Chapter 2

REVIEW OF LITERATURE

2.1 Introduction

Grouting, which has several applications in the field of civil engineering, was once considered as a mysterious operation. The effectiveness of grouting requires a lot of understanding, skill, meticulous attention and an intuitive perception. Even though grouting was started 200 years ago, it was treated for a long time, as an art which eluded scientific investigation and improvement (Nonveiller, 1989). Its performance was for some time, more or less a privilege and a well protected secret of a few specialist companies. The curious image of grouting is changing slowly, as research and development broaden our knowledge in this area.

Grouting is a procedure by means of which grout is injected into voids, fissures, crevices or cavities in soil or rock formation in order to improve their
properties, specifically to reduce permeability, to improve strength or to reduce
the deformability of formations. Grouting has a wide application in modern
civil engineering. It reduce the permeability of formations under the water
retaining structures, control the erosion of soil, increase the strength of
materials below foundation of heavy structures and or reduce the deformability
of the material in the foundation, fill the voids between rock and tunnel linings,
form cut off walls, fill voids for rehabilitation etc.

Grout is injected under pressure into the material to be grouted until it
fills the desired volume of material around the hole or until the maximum
specified pressure is attained and a specific minimum grout flow is reached.
From injected watery suspensions, injected water is squeezed out in the pores
and the compacted mass of the injected compound fills the fissures and voids.

2.2 Strength improvement on densification

Numerous instances arise of soils at a site being of inadequate strength
to support a proposed structure and for which the needed improvement cannot
be obtained using such method as vibration, rolling or preloading, either
because of the inapplicability of these methods at such sites or because of
economic considerations (Shroff and Shah, 1992).

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 in compaction
process carefully. The poor quality soils, especially their low bearing capacity,
make it necessary to improve their properties by stabilization. Soil compaction
requires geotechnical competence and careful planning on the part of the design
engineer. The selection of the most suitable method depends on a variety of
factors, such as: soil conditions, required degree of the compaction, type of structure 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, access to equipment and materials etc (Massarsch and Fellenius, 2002).

Bement and Selby (1997) investigated the compaction settlement of granular soils when exposed to vibrations typical of those generated in the ground by vibrodriving piles that the compaction of soil is strongly dependent upon vertical effective stress, the type and grading of the soils. Broadly, a well-graded soil compact more than a uniform soil, the moisture content is also a significant parameter and saturated soils compact the most, with much smaller settlements from dry soils.

For cohesionless soils with dominant particle-size increase, the angle of shearing resistance increases with increase of particle-size, at both constant density and constant relative density. However, the increase for constant density is insignificant compared to that in the case of constant relative density. For increase in relative density for any particle size of cohesionless soils, there is a definite increase in angle of shearing resistance. But the rate of increase of angle of shearing resistance with respect to relative density is much higher at bigger size particles, compared to that of lower sizes (Chattopadhya and Saha, 1981).

2.3 Grouting technique

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; in hydraulic engineering for the building of anti seepage curtains; for imparting mono-
lithicity and impenetrability to the concrete masonry of structures; in mining for the opening of shafts, side drifts, and other workings; and in foundation engineering for the reinforcement of existing foundations beneath buildings and structures as well for strengthening the soils in their beds. The primary merits of the method of grouting lie in its technical simplicity, convenience of use, and high reliability of the results achieved. Moreover, the method is sufficiently economic, and does not require complex equipment, and is also ecologically safe for the environment (Ibragimov, 2005)

Permeation grouting is commonly used in geotechnical engineering either to reduce the permeability or improve the mechanical properties of soil and rock. Success in a given grouting operation requires that the desired improvements in the properties of the formation are attained. Grouts are generally categorized as suspension, or particulate grouts, which are prepared with Ordinary Portland or other cements, clays, or cement-clay mixtures, and fine sand in some cases, and solution, or chemical grouts which include sodium –silicate acrylamide, acrylates, lignosulphonates, phenoplast and aminoplast as well as other material that have no particles in suspension (Zebovitz et al. 1989).

Jet grouting done to stabilize underlying marine clay, using double fluid system, a thick layer of jet grouting pile provided from 5m thick using ultra high pressure cement grout injection that cuts and mixes with the soil to be treated with cement grout under controlled insertion, rotation and withdrawal. The formed jet grouting pile, increase in shear strength and acts as a barrier forming impermeable strata, struts the sheet pile as structural support for excavation (Vadivel, 2006).
Compaction grouting could be effectively used to mitigate liquefaction of the susceptible soils. The greatest improvement from grouting was achieved in sands. Silts were also improved but the grouting was less effective (Miller and Roycroft, 2004).

Microfine cement suspensions with a water: cement ratio of 4 or higher can be successfully injected into fine sand (D10 as low as 0.15 mm with a hydraulic radius as small as 0.002 mm) under a pressure of about 10 psi and will have a depth of penetration of at least one-half meter. Cement particles are captured around the contact points between sand grains and are deposited on the grain surface to form a thick cake, which, upon hardening, provides the grouted mass with improved mechanical properties. Microfine cement grouts are being proposed increasingly as an alternative to chemical grouts (which often contain one or more toxic components) for grouting fine sands, but their successful use is influenced strongly by the relationship between the suspended solids (individual particles or particle aggregations) in the grout the pores in the porous medium. Although advocated by some practitioners, the use of concentrated (low water : cement ratio) suspensions and high injection pressures can lead to non-homogeneity in the grouting of a soil formation due to the development of preferential paths during injection or hydraulic fracturing of the soil mass (Arenzana et al., 1989).

The concept of a limiting effect or a boundary effect of grouting is of great value in both theoretical research and the practical application of grouted sand. The selection of grouting for a specific job is mainly affected by the amount of improvement, in strength and/or stiffness, that can be achieved, and the limitations for this improvement with increased depth or confinement (Ata and Vipulanandan 1999). Particle size distributions are used in characterizing...
the soil and to determine the groutability of soils (Vipulanandan and Orgurel, 2009).

The procedure adopted for preparation of a grouted bed in the laboratory was given by Dano et al. (2004). The sand was placed with a zero fall height in a transparent and rigid cylindrical column made of PVC of diameter of 80 mm and a height of 900 mm. A few simultaneous hammer stroke on the PVC tube compacted the soil. A fixed volume of grout equal to 1.2 times the initial volume of the granular skeleton was then injected from the base to the top of the column at a flow rate of 3cm³/s. Column was kept in a humid condition for a period of 28 days.


The safe construction and operation of many structures frequently require improvement of the mechanical properties and behavior of soils by permeation grouting using either suspensions or chemical solutions. The former have lower cost and are harmless to the environment but cannot be injected into soils with gradations finer than coarse sands. The latter can be injected in fine sand or coarse silts but are more expensive and, some of them pose a health and environmental hazard (Karol 1982, 1985). Grouting has a minimal effect on the angle of internal friction of sands or yields an increase of up to 4.5 °. There are strong indications that pulverized, cementitious, fly ash with appropriate additives can be effectively utilized for permeation grouting of coarse sands (Markou and Atmatzidis, 2002).
Boulanger and Hayden (1995) reported that, in many situations, the bottom-up method can be used as effectively as the top-down method if appropriate modification are adopted at shallow depths. Even with the extra cost of much modifications, it is likely that the bottom-up method will be the most economical choice.

Berry and Buhrow (1992) studied the settlement, structural failure and in-place repair of above ground storage tanks with many sizes and placed on foundations of varying nature. The causes of tank stress and failure are reviewed, including some environmental control concerns and causes, and related to tank foundation problems. The uneven movement and settlement of foundation soils can be stopped by grouting.

The permeability and strength of grouted sand is strongly influenced by the method of grouting because different mechanism govern the deposition and packing of cement particles within the pore structure. During the injection process, preferential flow paths allow the migration of cement particles into the soil, and micro-structural packing undoubtedly varies within the pores of the grouted sand, this is in contrast to the more uniform distribution of cement particles in hand-mixed specimens (Schwarz and Krizek, 1994).

The groutability ratio is not a universally applicable criterion, and values large or smaller than the limiting value of 25 do not necessarily indicated success or failure, respectively, of a specific grouting operation using a particulate grout; experimental evidence suggests that the grain size distribution and relative density of fine sands may control the grouting operation (Zebovitz et al. 1989).

The grouting technique in the MRRB project at Kaohsiung City in the southern part of Taiwan, shows a significant increase of horizontal stress within
the improved soil mass. Preloading effect was more significant in reducing wall
displacement than anticipated. Jet grouting also increases the overall strength
of improved soil mass. Other improvement methods, such as compaction grout
column and displacement pile driving may be even more effective than jet
grouting (Hsieh et al., 2003).

2.4 Grouting materials

The selection of the appropriate grout compound to be injected depends
on the effect to be achieved and on the properties of the injected materials to be
permeated. Two classes of grouting materials are generally recognized;
suspension type grouts and solution type grouts. The suspension type grout
include soil, cement, lime, asphalt, emulsion, etc. while the solution type grouts
include a wide variety of chemicals such as sodium silicates acrylamide,
lignosulphonates, aminoplast, phenoplast, etc (Shroff 2009).

Cement based grout mixtures can be investigated in soil laboratories in
order to study their flow characteristics, bleeding, consistency, gelation, time of
set, density, compressive strength and pH. Simple testing procedures such as
flow cone, bleeding and compressive strength tests are usually sufficient for
the development of thin grout mixtures which are not injected under flowing
water conditions and, therefore, gelling is not a fundamental requirement
(Coumoulos and Koryalos, 1983).

In order to take into account the effect of cement grout in the pores of
the granular material, adhesive forces were added at each contact point to the
mechanical forces determined from the external stresses applied on the granular
assembly. The magnitude of those adhesive forces depends on the nature of the
grout and on the concentration of the grout in cement particles. The expression
of this adhesive force as a function of cement content is based on extensive experimental work performed by Dano (2004) on grouted sand.

The groutability of sand with acrylamide grout was influenced by the fines content. The grout pressure fines content relationship was nonlinear. Unconfined compressive strength of grouted sand was influenced by the particle size and gradation, density, and fines content of sands (Ozgurel and Vipulanandan, 2005).

Soil-grout mix called soilcrete was used for ground improvement to prevent liquefaction in Jackson Lake Dam and Wickiup Dam in United States. While soilcrete was produced by deep soil mixing in Jackson Lake Dam, it was created by jet grouting in Wickiup Dam. Field tests showed that jet grouting was very successful and the strength attained were sufficient to make an appropriate design alternative as far as time and cost were concerned (Yilmaz et al. 2008).

Suspended particles with an equivalent diameter less than about one-third the hydraulic radius of porous medium will pass through the medium and be present in the effluent (Arenzana et al. 1989).

Improving ground strength, considerations should include the ease with which the cement may be introduced and the robustness of the strength. Portland cement gives a more ductile and strain hardening response compared with the other cements studied (Ismail et al. 2002).

Some recommendation can be advanced regarding the development of a standard method for laboratory preparation and testing of grouted specimens. Sand specimens should be grouted by injection to more closely simulate the field process. Longitudinally split moulds should be used to avoid jacking to minimize sample disturbance. Adequate curing time should be provided to
assure full development of the mechanical properties of the grouted mass (Christopher et al. 1989).

Cement and clay mixtures have found widespread use on Tennessee Valley Authority foundations composed largely of extremely porous limestone and dolomite. Cement-clay grout is more economical and is satisfactory from the porosity point of view for filling solution channels and caverns in rock subjected to erosion or leaching from hydrostatic pressures (Elston, 1958).

There are two basic factors which govern the penetrability of grout, the first one is the viscosity of the grout and the second is granulometry of the grout material vis-a-vis the permeability and dimensions of pore space in the alluvium. The viscosity of the grout into the intergranular spaces of the formation to be grouted depends much on the viscosity of the grout. The viscosity of an ideal grout mix should be sufficiently low so that it can be pumped easily and can penetrate through the fine interspaces, but not as low as to travel long distance without appreciable pressure drop (Datye, 1961). Among the various properties of grout suspensions, fluidity and stability are of prime importance (Nonveiller, 1989).

Fluidity is an inverse function of initial viscosity, bearing an approximately linear relationship with viscosity. In the case of coarse grout, fluidity is affected principally by dynamic interparticle forces of attraction and repulsion and/or by dilatancy of the moving suspended particles. A coarse grout can only be pumped easily when it contains sufficient fluid to prevent dilation of the particle matrix during shear while injecting. A reasonable percentage of fines is also desirable to increase the specific surface area of the grout particles and thereby prevent the separation of liquid and solid phase (Shroff and Shah 1992).
The rheological properties significantly influenced the case of injecting microfine cement grouts. This behavior was reflected in the maximum pressure required to satisfactorily grout the sand; a 2:1 grout required about a 35% higher maximum injection pressure compared to a 3:1 grout, and 1:1 grout required more than a 300% higher pressure than a 2:1 grout. In addition, there is a strong relation between the grout viscosity and the amount of particle sedimentation and accumulate bleed water that occur in the grout filled voids, hence, increasing the water to cement ratio of the grout improves its injectability, but has an adverse effect on bleed capacity (Schwarz and Krizek, 1994).

Sinroja et al. (2006) Through their studies using microfine slag cement grouts found that gel time increases with increase in w:c ratio of the grout. Bleeding potential is lowest for microfine slag cement grout with sodium hydroxide. With respect to rheological properties, it can be concluded that apparent viscosity increases with increase in time and decrease in w: c ratio.

Deere (1982) reported that in a very thin mix with a water-cement ratio 6:1 by volume there may be as much as 60 percent sedimentation of the cement grains in a 2 hour period. The thicker the mix, less is the sedimentation.

Lovely (1998) while investigating on the properties grouts found that the cement grouts are least stable and stability increases with cement-water ratio. This calls for continuous agitation of thin cement slurries. The tendency of cement grout to bleed can be significantly brought down
by addition of bentonite. The utility of bentonite as an excellent antibleeder of cement grout has been brought out.

According to John (1982) most of the U.S Army of Crop’s foundation grouting is done with the grout composed of Portland cement, bentonite and water. The additions of small percentages of sodium bentonite produce beneficial results. Settlement is almost eliminated without significant reduction in strength or increase insetting time.

Grouts with3% superplasticizer were easily injected into the soil samples and the strength of these samples increased as compared with those of cement-grouted samples (Akbulut and Saglamer 2002). The addition of latexes significantly improves the compressive strength, shear bond strength, stability, resistance to wet–dry cycles and resistance to sulphate attack. The use of latexes in cement grouts has a considerable effect on their physical and mechanical properties of grouts (Anagnostopoulos, 2007).

Jose et al. 2000 investigated on the effect of admixtures on the behaviour of cement grouts that at lower cement/ water ratios, the increase in viscosity is not significant but viscosity considerably increases with higher cement / water ratios. When admixtures are used in cement-grouting, their effects on viscosity and stability should be studied thoroughly. The accelerator such as, sodium silicate, increases the viscosity by a small amount well within the pumpable limits. But this admixture will not help much in reducing sedimentation. The retarder, triethanolamine, reduces viscosity, but it is not that effective in reducing
bleeding. The antibleeder, aluminium sulphate increases viscosity, at the same time reduces sedimentation to a considerable extent. Considering the behavior of the above admixtures, the addition of small percentages of bentonite increases the stability significantly. It has also been shown that the viscosity is not unduly altered by the addition of bentonite. Thus bentonite can be taken as a cheap and effective admixture for cement grouts with regard to stability.

Lovely et al. (1997) reported that the addition of small quantities of salts like sodium chloride, potassium chloride and calcium chloride reduces the viscosity of bentonite grouts significantly. This property can be made use of for injecting more grout material into the permeable medium.

Among the different methods available for measurement of viscosity of grouts, Marsh cone method is the most convenient one taking into consideration the field application also (Lovely et al., 1994).

Huang et al.(2003) reported that, compared with OPC, wet-ground fine cement (WFC) has shorter setting time, less bleeding and lower compressive strength. By adding suitable water-reducing agent, performance of WFC slurry can be greatly improved, but it is necessary to control grinding time in order to have a best mechanical properties.

The addition of accelerators caused a decrease in viscosity upto an optimum dosage beyond which it increased. This point is very useful in the field of grouting because the addition of bentonite makes a cement grout more stable at the same time the reduction in viscosity makes it
possible to inject more material into the formation voids. Retarders are found to be more effective in reducing the viscosity. Antibleeders also caused a reduction in viscosity up to an optimum dosage as in the case of accelerator beyond which it increased. Expander caused considerable increase in viscosity of cement-bentonite mixes. Commonly available expander, aluminium powder, causes boiling of the suspension accompanied by enormous heat evolution if added in excess (Lovely et al. 1998).

Variation in the grain size and grain size distribution of the grouted sand have a significant influence on the mechanical properties of the grouted mass; less important are the effects of initial density and degree of saturation by water. The influence of grain shape and mineralogy also appear to be relatively insignificant (Christopher et al. 1989).

Akbulut and Saglamer (2002) reported that the groutability of soil depends on the effective size D10 of soil, cement particle size d90, w/c ratio of grout (or viscosity) fine content of soil passing through 0.6mm sieve, grouting pressure and relative density of soil. The soil particle-size and cement maximum particle – size have important effects on successful grouting. The decrease of the grain – size of soil made the grouting impossible. Despite the increase in grouting pressure, soil with a grain-size smaller than 0.6 mm was not grouted by cement grouts. An increase in grouting pressure or the w/c ratio of grout increased the groutability of soil.
The most relevant factor for assessing grouting effectiveness is the amount of grout retained by the soil, which depends on grouting procedure (grouting pressure and time), moisture conditions, time and soil state variables (void ratio and initial water content) (Lirer et al. 2006).

2.5 Shear strength of grouted soils

Cement grouting can be profitably used for strengthening foundation beds. The shear strength parameters, $c$ & $\phi$, shows phenomenal increase when grouted with cement. The cement-water ratio of the grout act as a key parameter in the control of strength gain of sandy soils. The investigation on improvement of bearing capacity of sandy soils by grouting shows that there is considerable promise and scope for developing cement grouting as technique to improve foundation beds and their bearing capacity, especially in case of cohesionless soils (Glory et al. 2001).

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. The resulting microstructure is a heterogeneous material made up of sand grains, cement and pores. The injection by impregnation method does not modify the structure of the granular assembly. Several experimental studies on reference sand have been devoted to the increase of the strength due to cement grouting. These works show that the grouted material remains a frictional one, the strength of which is correctly modelled by Mohr–Coulomb criterion. Grouting is mainly responsible for the grain 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 (Maalej et al. 2007).

Axelsson and Gustsfson (2006) developed a robust method to determine the shear strength of cement-based injection grouts in the field. Based on that the method to determine the yield strength of a grout by letting a stick sink into the grout seems to be a robust method to measure the yield strength in the field.

At a medium porosity, the shear box gives angle $\varphi$ the same order as that of given by the triaxial. Denser samples give a higher angle in the shear box, looser samples a lower angle. (Nash et al. 1953)

Introduction of a cementing agent into sand produces a material with two components of strength- that due to the cement itself and that due to friction. The friction angle of cemented sand is similar to that of uncemented sands. Weakly cemented sand shows a brittle failure mode at low confining pressures with a transition to ductile failure at higher confining pressures. For brittle type cementing agents, the cementation bonds are broken at very low strains while the friction component is mobilized at large strains. Density, grain size distribution, grain shapes and grain arrangements all have a significant effect on the behavior of cemented sand (Clough et.al, 1981)

Generally, the strength of the soil is estimated by Mohr- Coulomb’s failure criterion. It is generally accepted that grouting effectively increased the compressive strength of the sand by filling the voids and by imparting a cohesion or adhesion factor, yet the grout contribution cannot simply be added to the sand strength. The introduction of silicate grout into the sand particles
and modifies the type of failure of grouted sand (brittle failure at strains less than 0.3%) (Ata and Vipulanandan 1999).

Yoshida et al. (1991) studied the effect of saturation on shear strength of soils and found that the cohesion intercept tends to decrease sharply with increasing saturation until it reaches a value of equal to about 80%, but it becomes almost equal to zero, irrespective of soil type and density, when the sample is fully saturated with the saturation ratio of 100%.

In low cement contents and low confining pressures the highest shear strength of cemented soils belongs to the soil cemented with Portland cement. Increasing the confining stress, the shear strength of soil cemented with Portland cement drops lower than the shear strength of the soil cemented with gypsum. However, it is still higher than the shear strength of soil cemented with lime. The rate of increase in shear strength of soils cemented with Portland cement reduces with increase in confining stress when the amount of cementation is low. When the cement content increases to 4.5% the shear strength of the soil cemented with Portland cement is always higher than the shear strength of the soil cemented with gypsum and lime (Haeri et al. 2006).

Cementation bond plays a dominant role on the strength characteristics of the cement admixed clay. Even if the cementation bonds is broken down, the shear resistance contributed from the cementation bond still persists. The shear resistance does not reduce with the increase in the effective confining pressures. The role of the cementation is not only to introduce the cohesion to the clay but also to enhance the friction angle. The friction angle is boosted considerably by only adding small amount of cement to the base clay. (Horpibulsuk et al. 2004).
The addition of a cementing agent to a wind-blown sand (cohesionless material) with uniform size distribution produces a material with two strength components - that due to cementation or true cohesion and that due to friction. The angle of internal friction for the treated sands is not much different from that of the untreated sand. Peak strength as well as initial tangent modulus values, increase with an increase in curing period, confining pressure, cement content and density (Aiban, 1999).

Ata and Vipulanandan (1998) investigated on cohesive and adhesive properties of silicate grout on grouted-sand behaviour and found that the grouted – sand strength is influenced by either the grout strength and / or the grout-sand adhesive strength, whichever is less. The grouted sand strength increases with the increase of grout strength, but this increase is limited where the grouted- sand strength approaches a limiting value. The relationship can be represented by the hyperbolic relationship. Similar relation also was reported by Ata (1993) for the cement-grout and the cement /fly ash system. It is therefore concluded that the unconfined compressive strength of grouted sand can be represented by a hyperbolic function, of both the grout strength and the adhesive tensile strength.

Grouted sand prepared in the laboratory by injection of very fine cement, the friction angle is almost unchanged by the injection treatment. 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 increase in proportion with the cement – to – water ratio (Dano et al. 2004).

The contributions of inter-particle friction and particle interlocking to the behavior are relatively more important at high densities, and that the contribution of the cementation is relatively more important at low densities. At
high densities, a significant proportion of the cement fills in the void spaces and does not contribute significantly to the inter-particle bonding. Thus the effectiveness of a given proportion of cement decreases as the density increases (Huang and Airey, 1998).

Cementation plays an important role in the stress-strain and strength behaviour of frictional materials (Lade and Overton, 1989). The larger particle are highly interlocked, thus producing greater rates of dilation during shearing, and this results in higher peak strengths. According to this, cementation results in effective cohesion as well as higher effective friction angle. Increasing amounts of cementation in granular soil increasing cohesion and tensile strength as well as increasing friction angle at low confining pressures.

The shear strength of the cemented soil measured in conventional triaxial tests can be determined as a function of the unconfined compressive strength and the uncemented friction angle (Schnaid et al. 2001).

The increase in the dynamic shear modulus of artificially cemented specimens at low levels of cementation (1-4% by weight) is determined to be due to an increase in stiffness coefficient (Acar and El-Tahir, 1986).

The strength of the grouted mass is not significantly affected by the water: cement ratio of the suspension, but it is dependent on the cake thickness and the hydration characteristics of the gel (Arenzana et al. 1989).

Consoli et al. (1998) studied the influence of fiber and cement addition on behaviour of sandy soil and found that the addition of cement to soil increases stiffness and peak strength. Fiber reinforcement increases both the peak and residual triaxial strengths decreases stiffness, and changes the cemented soil’s brittle behavior to a more ductile one. The triaxial peak strength increase due to fiber inclusion is more effective for uncemented soil.
Furthermore, the increase in residual strength is more effective when fiber is added to soil containing cement

**2.6 Compressive strength**

The gradation and type of sand influenced the compressive properties of grouted sand. The compressive strength increased with the increase of uniformity coefficient of the sand (better gradation) and with the increase of the particle’s angularity. For curing periods beyond 28 days and up to 2 years the variation in the unconfined compressive strength, modulus, and strain at peak were very small compared with the properties at 28 days. (Ata and Vipulanandan, 1999).

The structure of grouting media (porosity, permeability coefficient), grouting pressure, grouting time, water cement ratio are the four factors controlling the compressive strength of grouted gravels and diffusing radius of grout in sandy gravel layers. Compressive strength of grouted gravels increases with the increase of grouting pressure, porosity, grouting time and decreases with the increase of water cement ratio (Ping et al. 2008).

Yoon and Farsakh (2009) while carrying out laboratory investigation on the strength characteristics of cement-sand as base material that the standard Proctor maximum dry density of the cement-sand increases with the increase of cement content. This is because the finer cement particles will fill the voids in sands that have larger sizes. This will take place until all voids in sands are filled with cement particles.

The compressive strength of the grouted soil specimens was decreased and the permeability of grouted samples was increased due to an increase in water cement ratio. The $Dr$ of the soil affected the injection and an increase in
the Dr decreased the groutability of the soil. The compressive strength of grouted samples slightly decreased with an increase in the Dr. an increase in the finer content in soil increased the grouting pressure while decreasing the groutability of soil medium. The grouts with 3% superplasticizer were easily injected into the soil samples and the strength increased as compared with the cement grouted samples only (Akbulut and Saglamer, 2002).

Acar and El-Tahir (1986) studied the low strain dynamic properties of artificially cemented sand and found that, the relative increase in the stiffness coefficient with cementation could be expressed with stiffness ratio. This ratio is nonlinearly related to both the degree of cementation and void ratio. The stiffness ratio is higher for dense specimens. For weakly cemented specimens, the stiffness ratio could be estimated from knowledge of unconfined compressive strength or the cohesion intercept.

Das et al (1995) reported that the tensile strength increases with the increase of the cement content, accompanied by a decrease in the tensile strain at failure. Ribay et al. (2006) reported that microfine cement grout and mineral grout can be used as permanent soil treatment since they present high creep limits strengths compared to silicate grout which was essentially used for temporary treatment.

The compressive strength of silicate – grouted sand can be represented as a hyperbolic relationship of the grout compressive strength and the grout-sand adhesive strength. The failure strains of grouted sands tested in unconfined compression were reduced remarkably with increased curing and were less than 0.3% indicating that compressive failure strength is governed mainly by the grout cohesive and adhesive strengths. The modulus of unconfined grouted sand is mainly a function of the grout occupying the void space and the
adhesive bonds developed at the grout - particle interface. (Ata and Vipulanandan, 1998).

Consoli et al. (2007) reported that the addition of cement, even in small amounts, greatly improves the soil strength. The unconfined compression strength increased approximately linearly with an increase in the cement content. The rate of strength gain, increased with an increase in the dry density of the compacted soil cement, indicating that the effectiveness of the cement is greater in more compacted mixture. For a given dry density, the variation in moisture content affected the unconfined compression strength of the soil cement. Generally, an increase in strength is observed with increasing moisture content until a maximum value is reached, after which the strength decreases. It appears that this effect of moisture content varies with the cement content. The reduction in the porosity of the compacted mixture greatly improves the strength. Hence the unconfined compression strength increased approximately exponentially with a reduction in the porosity of the compacted mixture.

The determination of the cement content in concrete made with different types of cement is usually accomplished through the chemical analysis. This is a tedious and elaborate technique that has been standardized in ASTM. The error involved in this method should not exceed 5% (Ibrahim et al. 2004).

The cement content increased in cement admixed clay, while fixing clay water content, after curing the void ratio decreased and the strength increased. As the clay water content increased while maintaining the cement content constant, after curing void ratio increased and strength decreased (Lorenzo and Bergado, 2004). 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. the UCS of slag cement grout with sodium hydroxide and grouted sand is about two fold of grout with sodium silicate at 28 days. the flexural strength increases with decrease in w:c ratio. (Sinroja et al. 2006).

Unconfined compression tests on clay-cement mixes within the proposed working range show that water-cement ratio alone cannot account for the variation in strength; the influence of the soil-cement ratio must also be included. For a given water-cement ratio, the strength of the cement-treated soil appears to increase with the soil-cement ratio (Lee et al. 2005).

Grouting generally is used to fill voids in the ground (fissures and porous structures) with the aim to increase resistance against deformation, to supply cohesion, shear strength and uniaxial compressive strength or finally (even more frequently) to reduce conductivity and interconnected porosity in an aquifer (Moseley and Kirsch, 2004).

The strength of grouted sand was influenced by particle size and distribution and fines content of soil while the permeability of grouted sands did not vary with soil properties (Ozgurel and C. Vipulanandan).

The extent to which soil strength and stiffness can be improved by cement stabilization is very much dependent on the micro structural characteristic of the in-situ soil and the method of introduction of cement slurry into the soil. Unconfined compressive strength tests conducted on the soil samples from the mechanically treated and jet grouted portions revealed interesting relationships that can be explained by the differences in the soil properties; e.g., particle size and method of soil improvement (Jeyanathan, 1994).
Baig et al. (1997) investigated on low strain shear moduli of cemented sands that the relative density of the sand skeleton is not as influential as the degree of cementation on shear moduli.

Schnaid, et al. 2001 studied the stress-strain behaviour of an artificially cemented sandy soil, showed that the unconfined compressive strength seems to be a direct measure of the degree of cementation in triaxial compression. For the range of stress investigated, the deformation secant modulus of the cemented soil is not significantly affected by the initial mean effective stress.

The Coulomb-Mohr theory is not exactly applicable to concrete, the Mohr rupture diagram offers a way of representing the failure under combined stress states from which an estimate of the shear strength can be obtained. By this method it has been found that the shear strength is approximately 20 percent of the uniaxial compressive strength (Mehta and Monteiro).

2.7 Permeability studies on grouted sandy soils

Hydraulic conductivity defines the capacity of a porous medium to conduct a particular fluid, and is a function of both the medium and the fluid (Uppot and Stephenson, 1989).

The permeability and strength of grouted sand is strongly influenced by the method of grouting because different mechanisms governs the deposition and packing of cement particle within the pore structure (Schwarz and Krizek-1994).

Pandian et al. (1995) studied the permeability and compressibility behaviour of bentonite-sand/soil mixes, that the bentonite particles due to their very large specific surface form a coating around the coarser sand particles, thus preventing direct contact between grains. This results in a decrease in
compressibility at the same time the permeability coefficient is of the same order, as bentonite particles coat sand grains with the result that seepage control still affected.

Cement grouting was mostly confined to seepage control but it can be profitably used for strengthening foundation bed also (Glory, et al. 2001). 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. (Ibragimov, 2005).

Grouting of granular materials is usually done to arrest or reduce water movement, to strengthen the material for the purpose of increasing bearing capacity or reducing settlement under existing loads, or both of these functions. Grouting is also done to increase shearing resistance for stability against lateral movement (King and bush, 1961).

Grout fills cavities, joints and fractures by a process of sedimentation. It is forced into the openings and then has excess water squeezed out by the pressure exerted on the grout and by a combination of these two functions. With the above in mind it follows that both grout mixes and injection methods should be adjusted to fit the character of the openings to be filled with grout (Bussey, 1973).

The permeability of stabilized sand may increase remarkably due to flow channels caused by the shear stress increment and that the relationship between the permeability of stabilized sand and the shear stress increment depends upon density, grain size and type of chemical grout. In sands stabilized by silicate grout, the permeability of stabilized sand with large grain size increases remarkably owing to shear deformation, irrespective of density. On the other
hand, if the grain size of stabilized sand is small, the permeability does not
increase excessively as long as dilatancy does not occur (Mori and Tamura,
1986).

The permeability of a cement grout can be improved by increasing the
milling fineness of the cement, or by reducing or completely eliminating the
coarse fraction. Certain basic properties of the cement grout are improved with
increasing milling fineness; separation of the grout is reduced, a more uniform
structure is created with respect to density, the rate and volume of water is
lowered, and the strength of the cement stone is enhanced. (Ibragimov, 2005)

An increase in w/c ratio of grout increased the permeability of soils
decreased the strength of grouted samples and, therefore, some of the grouted
samples were not taken form moulds due to insufficient hardening. It also
negatively affected the permeability of grouted samples (Akbulut and Saglamer,
2002).

The latest tendency of the dam designers is to direct their efforts towards
a more precise analysis of rock masses and an estimate of the static and
dynamic effect of water seeping through the joints and fissures. When the
reservoir is filled, the water pressure builds up behind the rock slopes unless it
is relived by the curtain grouting and drainage. Positive drainage and grouting
is recommended for eliminating interstitial water pressure and developing
maximum possible bearing capacity of the foundation (Desmukh, 1978).

IS :4999 – 1991 gives the recommendations for grouting of pervious
soils for control of seepage. These are applicable wherever the primary purpose
of grouting is to reduce the permeability of the soil.

For grout injected specimens, decreasing the water to cement ratio of the
grout and increasing the curing time significantly lowered the permeability and
increasing the strength, whereas increasing the distance from the injection point had little effect on the permeability and produced meaningful reductions in strength. These trends are consistent with the sand acting as a filter for the grout suspension (Schwarz and Krizek, 1994).

For hand mixed specimens, in which a predetermined percentage of voids in the sand was filled with grout, the void volume percentage of grout filled voids was, by far, the most influential factor (as opposed to water to cement ratio and time) in decreasing the permeability of the sand, whereas the water to cement ratio of the grout and the curing time most influence the strength. cement content of injected specimens was than that of corresponding hand mixed specimens, the permeability of injected specimens was greater than that of hand mixed specimens, thus indicating that the permeability of grouted sand depends not only on the amount of cementitious particle in the void spaces but on the distribution of the cement and resulting structure of the grouted sand, which are influenced by the grouting procedure (Schwarz and Krizek, 1994).

The permeability of granular soils depends mainly on the cross-sectional areas of the pore channels. Since the average diameter of the pores in a soil at a given porosity increases in proportion to the average grain size, the permeability of granular soils might be expected to increase as the square of some characteristics grain size designated as the effective grain size. The permeability of granular soils may decrease substantially on account of the presence of even small amounts of fine silt and clay sized particles. The mineralogy and degree of aggregation or dispersion of the fines determine the magnitude of the decrease in permeability. Compacted mixtures of sand and bentonite are often used as blankets or liners to form seepage barriers against fluids, including leachates from disposal facilities. (Terzaghi et al. 1996)
The effectiveness of the grouting operation in terms of permeability and strength is controlled, to some extent, by the granulometry of the soil formation; the finer the sand is being grouted, the larger is the observed increase in strength and decrease in permeability (Zebovitz et al. 1989).

Eklund and Stille (2007) investigated the penetrability due to filtration tendency of cement-based grouts that grain-size and grain-size distribution are of great importance to filtration tendency. Experiments performed with inert and cement material; it seems to be advantageous for penetrability to have a grain-size distribution that does not contain too many fine or coarse grains. The value of \( d_{95} \) should be 4-10 times less than the aperture to be penetrated by the cement base mixture. Small amount of small grain-sizes are also important in achieving low filtration tendency of the grout. This is because of the increased tendency for small grains to flocculate into larger agglomerates, compared to larger grain-sizes.

### 2.8 Scope of the work

The constructional activities in the coastal belt of our country often demand deep foundations because of the poor engineering properties and the related problems arising from weak soil at shallow depths. The soil profile in coastal area often consists of very loose fine sandy soil extending to a depth of 3 to 4 m from ground level underlain by clayey soils of medium consistency. The very low shearing resistance of the foundation bed causes local as well as punching shear failure. Hence the structures built on these soils may suffer from excessive settlements. This type of soil profile is very common in coastal areas of Kerala, especially in Cochin. 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. Strengthening of these loose sandy
soils at shallow depths through economical techniques such as grouting could be a possible solution for these foundation problems.

Eventhough grouting has found several applications in the practice of civil engineering; studies on grouts and grouting have been very limited. Grouting often has to serve the primary purpose of filling the voids or replacing the existing fluids in voids by the grout with a view to improve the engineering properties of the grouted medium. Cement grouting is the most important and the most widely used method in the construction industries for reducing the mass permeability and increasing the strength of formations. They develop the strength and become impermeable when the cement hydrates and cures into a system of interlocking crystals. 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. Hence a systematic study on the behavior of cement grouted loose sandy soils will be of immense help to the engineering community.

2.9 Objectives of the present study

The objectives of the present investigation are

1. To study the improvement in load carrying capacity of different fractions of loose sandy beds.

2. To investigate the effect of cement grouts on the shear strength of loose sandy soils.

3. To study how the commonly used admixtures affect the strength of the cement grouted soils.

4. To arrive at a useful correlation between the shear strength and compressive strength of grouted sand.
5. To develop a grouting setup for conducting model studies in the laboratory.

6. To assess the grouting efficiency through various methods such as measurement of cross section dimensions of the grouted mass, determination of cement contents at different points and by conducting load tests on the grouted sand beds.

7. To study the effectiveness of grouting in reducing the permeability of granular medium.