The compressive behavior of grouted sand will depend on the cohesive behavior of the grout, the grout-sand adhesion (bonding), and the properties of the sand. The physical or chemical interaction, or both, of two materials at their interface is known as adhesion or bonding. The strength and type of this bond plays an important, though poorly understood, role in the mechanical behavior of chemically grouted geo-materials [4].

Cement grouting by impregnation in granular media is a widely used technique in civil engineering, applied in order to improve the mechanical characteristics of soils. The idea consists in incorporating a pressurized cement grout in the pore space of the soil. The setting of cement grout in the pore space increases both the strength and stiffness. Grouting is mainly responsible for the gain in cohesion by the material and only marginally affects the friction angle. The cohesion linearly varies with cement content, the magnitude of the cohesion gained by grouting and also the friction angle is a slightly increasing function of cement content. The increase in angle of friction is negligible with respect to cohesion [5]. The Mohr –Coulomb cohesion varies between 0.1 and 0.5 MPa depending on the cement content of the grout and the relative density of the soil and increases in proportion with the cement to water ratio [6].

Introduction of a cementing agent into sand imparts two components of strength, one due to the cement itself and the other due to friction. The friction angle of cemented sand is similar to that of uncemented sands [7]. In the process of cement grouting, cement is used to fill the voids of soil mass and to render it impervious to percolating water and improve the strength and elastic properties of soil. The strength of soil increases with increase in cohesive strength and angle of internal friction arising from the bonding between soil grains and hydrated cements. Unconfined compressive strength of micro fine slag cement grouts increases with increase in curing time from 7 to 60 days and decreases in water cement ratio from 2 to 0.8 [8]. The weakly cemented sand shows a brittle failure mode at low confining pressures with a transition to ductile failure at higher confining pressures. The shear strength parameters - cohesion and angle of internal friction increase when grouted with cement. The water cement ratios have much influence in the control of strength gain of sandy soils [9].

Admixtures are used in cement grouting as accelerator, retarder, antibleeder, fluidizer, expander, etc. These admixtures added to impart some additional properties, may affect the basic requirements such as viscosity and bleeding of cement grouts. At lower cement/ water ratios, the increase in viscosity is not significant but viscosity considerably increases with higher cement/ water ratios [10]. Significant contributions on the study of grout materials, properties, equipment and procedure for grouting has been made by several researchers [11,12&13].

As grouting reduces pore size and alters pore structure of soil, the engineering properties such as strength, stiffness etc, are also influenced to a great extent. Even today the grouting operations are based on thumb rules and existing practices rather than design principles and well defined procedures substantiated by research data. In this paper an attempt is made to study the improvement in the strength of grouted loose sand bed by cement grouting.

2. MATERIALS USED

River sand was used in the present study and was graded into fine (75 µm- 425 µm), medium (425 µm- 2 mm) and coarse (2mm- 4.75mm) fractions as per the ASTM and BIS classifications. The dry density of sand was kept at 14.5 kN/m^3. The cement used for the study was 43 grade Ordinary Portland Cement, the properties of which are given in table1.

For improving the properties of cement grouts, certain additives are sometimes used. Various admixtures such as sodium silicate (accelerator), tartaric acid (retarder), and aluminium sulphate (antibleeder) were used in the present study. The additives used in the present study and its dosages are given in table 2.

3. EXPERIMENTAL SET UP

The efficiency of the grouting process was also verified through load tests conducted on ungrouted/grouted sand beds.

The initial tests for the assessment of improvement in load carrying capacity through densification, were conducted by filling the sand at the desired densities in small tanks of size 30cmx30cmx30cm. The density at loosest state was13.1 kN/m^3 and at densest state, it was 16.2 kN/m^3.

Improvement in shear strength of the soil can be obtained by improving both the *c* and Ø values. Grouting which alters the pore structure and enhances the bonding and interlocking between particles can give considerable improvement in *c* as well as Ø values. To place the grout within the pores of the granular medium, two methods were adopted. In the first method, the grout was deposited within the pores by hand mixing in order to get a uniform grouted bed. In the second, previously prepared sand beds were grouted with grouting material using a grout pump similar to the grouting operations in the field.

In the first case, samples were obtained by thoroughly mixing soil and grouting material with hand. Sand sample of medium size range was taken in a tray. The predetermined percentage of cement by weight of sand was added to the sand and thoroughly mixed using a trowel. 10% or 20% of water by the combined weight of sand and cement was added to the sand cement mixture to get a uniform mix so that the viscosity of the cement grout will be within the pumpable limits ie, a Marsh funnel viscosity of 30-60 seconds. The mix was filled in the split mould of size 60mm x 60mm x 25mm (for conducting direct shear tests), in layers with uniform density, after hand impregnation of samples; it was kept under wet condition for 28 days for curing.

Table 1. Properties of the Cement

Sl. No.	Property	Characteristic value
1	Standard consistency	28 %
2	Initial setting time	131 minutes
3	Final setting time	287 minutes
4	Blaine's sp. Surface	298500 mm^2/g
5	Sp. gravity	3.14
6	Compressive strength (i) 7 days (ii) 28 days	 35.1 N / mm^2 44.0 N / mm^2

Table 2. Additives used in the present study

Sl. No.	Admixture	Chemical	Optimum dosage % cement wt
1	Accelerator	Sodium scilicate	0.5-3
2	Retarder	Tartaric acid	0.1-0.5
3	Antibleeder	Aluminium sulphate	Up to 20%

In second case, the grouting nozzle was kept in position(at lower level of tank) and sand bed was prepared in a tank of size 45cm x 45cm x 60cm at the loosest density of 13.1 kN/m^3 , density index Dr = 0 % corresponding to initial void ratio (e_{max}) of 0.98. The grouting setup consists of a grout chamber with agitator, air compressor, grouting nozzle and regulating valve. The grout was prepared at cement/ water ratio of 0.1 and agitated well to get uniform grout solution which was poured into the grout chamber. In order to reduce the chances of segregation of the grout, an agitator was provided inside the grout chamber. Grout was pumped under a uniform pressure of 500 kPa into the prepared sand bed. The grouting nozzle was raised during the grouting operation at regular intervals in order to get uniform flow of grout over the entire thickness of sand bed. The grouted sample was kept under moist condition, for curing.

4. RESULTS AND DISCUSSIONS

Earlier studies have indicated that the relative density of loose sandy soils can be substantially improved by different methods, and among these, vibration techniques are reported to be the most effective.

The values of safe bearing capacity computed from the results of direct shear tests conducted on samples of medium sand compacted at different relatives densities are given in table 3. It can be seen that the maximum safe bearing capacity achieved by maximum compaction in the laboratory is only 90.3 kN/m^2, which may not be sufficient in case of foundations for multistoried buildings. Further, these method will be quite expensive in the field. Hence, studies were initiated to see whether grouting with cement could be a simpler and economical alternative to this.

Direct shear tests were conducted on medium sand samples (both untreated and treated with different percentages of cement) in a shear box of 60 x 60x 25mm, to determine the strength,τ with cement content (varying from 2 to 25% by shear strength parameters. The variation in the shear in Fig. 1. As expected, the value of shear strength steadily weight of dry sand) at an initial water content of 20% is shown increases with increase in cement content. The figure also shows the influence of the curing period of the specimens on the τ value. Here also the results are as expected –ie. τ value increases with increase in the curing period.

Table 3. Characteristics of the sand used

Sand	In loosest state			At natural state			In densest state		
	Unit weight (kN/m^3)	Ø (degrees)	Safe bearing capacity (kN/m^2)	Unit weight (kN/m^3)	Ø (degrees)	Safe bearing capacity (kN/m^2)	Unit weight (kN/m^3)	Ø (degrees)	Safe bearing capacity (kN/m^2)
Medium	13.1	27	18.3	14.5	34	40.2	16.2	39	90.3

The variations of τ with cement content at different normal stresses are shown in Fig. 2. Here also, as one would expect, the shear strength increases with increase in normal pressure. Fig. 3 shows the plot between shear stress and shear strain.

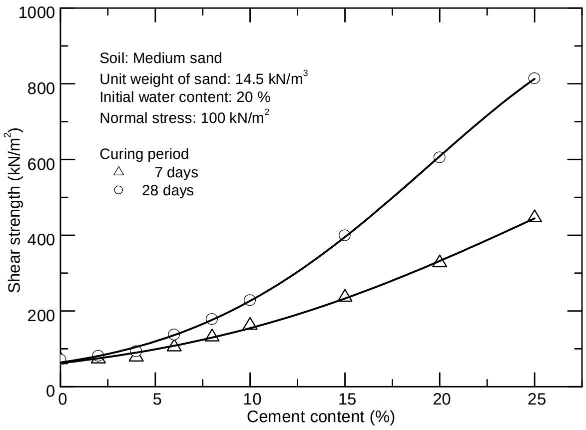

Fig 1 Effect of Cement Content on Shear Strength of Treated Medium Sand

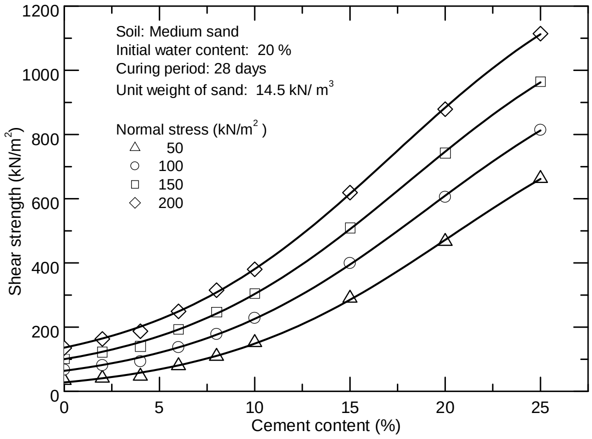

Fig 2 Effect of Cement Content on Shear Strength of Treated Medium Sand

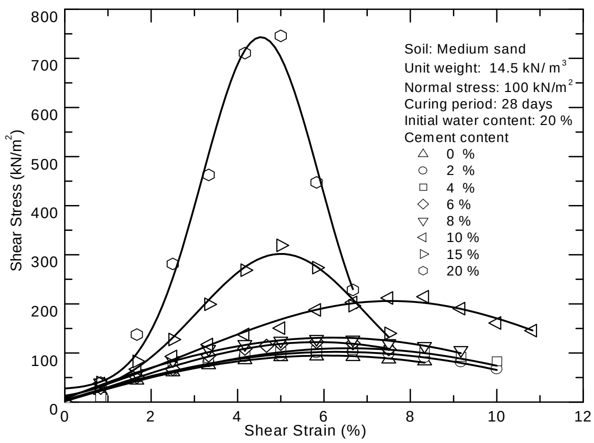

Fig.3 Shear stress – Shear strain Curve

Fig. 4 shows the effect of initial water content of the grout on the shear strength for a cement content of 4%. It can be seen that the shear strength increases upto around 5 % of initial water content and thereafter a slight decrease in shear strength is seen and remains almost constant upto 25 % of initial water content.

Stress – strain curves of grouted samples having different initial water contents are shown in Fig. 5. It can be seen that the peak stress (at failure) goes on decreasing with increase in initial water content. Fig. 6 shows the stress – strain curves of grouted samples having different cement contents. It can be noticed that the stress-strain response exhibit a linear relationship prior to the peak, for all cement contents.

Certain admixtures are used along with cement for improving the properties of grouts such as viscosity and stability [14]. But no study has been carried out on how this admixtures will affect the strength of the cement grout. Results of studies carried out in this direction are presented here. The effect of sodium silicate (used as accelerator) on shear strength of cement grouted medium sand having curing period of 7 & 28 days are presented in Fig. 7. It can be seen from the figure that addition of sodium silicate causes initially a reduction in shear strength of the cement grouted soil. Considering the improvement in properties like viscosity and stability [15], and the early setting of the grout, this reduction in strength (to the tune of only 10% to 20%) is within the tolerable limits.

The variation of shear strength with the use of a retarder like tartaric acid on cement grouted medium is shown in Fig. 8. At smaller percentage (upto around 0.15%), the value of shear strength is found to decrease, but thereafter it increases and almost reaches the initial value.

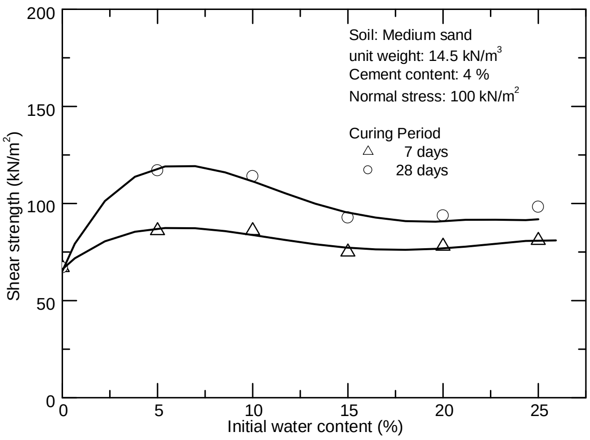

Fig 4 Effect of water Content on Shear Strength of Treated Medium Sand

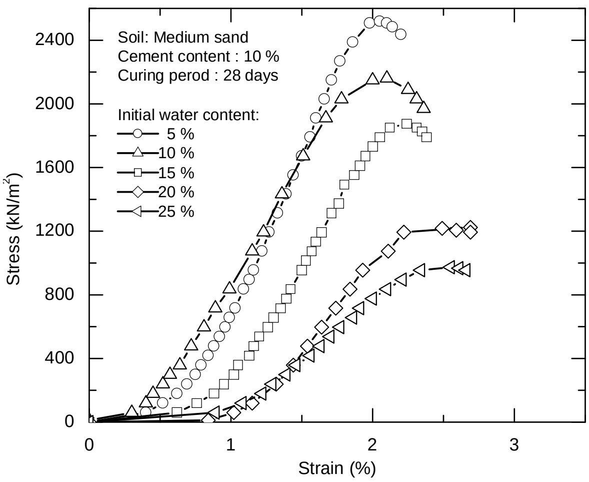

Fig. 5 Stress – Strain curves for treated medium sand for different cement contents.

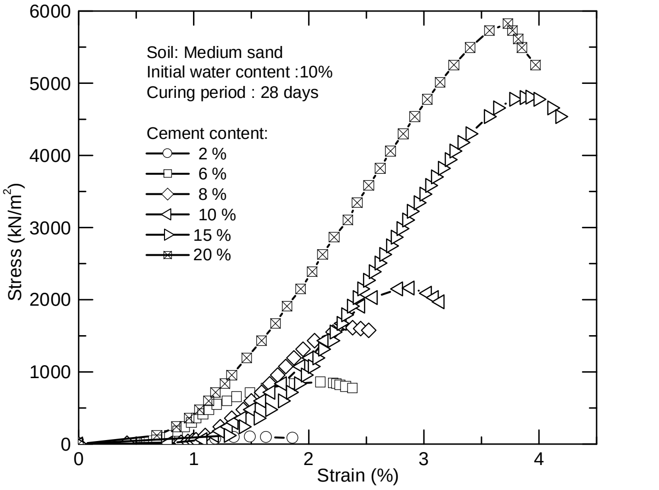

Fig. 6 Stress – Strain curves for treated medium sand for different initial water contents.

The effect of percentage of aluminium sulphate (used as antibleeder) on shear strength of cement grouted medium sand specimens cured for 7 and 28 days are presented in Fig. 9. The results of tests on specimens cured for 7 days indicated a marginal reduction in shear strength compared to the original value. But as the curing period increases (28 days), the shear strength is found to increase with increase in percentage of this salt with a slight reduction noticed at around 2 % of this salt content.

Results of load tests conducted on medium sand filled in tanks at the loosest density and grouted with cement content of 4 % using the grouting set up, are given as Fig.10. It can be seen from the figure that the ultimate stress at the loosest state (corresponding to a dry unit weight of 13.1 kN/m^3) is only 22.7 kN/m^2. Maximum compaction yielded a unit weight of 16.2 kN/m^3 and the corresponding ultimate stress was 367 kN/m^2. The ultimate load corresponding to 4% cement grout was 611 kN/m^2, which is around 27 times the ultimate stress at the loosest state. This figure clearly indicate the possibility of using cement grouting technique as an effective method for improving the bearing capacity of loose sandy soils.

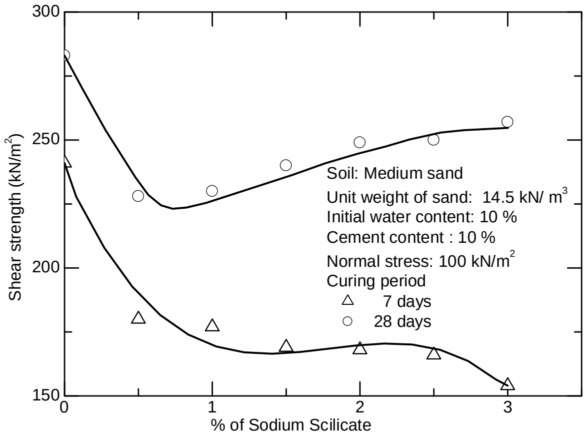

Fig 7 Effect of Sodium scilicate on Shear Strength of Treated Medium Sand.

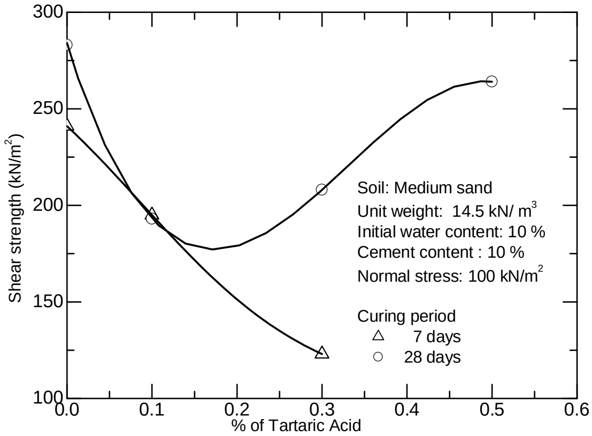

Fig 8 Effect of Tartaric acid on Shear Strength of Treated Medium Sand.

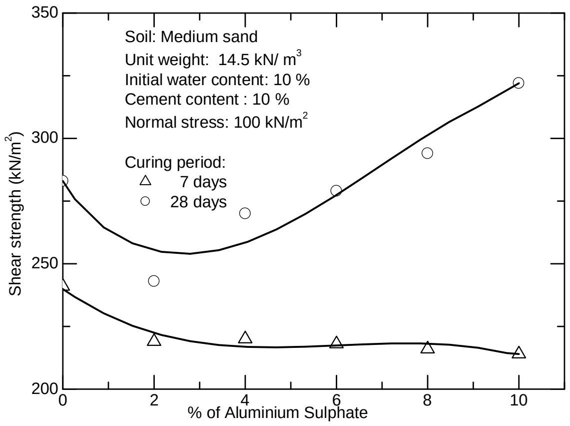

Fig 9 Effect of Aluminium sulphate on Shear Strength of Treated Medium Sand

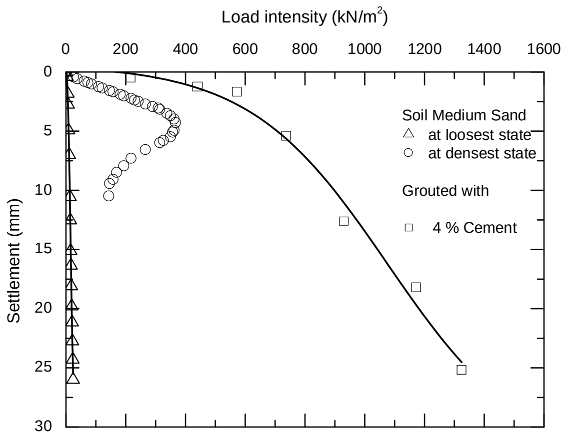

Fig.10 Load –Settlement Curves showing the effect of cement grouting

5. CONCLUSION

Based on the experimental investigations and test results, the following conclusions are made.
The shear strength of the loose sandy soil steadily increases with increase in cement content and also with curing period. The rate of increase in shear strength is very high at higher percentages of cement than at lower percentage. The stress strain response exhibit a linear relationship prior to the peak value for all cement contents and the peak stress decreases with increase in water content. The value of cohesion intercept *c* and angle of shearing resistance Ø steadily increase with increase in cement content and also with curing period. The rate of increase in Ø value is only marginal beyond a certain value of cement content (approx. 15%). The effect of curing period is more significant at higher percentages of cement than at lower percentages.

The effect of accelerator (sodium silicate) is to reduce the strength slightly, but while considering the other benefits such as improvement in properties like viscosity, stability and the early setting of the grout, this reduction in strength is within the tolerable limits. One has to be very careful in the use of tartaric acid (retarder) with cement grout. The results indicate a sharp decrease in shear strength value when the cement content is less than 0.15 %. The shear strength is found to increase with increases in percentage of aluminium sulphate (antibleeder), eventhough there is a slight reduction at lower percentage of this salt. Hence use of admixtures like sodium silicate, tartaric acid, and aluminium sulphate with cement do not adversely affect the strength of the grouted medium.

Load settlement curves of the loose sand grouted with cement show considerable improvement in the bearing capacity.

It can be concluded that cement grouting is an effective technique to improve the bearing capacity and reducing the settlement of loose sandy soils.

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