A STUDY ON THE ENGINEERING BEHAVIOUR OF GROUTED LOOSE SANDY SOILS

A Thesis

Submitted by

SANTHOSH KUMAR. T. G.

for the award of the degree
of

DOCTOR OF PHILOSOPHY
(Faculty of Engineering)

DIVISION OF CIVIL ENGINEERING
SCHOOL OF ENGINEERING
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY
KOCHI – 682 022

November 2010

Certificate

*Certified that this thesis entitled "**A Study on the Engineering Behaviour of Grouted Loose Sandy Soils**", submitted to Cochin University of Science and Technology, Kochi-22, for the award of Ph.D. Degree, is the record of bonafide research carried out by Sri. Santhosh Kumar. T. G, under my supervision and guidance at School of Engineering, Cochin University of Science and Technology. This work did not form part of any dissertation submitted for the award of any degree, diploma, associateship or other similar title or recognition from this or any other institution.*

Dr. Benny Mathews Abraham
(Supervising Guide)
Professor & Head of Civil Engineering
School of Engineering
Cochin University of Science & Technology

Kochi-22
26.11.2010

DECLARATION

I, **Santhosh Kumar.T.G** hereby declare that the work presented in the thesis entitled "**A Study on the Engineering Behaviour of Grouted Loose Sandy Soils**", being submitted to Cochin University of Science and Technology for the award of Doctor of Philosophy under the Faculty of Engineering, is the outcome of the original work done by me under the supervision of Dr. Benny Mathews Abraham, Professor and Head of Civil Engineering, School of Engineering, Cochin University of Science and Technology, Kochi- 22. This work did not form part of any dissertation submitted for the award of any degree, diploma, associateship or other similar title or recognition from this or any other institution.

Kochi-22	**Santhosh Kumar. T.G.**
26.11.2010	Reg.No. 2680

ACKNOWLEDGEMENTS

I take great pleasure in expressing my sincere gratitude to my guide and mentor Dr. Benny Mathews Abraham Professor & Head Division of Civil Engineering, School of Engineering, CUSAT, whose vision, genius and professional guidance made this work possible.

I express my sincere thanks to Dr. Babu T Jose Emeritus Professor, CUSAT and Doctoral Committee member, for his sincere help, discussions and advice during the various phases of this research work.

I place on record my profound sense of gratitude to Prof. (Dr.) A. Sridharan Former Deputy Director and Professor of Civil Engineering, IISC Bangalore for his valuable advice, discussions and critical evaluation, which were given at various stages of this work.

I express my sincere thanks to Dr. David Peter Principal School of Engineering, CUSAT, for the support given to me during the period of the work. I owe a very special thanks to Smt. Nishi Wilson Professor Govt. College, Tripunithura, for the support given to me in the preparation of this thesis. I would also like to thank the AICTE for the financial assistance provided for this study.

I am thankful to all the teachers of Civil Engineering especially Dr. Sobha Cyrus, Dr. Roy M Thomas, Dr. Glory Joseph, Dr. Dipak Kumar Sahoo and Prof. G. Madhu for the motivation and encouragement given to me. I also remain grateful to Dr. Biju N, Sri. S. Ramdass and Sri.P.A Job for their timely help in obtaining relevant literature for the research.

I owe a debt of gratitude to all the technical staff of SOE, especially Smt. Saramma E.J., Mr. Purushothaman K.T., Mr. Aboobacker, Mr. Pradeep K.N., Mr. Kunjumon V.C., Mrs Seena Skaria, Smt. Jinitha, Sri. Babu Varghese and Sri Binu, for the whole hearted help and laboratory assistance during the laboratory investigation. A special word of appreciation to Mr. Purushothaman K.T for the constructive suggestions and ideas given during for the fabrication of the experimental set up. I also express my

sincere thanks to Er. Joy K. M. of the Cochin University of Science and Technology for his invaluable help.

I express my thanks to the Technical Education Department for sanctioning the NOC for carrying out this work. I express my thanks to all my colleagues for the moral support given to me. I greatly acknowledge my gratitude to my friends whose prayers have been with me for the successful completion of the thesis. I take this opportunity to remember and thank all the teachers from my child hood who have been instrumental in moulding my career.

I am indebted to my beloved parents and family members for their affection, moral support, and prayers doing the period of this work. I express a deep sense of gratitude to my wife Bindu K for her continuous encouragement, patience and confidence which helped me to pursue my dreams. To my children, my son Gopikrishna and my daughter Gopika, a special hug &gratitude for their tolerance, support and prayers along this journey.

Last but never least I express my worshipful gratitude to The Almighty who guided me in my endeavour.

ABSTRACT

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 sandy soils extending to a depth of 3 to 4 m from the 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 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.

The present investigation was aimed at obtaining solutions for problems like this. The improvement in relative density and thereby the load carrying capacity of loose sandy soils of different gradations through different methods such as vibration technique was studied. The low values of bearing capacity estimated even after densification compared to the requirement in the case of foundations for multi-storey buildings prompted to try grouting as one of the possible solutions.

Grouting is quite a familiar term in foundation engineering, the primary purpose of which is to fill the voids of the formation material by replacing the existing fluids/air with the grout and thereby improving the engineering properties of the medium. The most commonly used grout material i.e. - ordinary Portland cement - has many advantages such as high strength, high durability, environmently free and of low cost. Two methods were adopted to place the grout within the pores of the sand medium. They are: (i) by hand mixing the grout uniformly with the soil and (ii) by pumping the grout into the sand medium with the help of a grout pump.

The effect of cement grouts on the shear strength and the shear strength parameters of loose sandy soils were investigated. The effect of the common admixtures used along with cement grouts (accelerators, retarders, fluidiser, antibleeders, etc.) on the shear strength of the grouted medium was also studied.

Compressive strength tests were also conducted on these grouted samples with the objective of arriving at a correlation between the shear strength and the compressive strength of the grouted medium.

A grouting setup was developed in the laboratory for grouting the sand beds prepared in steel tanks. The lateral flow of the grout and thereby the efficiency of grouting was assessed by three methods (i) from the cross section area of the grouted mass measured at different depths (ii) by determining the cement content at different radial distances at different depths and (iii) by conducting load tests on the grouted sand beds.

The effectiveness of grouting in reducing the permeability of granular medium was also studied. Constant head permeability tests were carried out on the sand medium treated with different materials such as cement, bentonite, lime, locally available clay and different combinations of the above materials.

The results of the various investigations conclusively proved that grouting can be used as an effective method for improving the strength characteristics significantly and reducing the permeability of loose sandy soils.

CONTENTS

Chapter 1

INTRODUCTION

The terms ground improvement and ground modification refer to the improvement in or modification to the engineering properties of soil that are carried out at a site where the soil in its natural state does not possess properties that are adequate for the proposed Civil Engineering activity.

Ground improvement refers to any procedure undertaken to increase the shear strength, decrease the permeability and compressibility, or otherwise render the physical properties of soil more suitable for projected engineering use. A large number of methods have been developed for ground improvement from ground surface to depths of 20 m or more by in-situ treatment. The improvement may be accomplished by drainage, compaction, preloading, reinforcement, grouting, electrical, chemical or thermal methods. Among the various soil stabilization procedures, the most suitable one is selected depending upon the type of soil available, time, cost involved etc.

Excavating the poor soil and replacing it with soil having desired properties is normally economical only when soil has to be treated down to a depth of 3 m and the water table is below 3 m. If the water table is high, lowering of water table prior to excavation has to be carried out by dewatering techniques, which are expensive.

Vibro-compaction is used to increase the density of loose sand. This technique is not useful for soils having greater than 20 percent fines.

Grouting is quite a familiar technique in the field of civil engineering, especially in foundation engineering. The technology of grouting finds applications in almost all the fields of foundation engineering such as seepage control in rock and soil under dams, advancing tunnels, cut off walls etc (Nonveiller, 1989). The primary purpose of grouting is to fill the voids of the formation material by replacing the existing fluids with the grout and thereby improving the engineering properties of the medium especially reducing the permeability.

Grouting is effective in both sand and silt deposits. Grouts are liquid suspensions or solutions that are injected into the soil mass to improve its behaviour. Such liquids can permeate into the void space of the soil and bind the soil particles together. For medium sands or coarser materials the grout used most often is a slurry of water and cement. This slurry however, cannot enter into the void space of fine sand and silts for which chemical grouts are used.

Grouts can be broadly classified as suspension grouts and solution grouts. Suspension grouts consist of small-size solid particles dispersed in a liquid medium. These include cement grouts, that is, slurry of cement in water; soil-cement grouts consisting of a slurry of soil and cement in water; and bentonite grouts comprising a slurry of bentonite in water. Cement grouts are the most widely used and usually have water and cement in the ratio ranging from 10:1 to 2:1.

Properties of a grout are described in terms of five parameters: groutability, stability, setting time, permanence and toxicity. Grouting methods for soils are classified as permeation grouting, compaction grouting, hydro-fracture grouting and jet grouting. Cement grout not only fills the voids and reduces permeability but also sets with time and binds the soil grains together. As a consequence, the strength of soil mass increases and its compressibility decreases. Sometimes cement in a grout is replaced by clay to reduce the cost. When the objective of grouting is only to reduce permeability, bentonite grouts can be used (Lovely 1998). However, the permanence of such grouts under high hydraulic gradients is questionable and often cement is added to the bentonite to improve its permanence.

Even though grouting has found several applications in the practice of civil engineering, available studies on grouts and grouting have been very limited. Even today, the grouting operations are based on thumb rules and existing practices rather than rational design principles or well defined procedures substantiated by research data (Shroff and Shah, 1992). In the present investigation on the engineering properties of grouted medium including methods to improve the same which can be effectively used in foundation soils for increasing the bearing capacity and in dam grouting or cut off walls for reducing the seepage to a minimum. The contents of the various chapters are briefly described below.

Chapter 2 presents a detailed review of the literature available on the investigations carried out by earlier researchers. Some important properties of grouted medium viz, strength, settlement and permeability are discussed. The behaviour of cement and bentonite grout together with the list of admixtures used in grouting are also presented. Previous works on the strength and permeability of grouted soils are presented and the scope of the present work is also brought out in this chapter.

An account of the materials used and the testing methods adopted in the present investigation are given in Chapter 3. The selection and preparation of grouting materials and the medium to be grouted are explained. Detailed accounts of the testing methods are also presented.

Chapter 4 presents the results of the investigations carried out on ungrouted and grouted sand. The effect of the grain size and improvement in load carrying capacity of sandy soils on densification is clearly brought out through load tests conducted on these sand beds. The improvement in the shear strength of the loose sandy soil on cement grouting is discussed in detail. The influence of the cement content, curing period and initial water content are discussed. The effect of the common admixtures used to improve the properties of cement grouts i.e. accelerators, retarders, fluidisers, antibleeders etc., on the strength of the cement grouted sand is also discussed in detail in this chapter. The results of shear strength tests conducted on samples prepared by using lime as the grouting material instead of cement are also presented.

Chapter 4 also presents the results of the compressive strength tests conducted on cement/lime grouted samples with cement content, curing period and initial water content as variables. A comparison between the results from shear strength tests and compressive strength tests and correlation between them are given in this chapter.

Chapter 5 discusses the design and fabrication of the grouting set up and results of investigations carried out on prepared sand beds in steel tanks, using this grouting set up. The results obtained from the measurement of cross section area of grouted mass and determination of cement content by chemical analysis at different radial distances and depths are presented. The results of the load tests conducted on the cement grouted sand beds and the influence of the admixtures in improving the lateral flow of the grout are also presented in this chapter.

Chapter 6 presents the results of permeability tests conducted on ungrouted and grouted sand samples. The effect of various grouting materials such as cement, bentonite, lime, locally available clay (Cochin marine clay) and certain combination of these materials on reducing the permeability of the sand medium, is also discussed.

Number of conclusions drawn based on the results obtained from the above investigations are presented in Chapter 7.

Chapter 2

REVIEW OF LITERATURE

Contents

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. Eventhough 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 monolithicity 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, lignosulfonates, 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 $3 cm^3/s$. column was kept in a humid condition for a period of 28 days.

Littlejohn (1982), Lowe and Standford (1982) Clarke et al. (1992) De Paoli et al. (1992) and Schwarz and Krizek (1992) made significant contribution on the study of grout materials, properties, equipment and procedure for grouting.

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 º.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 necessarly 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 upto 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* & Ø, 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 Ø 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 *D*r of the soil affected the injection and an increase in the *D*r decreased the groutability of the soil. The compressive strength of grouted samples slightly decreased with an increase in the *D*r. 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 on creasing 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 grtate 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 d95 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.

Chapter 3

MATERIALS AND METHODS

Contents

3.1 Introduction

The efficiency of grouting is mainly dependent on the properties of the grouting materials and appropriate grouting technique. The success of the grouting is dependent on selection and type of grout materials, type of grouted medium, grout mix design and suitable grouting techniques. The specific mechanical properties that are important in the selection of a grout for a specific job include mechanical permeance, penetrability and strength. The selection of particular grout is dependent on its geotechnical application along with the other factors (Shah & Shroff 1992).

The technology of grouting has wide range of applications, varying from filling large fissures in rock to alluvial grouting. The aim of the present investigation is to control the properties of grout materials and thereby to improve the bearing capacity and to reduce the permeability of loose sand medium. Wide range of grouting materials are available in the field of grouting, ranging from suspension grouts to solution grouts.

In the present study, suspension grouts have been used. Granular medium was chosen as the formation to be grouted. The details of the grouting materials, grouting medium, grouting procedure and testing methods are presented in the following sections.

3.2 Materials

The selection of proper grouting materials depends upon the type of granular medium and the purpose of grouting. Cement, bentonite, clay and lime are the grouting materials normally used for grouting a granular medium. In the present study sand was used as the grouting medium and cement (with or without admixtures), lime and clay were used as the grouting materials.

3.2.1 Sand

As mentioned, sand was used as grouting medium for this study. River sand procured from Kalady, which is a branch of the Periyar river - was dried and sieved into different fractions. River sand of three grades - fine (75 µm-

425 µm), medium (425 µm- 2 mm) and coarse (2mm- 4.75mm) fractions as per ASTM (D2487-10) and BIS (1498 -1970) classifications were used in the present study. The grain size distribution curves of different fractions of sand are shown in Fig.3.1.

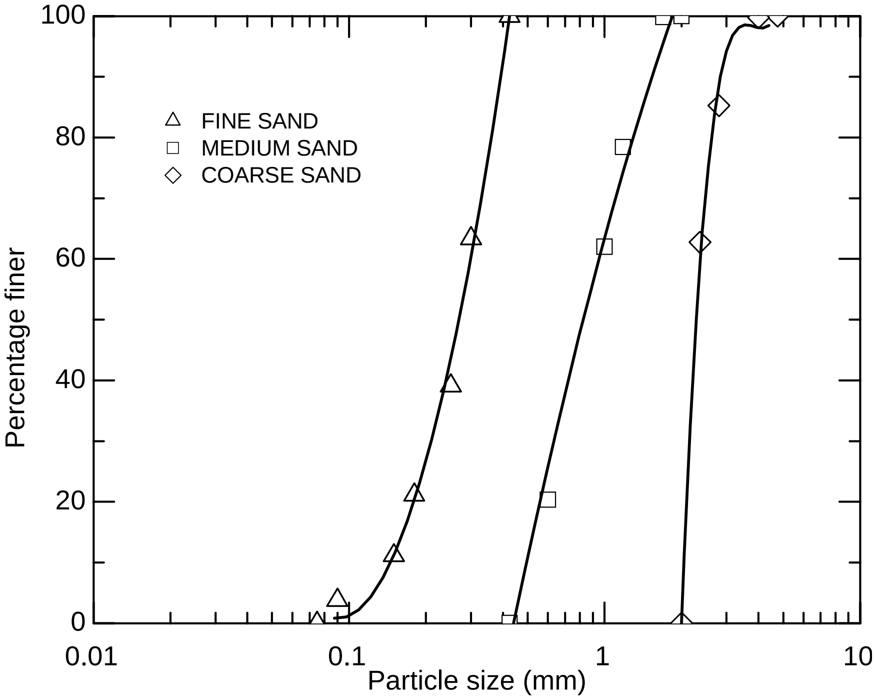


Fig 3.1 Grain size distribution curves of sand

3.2.2 Cement

43 grade Ordinary Portland cement conforming to IS 269 – 1989 was used for the preparation of cement grouts. The cement bags were kept in air tight bins to avoid any change in the properties with the time of storage. The experiments were planned in such a manner that once a bag of cement was opened, the whole cement was utilized within 10 days. The physical properties

of cement are presented in table 3.1. **a**nd its grain size distribution curve is shown in figure 3.2.

Table 3.1. Properties of the cement used.

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)7days (ii) 28days	 35.1 N/mm^2 44.0 N/mm^2

3.2.2.1 Physical properties of cement

The physical properties of the cement used were determined in accordance with IS 269: 1989 and IS 4031: 1988

i) Fineness

The fineness of cement was tested using Blaine's air permeability test method. This test gives an idea about the fineness of the cement and the specific surface of the cement grains. The test sample of cement was first enclosed in a 125g jar and shaken vigorously for two minutes to fluff the cement and brake up lumps or agglomerations. The weight of the sample was calculated using the expression given in IS: 4031: part 2: 1999. The perforated disc was placed on the ledge in the permeability cell, above which, a filter paper disc was also placed. The cement sample was placed in the cell and the surface was levelled. A filter paper disc was placed above the cement sample and then it was compressed with a plunger until the plunger collar was in contact with the top of the cell.

After removing the plunger, the permeability cell was attached to the manometer tube making sure that an air tight connection was obtained, without disturbing the prepared bed of cement. The air in one of the manometer U- tube was slowly evacuated until the liquid reached the top mark and the valve was closed. As the bottom of the meniscus of the manometer liquid reached the second mark, the timer was started and stopped as the meniscus reached the third mark. The time interval was noted in seconds. The specific surface was then calculated using the expression given in IS: 4031: part 2: 1999. As per IS: 269: 1989 the minimum value of specific surface is 2250 cm^2/g.

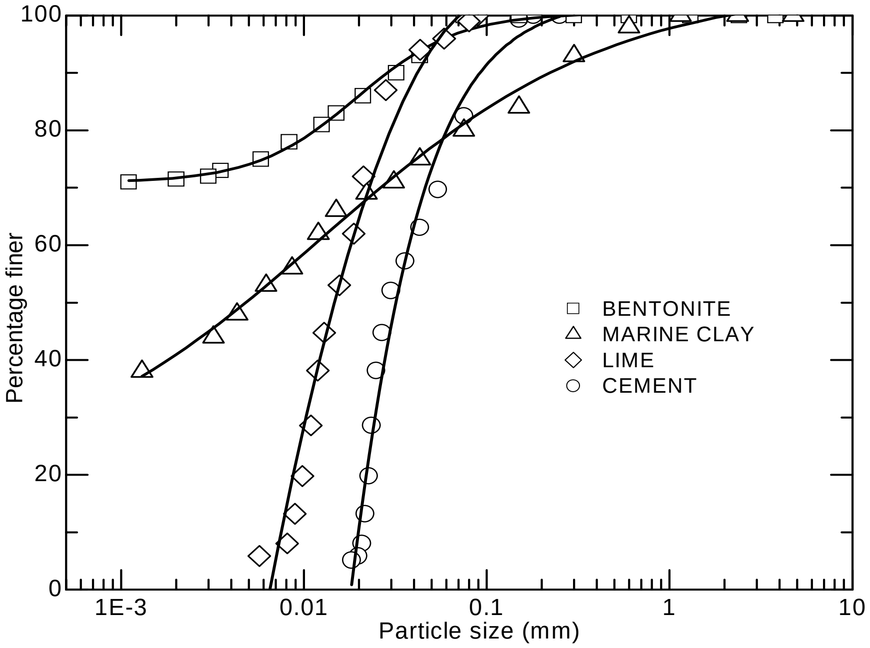


Fig. 3.2 Grain size distribution curves

ii) Standard Consistency

This test is used for finding out the amount of water required to make a paste of standard consistency. The standard consistency of a cement paste is defined as the consistency which will permit the specific Vicat plunger to penetrate to a point 5 to 7 mm from the bottom of the Vicat mould. 400g of cement was weighed and a paste was made by adding 26% of water, observing that the gauging time is below 5 minutes. The paste was filled in the Vicat mould and the plunger was released. The penetration of the plunger was less than the specified value in IS: 4031: part 4: 1988. The test was repeated by making fresh cement paste with 27 and 28 percentages of water. It was found that when 28 % water was added the penetration of the plunger was within the specified limits.

iii) Initial setting time

The starting of the setting process of a cement paste is based on this property. The working time available with particular cement depends on this. A neat cement paste was prepared with 400 gm of cement and 0.85times the water required for standard consistency. The Vicat mould was filled with this paste and the needle was released. The needle was observed to be piercing completely into the paste. The procedure was repeated until the needle failed to penetrate the cement paste for 5± 0.5mm measured from the bottom of the mould. The period elapsed between the time when water was added to the cement and the time at which the needle failed to penetrate the required amount was reported as the initial setting time.

iv) Final setting time

This time is used to describe the stiffening of cement paste. The needle for initial setting time was replaced by the annular attachment. The cement paste prepared to determine the initial setting time was placed beneath the attachment in the Vicat apparatus. The attachment was brought down to the surface of the cement paste. Initially, both the central needle and the surrounding attachment made impression on the surface of the paste. Later at 287 minutes, the needle alone made the impression and this was reported as the final setting time.

v) Compressive strength

This is obviously the most required property because it gives an idea about the mechanical strength of hardened cement. The compressive strength is determined by conducting tests on mortar cubes. For making one cube of standard dimensions, 200 gm of cement and 600 gm of specified sand are first mixed well in dry condition and mixed with $\left(\frac{P}{4}+3\right)$% of water where P is the percentage of water required to produce a paste of standard consistency as described in the earlier section. The prepared mortar was filled in previously cleaned and oiled cube moulds placed on the vibration table. Vibration was given for the specified time and the surface was smoothened with a trowel. The moulds with specimen were kept in a moist room for 24 hours and then detached from the specimens. The mortar cubes were kept in clean water for curing. Compressive strength was determined after 7 and 28 days. Three cubes were tested for each period and the average was reported as the compressive strength.

vi) Soundness

This property is essential that a cement paste, once it has set, does not undergo a large volume change. This test was conducted using a Le - Chatelier apparatus. The cement paste was prepared with 0.78 times the water required to give a paste of standard consistency. The mould was filled with this paste and the assembly was immersed in water for 24 hours. The distance between the indicator points was measured. Submerging the assembly in water, the water was brought to boiling in 25 to 30 minutes and then the distance between these indicator points was measured. The difference between these two measurements represented the expansion of the cement.

vii) Specific gravity

Specific gravity of cement was determined using a Le- Chartelier flask. The flask was filled with kerosene upto the specified portion of the flask and the level was noted. A weighed quantity of cement was poured into the flask carefully taking care to see that the cement did not spill out. The flask was shaken gently so that cement particles did not adhere to the inside of the flask. The final reading was noted. The specific gravity was calculated as the ratio of the weight of cement in grams to the weight of an equal volume of distilled water.

3.2.2.2 Admixtures

Little John (1982) has given a list of admixtures that can be used in cement grouting to improve the various properties of cement based grouts (Table 3.2). Various other authors have recommended a number of additives that can be used in cement as well as bentonite grouting. Admixtures are used in cement grouts to serve as accelerator, retarder, and lubricant or to increase the strength of the grout

Table 3.2. Common Admixtures used along with cement grout

Sl. No.	Admixture	Chemical	Optimum dosage (% by wt of cement)
1	Accelerator	Calcium chloride	1-2
2		Sodium silicate	0.5-3
3	Retarder	Tartaric acid	0.1-0.5
4		Triethanolamine	0.1-0.5
5	Fluidiser	Detergent	0.05
6	Expander	Aluminium powder	0.005-0.02
7	Antibleeder	Bentonite	2-10
8		Aluminium sulphate	Up to 20%

Among the accelerators, calcium chloride and sodium silicate were used in the present investigation. To study the effect of retarders, triethanolamine and tartaric acid were chosen. The fluidiser used was detergent, which is commercially available soap powder (sun light detergent powder was used here). Aluminium powder was used as the expander. Aluminium sulphate and bentonite were used as antibleeders.

3.2.3 Bentonite

The bentonite used in this study is a commercially available, highly expansive one. The properties of the bentonite are given in table 3.3. Bentonite shows great affinity towards moisture. The percentage of water present in a sample of bentonite varies depending upon the climatic condition. So the bentonite, which was thoroughly mixed uniformly, was preserved in double layer of polythene bags. Again these bags were stored in airtight bins.

Table 3.3 Properties of bentonite

Sl. No.	Property	Characteristic value
1	Specific gravity	2.8
2	Liquid limit (%)	410
3	Plastic limit (%)	45
4	Plasticity index (%)	365
5	Shrinkage limit (%)	1.34
6	Volume change (%)	97.5
7	Linear shrinkage (%)	49.61
8	Activity	5.03
9	Free swell index (cc/g)	17.5
10	Cation exchange capacity (meq/ 100g)	60.8
11	pH	7.4
12	Surface area (m^2/ g)	87.5
13	Conductivity (μs /cm^2)	10800
14	Organic matter (%)	1.48

Physical properties of Bentonite

i) Atterberg limits

The liquid limit and plastic limit were determined as per IS 2720: part 5: 1985. The liquid limit test was conducted using Casagrande apparatus, starting from a water content which required only around 10 blows for the groove to close. The paste was then allowed to spread over a glass plate to allow evaporation. This was then mixed thoroughly for the next test. The liquid limit was reported as the water content which took 25 blows to close the groove.

Plastic limit was found out as the water content required just to make hair line cracks for the clay thread of specific diameter of 3 mm.

ii) Grain size distribution

Grain size distribution of the grout suspension is a very important property in grouting practice. The sedimentation analysis was done using a hydrometer. Grain size distribution curve is shown in figure 3.2

3.2.4 Cochin marine clay

Marine clay was collected from a site at Elamkulam in Greater Cochin area on the Western coast of India. Bulk samples of the clay were collected from bore holes advanced by shell and auger method.

The boring operations were taken to the clay layers for collection of samples. The boring operations were carried out as per IS: 1892: 1979, Code of practice for subsurface investigations for foundations. Care was taken not to include bentonite slurry during the boring operations as it could contaminate the soil samples. Samples collected from different locations were put together and mixed thoroughly into a uniform mass and preserved in polythene bags. The grain size distribution curve of the marine clay is shown in figure 3.2

3.2.5 Lime

Specially selected uniform shells were used for preparation of lime for the study. The shells were burnt to remove CO_2 completely when they change to brittle white shells of calcium oxide which were preserved in airtight multilayer polythene bags. The required amount of water alone was sprinkled over the lone shells taken from these bags on each day of lime treated samples, till all the shells crumble to fine powder which was then sieved through IS 425 micron sieve. This method of preparation of lime was used because of its simplicity and the ease with which it can be prepared for field application.

3.3 Grouting operations

To place the grout within the pores of the granular medium, two procedures were adopted. In the first method, the grout material was deposited within the pores by hand mixing. In the second method, previously prepared sand beds were grouted with different grouting materials by using a grout pump to simulate the grouting operations in the field. The preparations of both these types are described in detail below.

3.3.1 Grout impregnation by hand mixing

The grouting materials like cement, lime, etc. with or without admixtures were hand mixed uniformly with the sand for the preparation of test specimens.

(i) Grouting with cement

A unit weight of 14.5 kN/m^3 for sand was chosen for the preparation of samples, so that the relative density is 51%. This was selected by considering the fact that it can be achieved relatively easily with very good reproducibility and by considering the difficulty experienced in preparing the samples at units weights corresponding to the loosest state. The required amount of sand of specific size range was taken in a tray. The predetermined quantity of cement (2, 4, 6, 8, 10, 15, 20 & 25% by weight of sand) was then added to the sand and thoroughly mixed with a trowel. Water was (5, 10, 15, 20 or 25% by weight of sand and cement) sprinkled over the cement sand mixture and thoroughly mixed with a trowel. This was filled in split moulds of size 60 mm x 60 mm x 25 mm in two layers to obtain specimens for direct shear tests and also filled in cube moulds of size 70.6 mm x 70.6 mm x 70.6 mm, to obtain specimens for compressive strength tests. These specimens were kept at room temperature for 24 hrs, then taken out from the moulds and kept for curing for periods of 7 and 28 days. Specimens prepared for direct shear tests like this are shown in Fig 3.3

(ii) Grouting with cement and admixtures

To the cement-sand mixture prepared as explained earlier, predetermined amount of admixture (% by weight of cement) dissolved in water (10% by weight of sand and cement put together) was added. This ensured uniform mixing of all the materials. This was then filled in split moulds of size 60 x 60 x 25 mm, in layers to obtain samples for direct shear tests and in cube moulds of size 70.6 mm to obtain samples for compressive strength tests. These specimens were cured before testing, as explained.

Fig 3.3 Samples for direct shear test

3.3.2 Grout impregnation by pumping

Predetermined quantity of cement with or without admixtures was taken and thoroughly mixed with a definite amount of water. The slurry was thoroughly mixed for 10 minutes at 3000 rpm using a standard stirrer. The grouting setup consists of a grout chamber with agitator, air compressor, grouting nozzle and regulating valve. The grouting nozzle was kept in position (at 5 cm above bottom level of tank) and the sand bed was prepared in a tank of size 45 cm x 45 cm x 60 cm / 1 m x 1 m x 0.60 m at the loosest state (unit weight of 13.1 kN/$m^3$and an initial void ratio of 0.98). Sand was filled in the tank by pouring through a funnel from a constant height of 1m from the top of the sand bed. Then the slurry (grout) was poured into the grout chamber. In order to reduce the possibility of settling of the grout in the grout chamber, an agitator was provided inside the grout chamber. Grout was pumped under a constant pressure of 5 kg/cm^2 (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 the sand bed. The grouted sample was kept for curing under moist condition.

3.4 Testing methods

In this investigation shear strength, compressive strength and permeability of cement grouted sand were studied in detail. The physical properties of grouting materials were also tested. The various test procedures are discussed in detail as follows.

3.4.1 Shear strength test

The shear strength can be determined in the laboratory by direct shear box test or triaxial test. In the present study, direct shear tests were conducted for the determination of the shear strength parameters. Saturated specimens (of size 60 mm x 60 mm x 25 mm) prepared as per the procedure given in section 3.3.1 were placed in the split mould. Perforated metal plates were placed above and below the specimen to allow free drainage. A pressure pad was placed on top and the entire box was placed in the trolley. A vertical load was applied to the specimen through a static weight hanger and the specimen was sheared by applying a horizontal force which causes the two halves of the box to move relative to each other. The shear was applied at a constant rate of strain of 0.25mm/ min. The magnitude of shear load was measured by means of a proving ring. The shear deformation as well as the vertical deformation was measured during the test with the help of dial gauges. The procedure was repeated on four specimens, each subjected to different normal loads. Normal stress and the shear stress on the failure plane were obtained by dividing the normal force and shear force by the nominal area of the specimen. Values of shear stress at failure were plotted against the normal stress for each test. The shear strength parameters c and Ø were obtained from the best fit straight line through those points.

3.4.2 Compressive strength test

The compressive strength of grouted specimens was determined by conducting tests on 70.6 mm cube specimens. Hand impregnated specimens were prepared in the mortar cube moulds and grouted specimens were cut into this size from the grouted mass by a diamond concrete cutter. The specimens were placed in the loading frame in the proper position and axial load was applied at a constant strain rate of 0.02mm /min. The magnitude of load and deformations were measured with the help of a proving ring and dial gauges. The compressive stress was obtained by dividing axial force by the cross sectional area of specimen. Three identical specimens were tested and the average value was taken as the compressive strength.

3.4.3 Cross sectional area of grouted mass

A preliminary idea about the grouting efficiency can be obtained from the cross section area of the actual grouted medium at different depths. For this purpose, once the grouting was over and sufficient time allowed for curing, the side walls of the tank were removed so that the dimensions of various cross sections of the intact grouted mass at different depths could be taken. Lateral measurements were taken from the centre of the grout hole to the corners and centers of the side walls and additional measurements were also taken in case of uneven shapes. For this purpose, a cage made of steel bars with the same lateral dimensions as that of the tank was fabricated. Keeping this cage encompassing the grouted mass facilitated easy measurements of the dimensions. All the measurements were taken at 10 cm intervals from the top of the grouted bed and recorded. With the help of these measurements cross sections were drawn and the area was calculated at different intervals.

Fig. 3.4 (a) Collection of test specimens from grouted samples in progress

Fig. 3.4 (b) Collection of test specimens from grouted samples in progress

3.4.4 Cement content determination

The efficiency of grouting and lateral flow of grouts were also analyzed by determining the cement content at various places of the grouted mass. For this purpose, samples were collected at different distances radially from the centre of the grout hole at different depths. The process of collecting the samples by cutting the grouted mass with the help of a diamond cutter is shown in Figs 3.4 (a) and 3.4 (b). Samples at the same radial distance (at a particular depth) were mixed together and were used for the purpose of cement content determination. The procedure adopted for the determination of cement content is given below.

This test method covers the determination of cement content by chemical analysis of hardened soil-cement mixtures. ASTM standards designation D806-00; Standard test method for cement content of hardened soil- cement mixtures were used in this test. A similar method was also presented in BIS (IS:4332 - 1973) “Method of test for stabilized soils part VII method of determination of cement content of cement stabilized soils”. This test method determines the cement content in mixtures of cement with soil by chemical analysis. It was developed primarily for testing samples for which a significant degree of cement hydration or hardening has taken place.

The method involves the determination of the CaO contents in the soil (sand), cement and in the grouted mass, separately. The procedure for conducting the chemical analysis is explained below.

Take 25 g of each of the above samples after drying in an oven at 110 ± 5°C to remove free water. Sieve the samples through a 425 µm sieve. Each sample is prepared in the following amounts: raw soil, 5 g; soil-cement mixture, 5 g; and cement, 1 g. Each sample is placed in a 250-ml beaker and 50 ml of

HCl (1 + 1) is added to each sample, then covered, and boiled gently for 5 min on the hot plate. Add 25 ml of hot water to this, stir well and allow to settle momentarily, and then decant the contents through a Whatman No. 1 filter paper. The filtrate should be received in a 250-ml volumetric flask. When the liquid has passed through the filter paper, wash the residue once by decantation, using hot water, then transfer it to the filter, using a stream of hot water. The beaker should be rapidly policed, the loosened material being transferred to the filter paper. The material on the filter should then be washed four times more, each washing consisting of 10 to 15 ml of hot water directed in a stream from the wash bottle. Very small amounts of residue would occasionally pass through the filter, which may be disregarded.

When washing is completed, discard the filter, and dilute the filtrate in the volumetric flask to 250 ml with cold water. Agitate the flask to mix the contents thoroughly, then remove a 50-ml aliquot and transfer it to the original 250ml beaker, using a 50ml pipette and dilute it to 100 ml. Make the solution slightly ammoniacal, boil it for 1 to 2 min, and allow the hydroxides to settle. Filter the hydroxides through an 11-cm Whatman No. 1 filter paper, receiving the filtrate in the 600-ml beaker. Wash the original 250-ml beaker into the filter once with a stream of hot NH_4NO_3 solution (20 g/l), and follow by washing the hydroxide precipitate once or twice with hot NH_4NO_3 solution. Set this aside, and place the original beaker under the funnel. Perforate the paper with a rod, and wash the hydroxides down into the original beaker, using a stream of hot NH_4NO_3 solution (20 g/l) to remove most of the precipitate from the filter paper. Treat the paper with 20 ml of hot HCl (1 + 3), directing the acid over the paper with a glass rod. Wash the paper several times with hot water, and then discard the paper and dilute the solution to 75 ml. Fig. 3. 5 shows the test set up for cement content determination.

Fig. 3. 5 Test set up for cement content determination

Make the solution slightly ammoniacal and boil it for 1 to 2 min, allow the precipitate to settle, then decant through a Whatman No. 1 paper as before, receiving the filtrate in the 600-ml beaker previously set aside. Wash and police the beaker in which precipitation take place, finally washing the precipitate on the filter three or four times with NH_4NO_3Solution (20 g/l). Discard the hydroxide precipitate. Add 2 ml of NH_4OH (sp gr 0.90) to the filtrate, which will now have a volume of 250 to 350 ml. Heat the solution to boiling and add 10 ml of hot saturated ammonium oxalate solution. Keep the mixture near boiling until the precipitate becomes granular; then set it aside on a warm hot plate for 30 min or more. Before filtering off the calcium oxalate, verify completeness of precipitation, and make sure that a slight excess of NH_4OH is present. Filter the mixture through an 11-cm or 15-cm Whatman No. 2 filter paper, or if preferred a Whatman No. 42 paper, making sure that all the precipitate is being retained. Thoroughly clean with a rubber policeman, the beaker in which precipitation took place and transfer the contents to the filter with a stream of hot water. Wash the filter eight to ten times with hot water (not more than 75 ml), using a stream from the wash bottle.

Carefully open the filter paper and wash the precipitate into the beaker in which the precipitation was effected. Dilute it to 200 ml and add 10 ml of H_2SO_4 (1 + 1). Heat the solution just short of boiling, and titrate with the standard $KMnO_4$ solution to get a persistent pink colour. Add the filter paper and macerate it. Continue the titration slowly until the pink color persists for 10 s.

Make a blank determination, following the same procedure and using the same amount of all the reagents.

Calculation

The cement content of the grouted sample is computed as follows

The percentages of CaO in the soil, in the cement, and in the grouted samples can be calculated as:

$$\text{CaO, \%} = \frac{0.028\,(A - B)\,C}{D} \times 100$$

Where:

A = KMnO4 solution required for titration of the sample in ml,

B = KMnO4 solution required for titration of the blank in ml,

C = normality of the KMnO4 solution,

D = sample represented by the aliquot titrated in gms and

0.028 = CaO equivalent of 1 ml of 1.0 N KMnO4 solution.

Percentage of cement by mass of soil can be determined as

$$\text{Cement, \%} = \frac{(G - F)}{(E - F)} \times 100$$

E = CaO in the cement (%)

F = CaO in the soil (%) and

G = CaO in the grouted sample (%).

3.4.5 Load tests

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. For estimating the load carrying capacity of grouted beds, the grouting operations were done in large tanks of size 1mx1mx0.6m. Uniform sand beds in the loosest state (unit weight 13.1 kN/m^3) were prepared after keeping the detachable side walls of the tank in position. Grouting was done as per the procedure given in section 3.3.2. The disturbed portion at the top for a depth of 10cm was removed, and after curing for a period of 28days,load test was conducted in this grouted bed. The load was applied through a 20cm square plate with the help of a hydraulic jack. Dial gauges mounted on the opposite corners of the plate gave the settlement corresponding to the load (read from the pressure gauge).

3.4.6 Permeability

Permeability is defined as the property of a porous material which permits the passage or seepage of water or other fluids through its interconnecting voids. Gravel is highly permeable while stiff clay or high plastic clay is least permeable. The flow of water through soils may be laminar or turbulent. In most of the practical flow problems in geotechnical engineering, the flow is laminar. The flow of water through soil obeys Darcy's law which states that the rate of flow is proportional to the hydraulic gradient. The coefficient of permeability can be determined in the laboratory by constant head test or falling head test. In the present study, constant head tests were conducted for the determination of the permeability. Rigid wall permeameters (standard concrete permeability test apparatus) of size 150 mm x150 mm x150 mm were used. The sand was filled in the mould keeping the dry unit weight of sand as 14.5 kN/m^3. Water was permitted through the sand medium under a constant head of 2m (20 kPa). The discharge was measured once a steady state condition is reached. The test setup is shown in figure 3.6

Fig. 3.6 Permeability test set up for grouted samples.

For preparing the hand impregnated cement/bentonite grouted samples, medium sand (unit weight 14.5 kN/m^3) was mixed with predetermined percentages of cement/benonite (2, 4, 6, 8 & 10 % by weight of sand) in the dry condition. Then 10% of water (by weight of sand + cement mixture) was added to this, thoroughly mixed and filled in the mould in layers to achieve a uniform mass. These permeability specimens were allowed to cure under saturated condition by permitting the flow at a very small head.

Discharge measurements were taken at a constant head of 2m at different curing periods (in the case of a few specimens) in order to check whether the permeability is affected by the curing period of the grouted specimens. From a series of experiments, it was found that the permeability goes on reducing upto a curing period of around 15 days. Hence permeability tests on subsequent samples were done after the specimen has undergone a curing for 15 days.

To study the effect of grouting with locally available clay on the permeability of the sand medium, Cochin marine clay in moist condition (at natural water content) was mixed with sand before filling in the permeability moulds. Similarly for preparing specimens to study the effect of additives such as cement/lime, the predetermined percentage of cement/lime in powder form was mixed with Cochin Marine clay (in moist condition) and then mixed with sand before filling in the permeability moulds. For all these tests, care was taken to keep the unit weight of sand in the mould as 14.5 kN/m^3.

Chapter 4

STRENGTH STUDIES ON UNGROUTED & GROUTED SAND

Contents

4.1 Introduction

Construction of structures on weak ground often requires the soil to be improved in order to ensure the safety and the stability of foundations. Ground improvement in granular soils can be achieved by different methods such as vibro-flotation, compaction piles, compaction with explosives, excavation and replacement, reinforced earth, grouting etc. Soil compaction requires intricate 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 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 equipment and materials etc.

The compaction of soils is intrinsically dependent upon the type and gradation of soil. Broadly, a well-graded soil compacts better than a uniformly graded soil and moisture content is also a significant parameter to be considered (Bement and Selby, 1997). 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 (Yilmaz et al. 2008).

4.2 Strength improvement on densification

Earlier studies have indicated that the relative density of loose sandy soils can be substantially improved by different methods. Among the different methods available, vibration technique is reported to be the most effective one.

A question has been raised on 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 improving the density and strength of loose sand at shallow depths are required.

The effect of grain size of cohesionless soils on its shear strength characteristics was studied by Chattopadhya and Saha(1981). They found that as the particle size increases, the angle of shearing resistance also increases at both constant density and constant relative density. However, the increase of angle of shearing resistance for constant density is insignificant compared to that in the case of constant relative density.

Several researchers have conducted analytical and experimental investigations of soil – tamper interaction and impact response of granular soil. Forssblad (1965) suggested that the kinematic impact energy can be equated to the volumetric strain energy in the affected soil mass by integration over the affected volume. Ellis (1986) reported on dynamic compaction laboratory tests and crater development in different soils.

Heh (1990) and Poran (1992) have conducted extensive laboratory model testing programs to investigate the impact response of dry sand. They found that, beyond the maximum density, additional compaction energy would be detrimental to both clays and sand as breakdown can occur causing a decrease in density.

Experiments were conducted in the laboratory in order to assess the improvement in the load carrying capacity of sand beds on densification. For this purpose, uniform sand beds with different densities (achieved through vibration of the predetermined weight of sand) were prepared in tanks- starting with the loosest state. Load tests were conducted on these beds, the results of which are discussed here.

Fig. 4.1 shows the load- settlement curves of medium sand compacted at different densities. At lower unit weights as one would expect, the peak is not well defined. It can be seen from the figure that the ultimate stress at the loosest state is only 22.7 kN/m^2. At higher unit weights the failure is easily identifiable by distinct peaks. Maximum compaction yielded a unit weight of 16.2 kN/m^3 and the corresponding ultimate stress is 367 kN/m^2 which is more than 16 times the value for the sand at the loosest state. In the loosest state (corresponding to a dry unit weight of 13.1 kN/m^3 and void ratio of 0.98), the angle of shearing resistance (Ø) is only 27^0 (Table 4.1) and at the densest state (corresponding to a dry unit weight of 16.2 kN/m^3 and void ratio of 0.61), the Ø value increases to 39^0. At natural state (corresponding to a dry unit weight of 14.5 kN/m^3 and relative density of 51%), the angle of shearing resistance obtained is 34^0, the ultimate stress being 93 kN/m^2, which is 4 times more than that at loosest state. As expected, the ultimate stress steadily increases with increase in density; this rate of increase being phenomenal beyond a unit weight of 14.5kN/m^3.

The load – settlement curves of coarse sand compacted at different unit weights are given in Fig. 4.2. The plot shows that the ultimate stress at the loosest state (unit weight 14kN/m^3) is only 16.9kN/m^2. Here also the ultimate stress is not well defined, but at higher unit weights it is easily identifiable by distinct peak at failure. At unit weight of 15.0kN/m^3 the ultimate stress is 78kN/m^2 and at maximum compaction yielded a unit weight of 16.2kN/m^3 and the corresponding ultimate stress is 301kN/m^2.

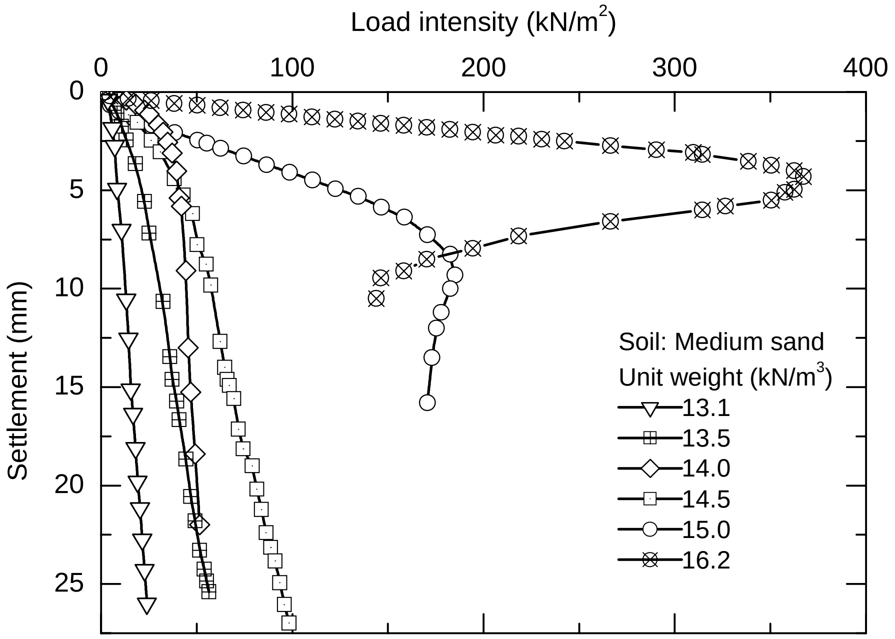


Fig.4.1 Load –settlement curves at different unit weights of medium sand

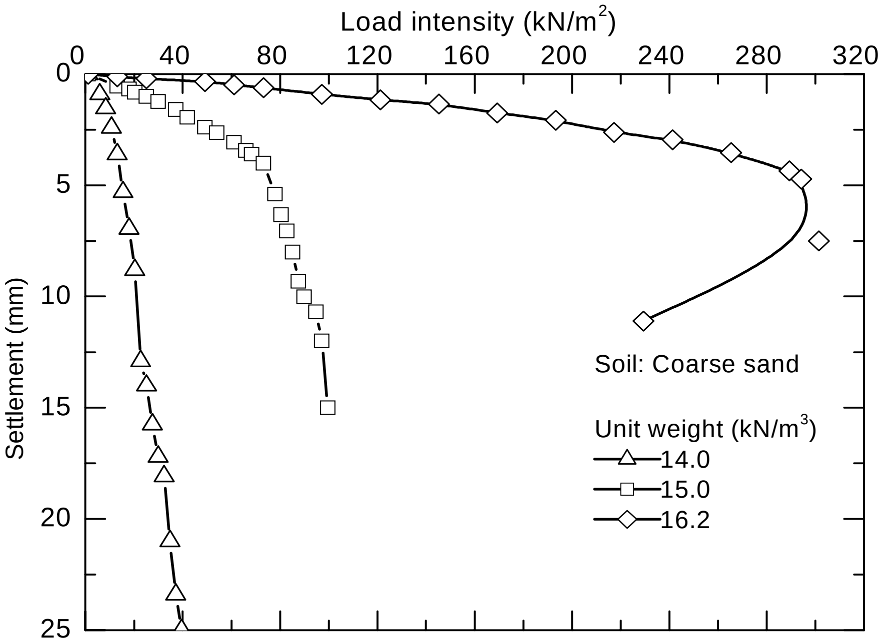


Fig.4.2 Load – settlement curves at different unit weights of coarse sand

Fig. 4.3 shows the load- settlement curves of fine sand compacted at different unit weights. The plot shows that upto around a unit weight of 14.0 kN/m^3 the failure peak is not well defined. The ultimate stress corresponding to unit weight of 12.3, 13.0 and 14.0 kN/m^3 are 11.0, 44.0 and 125 kN/m^2 respectively. At higher compaction (unit weights being 15.0 and 16.2 kN/m^3), the failure is easily identifiable by distinct peaks, the ultimate stress being 658 and 694 kN/m^2 respectively.

Fig. 4.4 shows the load – settlement curves of fine, medium and coarse sand compacted in layers in the mould so that the unit weight is kept constant i.e., 14.0 kN/m^3. At this unit weight the ultimate stress of coarse sand is only 16.9 kN/m^2, whereas for medium sand it is 38.3 kN/m^2 and for fine sand it is as high as 125 kN/m^2. Eventhough the void ratio of the sand medium is same in all the three cases, fine sand gave very high value (≅ 7 times) compared to the coarse sand.

Fig. 4.5 shows a similar trend of the load – settlement curves of fine, medium and coarse sand at a unit weight of 15.0 kN/m^2. The peak load for coarse, medium and fine sand are 78, 185 and 658 kN/m^2 respectively. But at still higher unit weights (unit weight of 16.2 kN/m^3), the peak load in case of coarse, medium and fine sand are 301, 367 and 694 kN/m^2 respectively (Fig. 4.6).

From the above, it can be concluded that the load carrying capacity of the sand medium depends not only on the density, but also on the gradation. Further, the load carrying capacity of finer fractions is always higher compared to the coarser fraction irrespective of the density. This can be attributed to the increased contact area between the particles, in case of finer fractions.

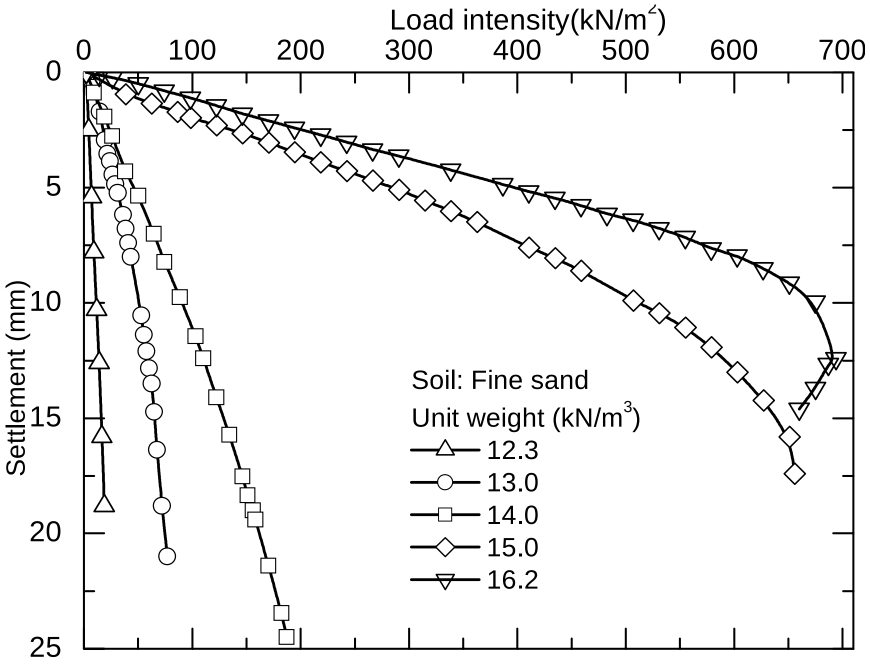


Fig.4.3 Load – settlement curves at different unit weights of fine sand

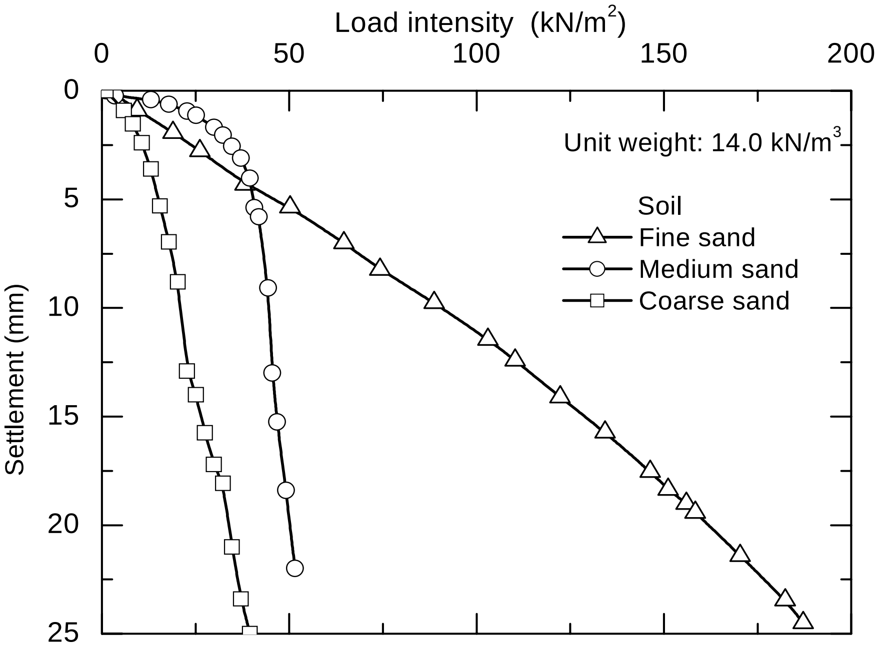


Fig.4.4 Load – settlement curves of sand at different gradations

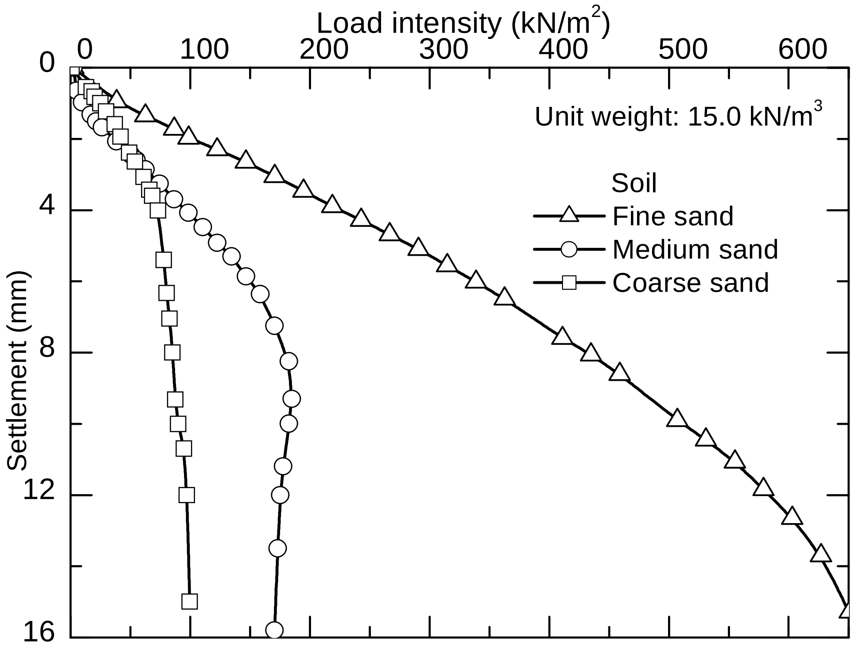


Fig.4.5 Load – settlement curves of sand at different gradations

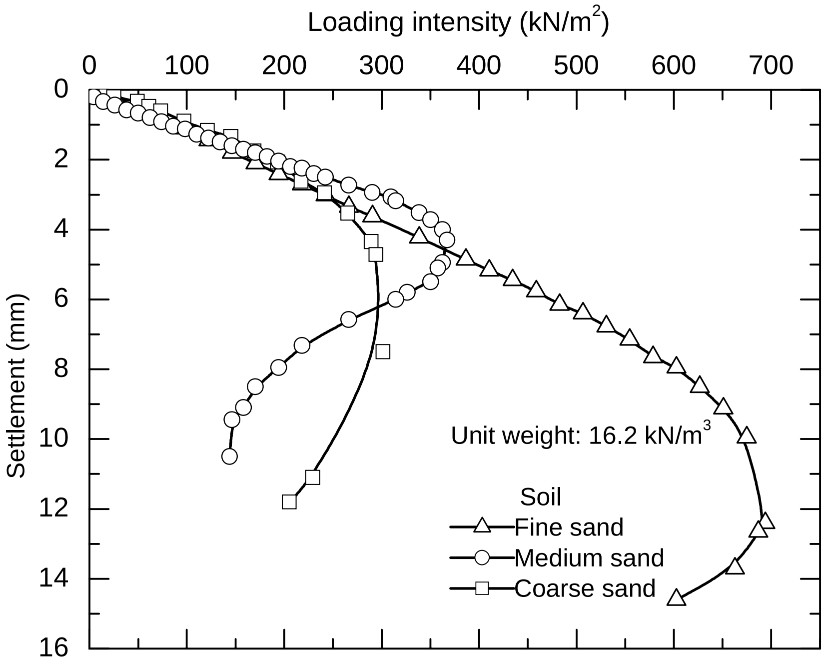


Fig.4.6 Load – settlement curves of sand at different gradations

Direct shear tests were conducted on fine, medium and coarse sand specimens in a shear box apparatus of 60 x 60 x 25 mm to determine the shear strength parameters at different unit weights. The unit weights at the loosest state were 12.3 kN/m^3 (fine sand), 13.1 kN/m^3 (medium sand), 14.0 kN/m^3 (coarse sand) and the corresponding Ø values were 23^0,27^0 and 34^0 respectively (Table 4.1). Similarly the Ø values obtained for fine sand, medium sand and coarse sand were 27, 34 and 37^0 respectively, at a unit weight of 14.5 kN/m^3. But in the densest state (unit weight 16.2 kN/m^3), all the fractions give the same value of angle of shearing resistance (39^0).

The values of safe bearing capacity computed (using Terzaghi's bearing capacity equation with a factor of safety of 3) from these Ø values are also given in Table 4.1. It can be seen that the maximum safe bearing capacity achieved is only 90.3 kN/m^2, which may not be sufficient in the case of multistoried buildings. Further, these methods would 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.

Table 4.1 Characteristics of the sand used

Sand	In loosest state			At natural state			In densest state		
	Unit weight (kN/m^3)	Ø (degree)	Safe bearing capacity (kN/m^2)	Unit weight (kN/m^3)	Ø(degree)	Safe bearing capacity (kN/m^2)	Unit weight (kN/m^3)	Ø (degree)	Safe bearing capacity (kN/m^2)
Fine	12.3	23	11.4	14.5	27	18.3	16.2	39	90.3
Medium	13.1	27	18.3	14.5	34	40.2	16.2	39	90.3
Coarse	14	34	40.3	14.5	37	69.4	16.2	39	90.3

4.3 Strength improvement on grouting

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. Density, grain size distribution, grain shapes and grain arrangements all have a significant effect on the behavior of cemented sand (Clough et.al, 1981)

The groutability of soil depends on the effective-size D_{10} of soil, cement particle-size d_{90}, water cement ratio of grout (or viscosity), fine content, grouting pressure and relative density of the soil. Grouting becomes difficult as the grain-size of soil decreases. An increase in grouting pressure or the water cement ratio of grout can increase the groutability of a soil. However, an increase in water cement ratio of grout decreases the strength of grouted samples (Akbulut and Saglamer, 2002).

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 modeled by Mohr –Coulomb criterion. Grouting is mainly responsible for the gain in cohesion by the material and only marginally affects the friction angle (Maalej et al. 2007).

Direct shear tests were conducted in moulds of size 60 x 60 x 25 mm (the details given in section 3.4.1) to determine the shear strength of the grouted soil samples.

4.3.1 Grouted with cement alone

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 mixing the sand with the required quantity of the grout material (cement/lime) and soil specimens were prepared in the moulds at desired unit weights and kept for curing under humid conditions as explained in section 3.3.1. In the second method, previously prepared sand beds were grouted with different grouting materials using a grout pump similar to the procedure used in the field.

The variation in the shear strength $\boldsymbol{\tau}$ with cement content (varying from 2 to 25 % by weight of dry sand) at an initial water content of 10 % is shown in figure 4.7. As expected, the value of shear strength steadily increases with increase in cement content. In the case of 2 % cement content, the increase in shear strength is only 3 % (after 7days of curing) and 24 % (after 28days of curing) when compared with the shear strength of sand without addition of any cement. The percentage increase in shear strength at 4, 6 10 & 25 % of cement contents after the 7 days of curing is 28, 109, 263% and 897% respectively, whereas the percentage increase is 70 %, 150 %, 322 % & 1300 % in case of specimens cured for a period of 28 days. The results are as expected –i.e. τ Value increases with increase in the curing period.

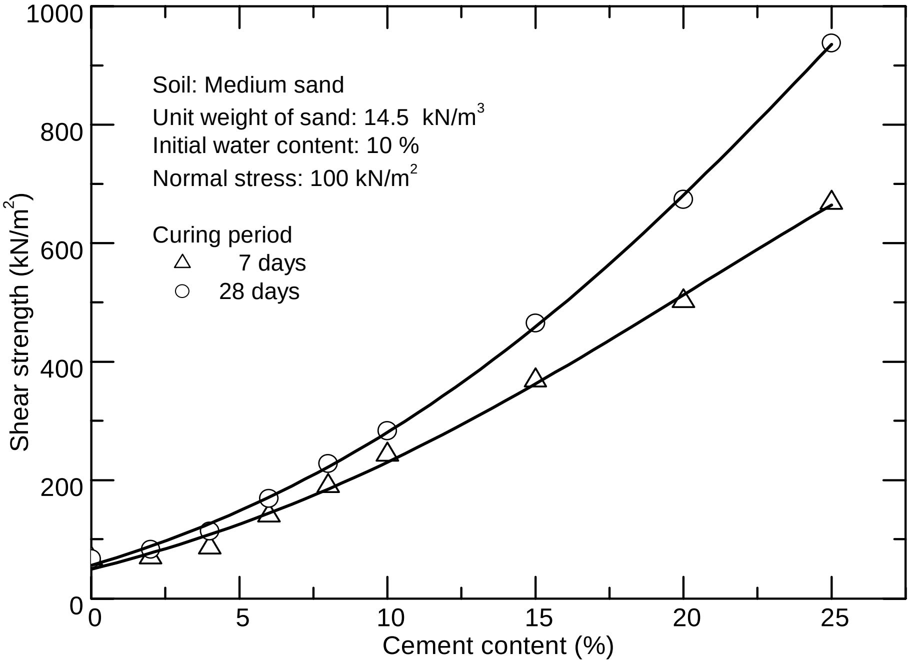


Fig. 4.7 Variation of shear strength with cement content

Fig. 4.8 shows the variation in shear strength with cement content for specimens prepared at an initial water content of 20 % for a normal stress of 100 kN/m^2. It can be seen that the shear strength keeps on increasing with increase in cement content and curing periods. The percentage of increase in shear strength is from 3 to 528 % for a corresponding increase in cement content of 2 to 25 % after 7days curing. For the specimens cured for 28 days, the increase in shear strength is from 14 to 1046 % for the corresponding cement content of 2 to 25 %.

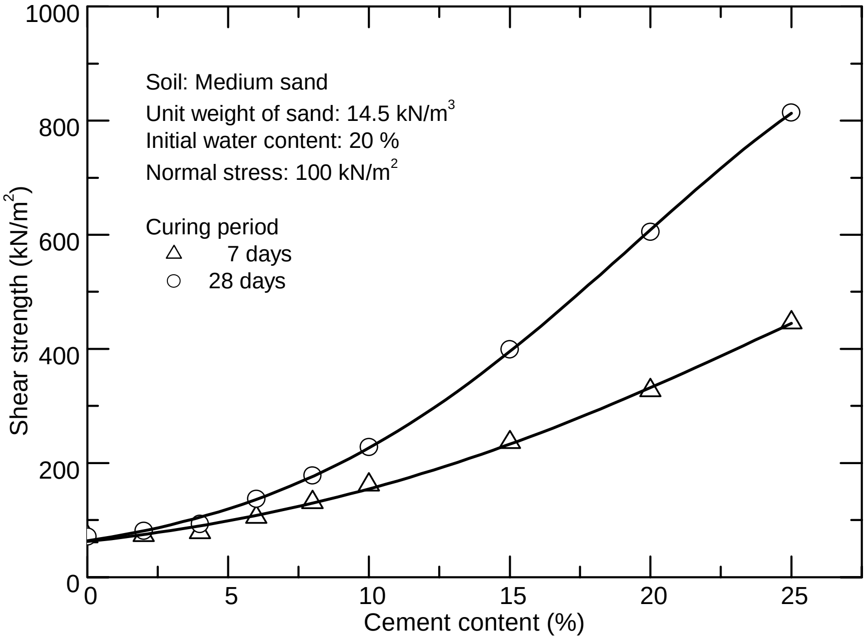


Fig. 4.8 Variation of shear strength with cement content

The variation in shear strength with cement content at initial water contents of 10 and 20 % after 28 days of curing are shown in fig 4.9. At constant cement content, a marginal decrease in shear strength is seen with increase in initial water content.

Fig 4.10 shows the variation of shear strength with initial water content at a cement content of 4 % after 7 and 28 days of curing. As expected, the shear strength decreases with increase in initial water content. It is noted that the shear strength increases upto around 5 % of initial water content and thereafter a slight decrease in shear strength is seen which is constant upto 25 % of initial water content. Fig 4.11 shows the effect of water content of the grout on shear strength for a cement content of 10 %. Here also the increase in strength is upto around 5 % of the initial water content and beyond that a marginal decrease in strength with increase in initial water content is seen. It is also noted that as expected the shear strength increases with curing periods, whereas at 25 % of initial water content, the shear strength value after 28 days of curing is much closer to 7 days curing strength.

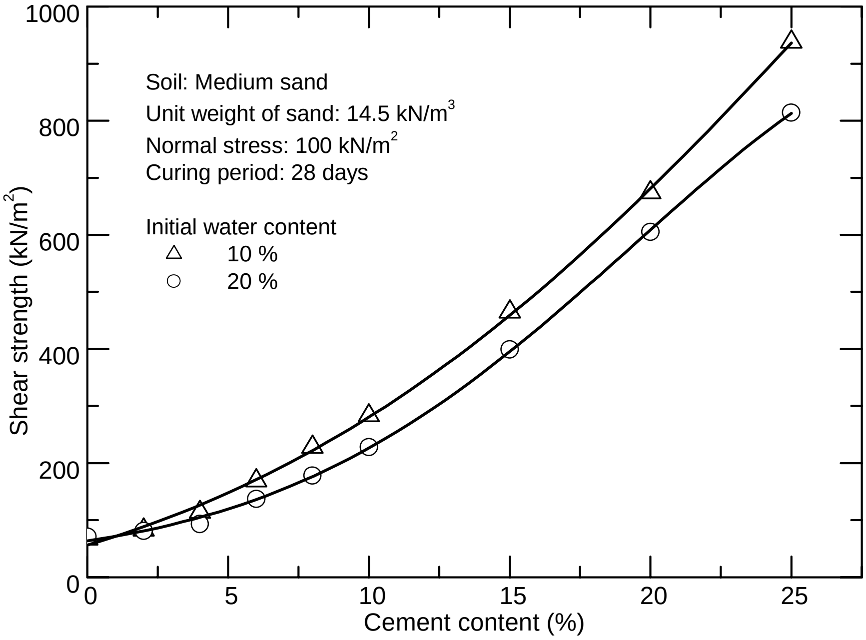


Fig. 4.9 Variation of shear strength with cement content

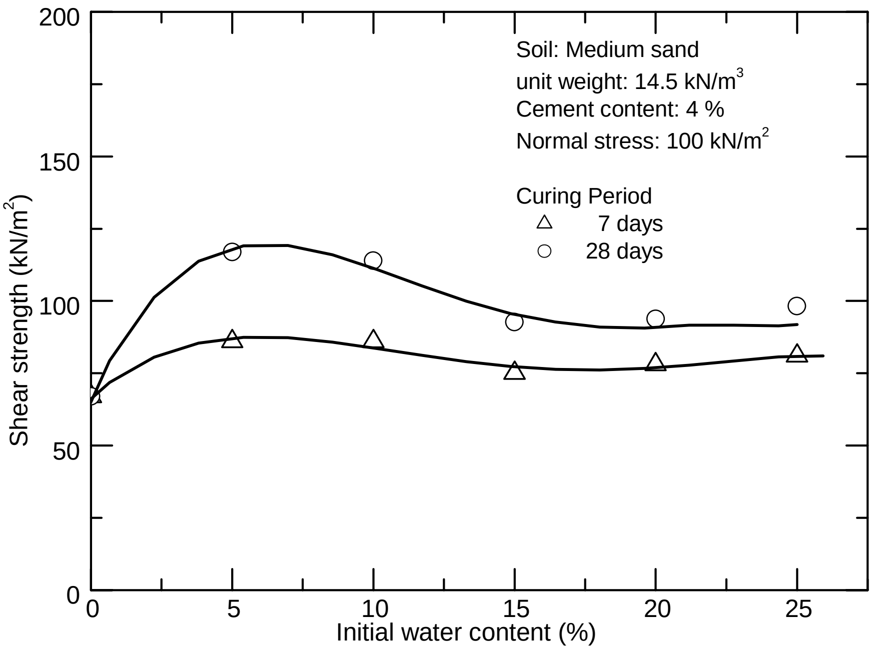


Fig. 4.10 Variation of shear strength with initial water content

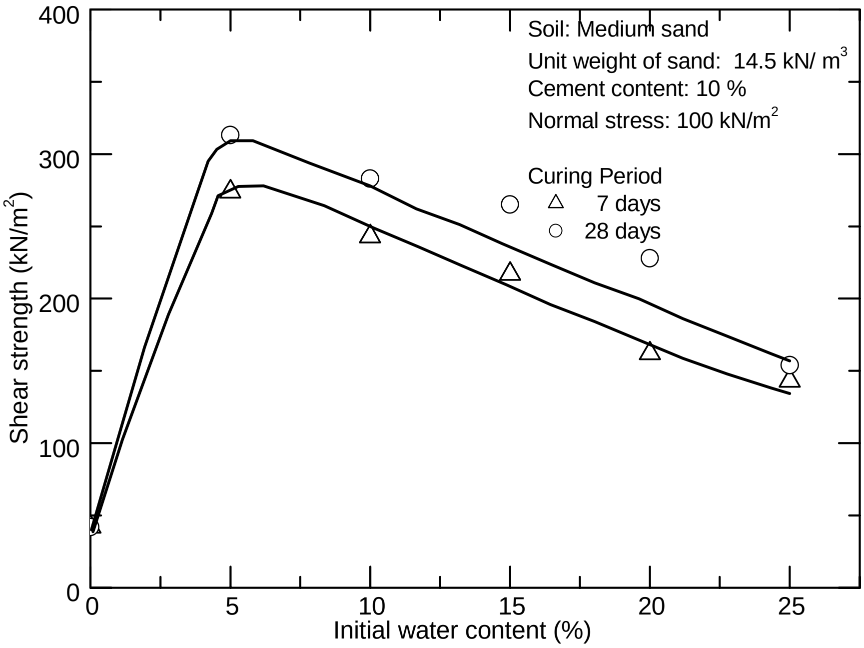


Fig. 4.11 Variation of shear strength with initial water content

The variation in shear strength with initial water content for 4 and 10 % of cement contents after 28 days of curing is shown in fig. 4.12. In both cases, the maximum value of shear strength is at around 5 % of initial water content. Eventhough the shear strength decreases with increase in initial water content, the decrease is more significant at higher percentage of cement content. It may be noted that the effect of initial water content is more if the cement content is more.

Fig. 4.13 shows the variation of shear strength for coarse sand with cement content for specimens prepared at an initial water content of 10 % and cured for 7 and 28 days. As the cement content increases from 4 to 20 %, the rate of increase in shear strength is marginal initially (upto around 8%) but thereafter the rate of increase is phenomenal. The curves also show the pronounced effect of curing period at higher cement contents.

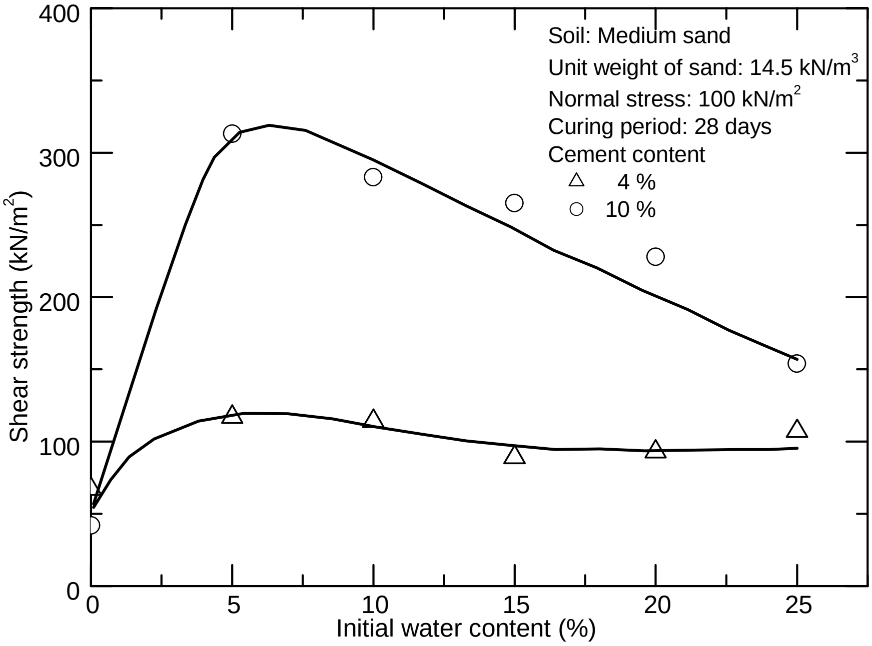


Fig.4.12 Variation of shear strength with initial water content

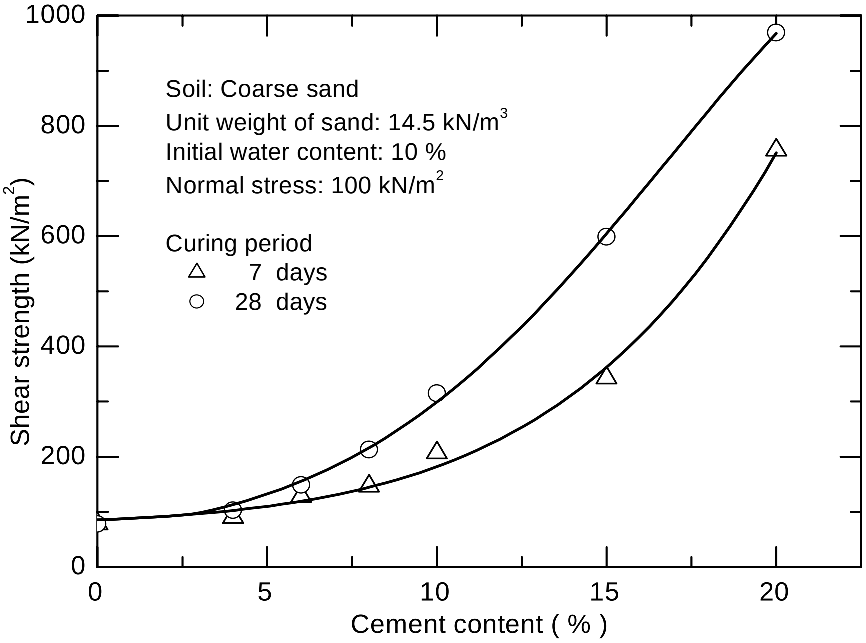


Fig. 4.13 Variation of shear strength with cement content (Coarse sand)

Fig. 4.14 shows the variation in shear strength with cement content for specimens prepared using fine sand at an initial water content of 10% and cured for 7 and 28 days. As in the case of medium and coarse sand, the shear strength of fine sand is also seen increasing with the percentage of cement content. As the percentage of cement content increases from 2 to 25%, the corresponding increase of shear strength is from 0.4 to 10.3 times that of fine sand without cement content. Here also the rate of increase in shear strength is very high at higher percentages of cement content. A marginal increase of shear strength due to the effect of curing is shown in the figure.

The effect of initial water content on shear strength of fine sand, at normal stress of 100 kN/m^2 and grouted with a cement content of 10% is shown in the fig. 4.15. The plots show that upto and around 15% of initial water content the shear strength increases, thereafter a reduction in shear strength is seen with increase of initial water content. It is thus seen that there is an optimum initial water content at which the shear strength is maximum. Fig. 4.16 shows the effect of cement content on shear strength of grouted medium for different gradation of sand such as fine, medium and coarse sand fractions. Eventhough the value of shear strength. increases with cement content, the influence of grain size on τ is significant. At lower cement contents, its influence is marginal. Eventhough medium sand specimens give higher τ than coarse sand specimens at lower cement contents; the coarse sand specimens register higher strength as the cement content increases.

The variations in shear strength τ with cement content at different normal stresses are shown in figures 4.17, 4.18, 4.19 and 4.20. As one would expect, the shear strength increases with increase in normal pressure. The rate

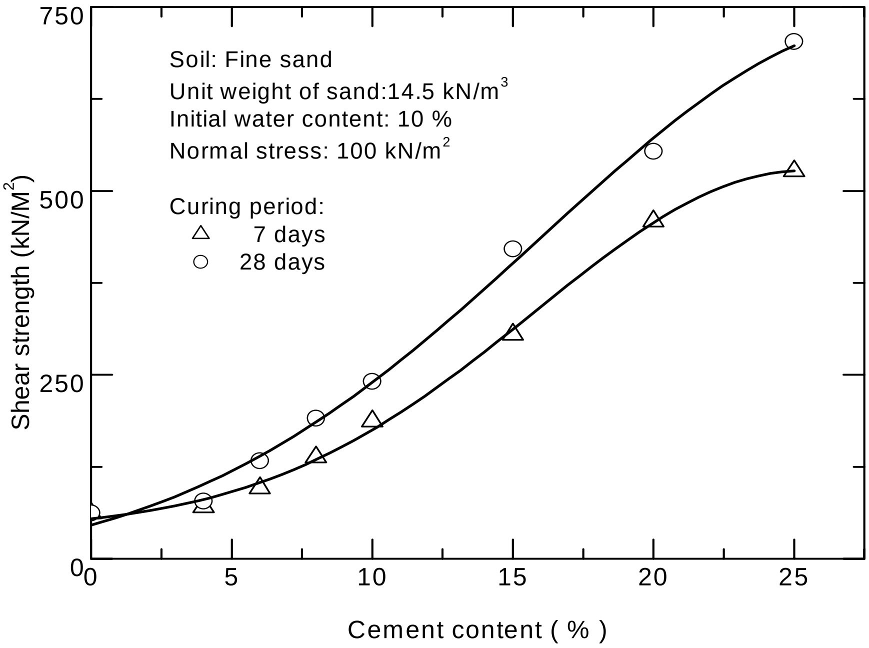


Fig. 4.14 Variation of shear strength with cement content (Fine sand)

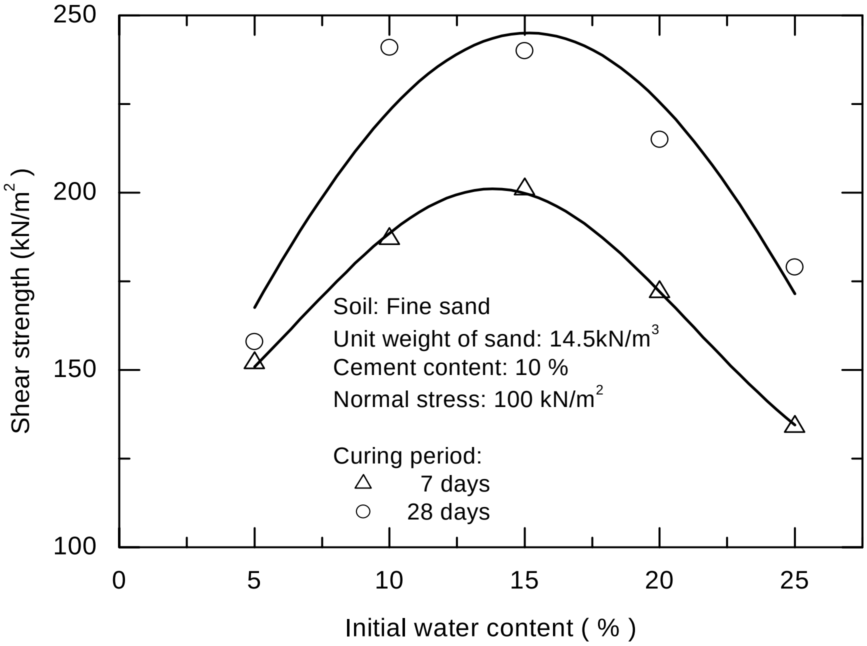


Fig. 4.15 Variation of shear strength with initial water content (Fine sand)

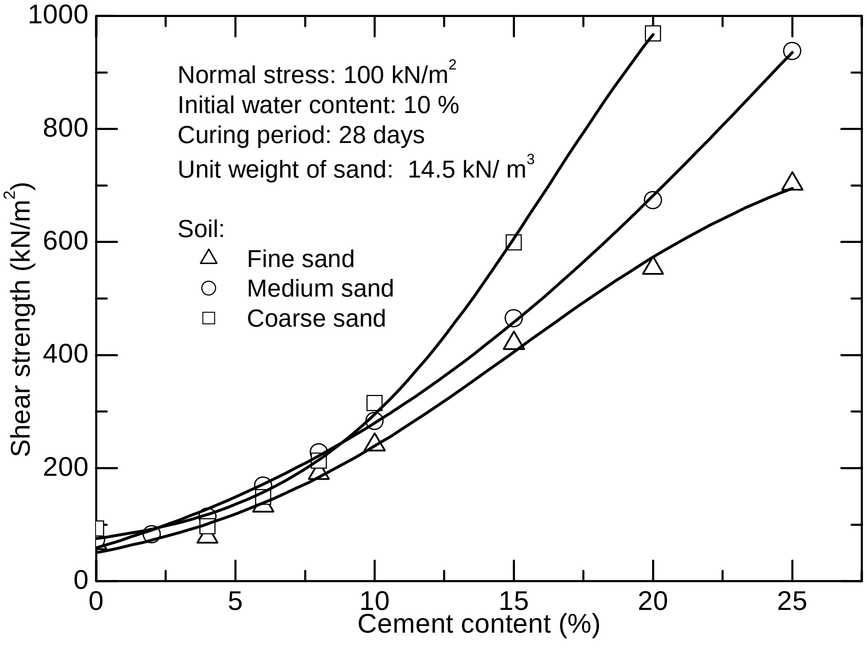


Fig. 4.16 Variation of shear strength with cement content for different gradation

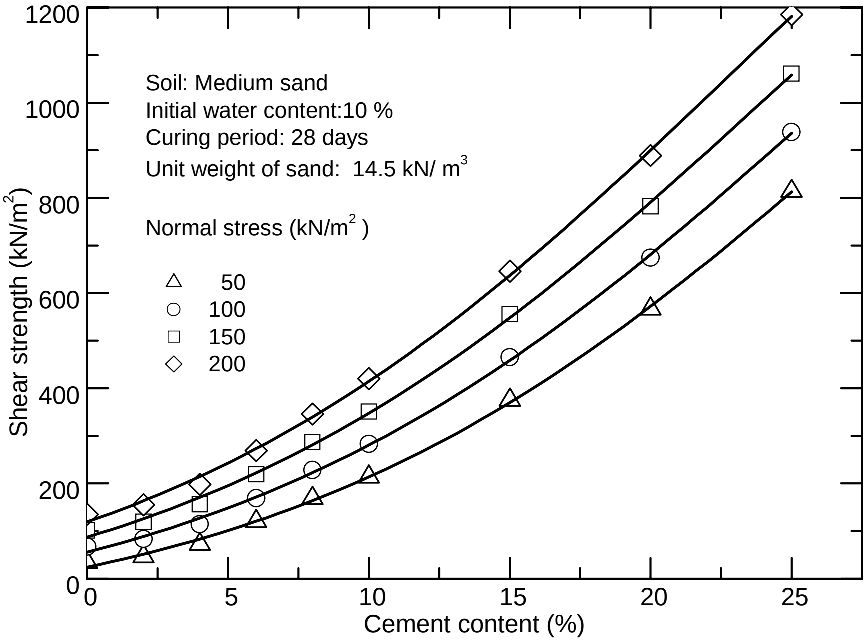


Fig.4.17 Variation of shear strength with cement content at different normal stresses

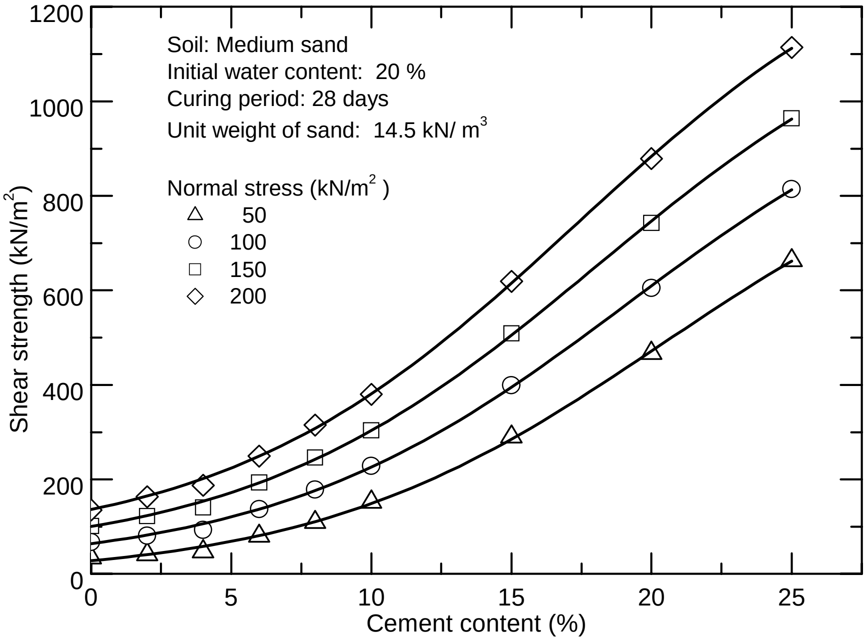


Fig.4.18 Variation of shear strength with cement content at different normal stresses

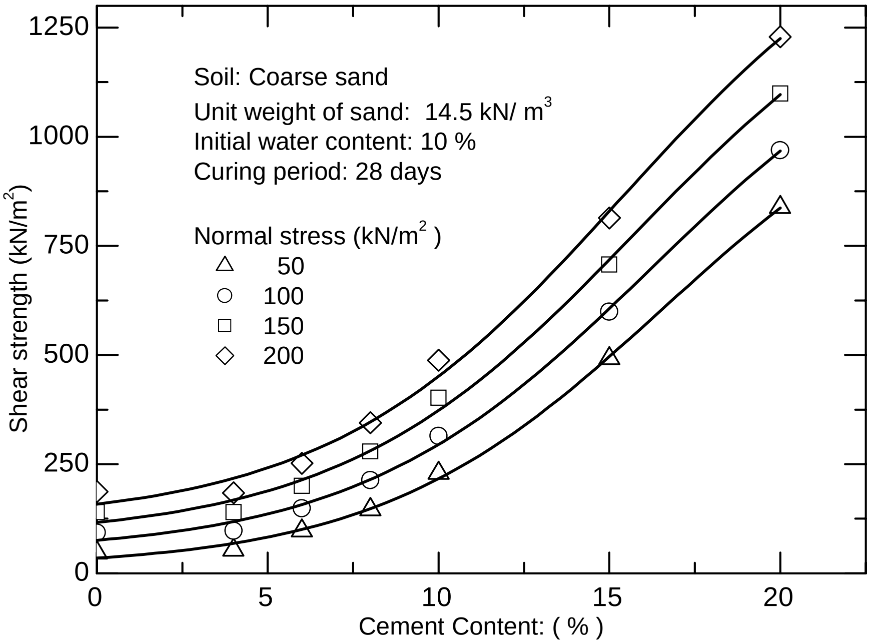


Fig.4.19 Variation of shear strength with cement content at different normal stresses

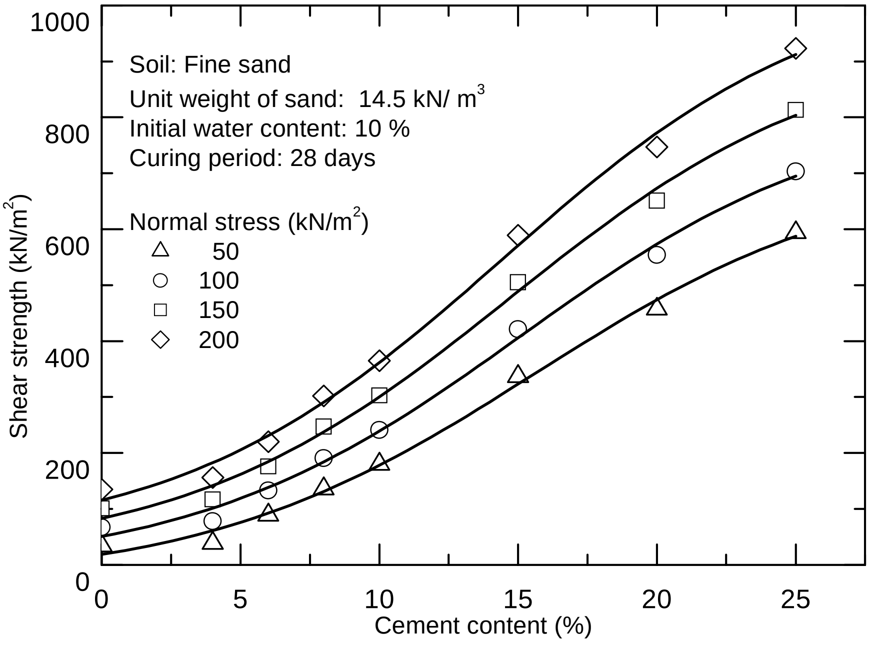


Fig.4.20 Variation of shear strength with cement content at different normal stresses

of increase is very high at higher percentage of cement content than at lower percentage of cement content for all cases of sand fractions.

The effect of initial water content on shear strength, at different normal stresses of 50, 100, 150, 200 kN/m^2 and grouted with a cement content of 4 & 10% are shown in figs. 4.21 & 4.22 respectively. Here also as one would expect, the shear strength increases with increase in normal pressure.

Figures 4.23, 4.24 & 4.25 show typical plots showing the relation between shear stress and shear strain. It can be noticed from the figures, that the stress–strain response exhibit a linear relationship prior to the peak, for all cement contents. As expected, the value of shear strength steadily increases with increase in cement content. Figure 4.25 shows the influence of the initial water content of the specimens on stress–strain response.

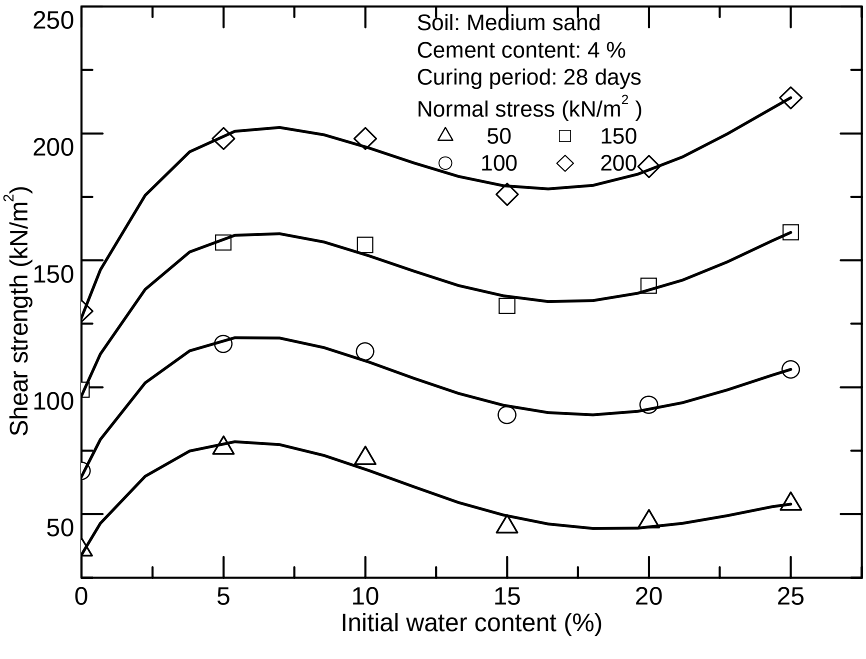


Fig.4.21 Variation of shear strength with initial water content at different normal stresses

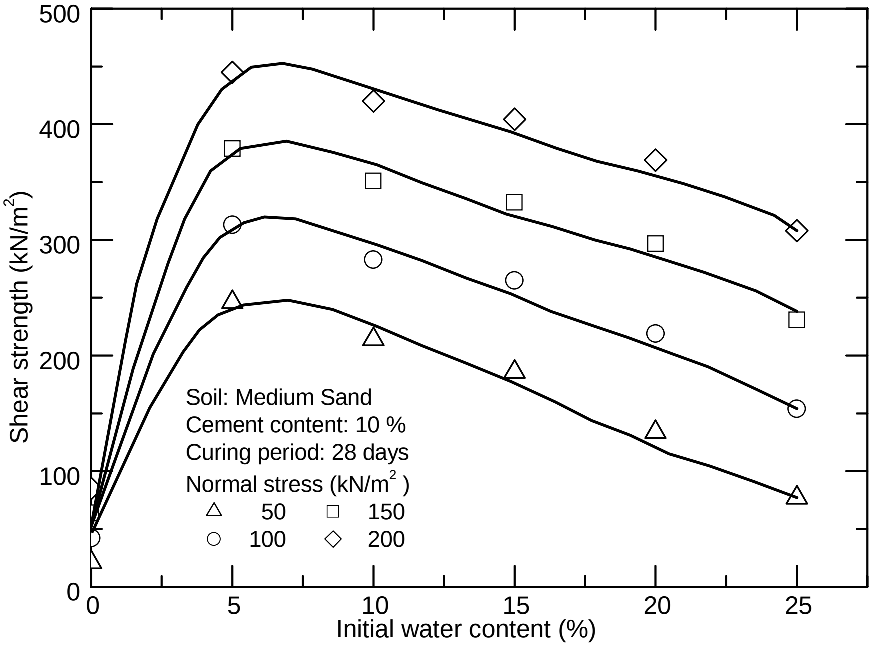


Fig.4.22 Variation of shear strength with initial water content at different normal stresses

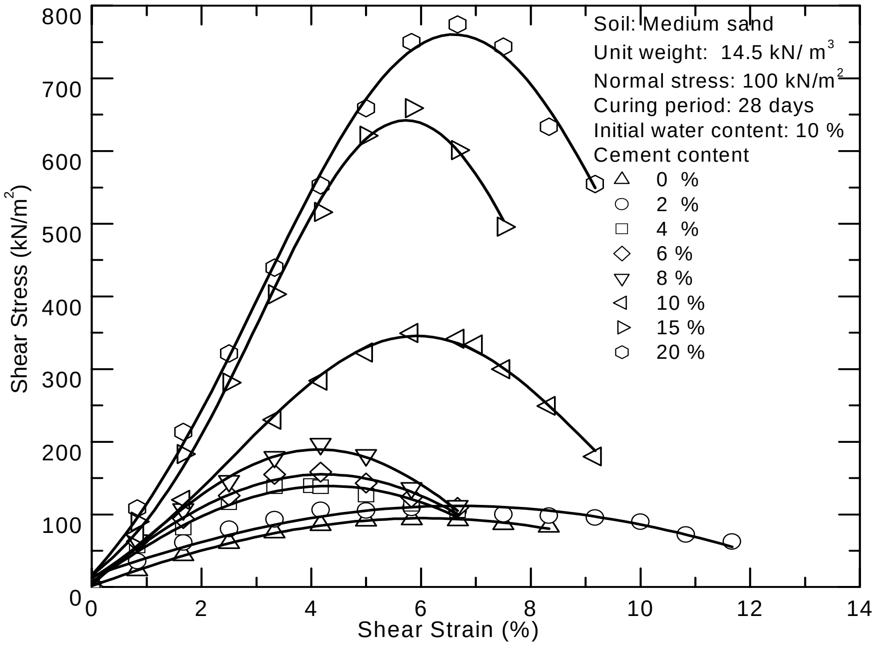


Fig. 4.23 Shear stress- shear strain curves

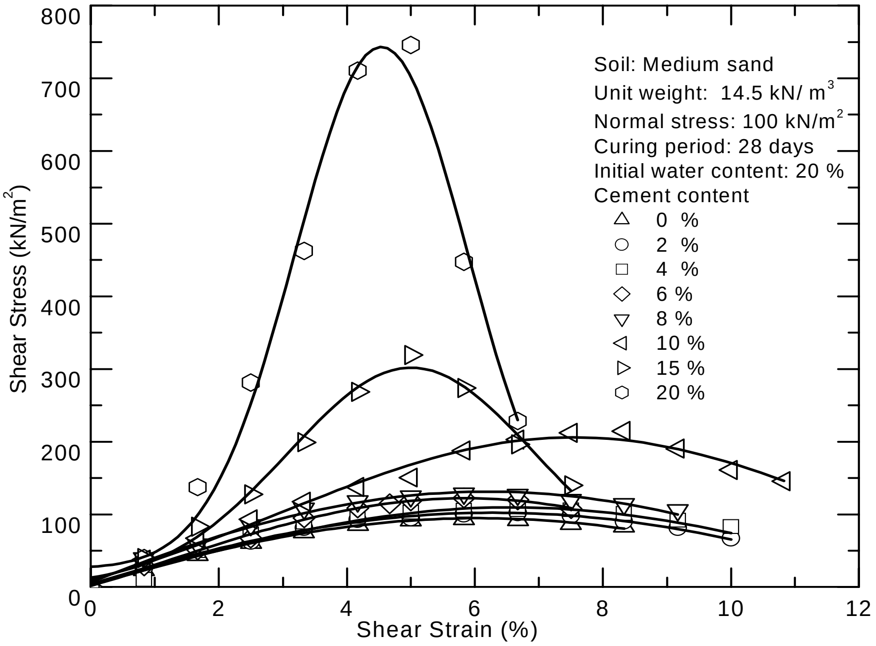


Fig. 4.24 Shear stress- shear strain curves

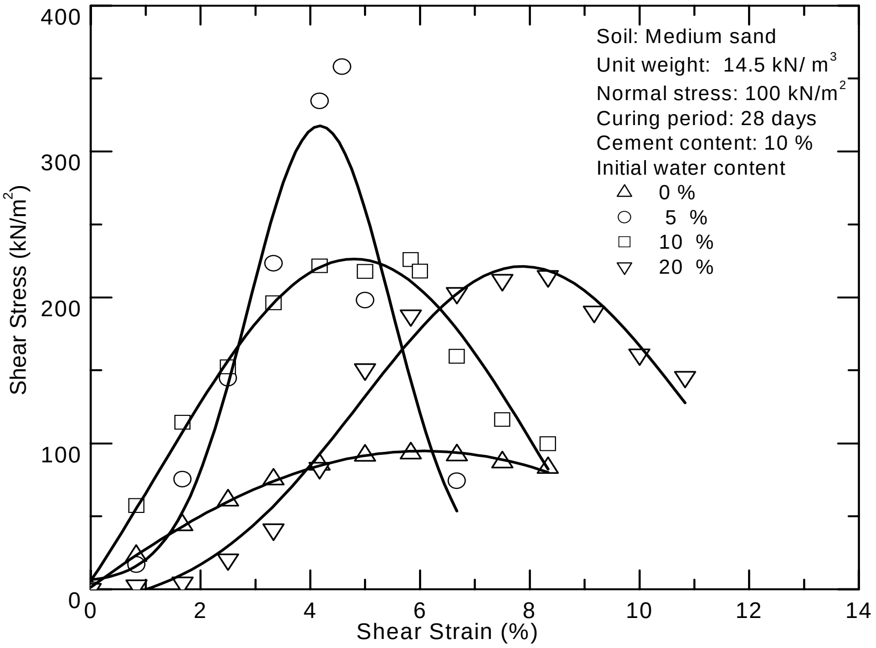


Fig. 4.25 Shear stress- shear strain curves

4.3.2 Cement with admixtures

Certain admixtures are used along with cement for improving the properties of grouts such as viscosity and stability (Lovely 1998). But no study has been reported on how these admixtures will affect the strength of the cement grouts. Various admixtures such as calcium chloride and sodium silicate (accelerators), triethanolamine and tartaric acid (retarders), aluminium powder (expander), detergent (fluidizer), and aluminium sulphate and bentonite (antibleeders) are used in the present study.

The effect of Calcium chloride on shear strength of cement grouted medium having curing periods of 7 & 28 days are presented in fig.4.26. A slight reduction in the shear strength is noted at around 1% of $CaCl_2$, but further increase in percentage of the salt will cause an increase in shear strength. Fig. 4.27 shows the variation of shear strength with percentage of sodium silicate which is also an accelerator, in cement-grouted soils. 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 (as reported by Lovely et al. 2000), and the early setting of the grout, this reduction in strength (to the tune of only 10% to 20%) is within the tolerable limits.

Fig. 4.28 shows the effect of sodium silicate/ calcium chloride content on shear strength of cement grouted medium sand after a curing period of 28 days. It can be seen that among the accelerators, the performance of calcium chloride is better than sodium silicate with regard to shear strength.

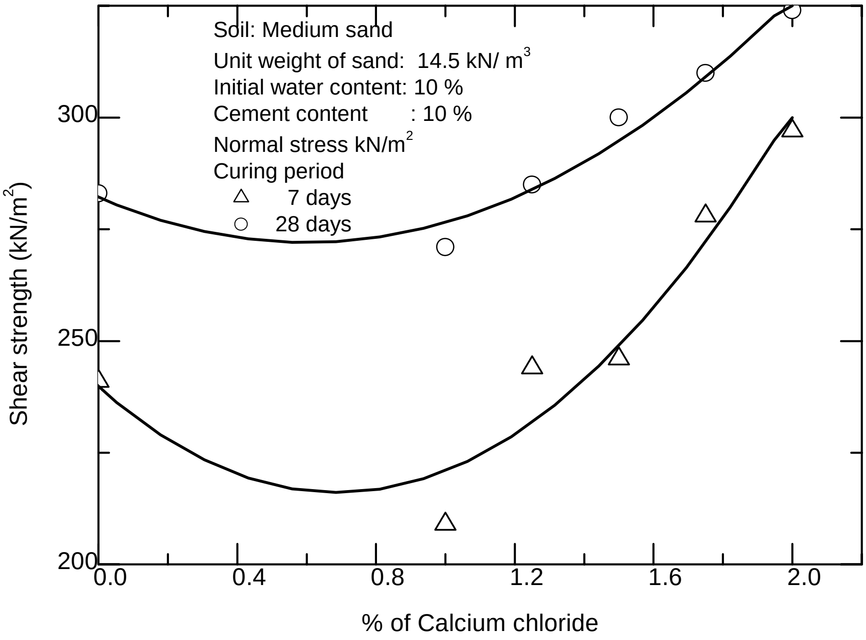


Fig. 4.26 Effect of Calcium chloride content on Shear strength of cement grouted Medium Sand

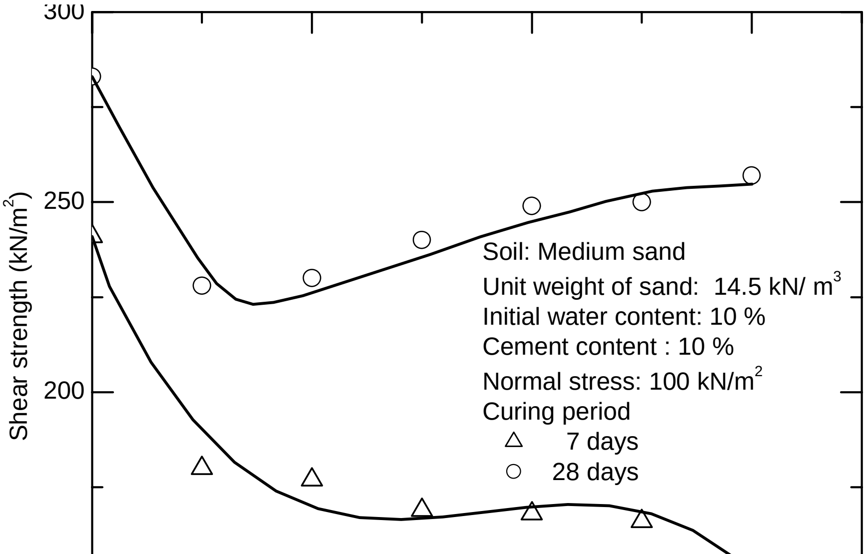


Fig. 4.27 Effect of Sodium silicate content on Shear strength of cement grouted Medium Sand

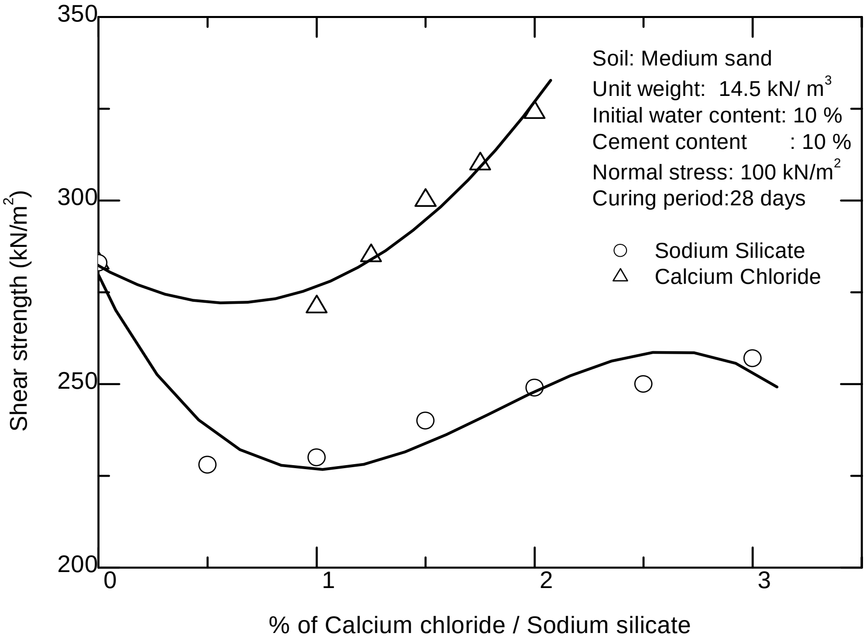


Fig. 4.28 Effect of Sodium silicate / Calcium chloride content on Shear strength of cement grouted Medium Sand

Fig. 4.29 shows the effect of percentage of tartaric acid on the shear strength of sand grouted with cement. 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. The variation of shear strength with the addition of triethanolamine which is also a retarder along with cement is shown in figure 4.30. Eventhough the shear strength increases at lower percentage of salt content, a marginal reduction is noticed as the percentage of salt increases.

Fig.4.31 shows the effect of both these retarders on shear strength of cement grouted medium sand. It can be seen that triethanolamine gives much higher shear strength even at lower percentages and hence can be considered as a better retarder compared to tartaric acid.

The effect of detergent on shear strength of cement grouted sandy soils cured for 7 & 28 days are presented in fig. 4.32. The optimum dosage of this salt as a fluidiser is 0.05 percent, as recommended by Shroff and Shah (1992). The present study also indicates that the shear strength increases upto an optimum dosage of 0.05%, thereafter the value of shear strength is found to decrease with increase in salt content.

Fig. 4.33 shows the effect of aluminium powder (used as expander) on shear strength of grouted medium sand for a cement content of 10%. The optimum dosage of this salt as expander is below 0.02 percent, as recommended by Littlejohn (1982). At lower percentage of this additive (0.005%) a sudden increase in shear strength is noticed, but as the percentage increases, there is a slight reduction in shear strength, which is still higher than the original value. The present study indicated that the use of optimum dosage of this salt increases the shear strength of the grouted sand.

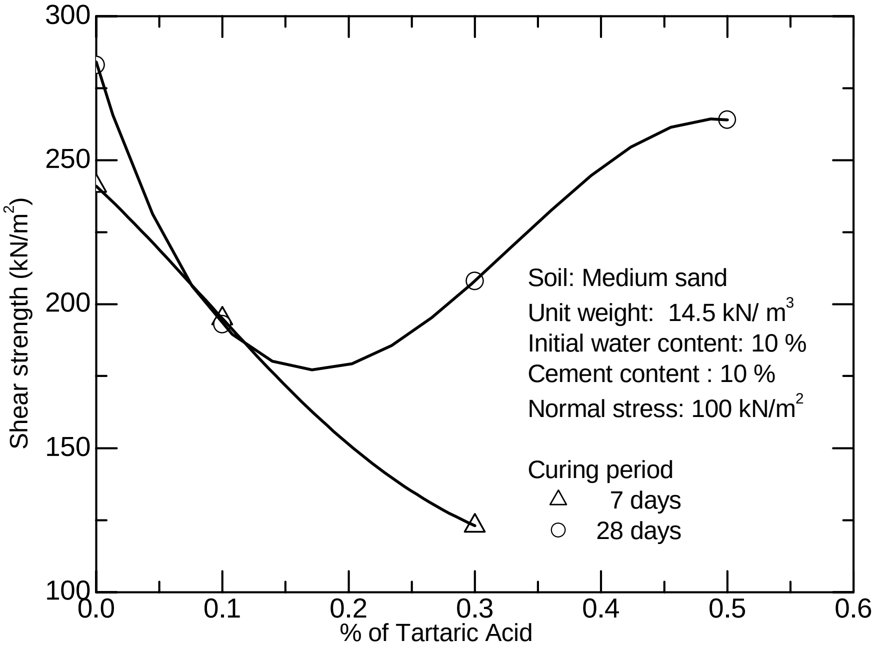


Fig. 4.29 Effect of Tartaric acid content on Shear strength of cement grouted Medium Sand

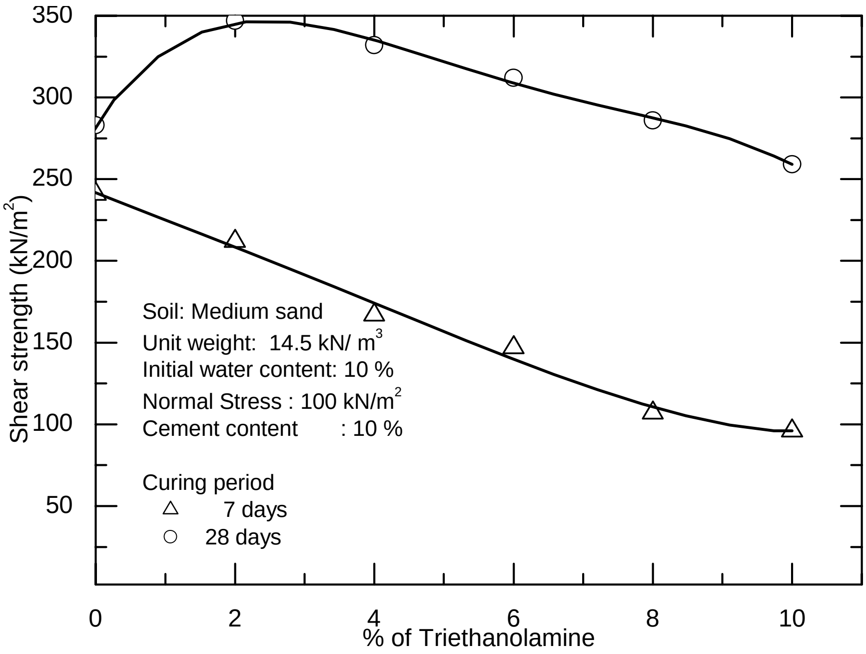


Fig. 4.30 Effect of Triethanolamine content on Shear strength of cement grouted Medium Sand

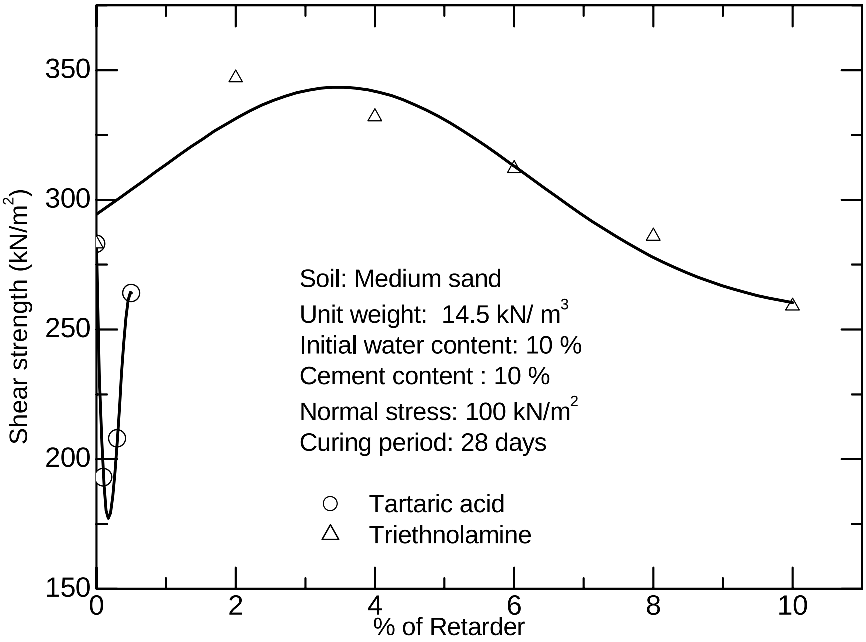


Fig. 4.31 Effect of retarder on Shear strength of cement grouted Medium Sand

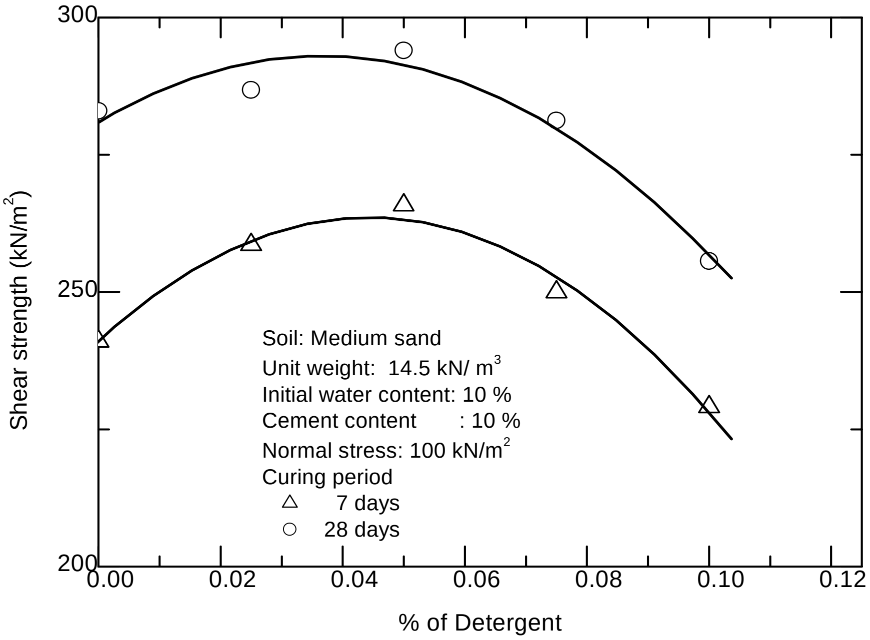


Fig. 4.32 Effect of detergent content on Shear strength of cement grouted Medium Sand

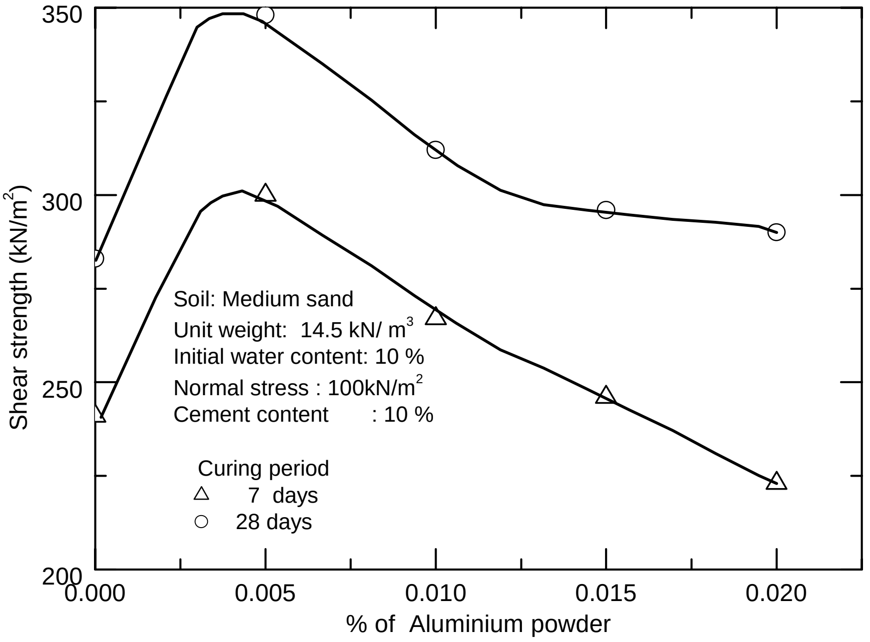


Fig. 4.33 Effect of Aluminium powder content on Shear strength of cement grouted Medium Sand

The effect of percentage of aluminium sulphate on shear strength of cement grouted medium sand specimens cured for 7 and 28 days are presented in fig. 4.34. 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.

The effect of bentonite on shear strength of cement grouted sand at an initial water content of 10 % having curing periods of 7 & 28 days are presented in fig. 4.35. There is a reduction in shear strength of approx 10 to 15 % with the addition of bentonite to the cement grout after 7 & 28 days of curing. Fig. 4.36 shows the variation in shear strength with percentage of bentonite having an initial water content of 20 %, and cured for 7 & 28 days. In this case, the reduction in shear strength is approx 15 to 30 %, which is more compared to the 10 to 15 % than the 10 % of initial water content. Hence proper control over the initial water content of the grout is essential in order to ascertain the required strength. It may be further seen that the increase in shear strength due to curing from 7 days to 28days is almost the same irrespective of % of bentonite

Figure 4.37 shows the variation of shear strength when different percentages of these antibleeders are used along with cement grout. In the case of aluminium sulphate, eventhough there is slight decrease in strength initially, as the percentage increases, the shear strength increases, even exceeding the original value. But in the case of bentonite, there is a reduction in shear strength (approx 15 %) irrespective of the percentage of bentonite added to the cement grout.

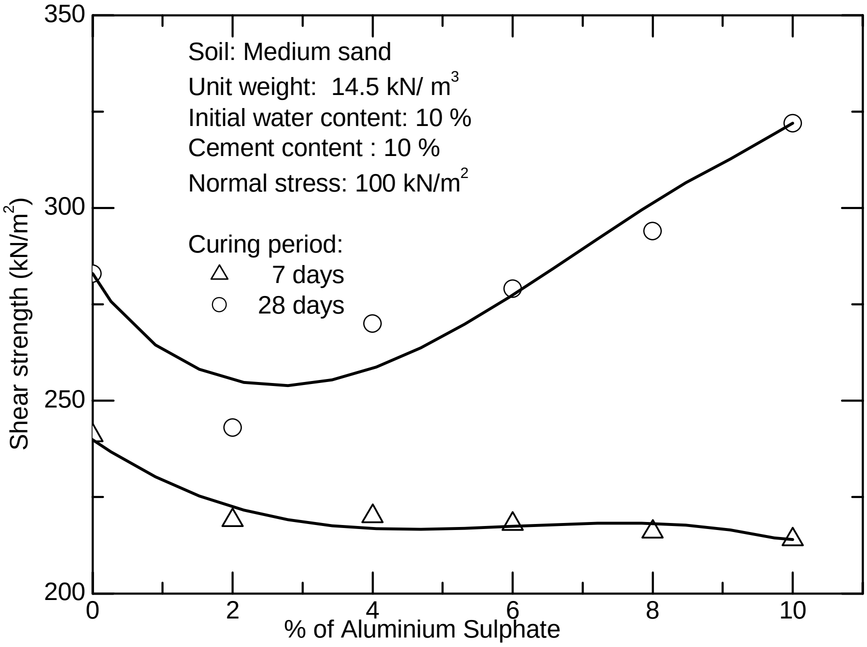


Fig. 4.34 Effect of Aluminium sulphate content on Shear strength of cement grouted Medium Sand

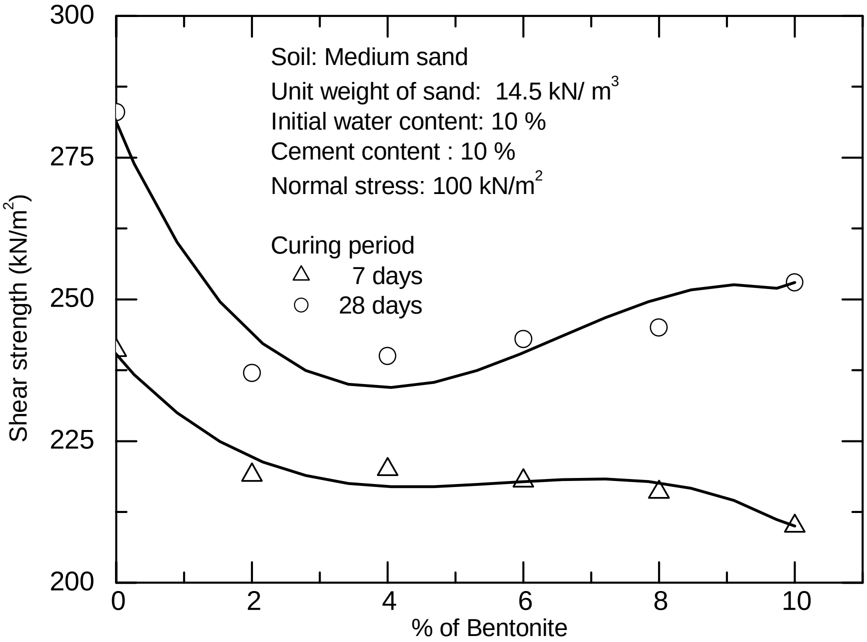


Fig. 4.35 Effect of Bentonite content on Shear strength of cement grouted Medium Sand

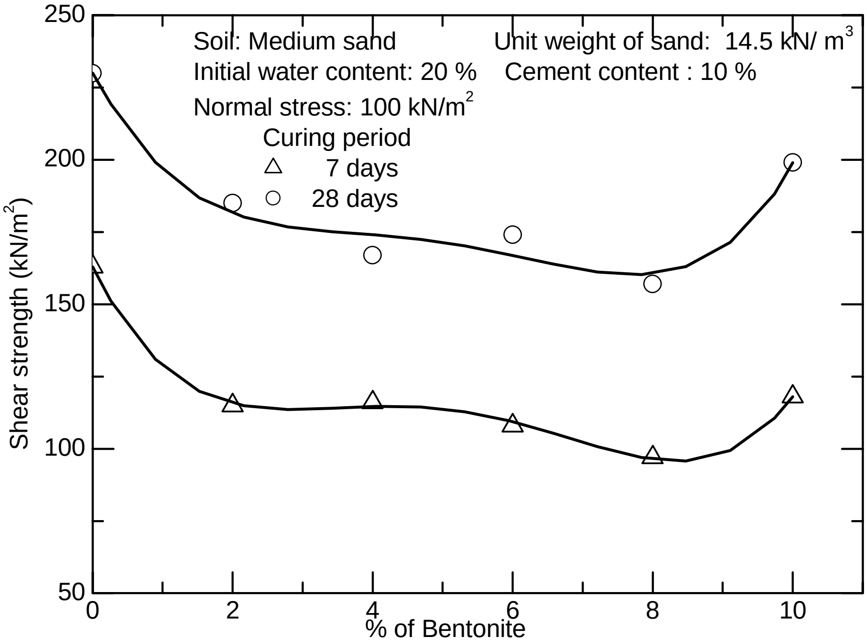


Fig. 4.36 Effect of Bentonite content on Shear strength of cement grouted Medium Sand

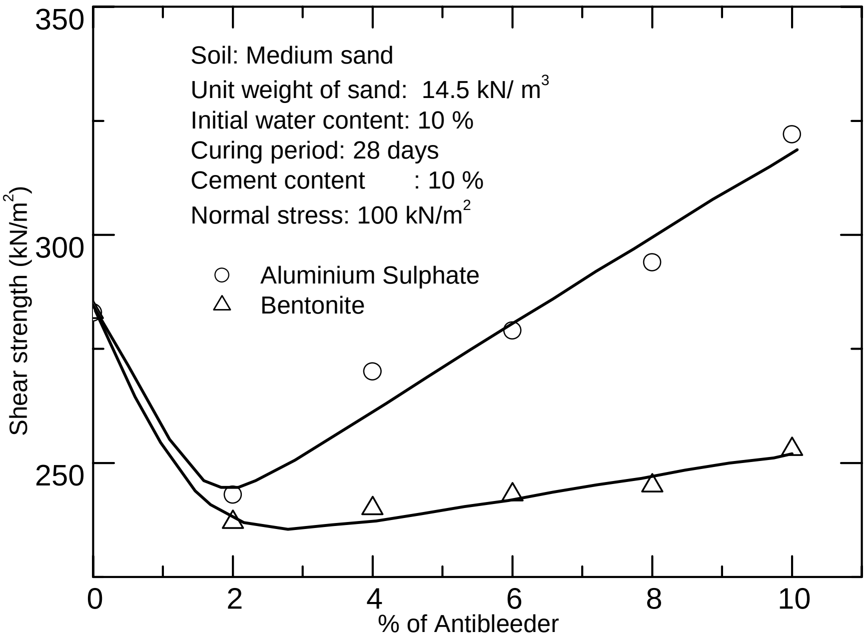


Fig. 4.37 Effect of Antibleeder on Shear strength of cement grouted Medium Sand

4.3.3 Lime

Little and Yusuf (2001) found that the unconfined compressive strength of soil specimens stabilised with lime increases with lime content.

The variation in shear strength with lime content (varying from 6 to 25% by weight of dry sand) in lime grouted medium sand having an initial water content of 10% is shown in figure 4.38. As expected, the shear strength increases with increase in lime content. The figure also shows the influence of curing periods of the specimen on the shear strength value. Fig. 4.39 shows the variation in shear strength with lime content in lime grouted medium sand at initial water content of 20%. Here also a similar trend is seen. Fig. 4.40 shows the effect of lime on shear strength of lime grouted sand having curing periods of 28 days. The figure also shows the influence of the initial water content (in other words the lime /water ratio of the grout) of the specimen on the shear strength value. Fig. 4.41 shows the effect of bentonite content with shear strength of sand grouted with 10% lime having an initial water content of 10%. Shear strength initially decreases and then increases to initial value at 10% bentonite content. Bentonite does not show any significant effect of increase in shear strength especially when the curing period is 28 days.

Fig. 4.42 shows variation of shear strength with cement/ lime content having initial water content of 10%, after a curing period of 28 days. It can be seen that the shear strength significantly increases with increase in percentage of cement content where as lime content does not have much effect on the shear strength values. Fig. 4.43 also shows variation of shear strength with cement/ lime content having an initial water content of 20%, after a curing period of 28 days. This also shows tremendous effect of cement content, compared to lime in improving the shear strength of loose sandy soils.

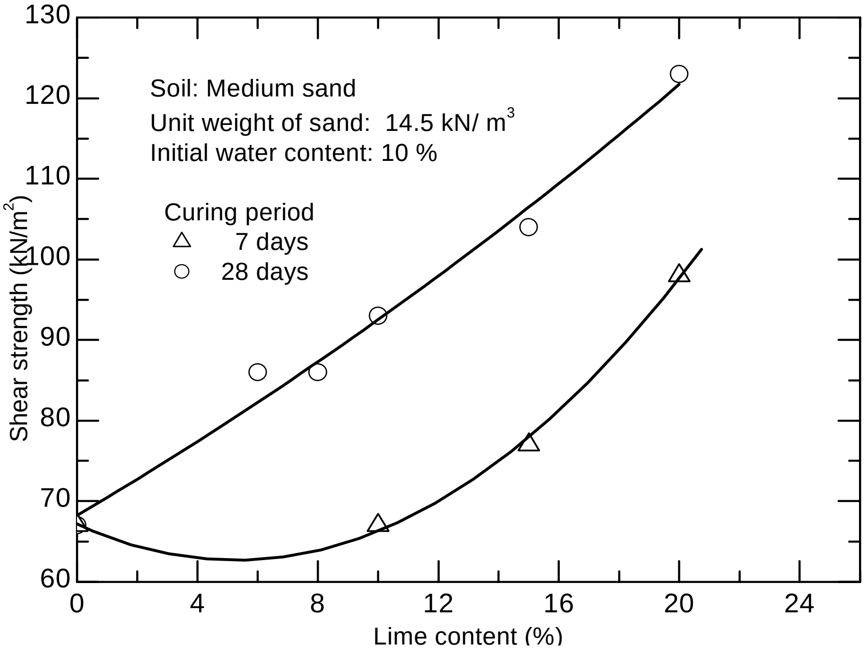


Fig. 4.38 Variation of shear strength with lime content

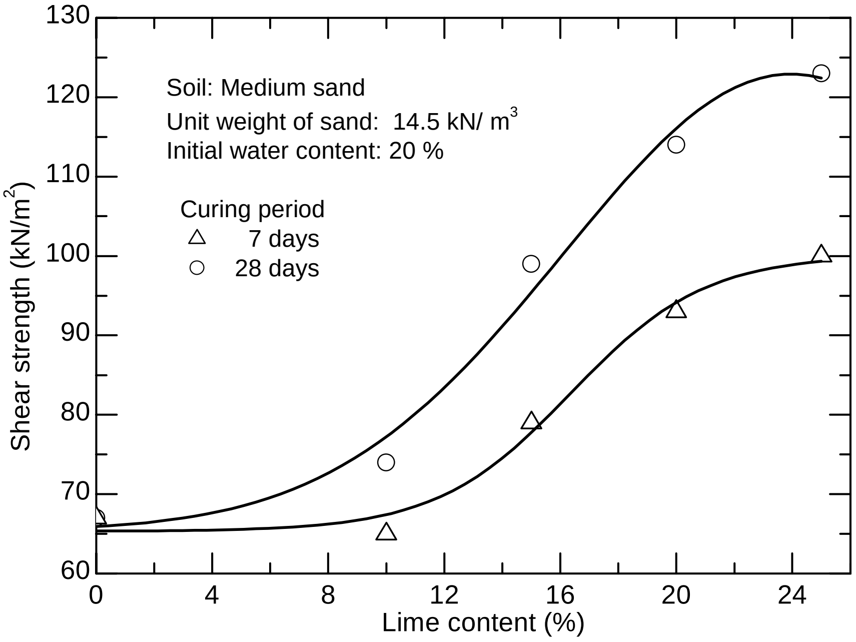


Fig. 4.39 Variation of shear strength with lime content

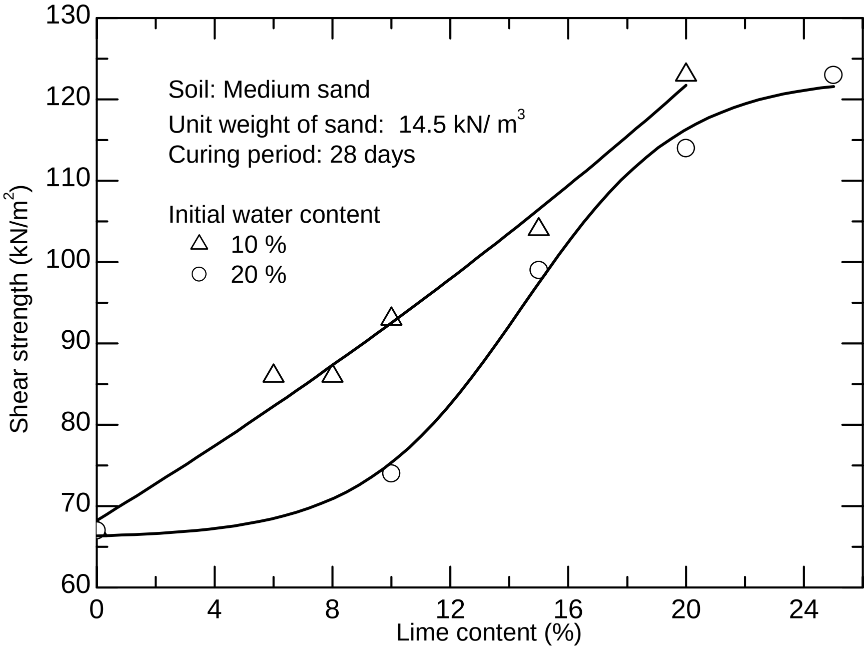


Fig. 4.40 Variation of shear strength with lime content

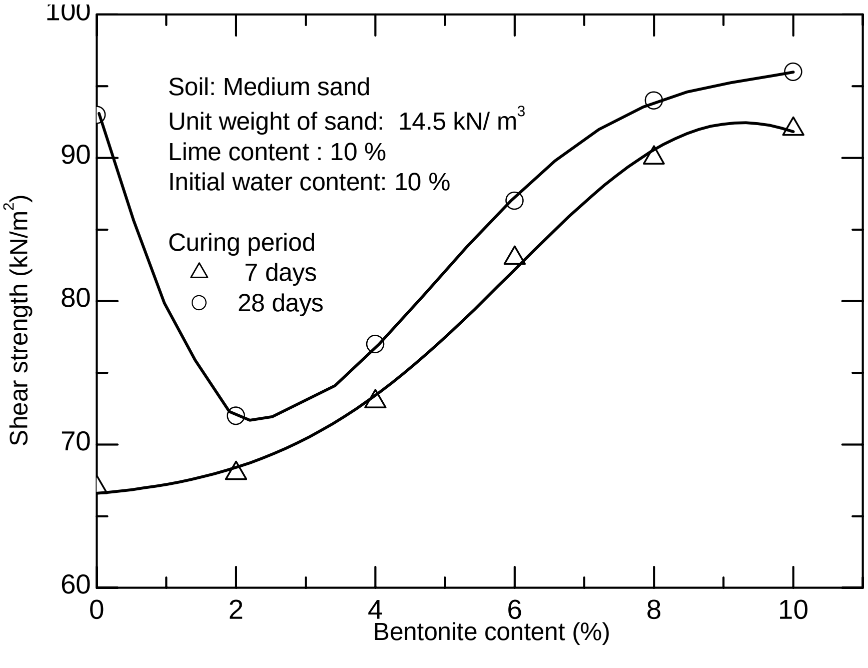


Fig. 4.41 Variation of shear strength with bentonite content on lime grouted sand

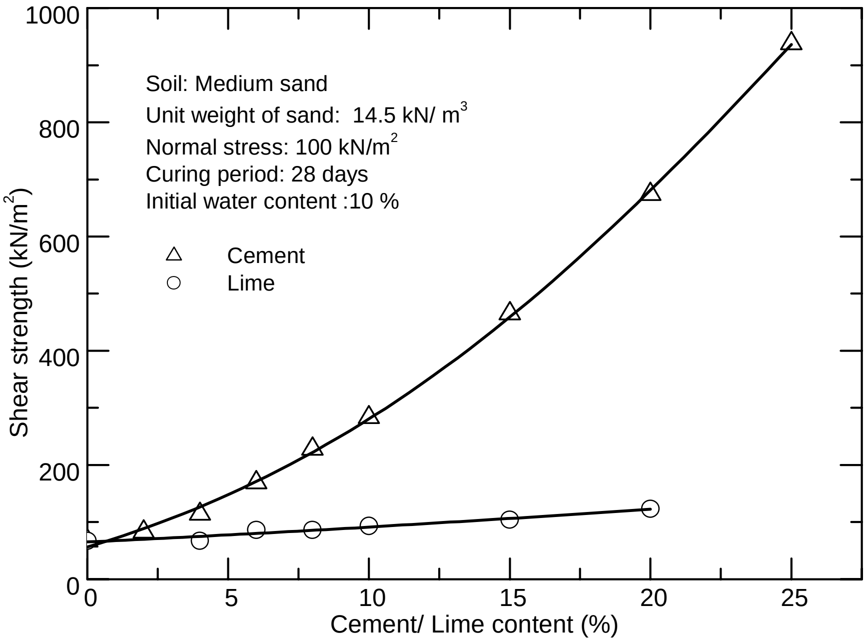


Fig.4.42 Variation of shear strength with cement / lime content

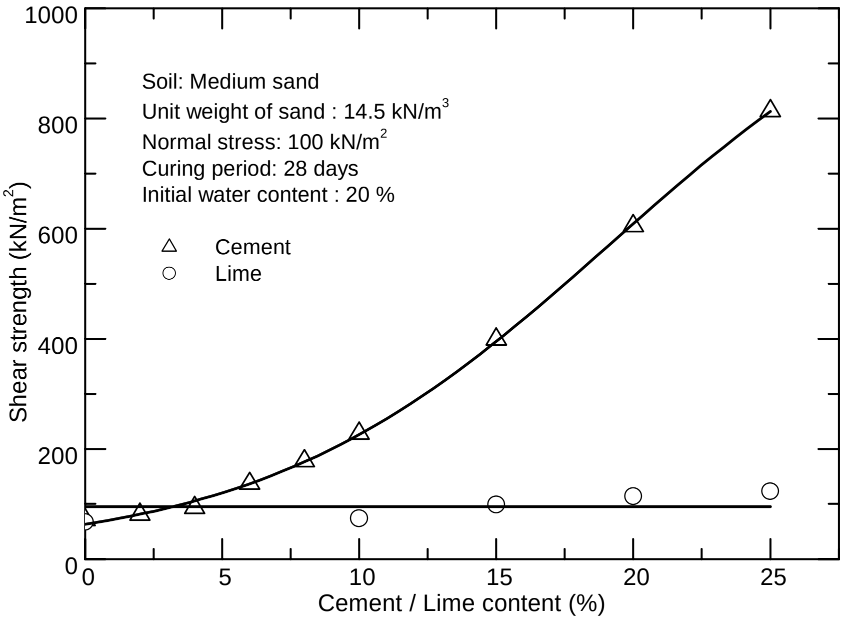


Fig.4.43 Variation of shear strength with cement / lime content

4.4 Shear strength parameters

Cement grouting can be profitably used for strengthening foundation beds. The shear strength parameters, *c* & Ø, shows phenomenal increase when grouted with cement. The cement-water ratio of the grout acts as a key parameter in the control of strength gain of sandy soils, increasing amounts of cementation in granular soil increasing cohesion and tensile strength as well as increasing friction angle at low confining pressures (Lade and Overton, 1989).

Generally, the strength of the soil is estimated by Mohr- Coulomb's failure criterion. It is generally accepted that grouting effectively increases 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 (Ata and Vipulanandan 1999).

4.4.1 Cohesion intercept

The cohesion intercept 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 (Maalej et al. 2007).

4.4.1.1Grouted with cement alone

The variation in the shear strength parameter *c* with cement content (varying from 2 to 25% by weight of dry sand) is given in fig 4.44. As expected, the value of *c* steadily increases with increase in cement content. The cohesion intercept at 2% of cement content is 10 kN/m^2, which increases to 145 kN/m^2 at 10% of cement and at 25% cement it becomes 690 kN/m^2. The effect of curing period is more significant at higher percentages of cement content than at lower percentages.

Fig.4.45 shows the variation of cohesion intercept with cement content having an initial water content of 20%. The results are as expected - c value increases with increase in cement content. Fig.4.46 shows the variation of cohesion intercept with cement content for a curing period of 28 days. The figure shows the influence of the initial water content on cohesion intercept. As one would expect, the cohesion intercept decreases with increase in the initial water content. As the water content increases from 10 to 20%, the *c* value reduces to around 50 %, whereas at 25% cement it reduces to around 25%.

Figs.4.47, 4.48 & 4.49 show the influence of the initial water content (i.w.c) and curing periods on the cohesion intercept of grouted medium. The results show that *c* initially increases upto an i.w.c of 5% and then decreases with increase in i.w.c, both for 4% and 10% cement content. The results are as one would expect- the cohesion intercepts decrease with the increase in i.w.c, but the value increases with increase in the curing period. It is to be noted that there is an optimum initial water content at which cohesion intercept is maximum and this happens to be around 7%.

Figs. 4.50 and 4.51 shows the variation of cohesion intercept with cement content in case of coarse sand and fine sand having an i.w.c of 10%. It can be seen from the figures that in both the cases, the *c* value increases with increase in cement content and also with increase in curing periods.

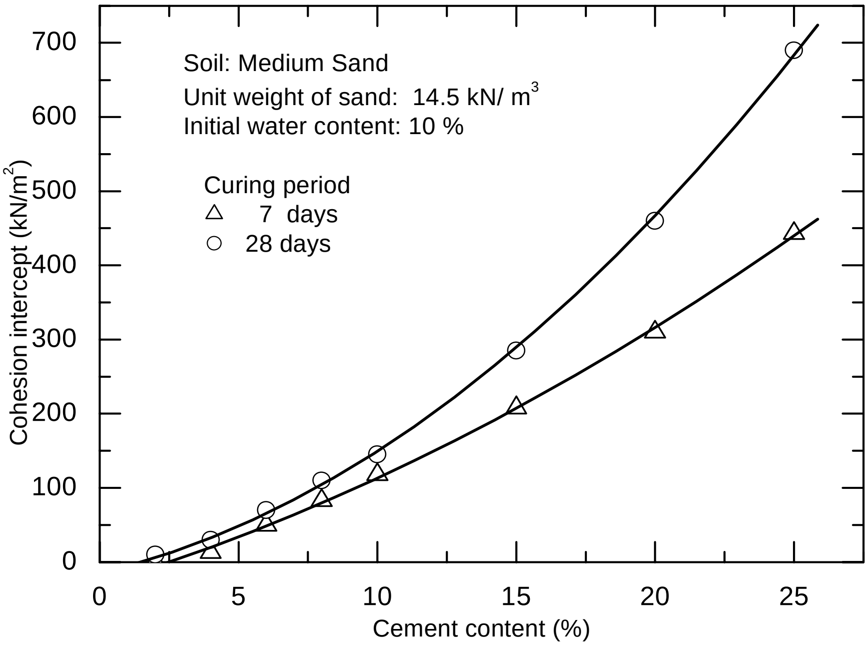


Fig. 4.44 Variation of cohesion intercept with cement content

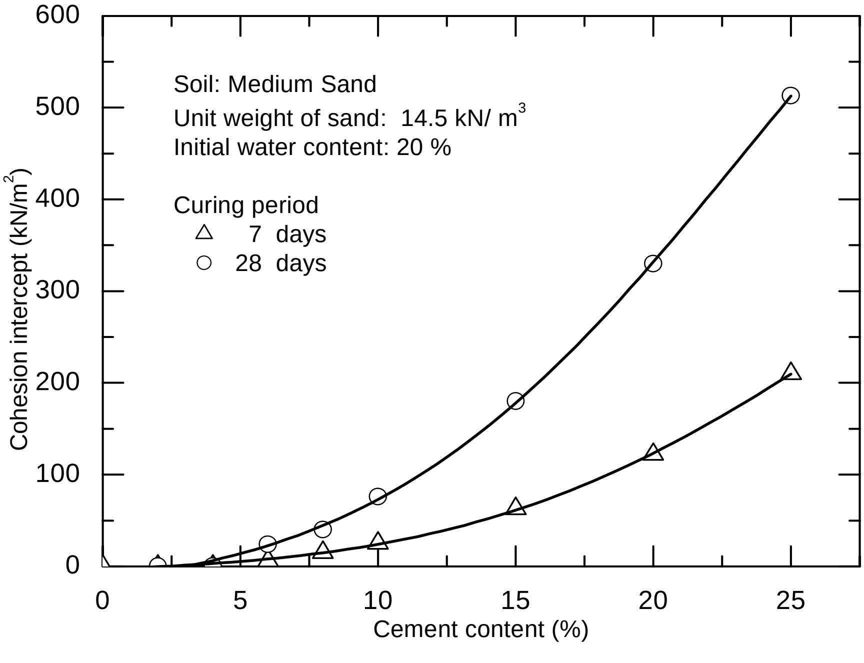


Fig. 4.45 Variation of cohesion intercept with cement content

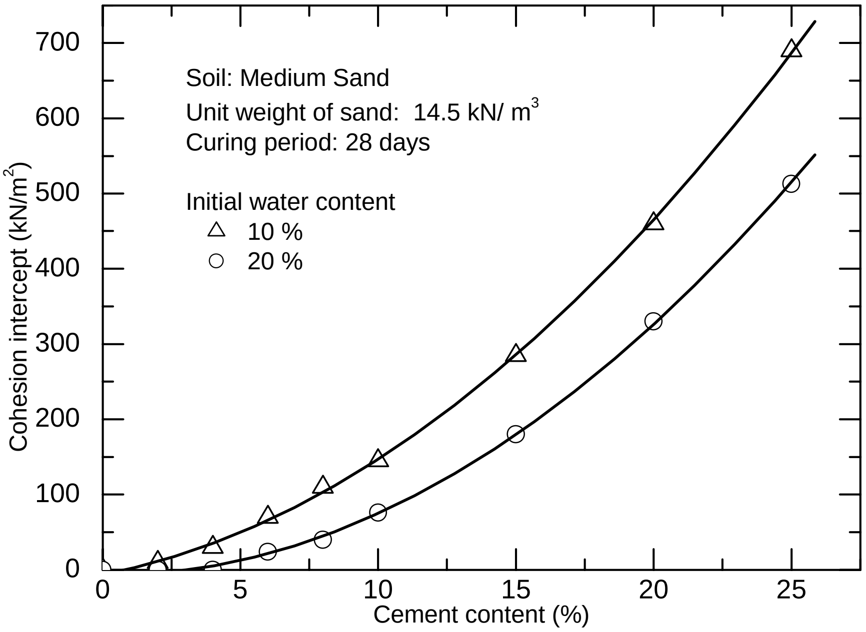


Fig. 4.46 Variation of cohesion intercept with cement content

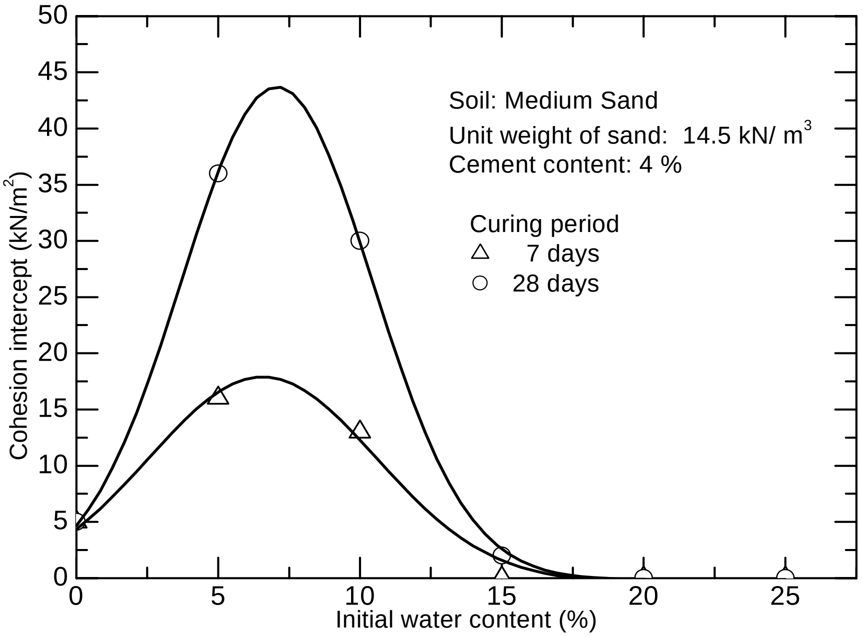


Fig. 4.47 Variation of cohesion intercept with water content

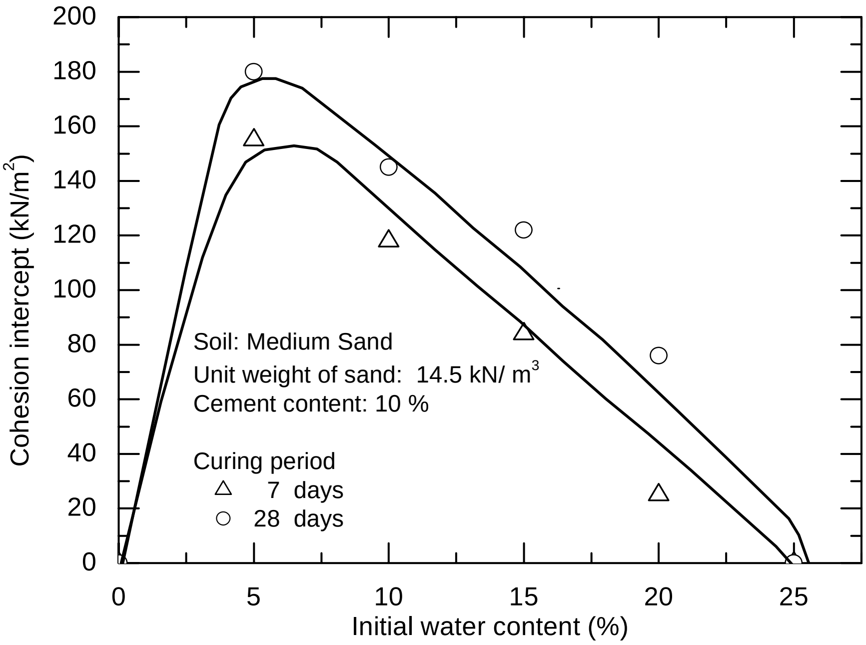


Fig. 4.48 Variation of cohesion intercept with water content

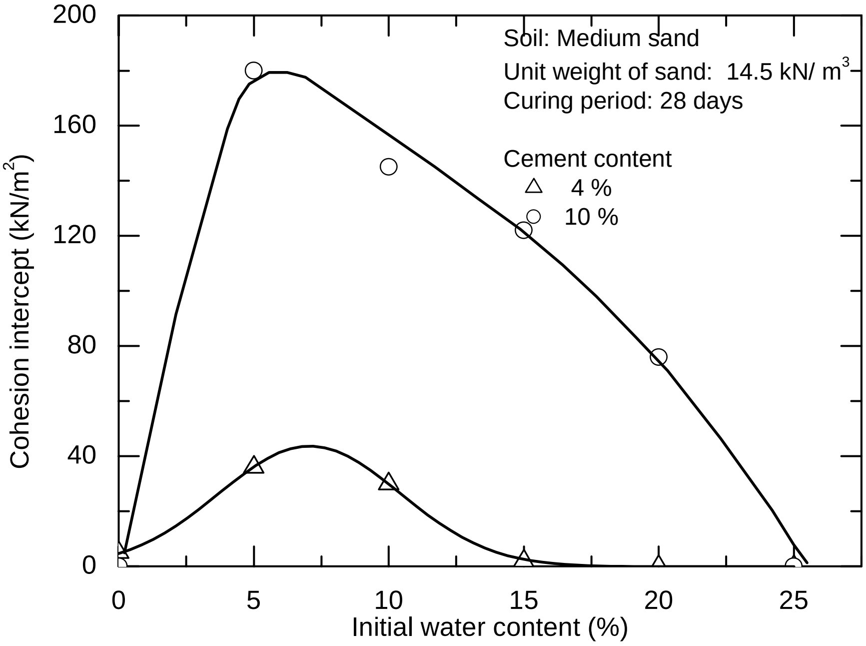


Fig. 4.49 Variation of cohesion intercept with water content

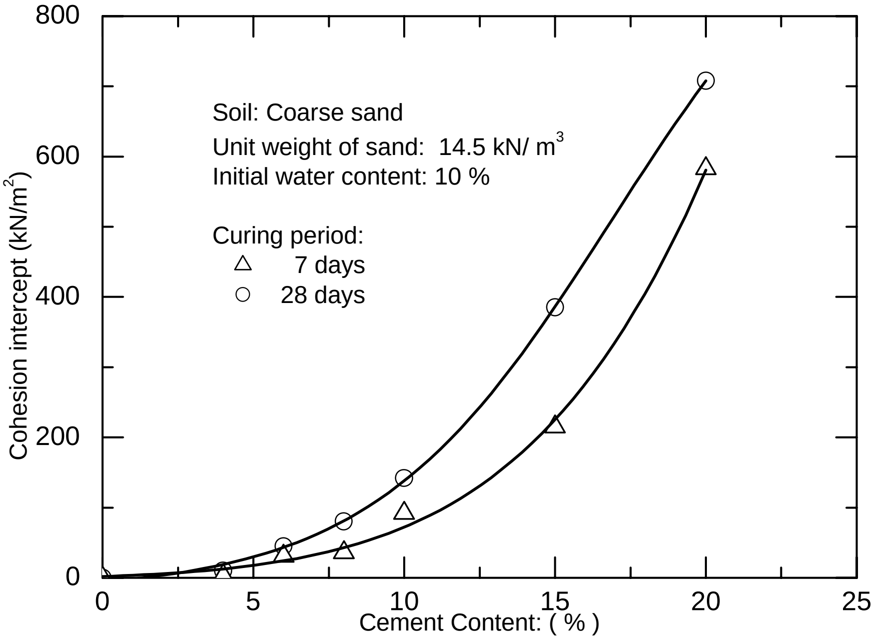


Fig. 4.50 Variation of cohesion intercept with cement content (coarse sand)

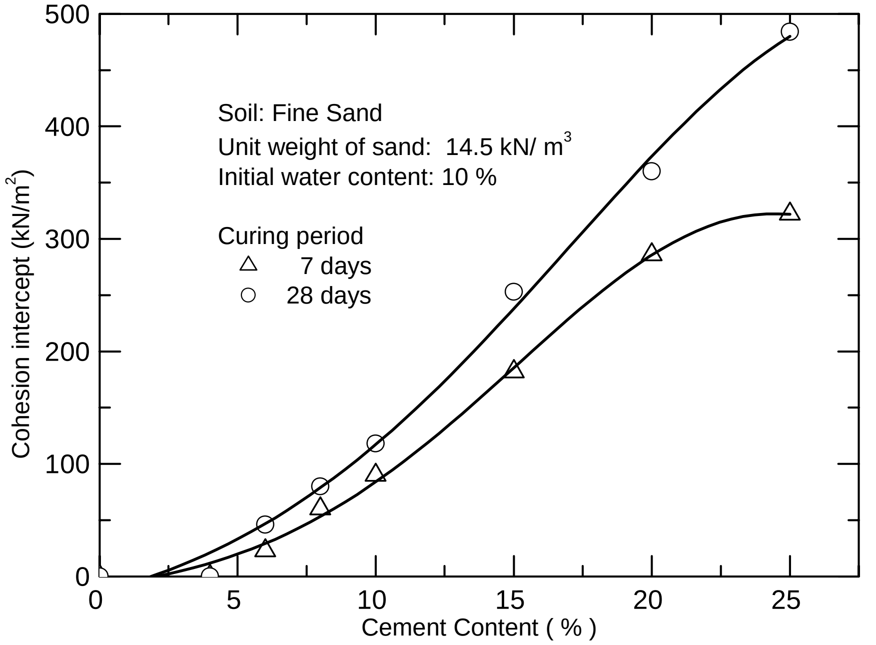


Fig. 4.51 Variation of cohesion intercept with cement content (fine sand)

Fig. 4.52 shows the variation of cohesion intercept with initial water content for fine sand having a cement content of 10%. It is clear from the figure that the c value increases upto an i.w.c. of around 15% and then decreases with further increase in water content.

The variation of the shear strength parameter *c* with cement content for specimens made of medium, coarse and fine sand fractions are shown in figures 4.53. It can be seen that the value of *c* steadily increases with increase in cement content. It can also be seen from the figure that there is not much variation in c value upto cement content of 10%, the rate of increase of c value is substantial with increase in particle size at higher cement contents.

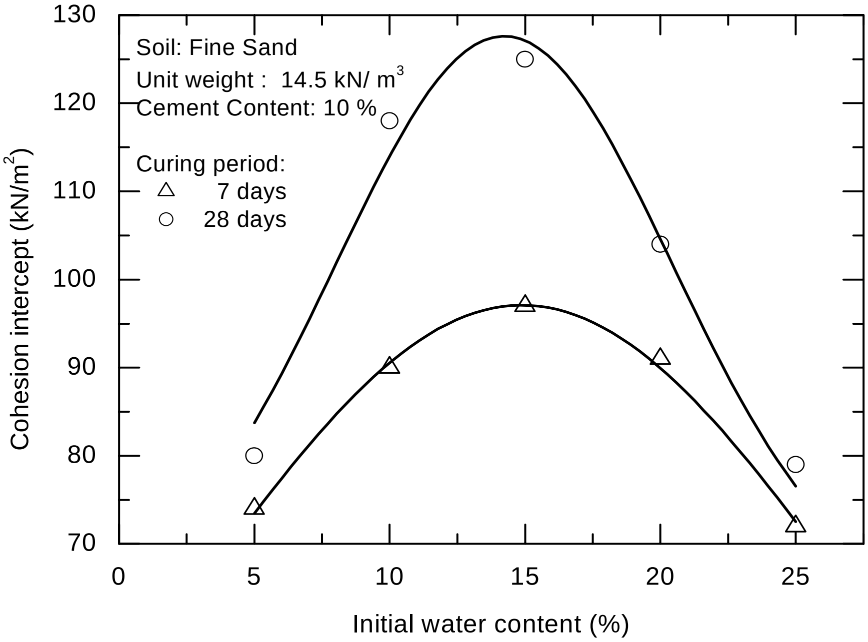
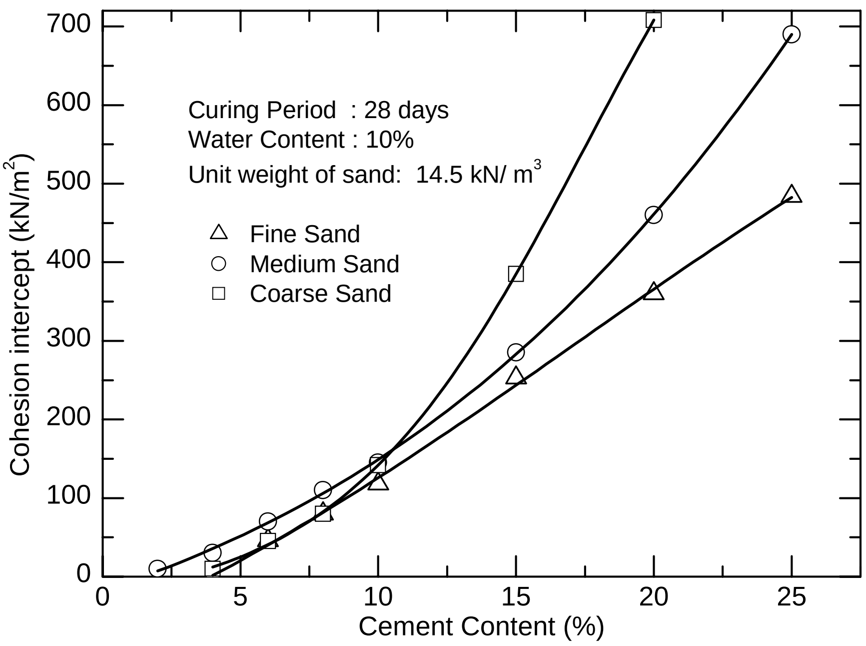


Fig. 4.52 Variation of cohesion intercept with initial water content (fine sand)



4.53 Variation of cohesion intercept with cement content and gradation of sand

4.4.1.2 Cement with admixtures

The effect of calcium chloride (used as accelerator) on shear strength parameter *c* of cement grouted medium having curing periods of 7 & 28 days are presented in fig.4.54. A slight reduction in the *c* value is noted at around 1% of $CaCl_2$, but further increase in percentage of the salt will cause an increase in *c* value.

Fig. 4.55 shows the variation of cohesion intercept with the percentage of sodium silicate added to the cement grout. Addition of this salt causes slight reduction in *c* value after 7days curing. Eventhough the value of cohesion intercept decreases by a very small percentage (approx. 0.5%) after curing of 28 days, it then increases and attains the original value of cohesion intercept without the addition of any admixture.

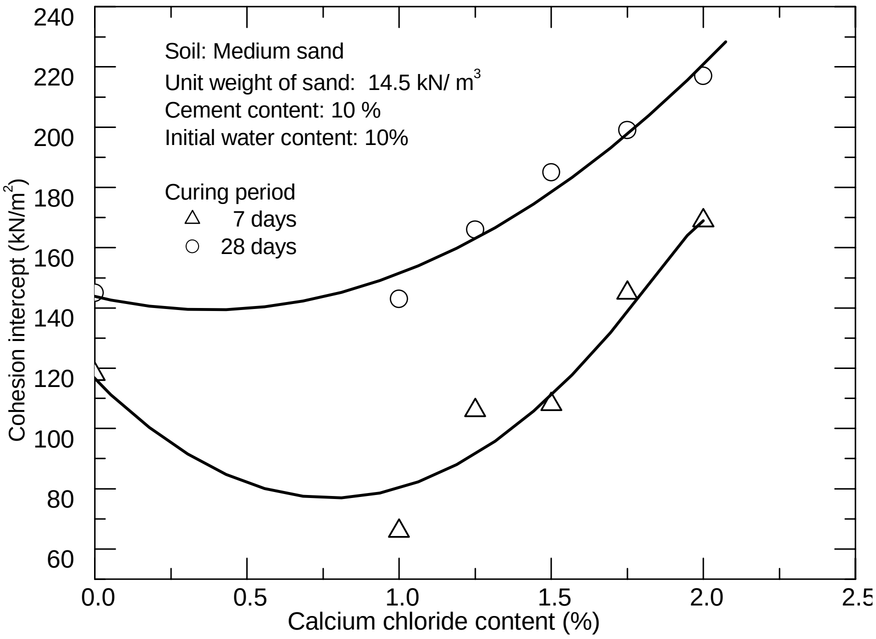


Fig. 4.54 Variation of cohesion intercept with percentage of calcium chloride

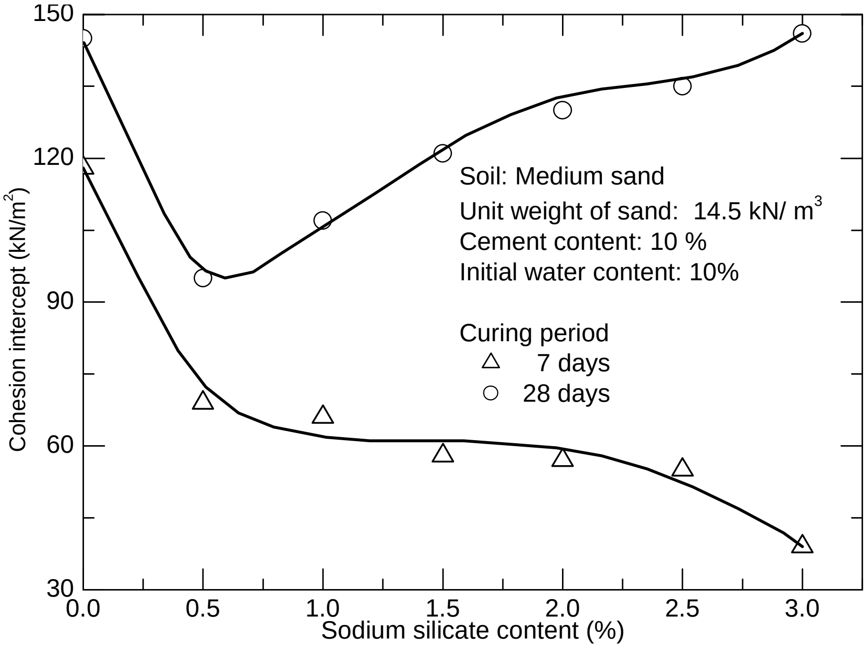


Fig. 4.55 Variation of cohesion intercept with percentage of sodium silicate

Figure 4.56 shows the variation of cohesion intercept when different percentages of these accelerators are used along with cement grout. When sodium silicate is used, eventhough there is slight decrease in *c* value initially, as the percentage increases, the *c* value increases and attains the original value. But in the case of calcium chloride, eventhough there is a slight reduction in *c* value initially (approx 1%) it increases with increase in percentage of calcium chloride added to the cement grout.

The effect of tartaric acid on cohesion intercept is shown fig.4.57. It can be seen that, the cohesion intercept decreases drastically with increase in percentage of tartaric acid in the case of grouted specimens cured for 7 days, whereas for specimens cured for 28 days, the cohesion intercept initially decreases and then increases and even overtakes the initial value with increase in the percentage of tartaric acid. Hence one has to be careful in selecting the dosage when tartaric acid is used as retarder.

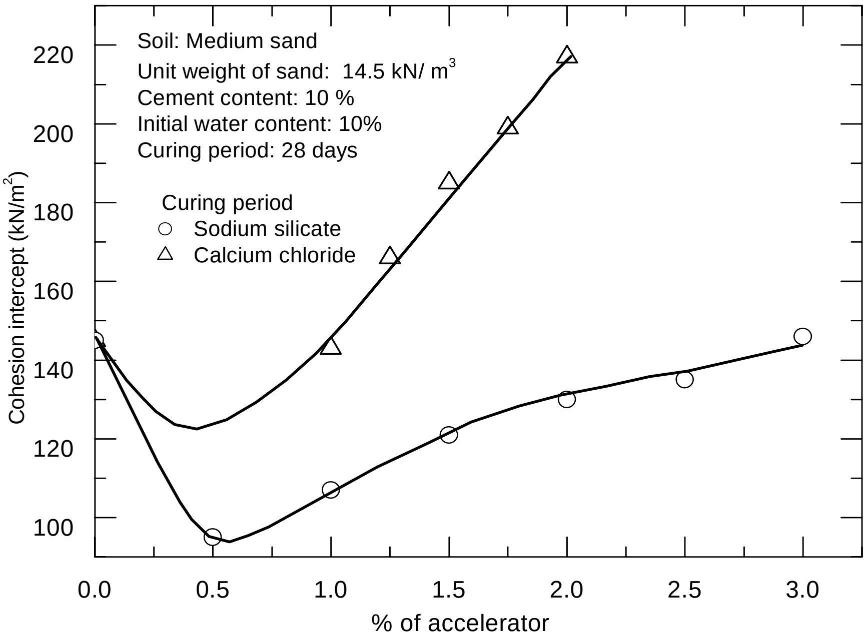


Fig. 4.56 Variation of cohesion intercept with percentage of Accelerators

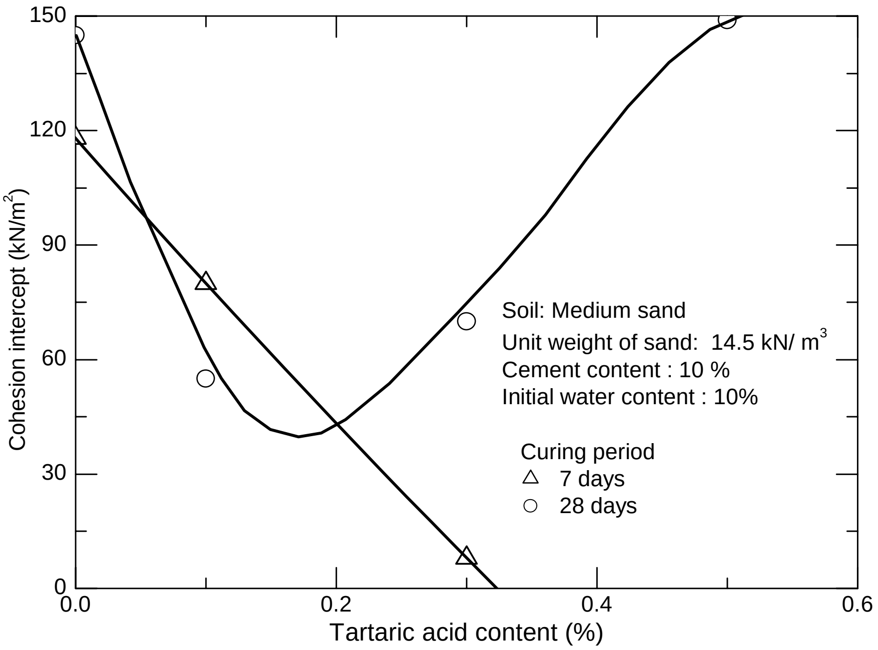


Fig. 4.57 Variation of cohesion intercept with percentage of tartaric acid

The variation of cohesion intercept with percentage of triethanolamine is presented in fig. 4.58. Eventhough there is considerable reduction in the cohesion intercept with increase in percentage of the salt on 7 days of curing, there is an initial increase in cohesion intercept (at around 2%) and as the percentage of the salt increases there is a marginal reduction in cohesion intercept, but not below the original value.

Fig. 4.59 shows the variation of cohesion intercept with the different percentage of retarders when used along with cement grout. It can be seen that there is no reduction in strength when the optimum dosage with respect to viscosity reported in literature (tartaric acid- 0.05 % and triethanolamine 2 to 10 %) of the retarder is used.

Fig. 4.60 shows the effect of detergent (used as fluidiser) on cohesion intercept of cement grouted sand cured for 7 & 28 days. Eventhough the cohesion intercept remains almost constant with percentage of detergent in case of specimens cured for 7 days, there is marginal reduction for specimens cured for 28 days. Here also one has to be selecting the optimum dosage of the detergent.

Fig. 4.61 shows the effect of aluminium powder (expander) on cohesion intercept of the grouted medium for a cement content of 10%. From the figure, it is clear that, as far as the strength is concerned there is an optimum dosage (0.005 %) irrespective of the curing period. Further, detergent percentage will not adversely affect the strength of the cement grouted medium as seen from the graph for a curing period of 28 days.

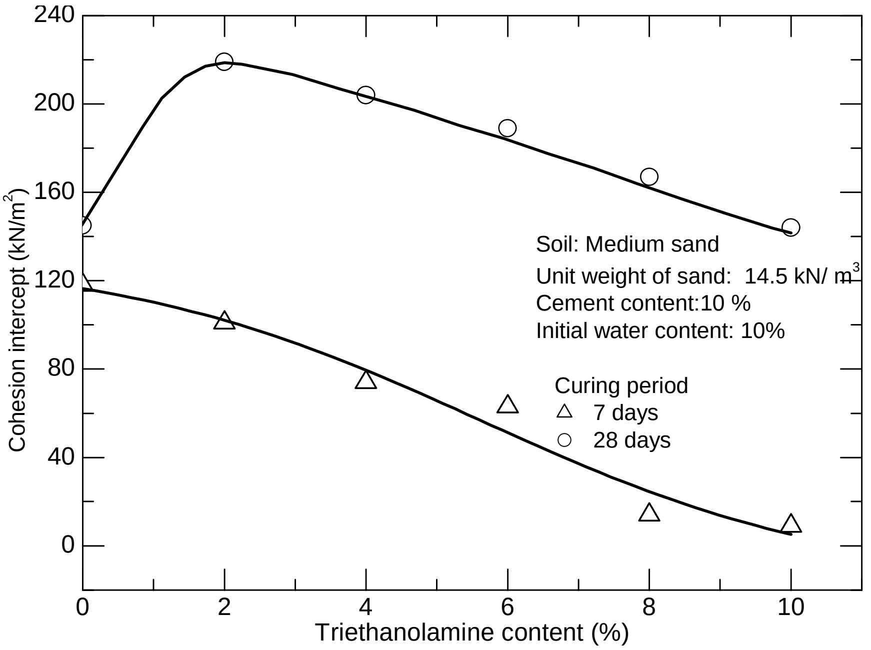


Fig. 4.58 Variation of cohesion intercept with percentage of triethanolamine

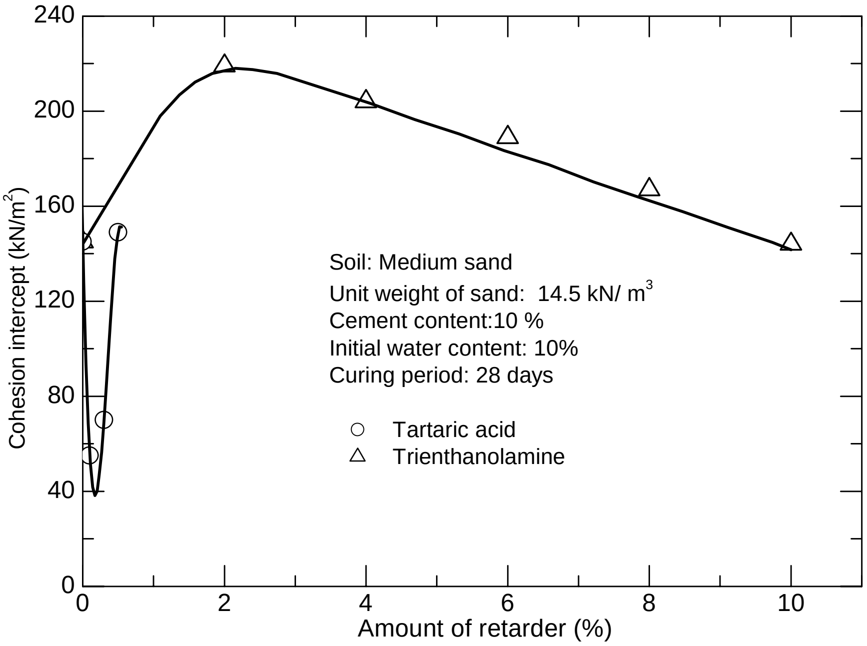


Fig. 4.59 Variation of cohesion intercept with percentage of retarders

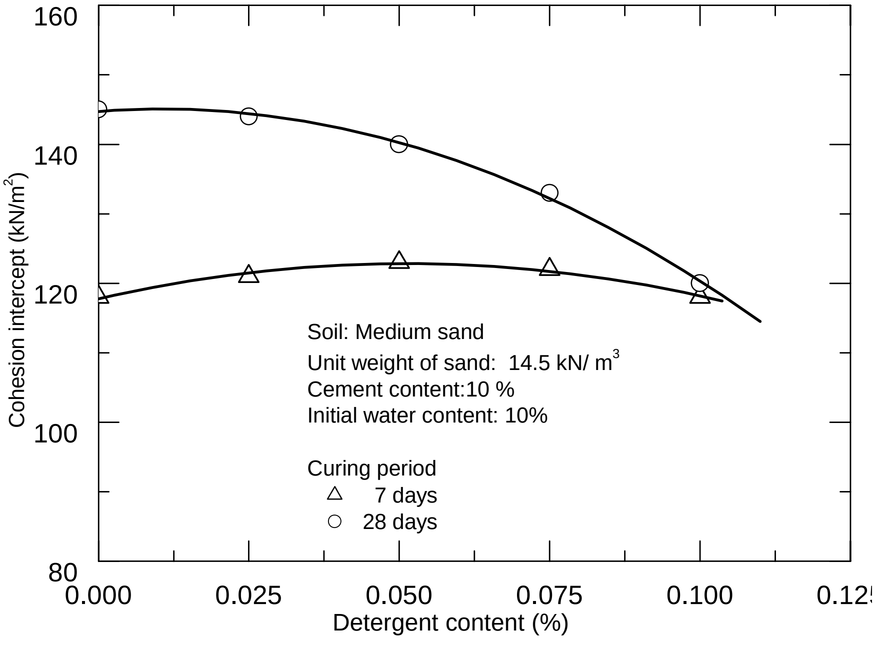


Fig. 4.60 Variation of cohesion intercept with percentage of detergent

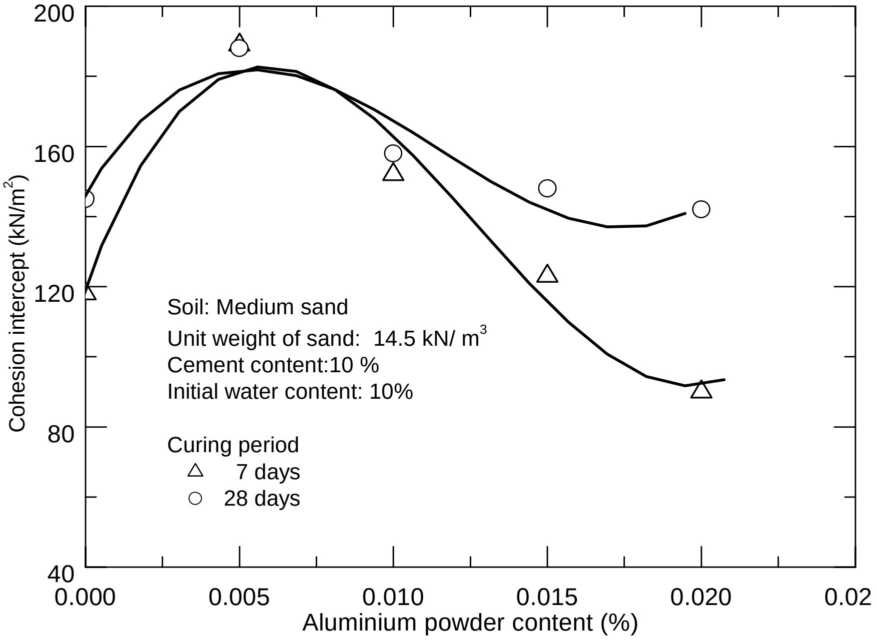


Fig. 4.61 Variation of cohesion intercept with percentage of aluminium powder

Fig. 4.62 shows the variation of cohesion intercept with percentage of aluminium sulphate (used as antibleeder) in the cement grout. Eventhough there is a marginal decrease in cohesion initially (at around 2%), increase in percentage of aluminium sulphate increases the cohesion intercept. The plot also shows the effect of curing, which is significant in the case of aluminium sulphate.

Fig. 4.63 shows the variation of cohesion intercept with bentonite content in the cement grout, the initial water content of the sand- cement-bentonite mixture being 10%. Eventhough there is a slight improvement in cohesion intercept after an initial reduction for specimens cured for 7 days; it goes on decreasing with bentonite content in case of specimens cured for 28 days.

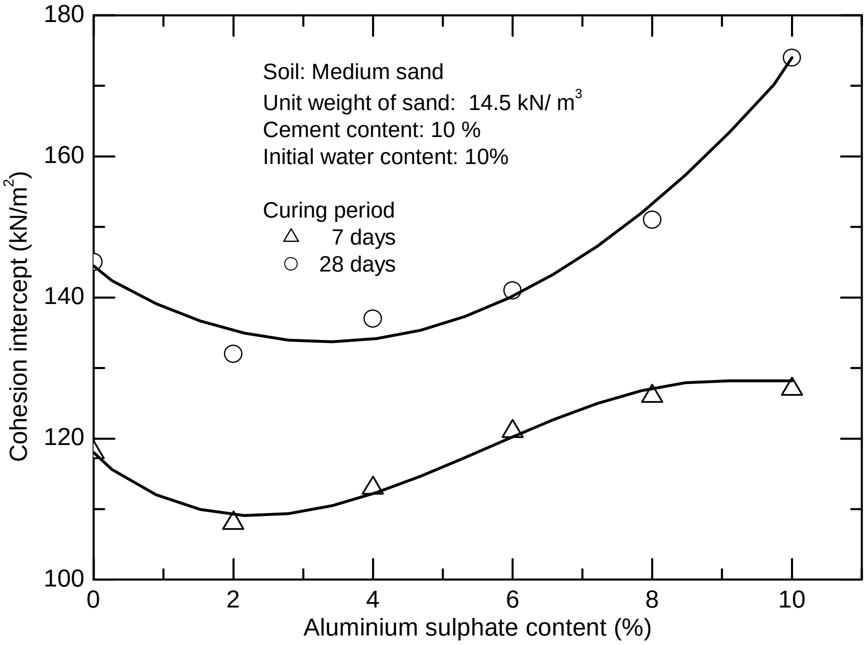


Fig. 4.62 Variation of cohesion intercept with percentage of aluminium sulphate

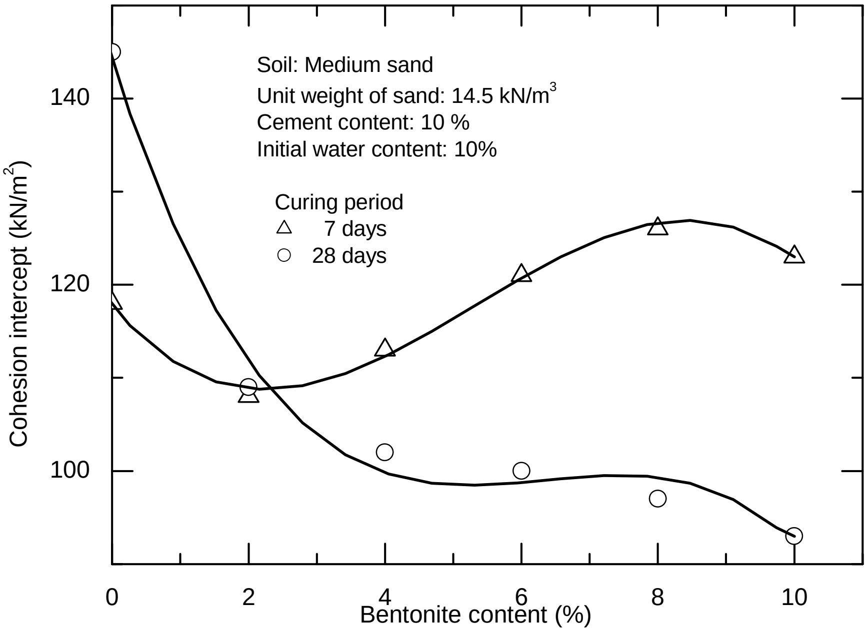


Fig. 4.63 Variation of cohesion intercept with bentonite content

Fig. 4.64 also shows the effect of bentonite on cohesion intercept of the grouted medium for a cement content of 10% , the initial water content being 20%, cured after 28 days. The effect of bentonite is initially to increase in cohesion (at 2%) around 32%, whereas when the percentage of bentonite increases, decrease in cohesion is around 30%. Eventhough the variation is similar as the above case for specimens cured for 7 days, there is not much reduction in the cohesion intercept in case of specimens cured for 28 days.

A comparison between the effects of these two antibleeders ie, aluminium sulphate and bentonite on the cohesion intercept is given in Fig. 4.65. The effect of aluminium sulphate is to increase the cohesion whereas addition of bentonite causes a reduction in the value of cohesion.

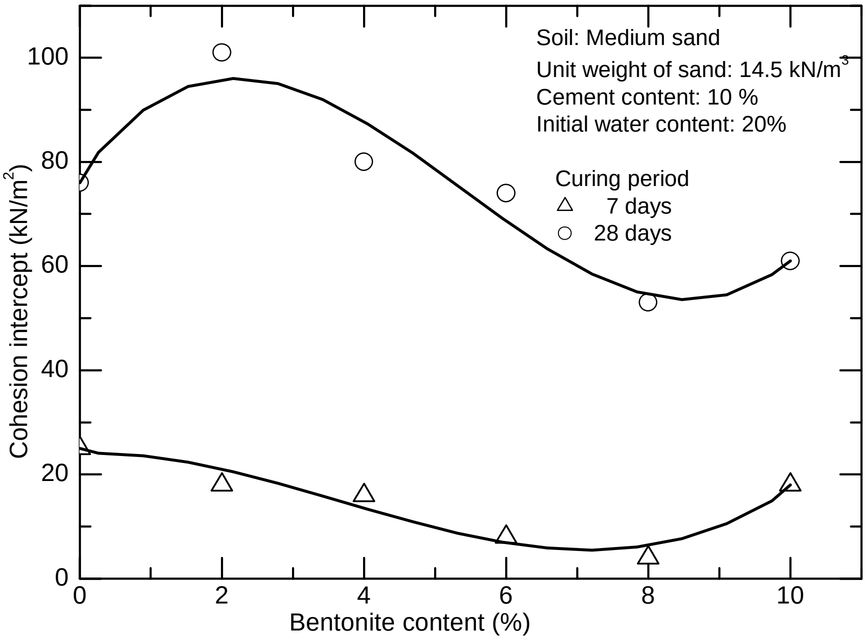


Fig. 4.64 Variation of cohesion intercept with bentonite content

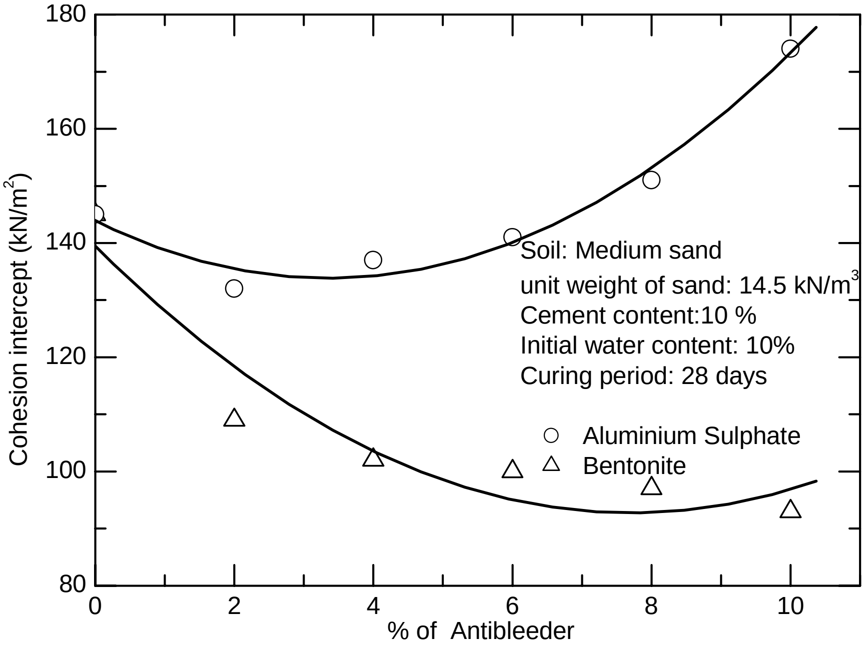


Fig. 4.65 Variation of cohesion intercept with percentage of antibleeders

4.4.1.3Lime

The variation of cohesion intercept with lime content incase of specimens prepared at an initial water content of 10 % is presented in fig. 4.66. It can be seen that cohesion increases with increase of lime content. The marginal increase in cohesion during curing is also shown in the figure. Fig. 4.67 shows the variation of cohesion intercept with lime content having an initial water content of 20%. At lower percentages of lime content (upto 8%), no significance in cohesion intercept is seen. The effect of initial water content on cohesion intercept is shown in fig. 4.68. It can be seen that the cohesion intercept decreases with increase in initial water content.

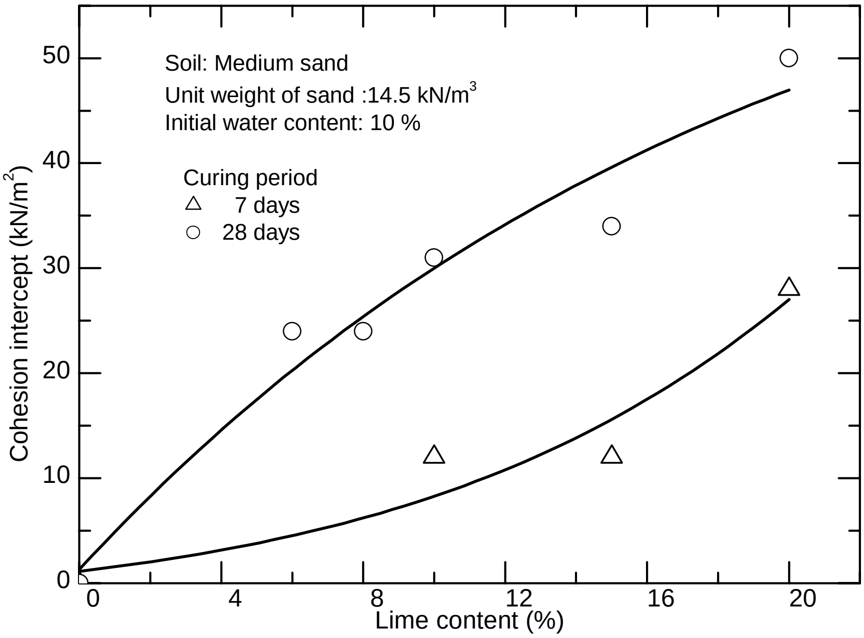


Fig. 4.66 Variation of cohesion intercept with lime content

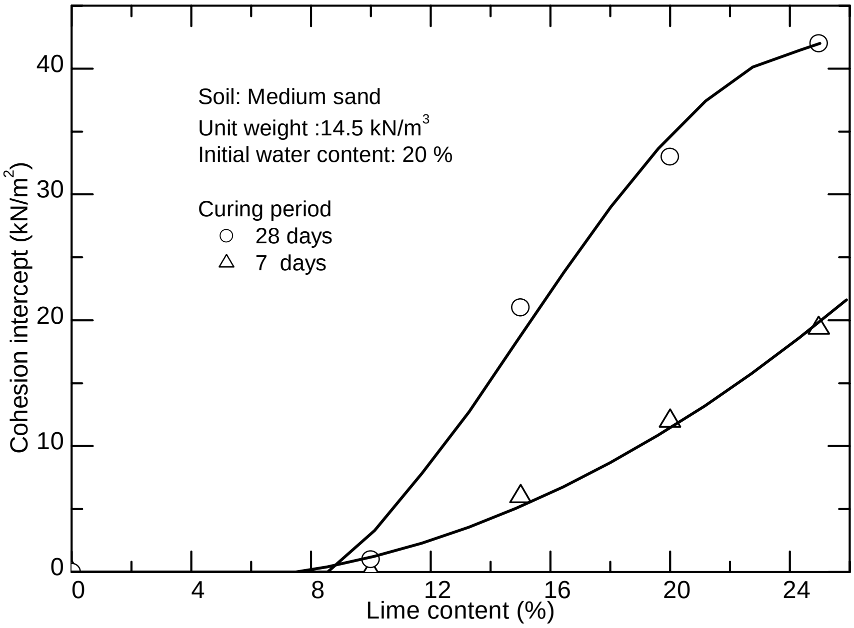


Fig. 4.67 Variation of cohesion intercept with lime content

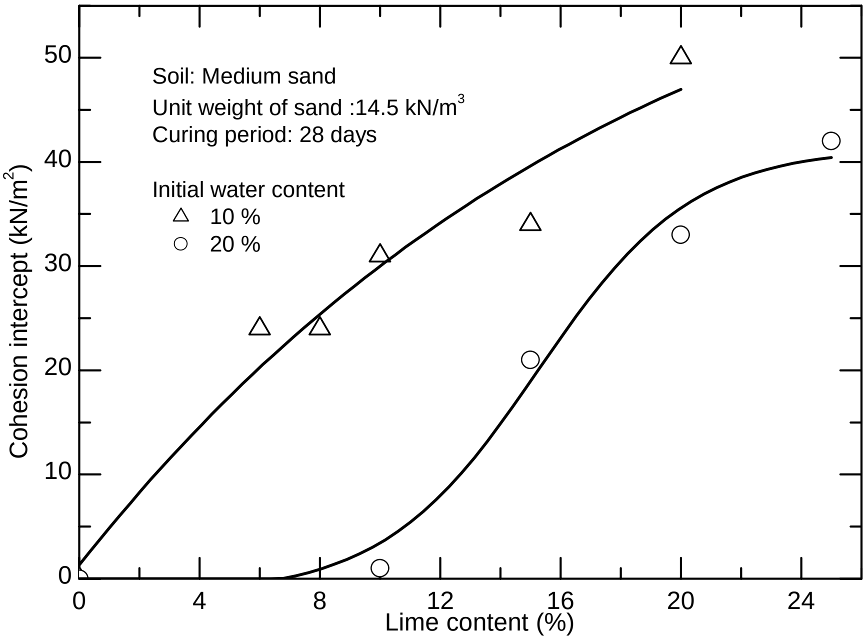


Fig. 4.68 Variation of cohesion intercept with lime content

Fig. 4.69 shows the variation of cohesion intercept with percentage of bentonite, grouted with 10% lime having an initial water content of 10%. After an initial reduction, the cohesion intercept goes on increasing with increase in bentonite content. The effect of the two suspension grout materials i.e. cement and lime on the cohesion intercept is presented in Figs. 4.70 and 4.71. The superiority of cement compound to lime as a grout material irrespective of the initial water content is quite clear from these figures.

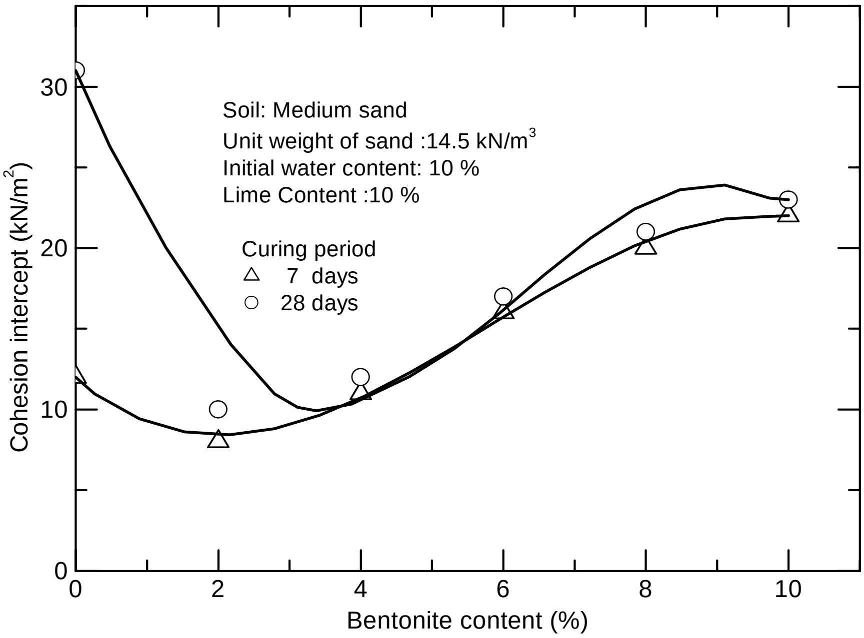


Fig. 4.69 Variation of cohesion intercept with bentonite content

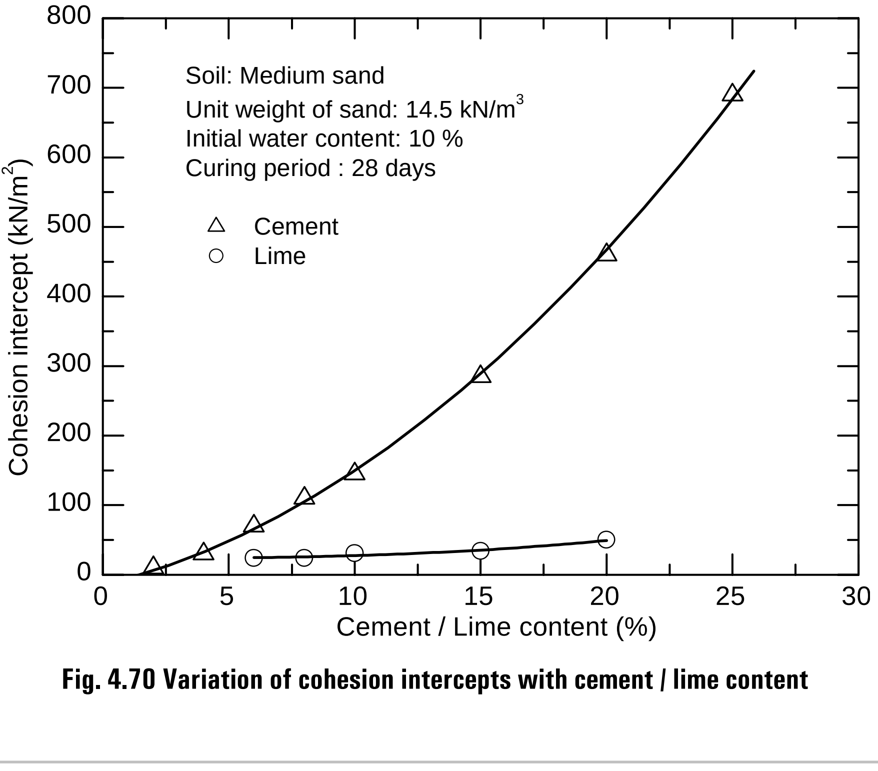


Fig. 4.70 Variation of cohesion intercepts with cement / lime content

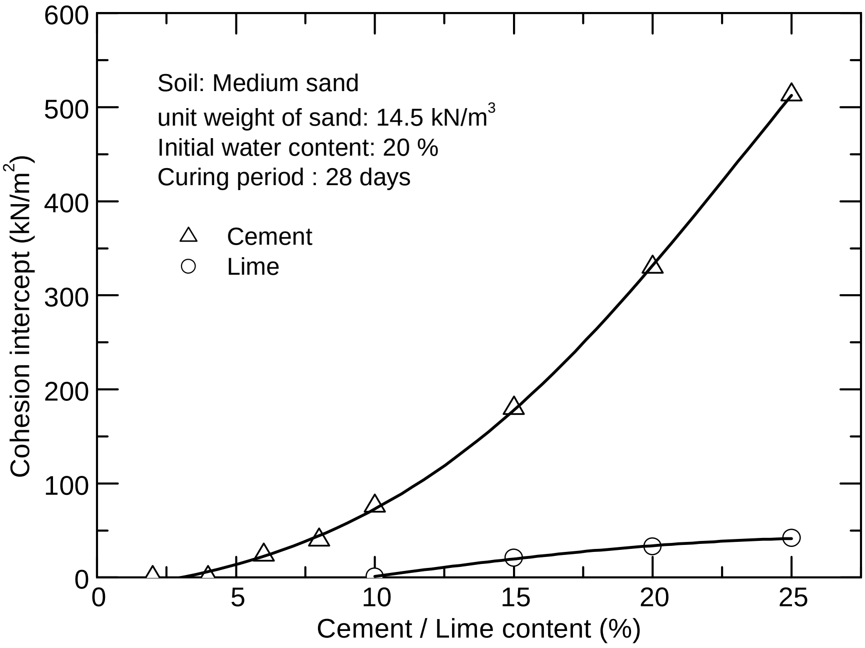


Fig. 4.71 Variation of cohesion intercepts with cement / lime content

4.4.2 Angle of shearing resistance

The contributions of inter-particle friction and particle interlocking to the behaviour are relatively more important at high unit weights, and the contribution of the cementation is relatively more important at low unit weights. (Huang, and Airey, 1998). Grouting is mainly responsible for the gain in cohesion by the material and only marginally affects the friction angle. The increase in angle of friction is negligible with respect to cohesion (Maalej et al. 2007).

4.4.2.1 Grouted with cement alone

Fig. 4.72 shows the variation in the shear strength parameter Ø with cement content. Eventhough the Ø value increases with increase in cement content, the rate decreases beyond a certain value of cement content (approx. 15%). The Ø at 4% of cement content is 40 degrees, and increases to 50 degrees at 8% of cement and at 25% cement it becomes 68 degrees. Fig. 4.73 also shows the variation in the shear strength parameter Ø with cement content having an initial water content of 20%. The Ø value increases with cement content, but beyond 15% of cement content the rate of increase is marginal.

Another interesting observation is that the value of Ø increases with increase in water content, which is not in line with the variation of *c* value, which is clearer from the subsequent figure 4.74.

Figs. 4.75 & 4.76 show the effect of the initial water content and curing periods on the Ø value of grouted medium. The shear strength parameter Ø increases with curing periods and increases with i.w.c. Fig. 4.77 shows the variation of Ø with initial water content. It can be seen that the variation of Ø increases with increase in i.w.c and % of cement content.

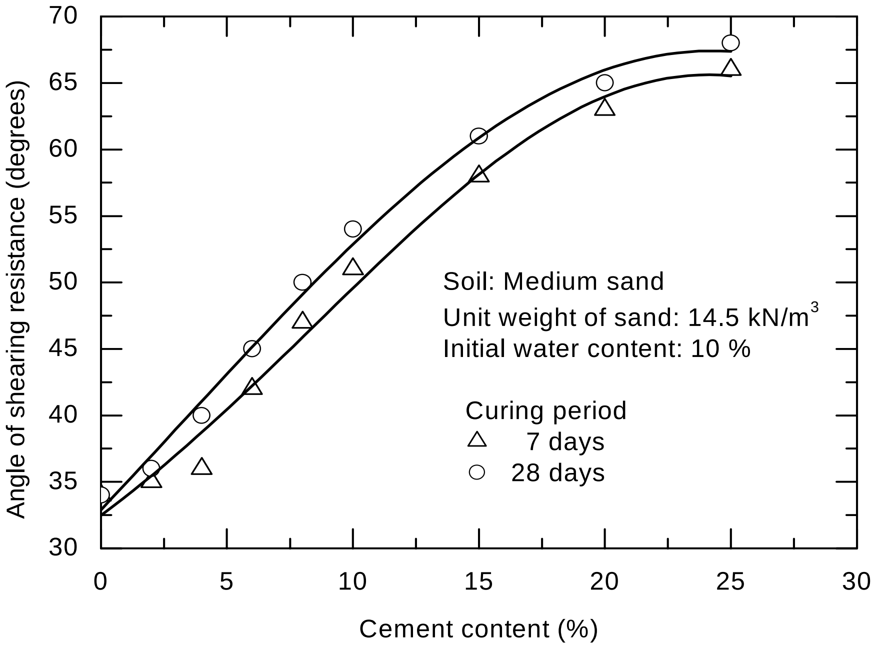


Fig.4.72 Variation of angle of shearing resistance with cement content

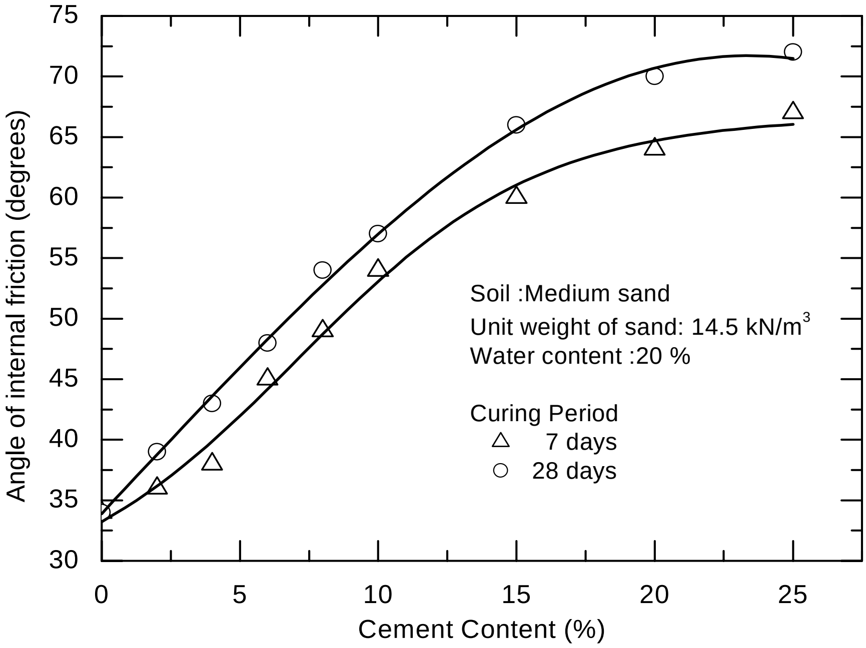


Fig. 4.73 Variation of angle of shearing resistance with cement content

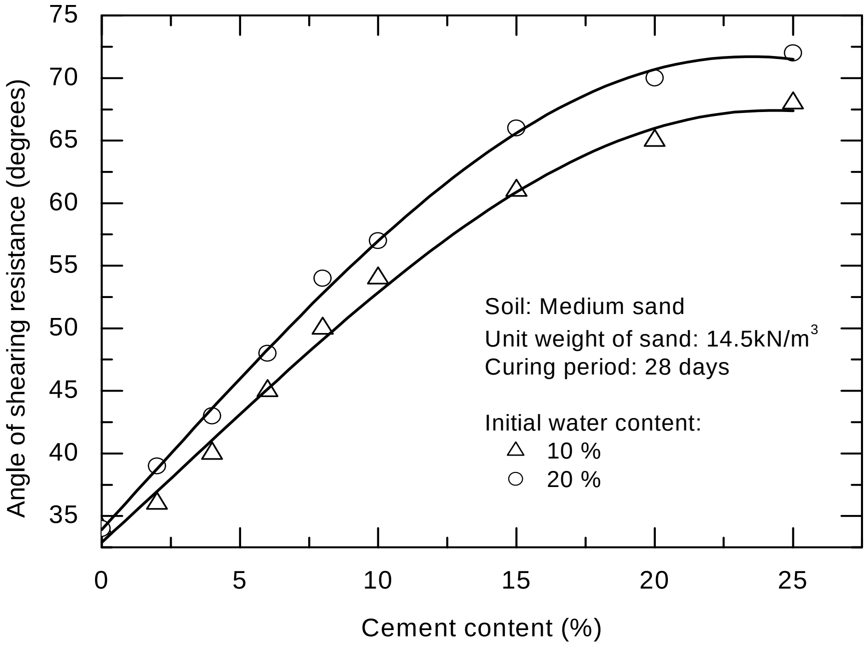


Fig. 4.74 Variation of angle of shearing resistance with cement content

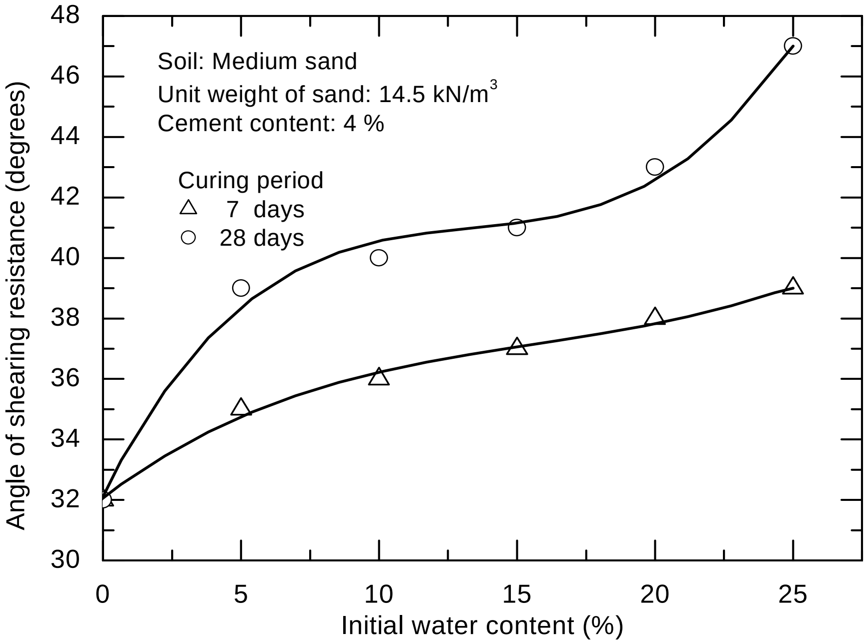


Fig. 4.75 Variation of angle of shearing resistance with water content

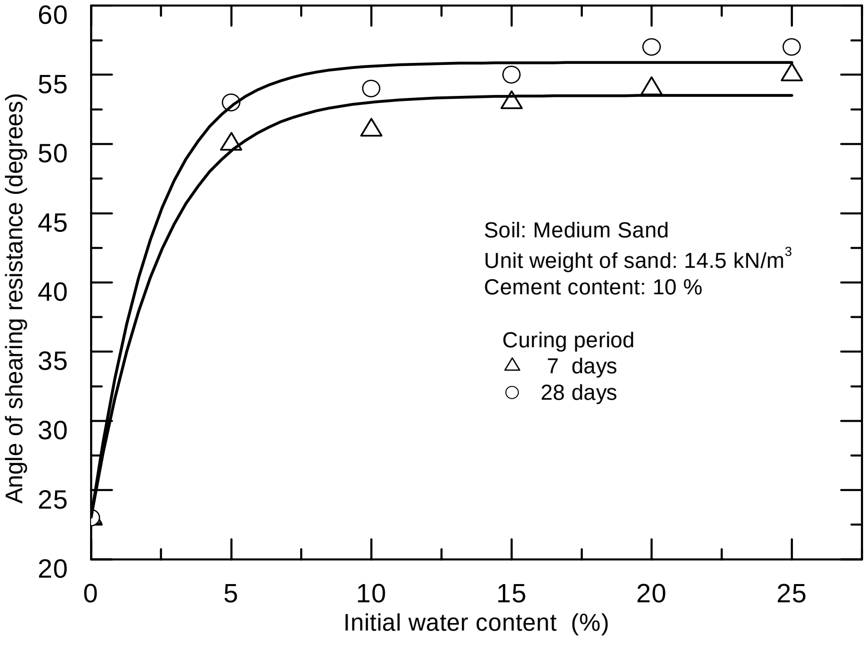


Fig.4.76 Variation of angle of shearing resistance with water content

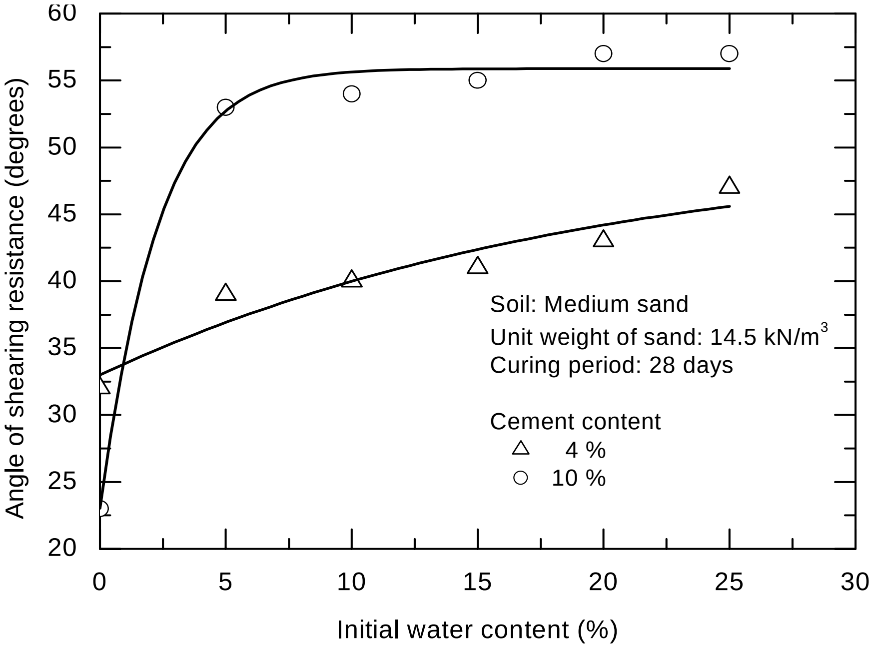


Fig. 4.77 Variation of angle of shearing resistance with water content

The effect of cement content on Ø-value of cement grouted coarse sand is presented in fig. 4.78. In the case of specimens cured for 7 days, the increase in Ø-value is linear with increase in cement content. But in specimens cured for 28 days eventhough the linear increase in Ø-value is marginal with cement content upto a certain cement content (approx. 15%), the rate of increase is marginal thereafter.

The variation in Ø-value with cement content of fine sand is shown in fig. 4.79. Here also the Ø-value increases with increase in cement content and curing periods.

Fig. 4.80 shows the effect of the initial water content and curing periods on the Ø- value of cement grouted fine sand. The Ø- value increases upto an initial water content of 10-15% and further increase of water content decreases the Ø- value. These curves are similar to the compaction curve for soils i.e., there is an optimum value of initial water content of the grout with regard to the value of angle of shearing resistance.

Fig. 4.81 shows the variation of angle of shearing resistance with cement content for various gradations of the grouting medium. As expected, the Ø-value increases with gradation of sand and cement content.

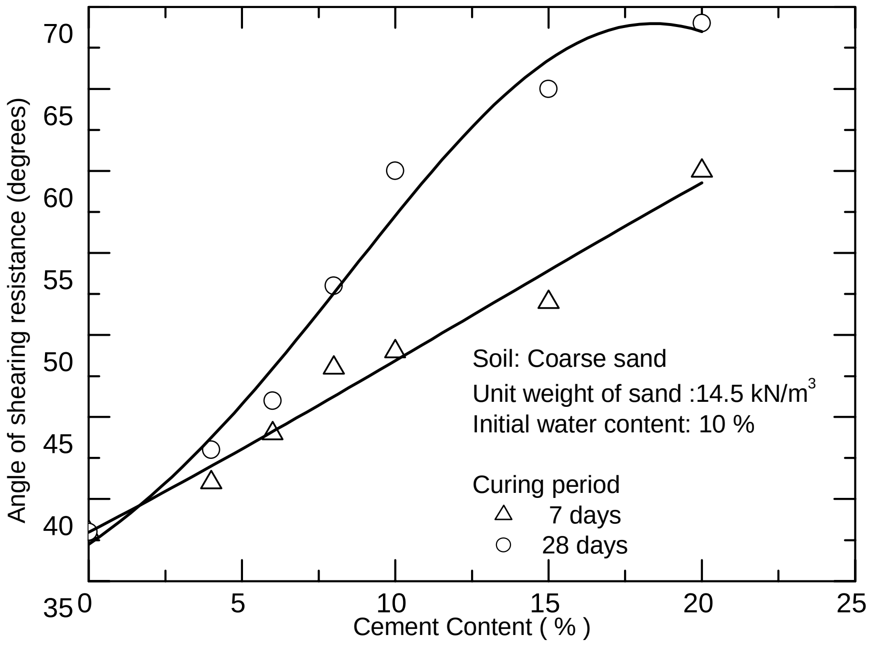


Fig. 4.78 Variation of angle of shearing resistance with cement content (coarse sand)

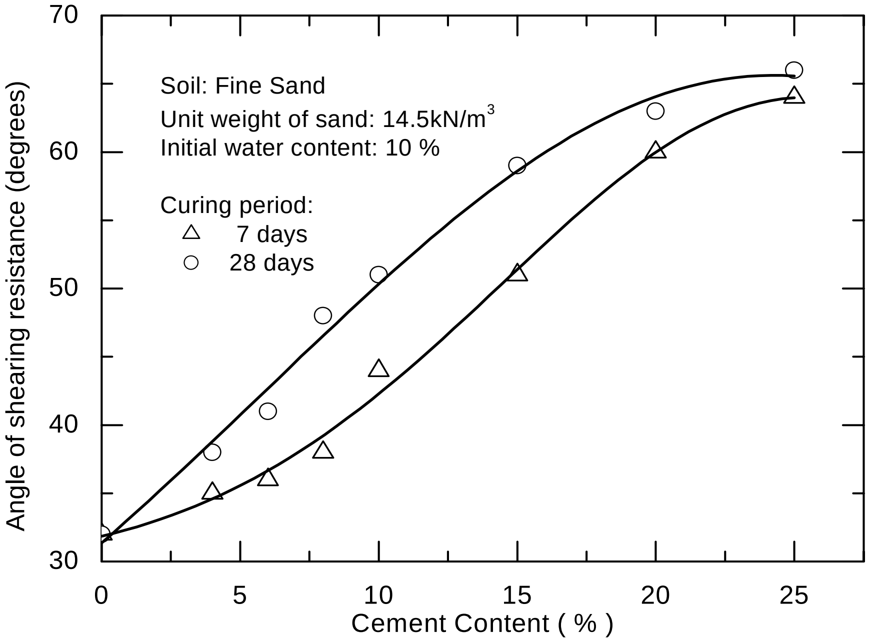


Fig. 4.79 Variation of angle of shearing resistance with cement content (fine sand)

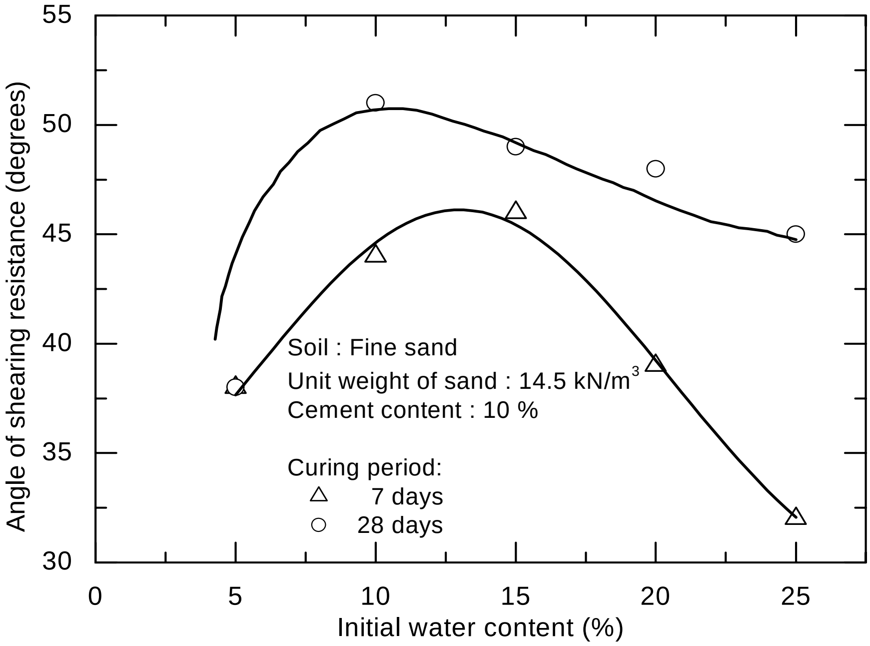


Fig. 4.80 Variation of angle of shearing resistance with initial water content (fine sand)

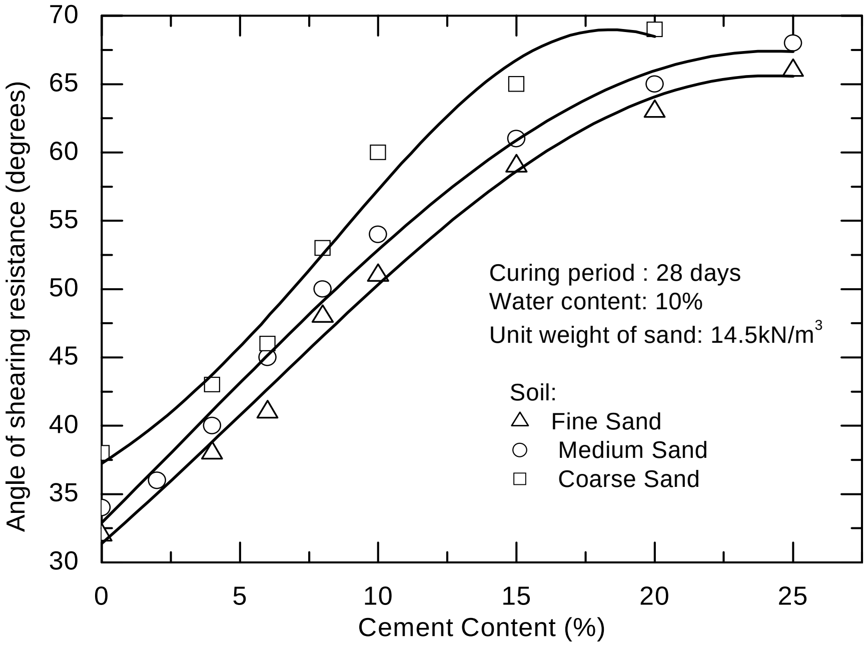


Fig. 4.81 Variation of angle of shearing resistance with cement content

4.4.2.2 Cement with admixtures

Fig. 4.82 shows the variation of Ø- value with percentage of calcium chloride (used as accelerator). It can be seen that after a marginal initial increase (at around 1%), the Ø- value decreases in the case of specimens cured for 7 days whereas in the case of specimens cured for 28 days, the value continuously decreases with increase in the calcium chloride content. Eventhough there is a decrease in angle of shearing resistance, the greater increase in cohesion intercept results in increased shear strength.

Fig. 4.83 shows the variation of Ø- value with percentage of sodium silicate which is also used as an accelerator. In this case also there is a reduction in Ø- value with increase in the percentage of sodium silicate. It can be seen from the figure that, at higher percentages of the salt, the curing period does not have much effect on the Ø- value.

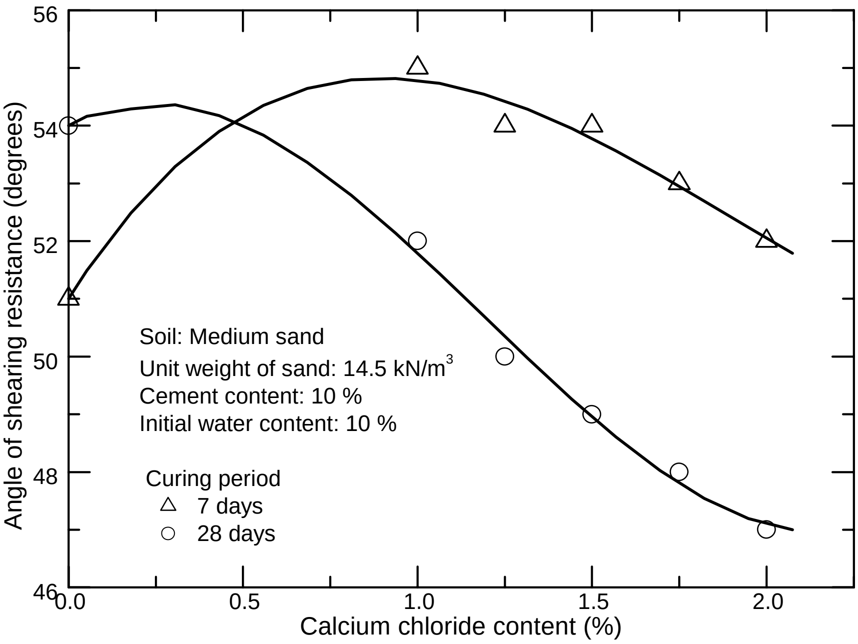


Fig.4.82 Variation of angle of shearing resistance with percentage of calcium chloride

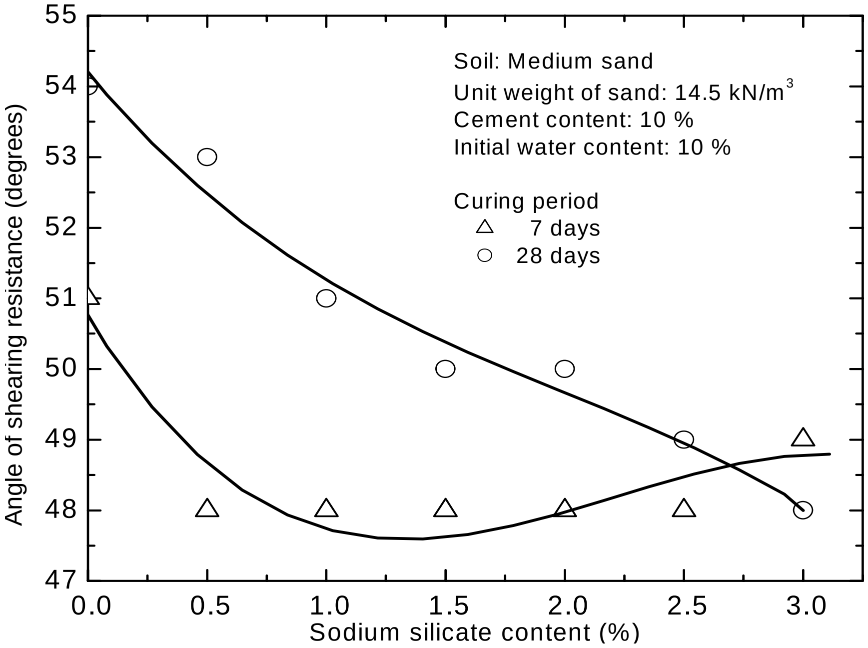


Fig.4.83 Variation of angle of shearing resistance with percentage of sodium silicate

The variation of Ø- value with percentage of accelerator is shown in fig. 4.84. In both cases, Ø- value decreases with the increase in percentage of the salt. The reduction in Ø- value is more, with the addition of Calcium Chloride compared to Sodium Silicate.

But these small reductions in Ø- value is compensated by the increase in the cohesion intercept which is reflected on the shear strength values.

Fig. 4.85 shows the variations of Ø- value with percentage of tartaric acid, which is used as retarder. The angle of shearing resistance remains almost constant initially, but there is marginal decrease in the value with increase in the percentage of tartaric acid specimens cured for 28 days.

The effect of triethanolamine (also used as retarder) on Ø- value is presented in fig. 4.86. The marginal reduction in angle of shearing resistance is compensated by the increase in cohesion intercept and it can be concluded that this admixture will also cause no reduction in shear strength.

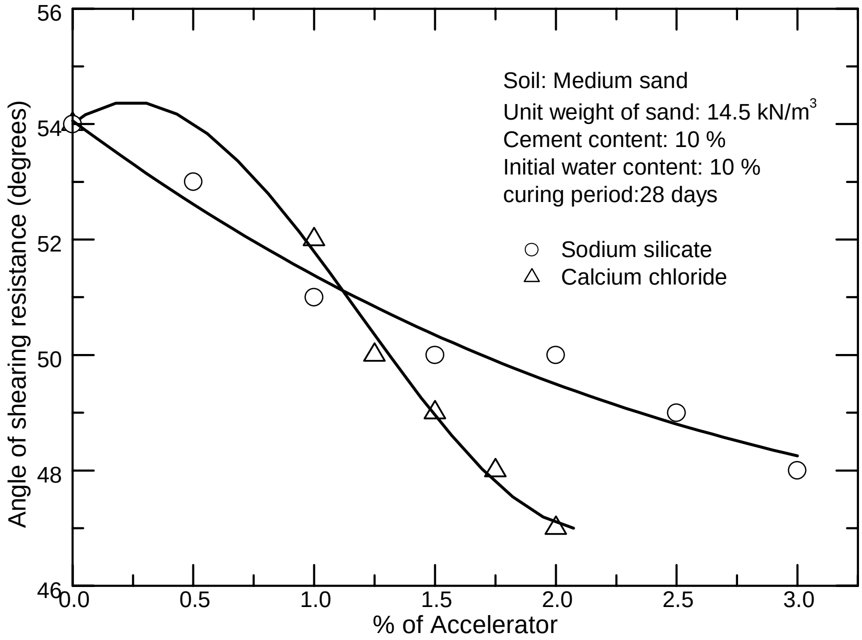


Fig.4.84 Variation of angle of shearing resistance with percentage of accelerator

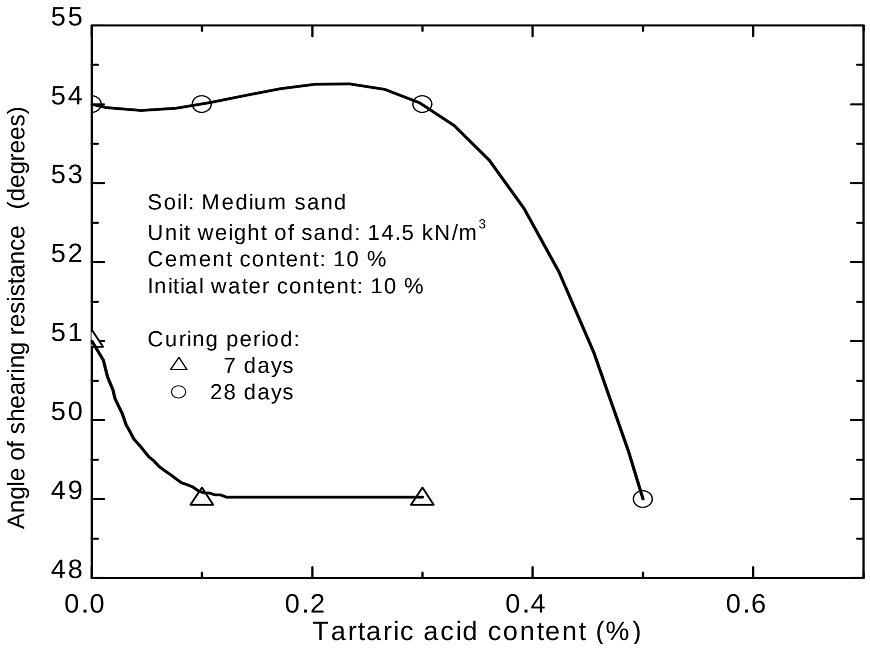


Fig.4.85 Variation of angle of shearing resistance with percentage of tartaric acid

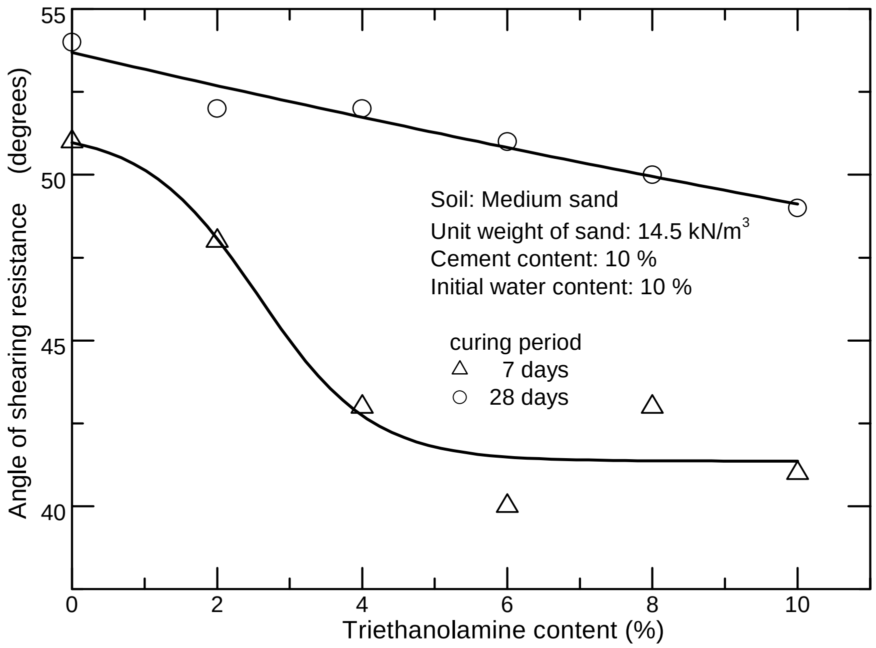


Fig.4.86 Variation of angle of shearing resistance with percentage of triethanolamine

Fig. 4.87 gives a comparison between the two retarders- its effect on the Ø- value. Even the addition of very small percentage of tartaric acid (around 0.5%) brings down the Ø- value by 10%, the same amount of reduction is experienced only at high percentages (8 to 10%) of triethanolamine. Hence one has to be very careful in the use of tartaric acid as a retarder along with cement grouts.

Fig. 4.88 shows the effect of percentage of detergent on Ø- value of cement grouted sand. The Ø- value increases upto 0.05% of detergent, whereas further increase of this admixture, decreases in the Ø- value of cement grouted sand. It can also be seen that the curing periods has very little effect on the Ø- value, the trend remaining the same.

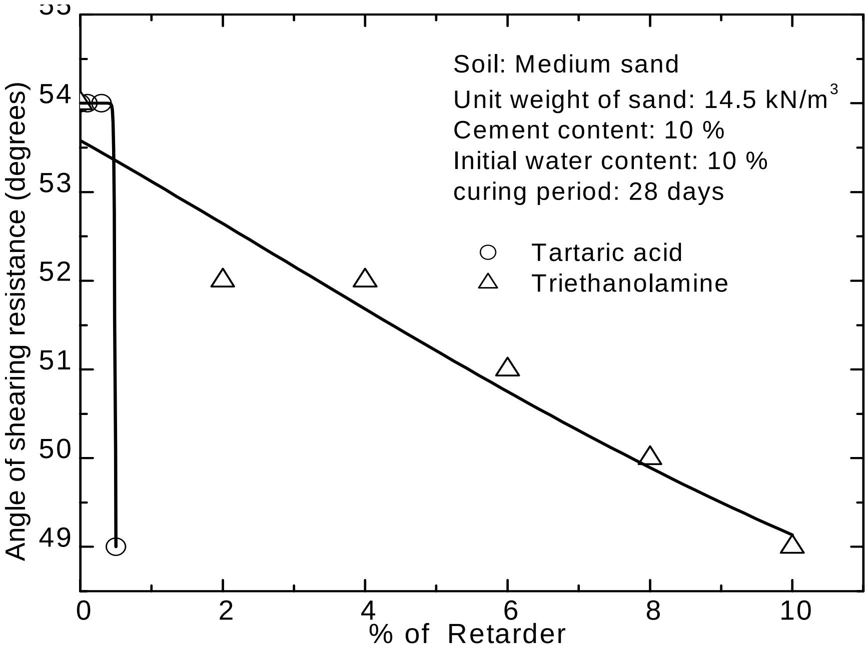


Fig.4.87 Variation of angle of shearing resistance with retarder

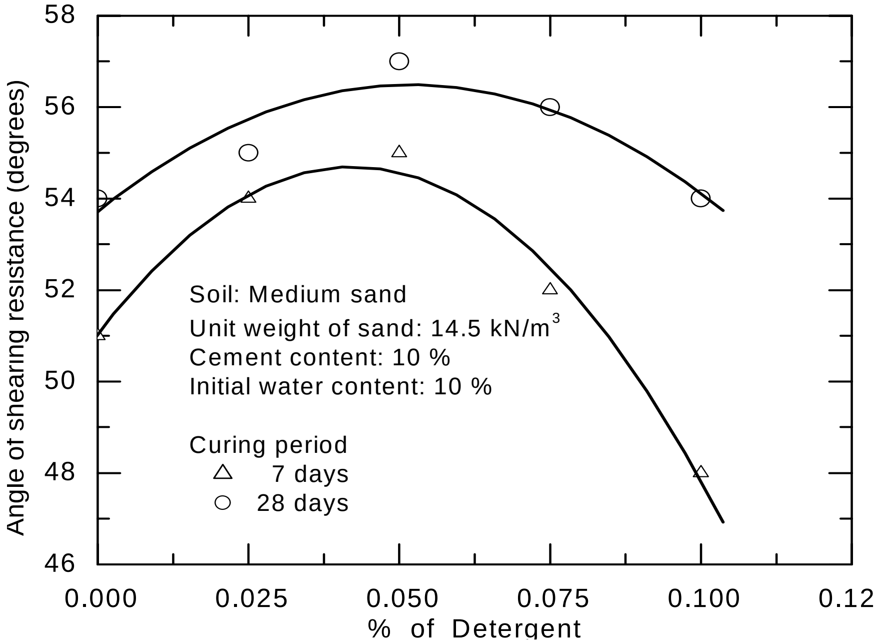


Fig.4.88 Variation of angle of shearing resistance with detergent

Fig. 4.89 shows the variation of Ø- value with percentage of Aluminium powder (which is used as expander) in cement grouted sand. Eventhough there is a slight decrease in Ø- value initially, it increases with 4% of the salt in case of specimens cured for period of 7 days. But in the case of specimens cured for 28 days, after an initial increase, the Ø- value remains more or less constant irrespective of the increase in the dosage. It is interesting to see that unlike other admixtures, the addition of aluminium powder increases the Ø- value of the grouted medium.

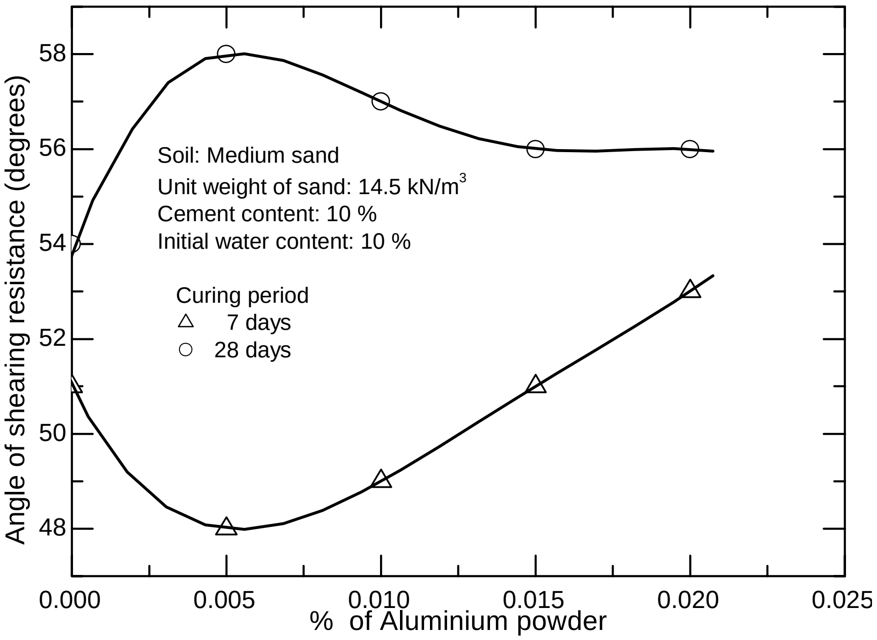


Fig.4.89 Variation of angle of shearing resistance with percentage of aluminium powder

Fig. 4.90 shows the variation of Ø- value with percentage of bentonite (antibleeder) used along with cement grouts. The test specimens were prepared at an initial water content of 10% and tested after curing for 7 and 28 days. Eventhough the Ø- value goes on reducing with percentage of bentonite in case of specimens cured for 7 days, it shows an increasing trend in case of specimens cured for 28 days. When the initial water content is increased to 20% there is a reduction in Ø- value for bentonite contents up to around 4%. But thereafter the Ø- value gradually increases as can be seen from Fig. 4.91.

Fig.4.92 shows the variation in Ø- value with percentage of aluminium sulphate which is also used as an antibleeder. A gradual decrease in Ø- value is seen incase of specimens cured for 7 days, with the increase in percentage of aluminium sulphate; but in case of specimens cured for 28 days, after an initial reduction (at around 2%) the Ø- value increases with increase in percentage of the salt

A comparative behaviour of the above two antibleeders when used along with cement grout is given in Fig. 4.93. It can be seen that the behaviour is exactly the same – ie. the Ø- value increases with increase in percentage of the salt after an initial reduction at around 2% of the salt.

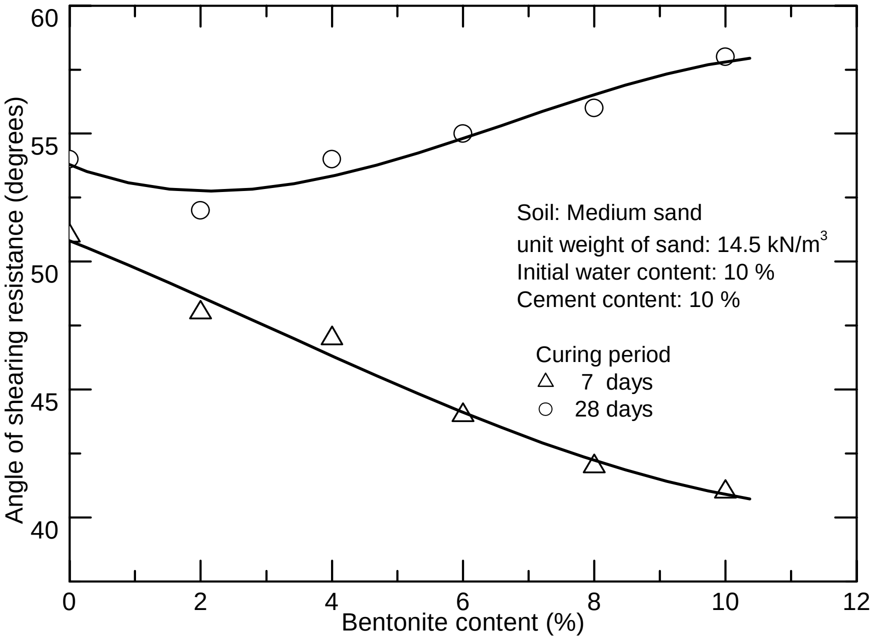


Fig.4.90 Variation of angle of shearing resistance with bentonite content

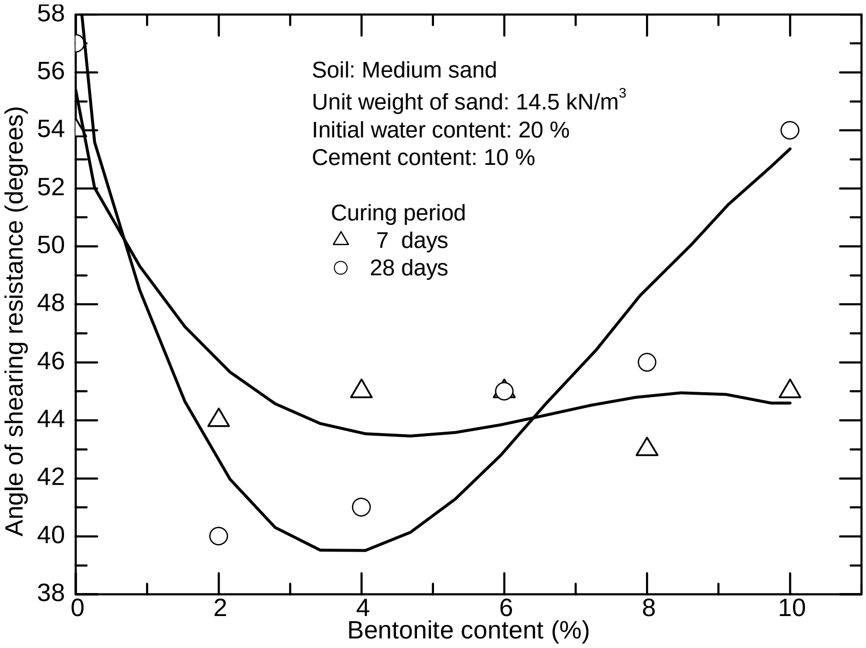


Fig.4.91 Variation of angle of shearing resistance with bentonite content

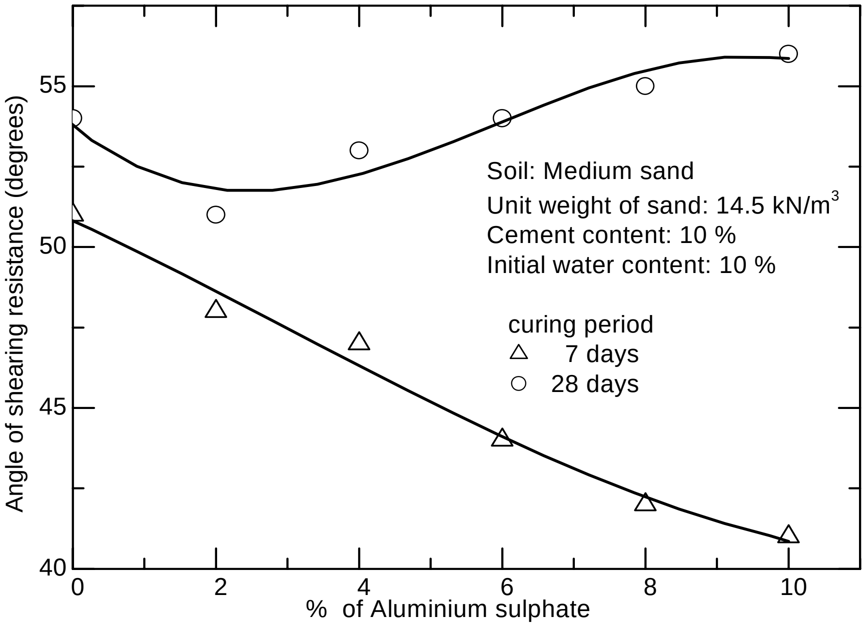


Fig.4.92 Variation of angle of shearing resistance with percentage of aluminium sulphate

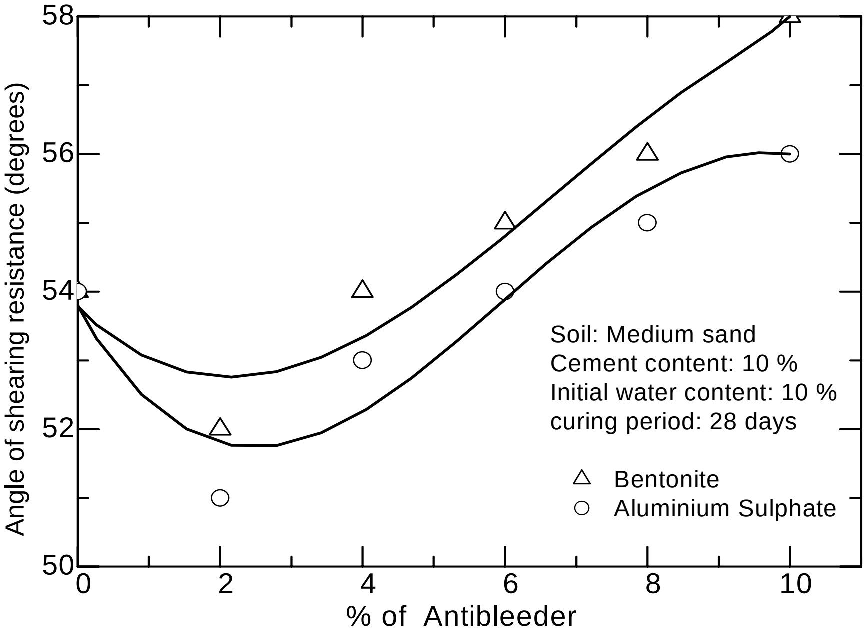


Fig.4.93 Variation of angle of shearing resistance with percentage of antibleeders

4.4.2.3 Lime

The variations in Ø- value with lime content are shown in Figs. 4. 94, 4.95 & 4.96. Eventhough the Ø value remains more or less constant at the initial stages, the value increases beyond a certain value of lime content (approx. 15%). Another interesting observation is that the value of Ø increases with increase in water content, which is not in line with the variation of *c* value.

Fig. 4.97 shows the variation in angle of shearing resistance with bentonite content. It can be seen that when bentonite is used with lime grout, a marginal increase in Ø- value with increase in bentonite content takes place. It can also be seen from the figure that increase in curing period has no significant effect on Ø- value.

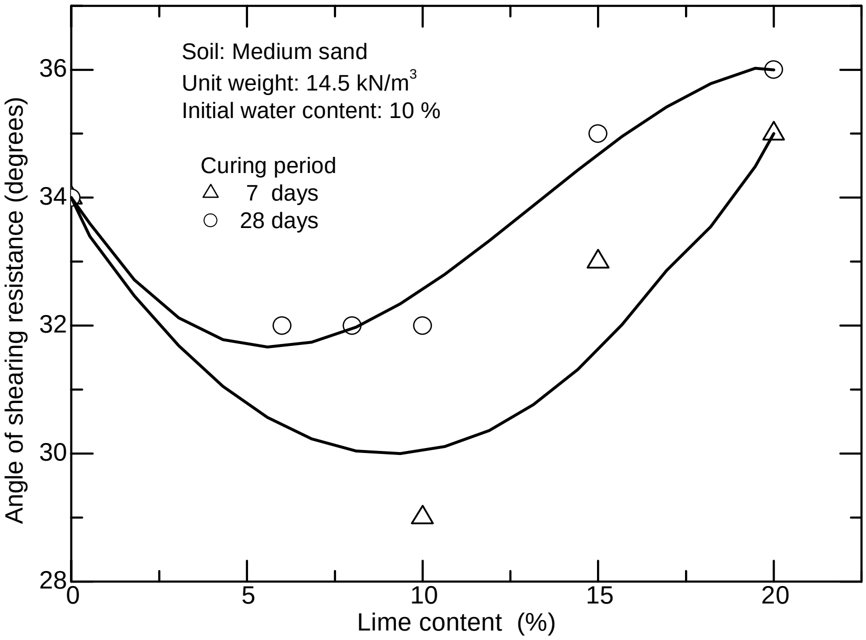


Fig.4.94 Variation of angle of shearing resistance with lime content

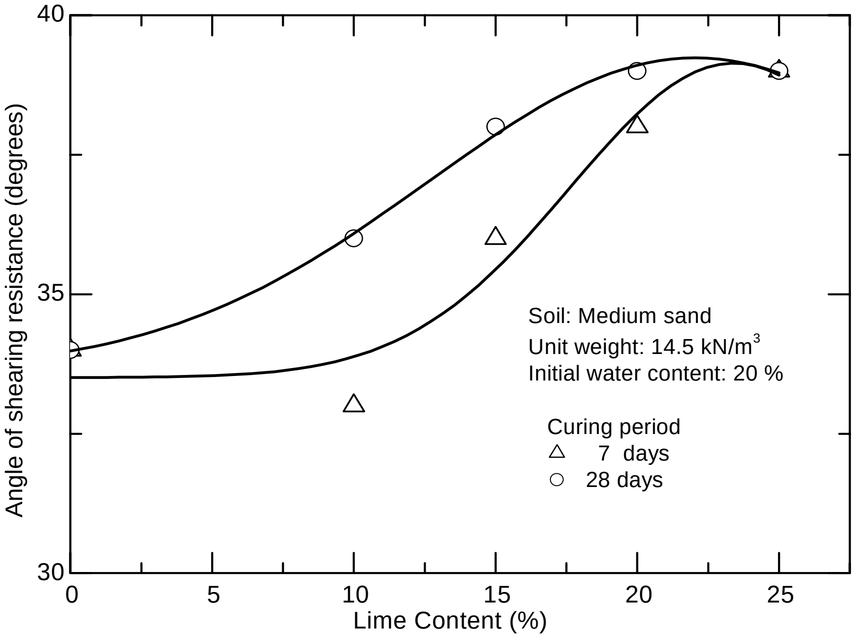


Fig.4.95 Variation of angle of shearing resistance with lime content

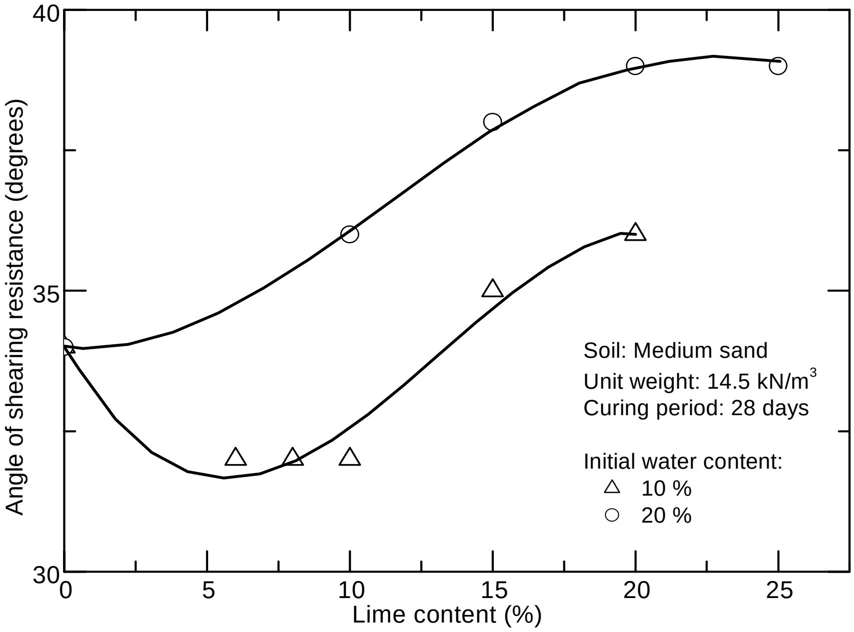


Fig.4.96 Variation of angle of shearing resistance with lime content

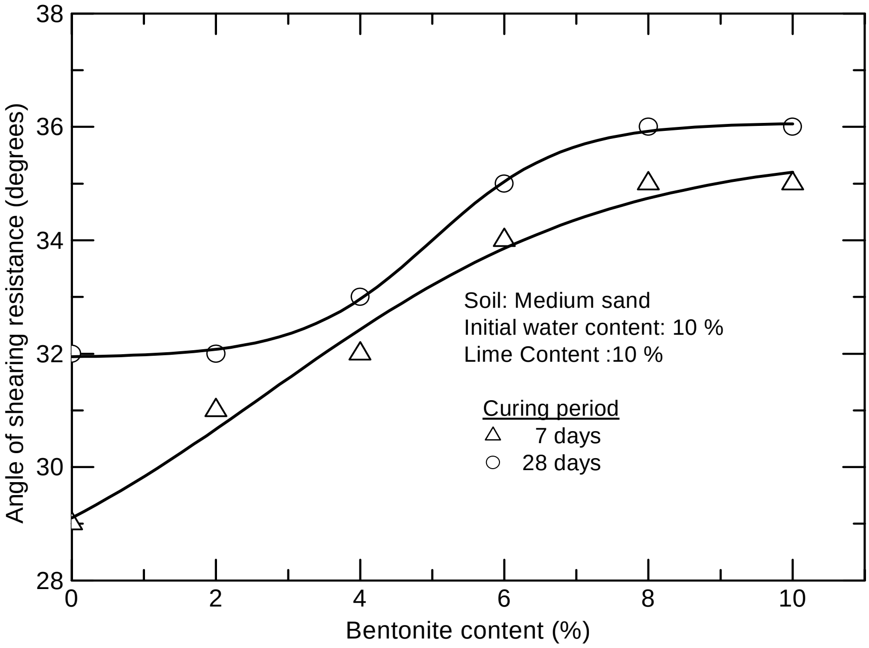


Fig.4.97 Variation of angle of shearing resistance with bentonite content

A comparison between the effect of the two suspension grouts – cement and lime on the Ø- value is presented in Figs. 4.98 and 4.99. The specimens were prepared at an initial water content of 10% in the former whereas the initial water content was increased to 20% in the latter. In both cases the advantage of using cement as a grout material compared to lime is quite clear from the significant increase in Ø- value with increase in cement content.

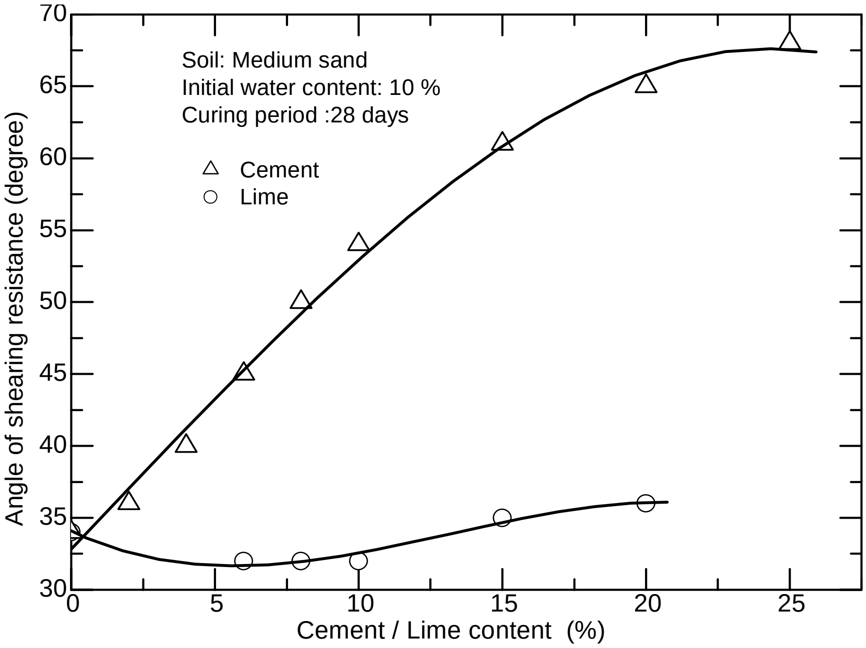


Fig.4.98 Comparisons between angle of shearing resistance and cement / lime content

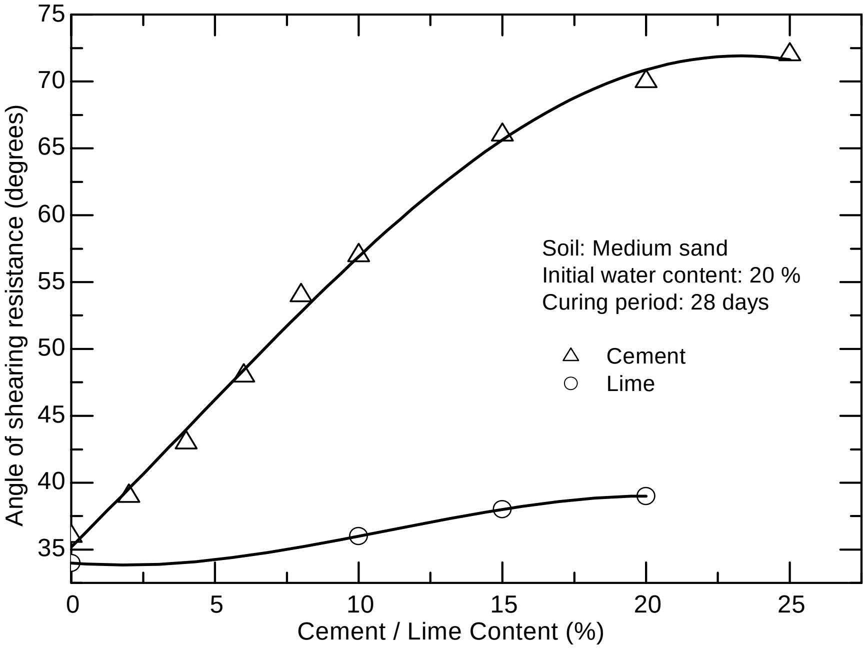


Fig.4.99 Comparisons between angle of shearing resistance and cement / lime content

4.5 Compressive strength

Determination of shear strength through direct shear test is a time consuming process and also requires at least three to four specimens. Further, at higher cement content, it is very difficult to conduct the tests till the failure of the specimens with the normal test set up. But determination of compressive strength in such cases is very easy and can be done very accurately. Hence attempts have been made to correlate the compressive strength with the shear strength / shear strength parameters of the cement grouted soils.

The gradation and type of sand influenced the compressive properties of grouted sand. The compressive properties strength increased with the increase of the coefficient of uniformity of the sand (better gradation) and with the increase of the particle's angularity (Ata and Vipulanandan, 1999). 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 (Sinroja et al. 2006).

4.5.1 Grouted with cement alone

Fig. 4.100 shows the variation in compressive strength with cement content in the case of specimens prepared at an initial water content of 10%. As one would expect, the compressive strength goes on increasing with increase in percentage of cement content. The compressive strength of the grouted sand also increases with the curing period.

Fig. 4.101 also shows the variation of compressive strength with cement content, the initial water content being 20%. Here also, as expected, the compressive strength increases with increase in cement content and curing period. The effect of the initial water content on the compressive strength of the grouted soil samples is shown in Fig. 4.102. It can be seen that the compressive strength decreases with increase in initial water content.

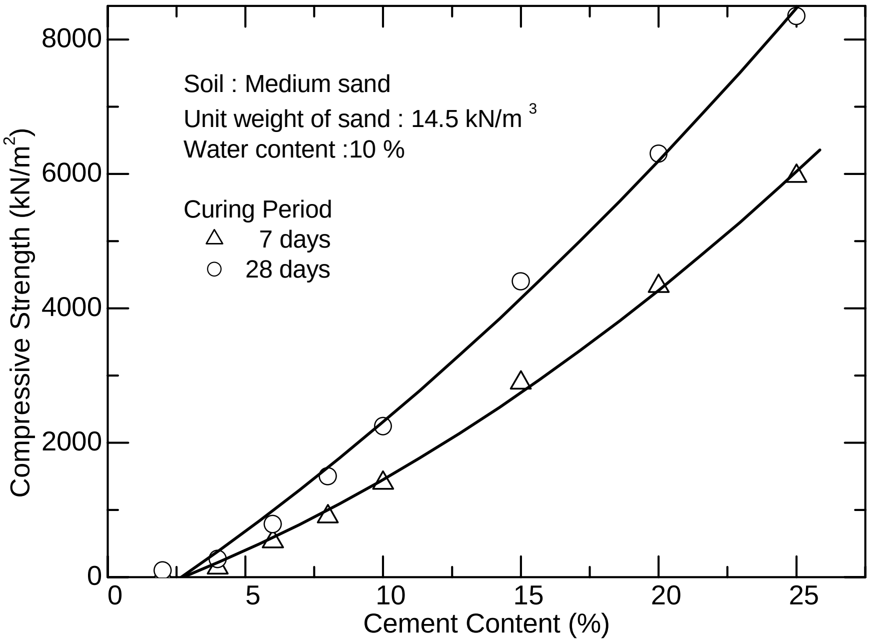


Fig. 4.100 Variation of compressive strength with cement content

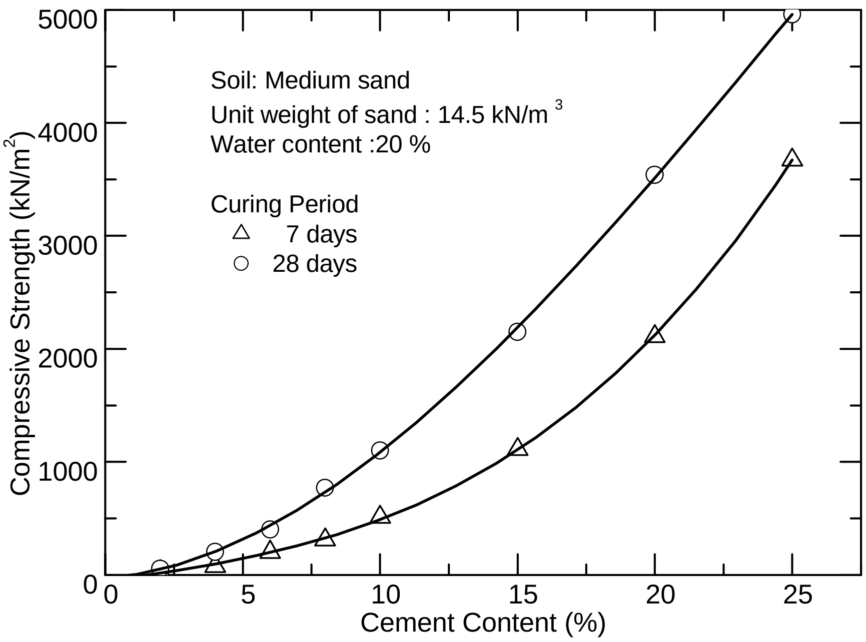


Fig. 4.101 Variation of compressive strength with cement content

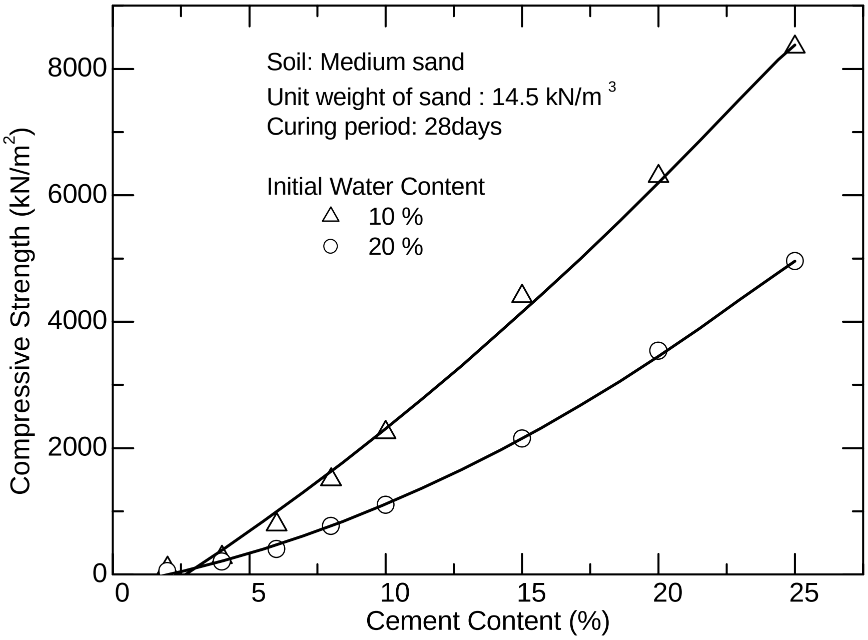


Fig. 4.102 Variation of compressive strength with cement content

The above fact is conclusively proved through tests conducted on samples prepared at different initial water contents and at cement contents of 4% and 10%, the results of which are given in Figs. 4.103, 4.104 and 4.105. As expected, the compressive strength increases with percentage of cement and curing period. But the strength goes on decreasing as the initial water content increases, irrespective of the cement content and curing period. Experiments were repeated with specimens prepared with fine sand and coarse sand and the results are presented in Figs. 4.106 and 4.107. It can be seen that, as in the case of medium sand, here also the compressive strength increases with cement content and curing period.

The effect of gradations of soil in the compressive strength of grouted specimens is given in Fig. 4.108. The compressive strength increases with increase in cement content in all the three fractions – ie, fine, medium and coarse sand. An interesting observation is that, eventhough the coarse fraction shows less strength than the fine & medium sand, it overtakes the other two, as the cement content increases (beyond 15%).

Another interesting observation is about the influence of initial water content in the compressive strength of grouted specimens prepared with fine sand. The results presented in Fig. 4.109 show an increase in strength upto a certain amount of water content (approx. 12%). But as the water content increases, the compressive strength decreases, giving an optimum initial water content to attain the maximum compressive strength, the shape of the curve being similar to a compaction curve, irrespective of the curing period. This behaviour is not in line with that of medium sand (Fig. 4.104) where the compressive strength goes on decreasing with increase in initial water content.

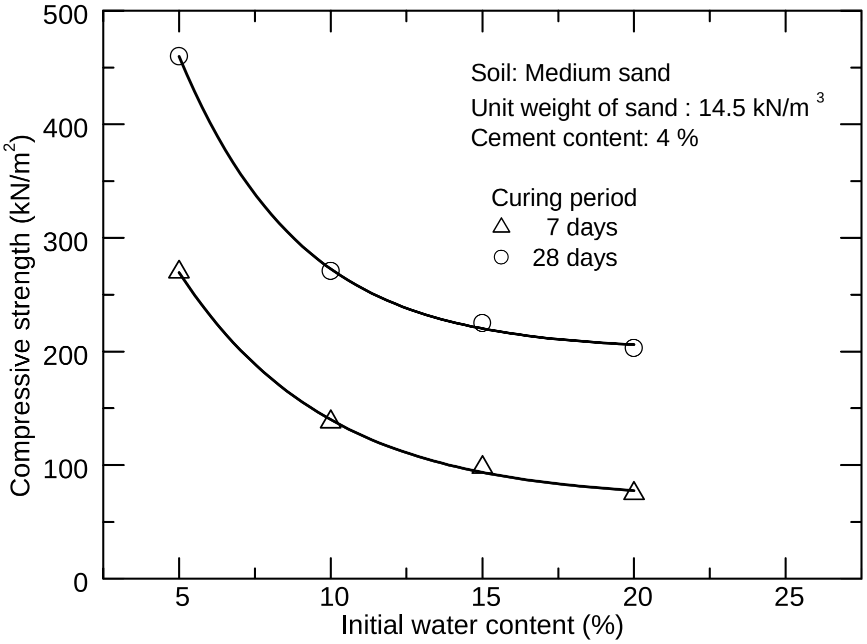


Fig. 4.103 Variation of compressive strength with initial water content

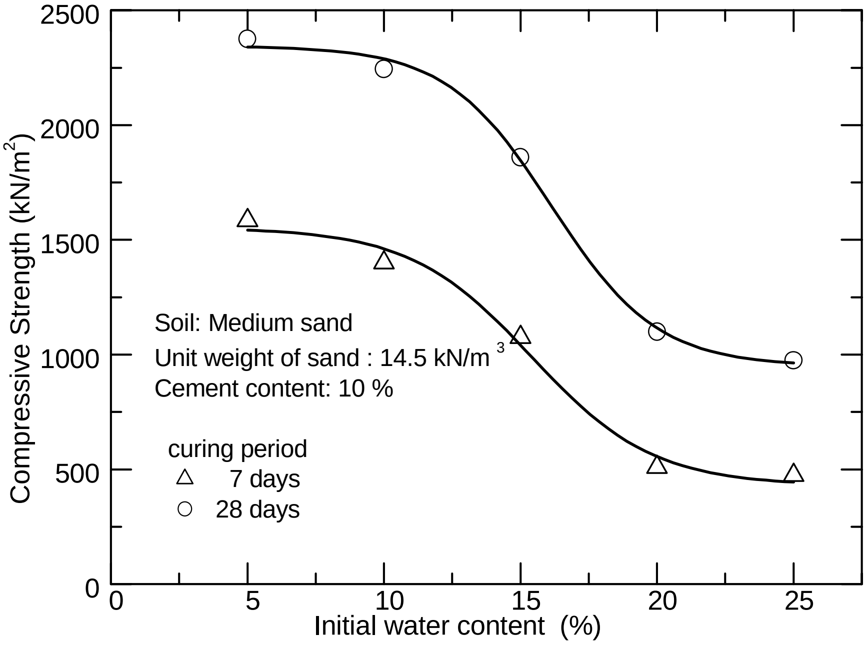


Fig. 4.104 Variation of compressive strength with initial water content

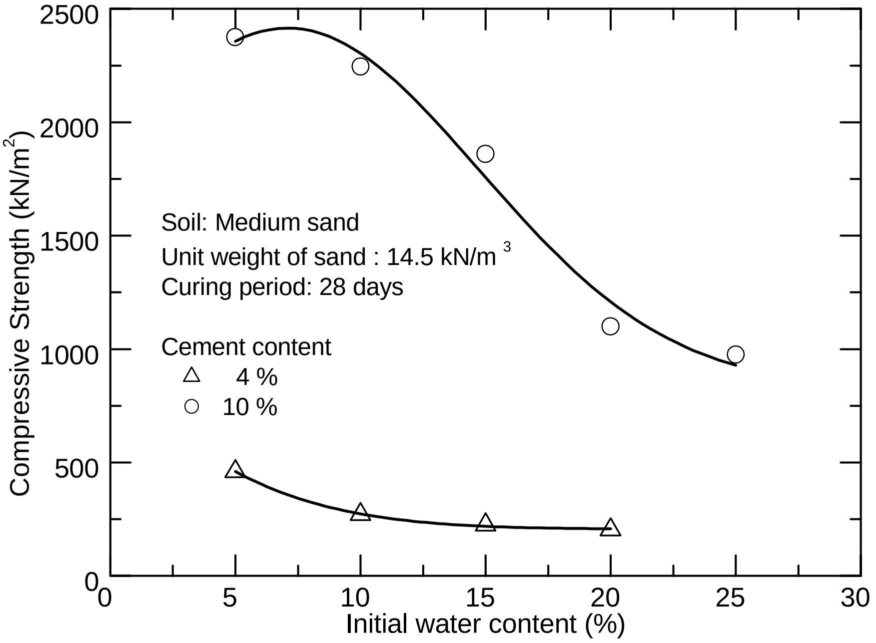


Fig. 4.105 Variation of compressive strength with initial water content

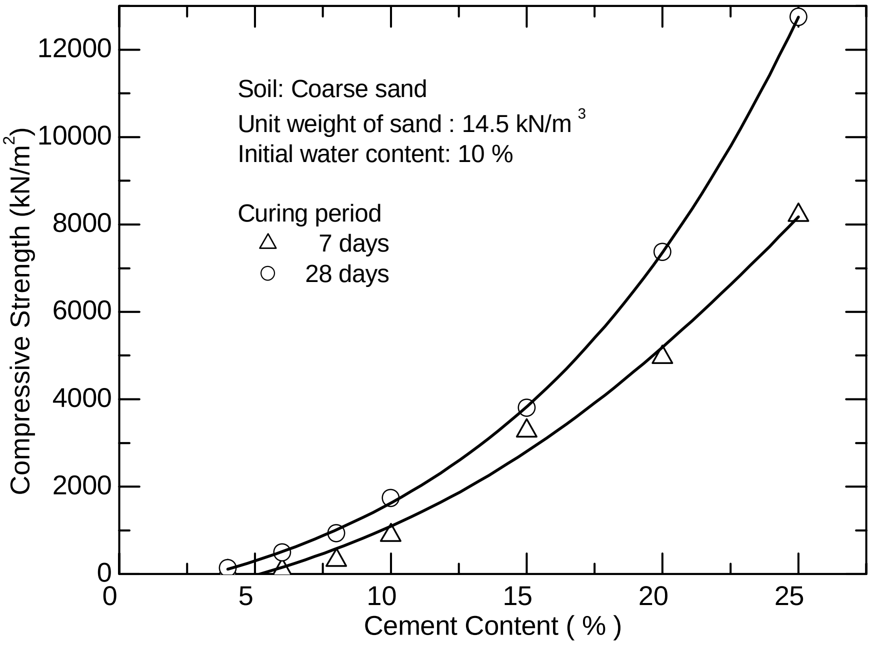


Fig. 4.106 Variation of compressive strength with cement content

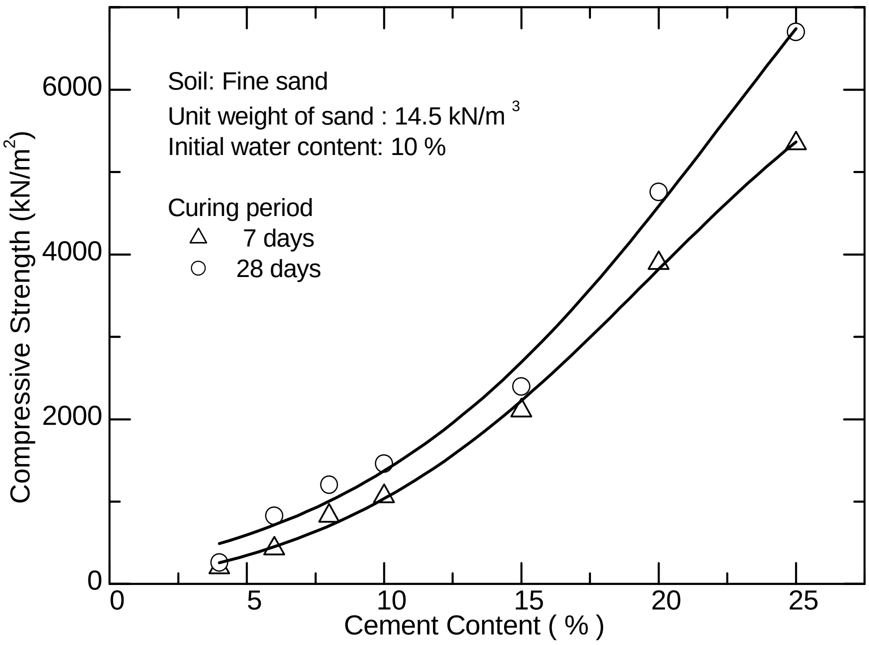


Fig. 4.107 Variation of compressive strength with cement content

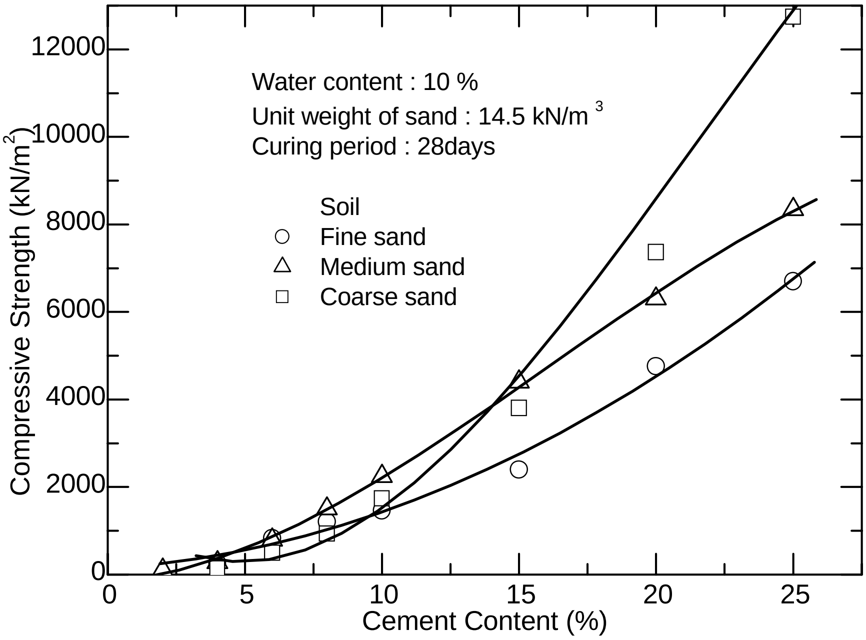


Fig. 4.108 Variation of compressive strength with cement content

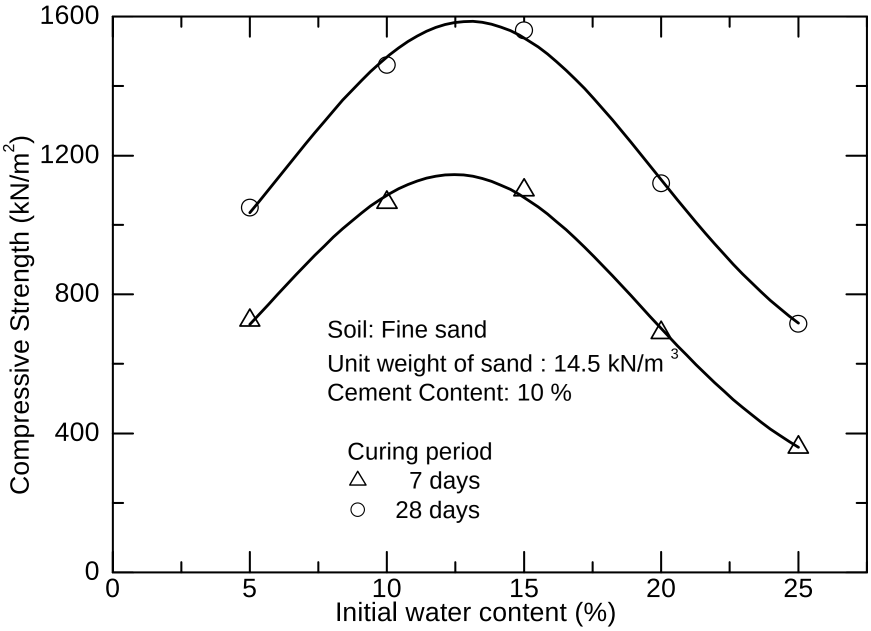


Fig. 4.109 Variation of compressive strength with initial water content

4.5. 2 Cement with admixtures

Fig. 4.110 shows the variation in compressive strength with percentage of calcium chloride (used as accelerator along with cement grout) on cement grouted sand. The effect of this admixture is to improve the strength (though not significantly), in addition to the benefit of serving as an accelerator. Fig. 4.111 shows the effect of sodium silicate (another admixture – which is also used as an accelerator) on the compressive strength of cement grouted sand. The results indicate a reduction in strength with increase in percentage of this admixture. Comparisons between the performance of these two accelerators are given in Fig. 4.112. This plot underlines the superiority of calcium chloride over sodium silicate when used as an admixture along with cement grout.

The compressive strength of cement grouted soil on the addition of a retarder such as tartaric acid is presented in fig. 4.113. It is observed that addition of even a very small percentage (0.5 %) of tartaric acid reduces the compressive strength by 45 %.

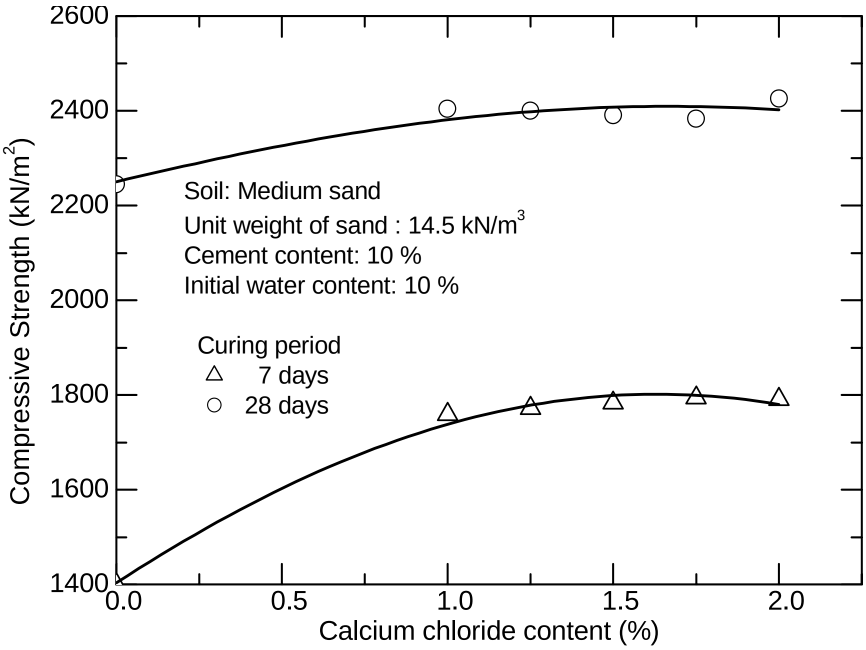


Fig. 4.110 Effect of Calcium chloride content on compressive strength of cement grouted Medium Sand

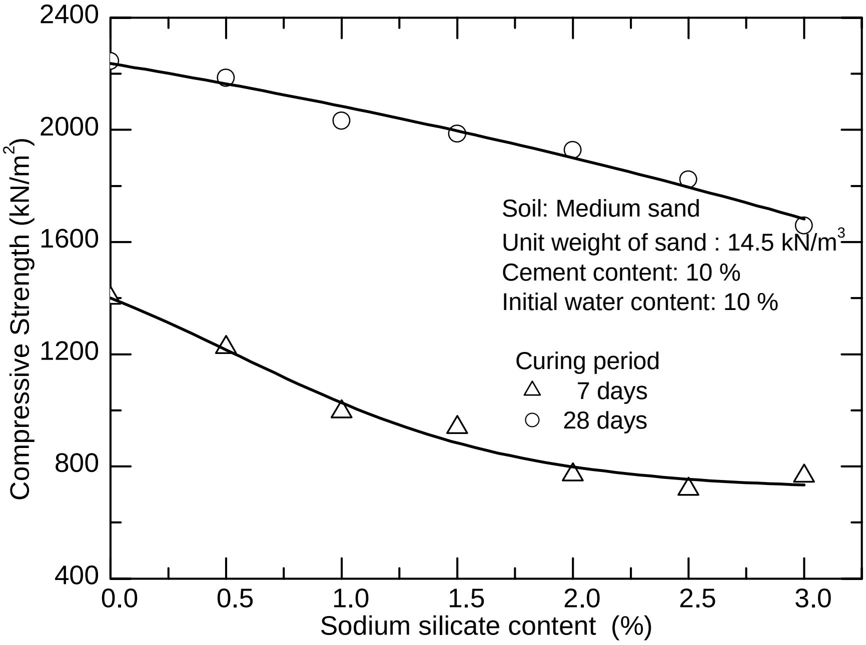


Fig. 4.111 Effect of Aluminium sulphate content on compressive strength of cement grouted Medium Sand

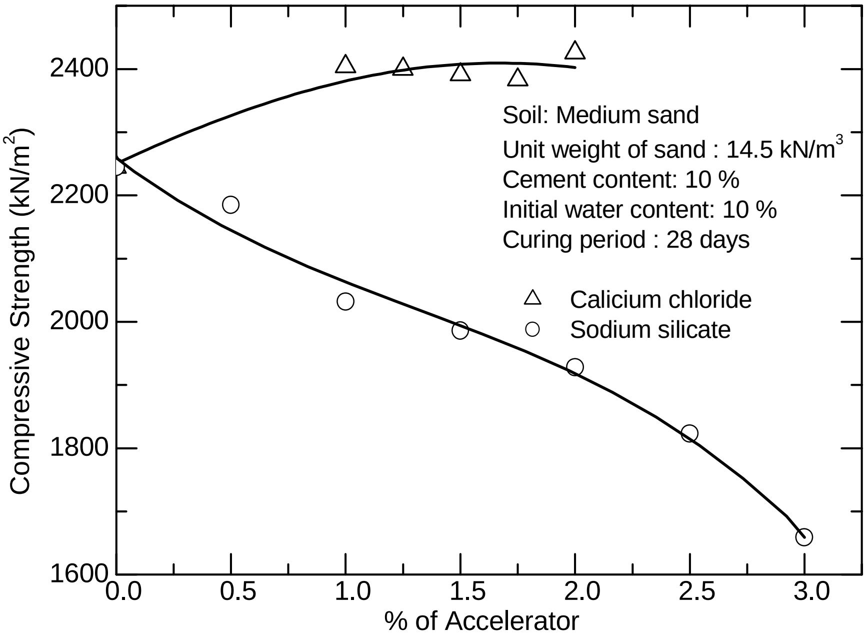


Fig. 4.112 Effect of accelerator on compressive strength of cement grouted Medium Sand

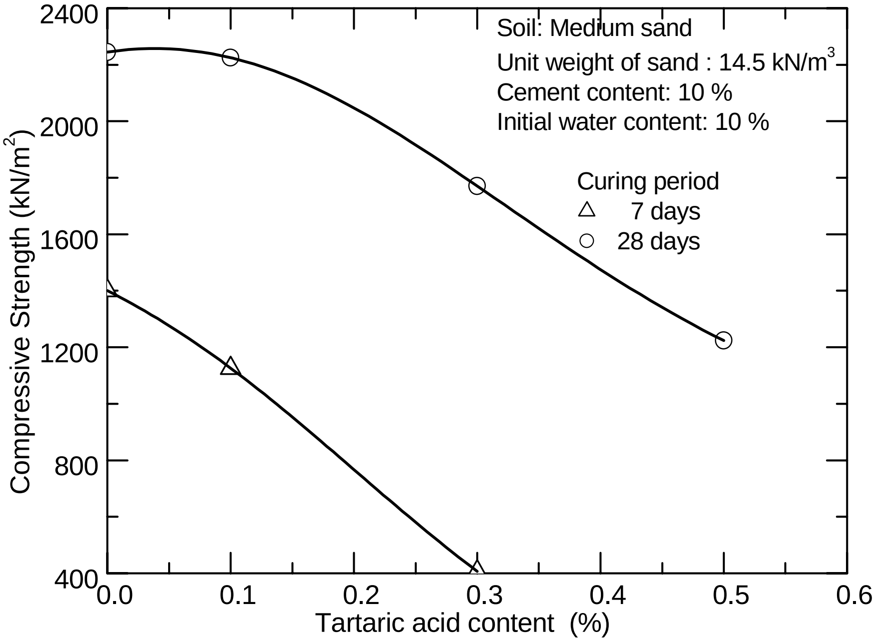


Fig. 4.113 Effect of Tartaric acid content on compressive strength of cement grouted Medium Sand

The effect of triethanolamine - another retarder - on compressive strength is given in fig. 4.114. The compressive strength of cement grouted sand reduces with the increase in percentage of triethanolamine.

Fig. 4.115 shows the effect of the above two retarders on compressive strength of cement grouted sand. Eventhough there is a reduction in compressive strength on the addition of both the retarders, the reduction in strength is far less in the case of triethanolamine compared to tartaric acid. Further the property of triethanolamine in reducing the viscosity of cement grouts (Lovely, 1988) can be taken advantage of.

Fig. 4.116 gives the results of the compressive strength of cement grouted sand specimens on addition of aluminium powder, which is an expander used in cement grouting. It can be seen that the compressive strength remains more or less constant on addition of this admixture.

The effect of antibleeders - aluminium sulphate and bentonite - on compressive strength of cement grouted sand is presented in Figs. 4.117 and 4.118. The behaviour of both these admixtures is almost the same. Eventhough there is an initial reduction in strength at smaller percentages; the strength picks up as the percentage increases. Hence, both these admixtures can be used as antibleeders along with cement grouts, without adversely affecting the compressive strength.

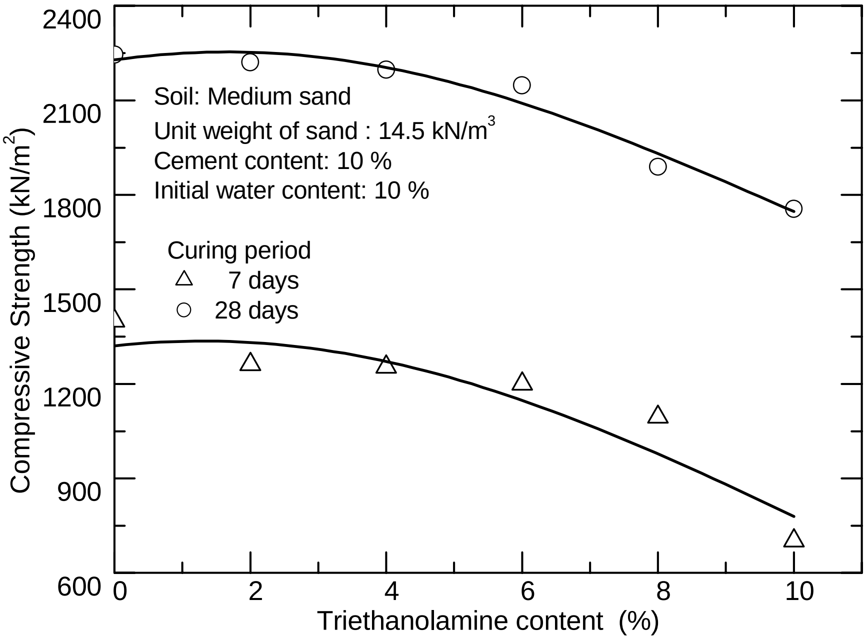


Fig. 4.114 Effect of Triethanolamine content on compressive strength of cement grouted Medium Sand

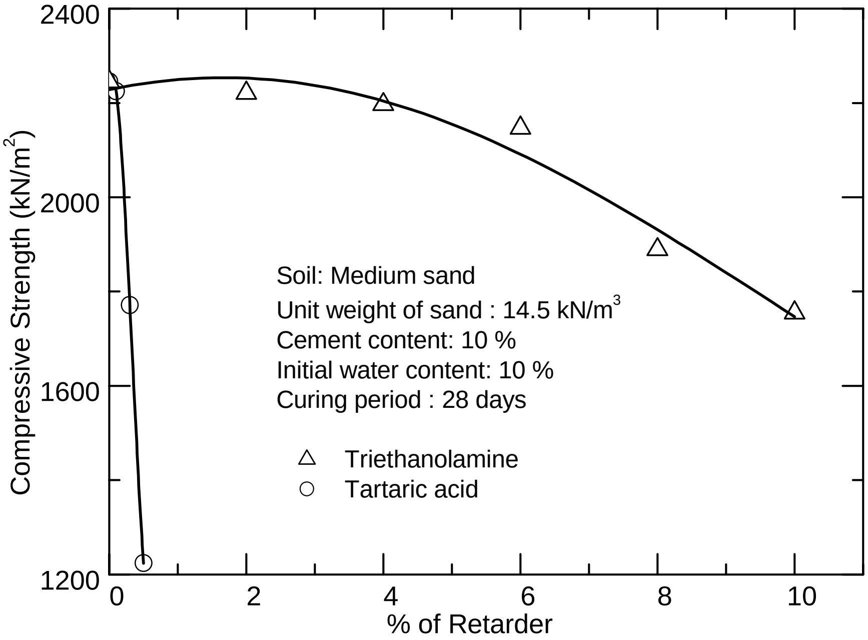


Fig. 4.115 Effect of retarder on compressive strength of cement grouted Medium Sand

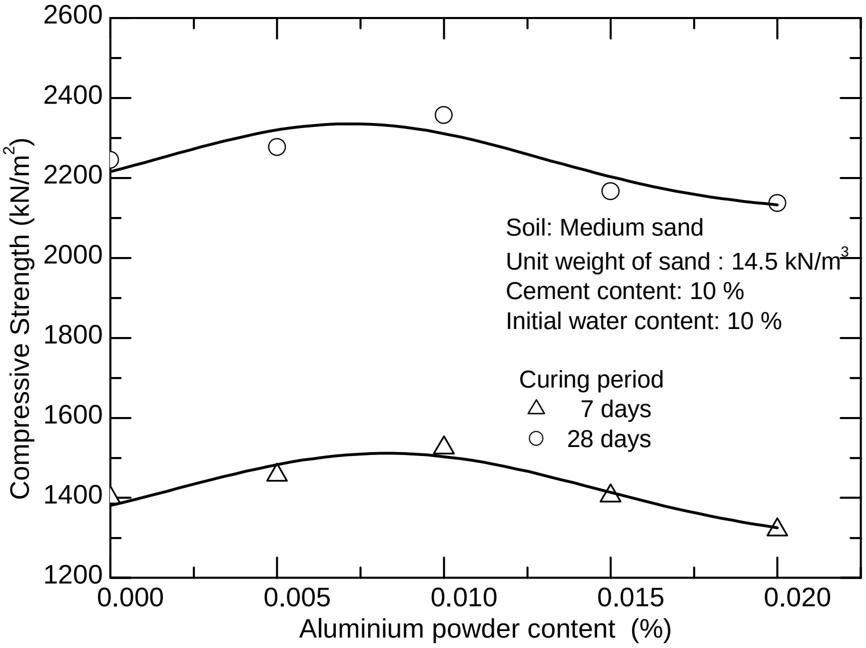


Fig. 4.116 Effect of Aluminium powder content on compressive strength of cement grouted Medium Sand

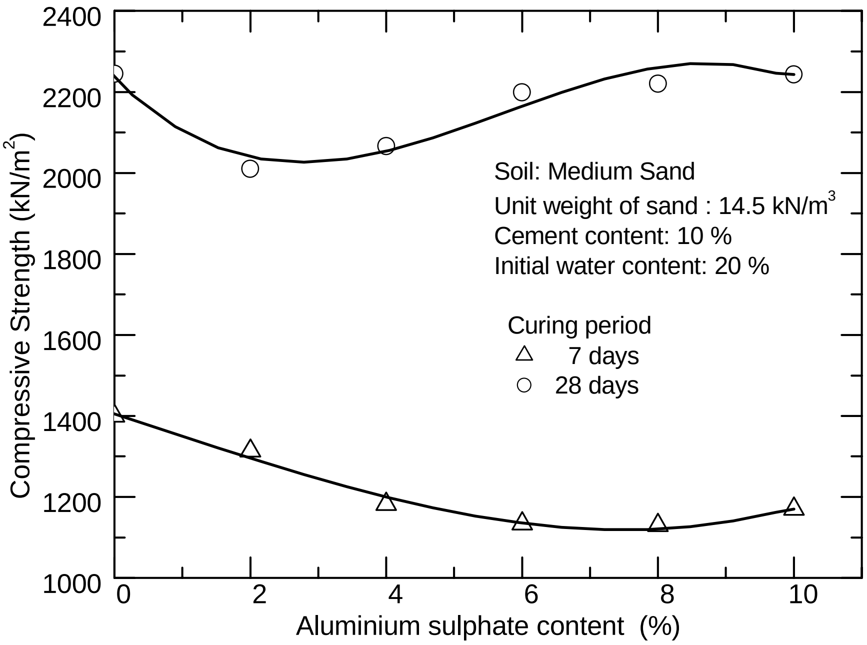


Fig. 4.117 Effect of Aluminium sulphate content on compressive strength of cement grouted Medium Sand

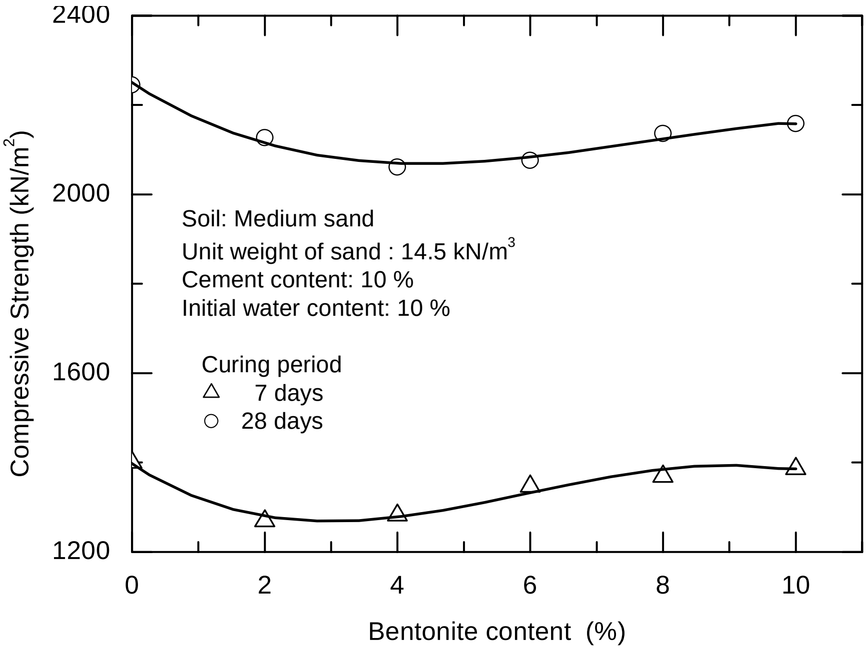


Fig. 4.118 Effect of Bentonite content on compressive strength of cement grouted Medium Sand

The compressive strength of cement grouted sand decreases marginally with addition of bentonite contents at an initial water content of 10%. As the percentage of initial water content increases (20%) the compressive strength decreases with increase of bentonite contents which is presented in fig. 4.119.

Fig.4.120 shows the variation of compressive strength when different percentage of antibleeder is used along with cement grouts. When aluminium sulphate is used, eventhough there is a decrease in compressive strength initially, as the percentage increases the strength increases and reaches to its original value. But in the case of bentonite, there is a reduction in compressive strength initially, thereafter a slight increase which is less than the original value.

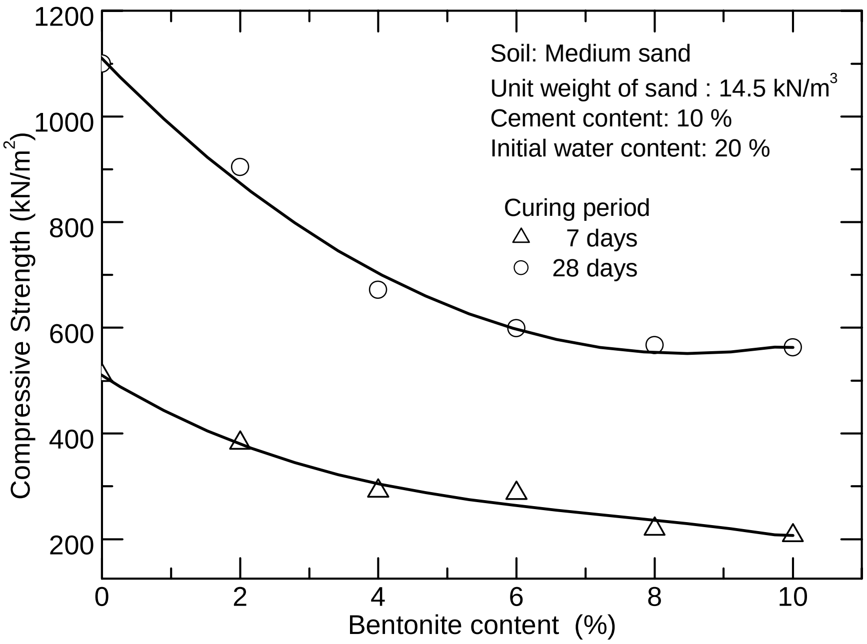


Fig. 4.119 Effect of Bentonite content on compressive strength of cement grouted Medium Sand

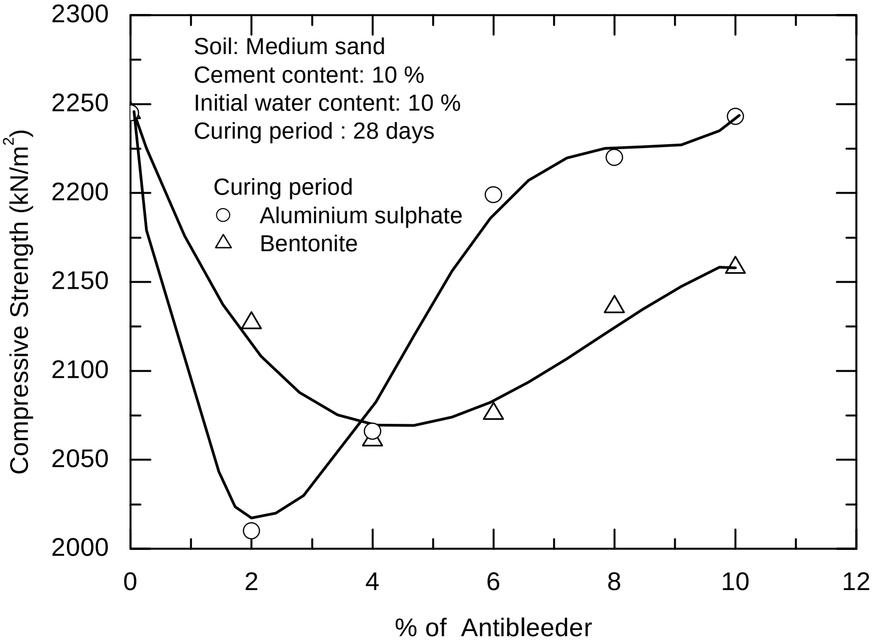


Fig.4.120 Effect of antibleeder on compressive strength of cement grouted Medium Sand

4.6 Relation between compressive strength and shear strength

As mentioned earlier, the main purpose of conducting the compressive strength tests was to search for a correlation with the shear strength/shear strength parameters of the grouted soil because of the difficulty in conducting the shear tests on these grouted soils having high strength.

The cohesion intercept (apparent cohesion) is a measure of the degree of grain to grain bonding. Therefore, it might correlate with the uniaxial compressive strength which is also a measure of grain to grain bonding magnitude. (Al-Awad, 2002).

To obtain a correlation between the shear strength and compressive strength of the grouted soils, results obtained from the direct shear test and compressive strength tests on soil specimens having same composition were plotted. Such a plot is given in fig 4.121 in which the compressive strength results are plotted against the corresponding cohesion intercept obtained form the results of the direct shear tests. The plot gives an excellent straight line relationship with a high correlation coefficient of 0.95.

The relationship can be expressed as;

$$c = 0.079\,p - 2.21$$

Where

c = cohesion intercept in kN/m^2

p = compressive strength in kN/m^2

Fig. 4.122 represents the relation between the measured and predicted cohesion intercept (from the above equation) values. It can be seen that most of the data points are located very close to the 45^0 line, as evident from a high correlation coefficient of 0.95. A similar result was obtained in the case of the plot between the measured and predicted compressive strength values shown in Fig 4.123.

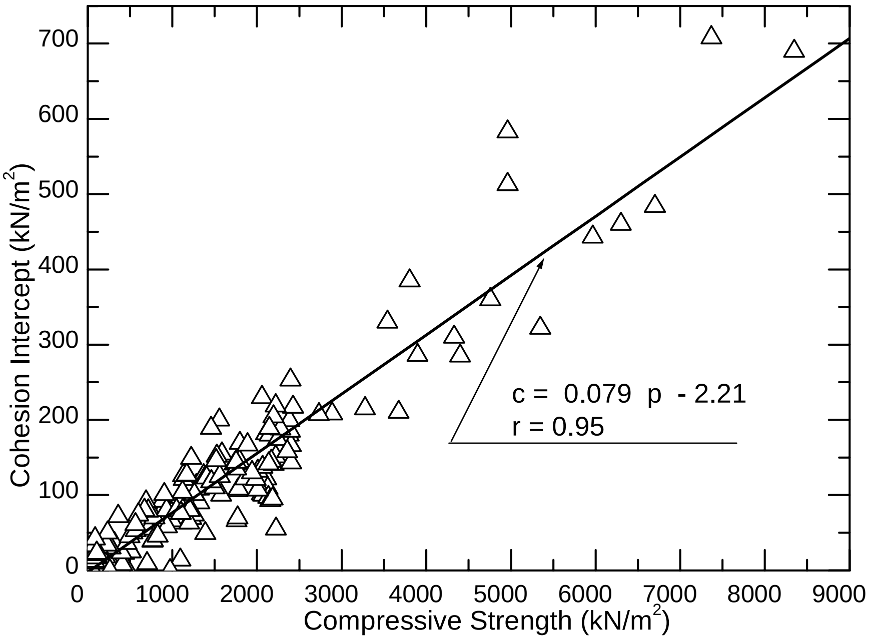


Fig. 4.121 Relation between compressive strength and cohesion intercept

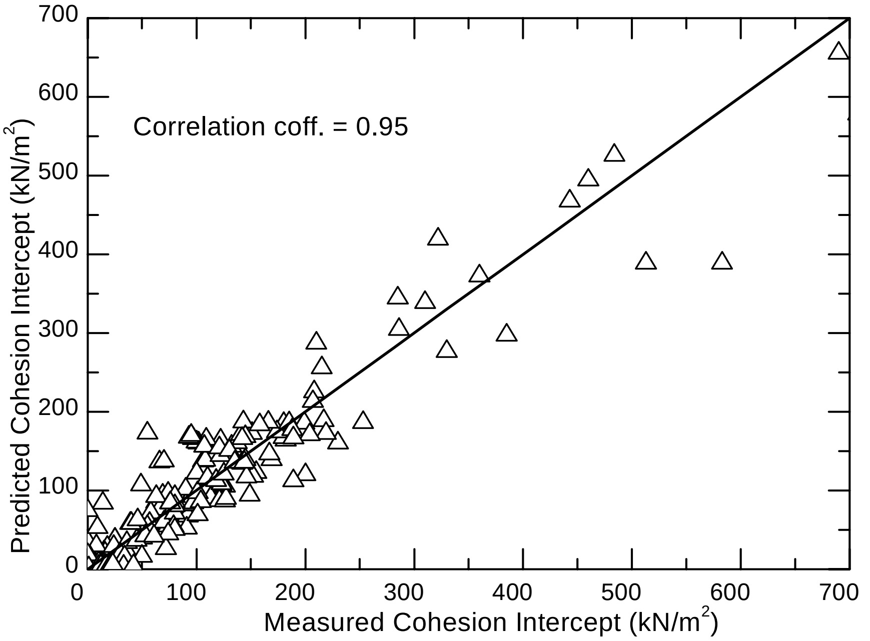


Fig. 4.122 Relation between measured cohesion intercept and predicted cohesion intercept

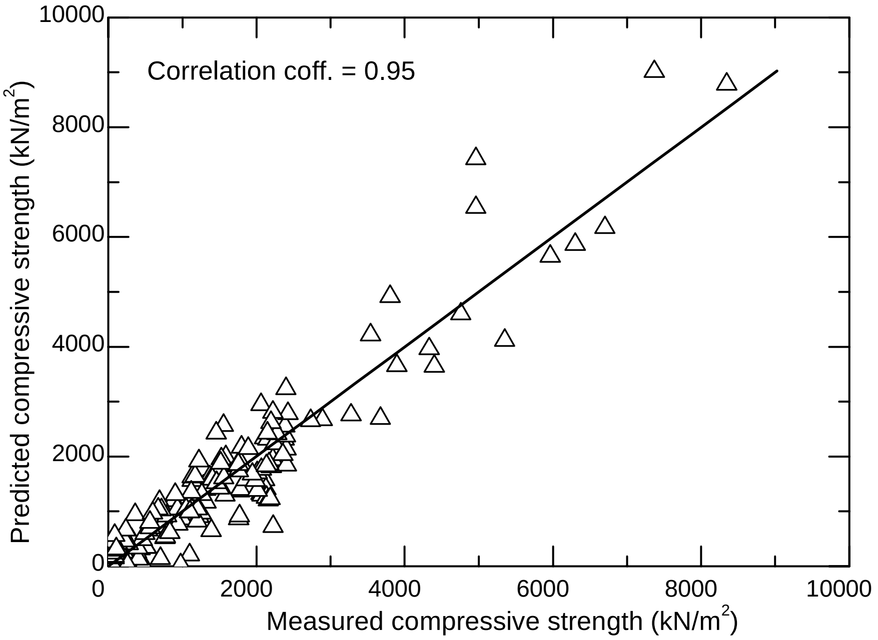


Fig. 4.123 Relation between measured compressive strength and predicted compressive strength

Fig 4.124 gives the relation between the compressive strength and the angle of shearing resistance (obtained from results of direct shear tests). The plot gives a non-linear relationship, the equation being,

$$Ø = 37.52 + 0.009\,p - 7.58\,E^{-7}\,p^2$$

and the correlation coefficient in this case is only 0.83.

A linear relationship between Ø and p will yield an equation

$$Ø = 0.005\,p + 40.50$$

with a low correlation coefficient of 0.78.

The main purpose of this attempt is to arrive at a reasonable relationship between the shear strength and the corresponding compressive strength of the grouted soils. Hence the values of shear strength computed from the results of direct shear tests were plotted with the compressive strength of the 199 samples and are shown in fig 4.125. It can be seen that the plot gives an excellent linear relationship with a high correlation coefficient of 0.96.

The relationship between shear strength and compressive strength is given by

$$\tau = 0.104\, p + 80.12$$

where

τ - shear strength in kN/ m^2

p - compressive strength in kN/m^2

Fig. 4.126 shows the comparison between Predicted (computed from the above equation) and Measured Shear Strength of Grouted samples. It can be seen that most of the points are located close to the 45^0 line, the correlation coefficient being 0.95.

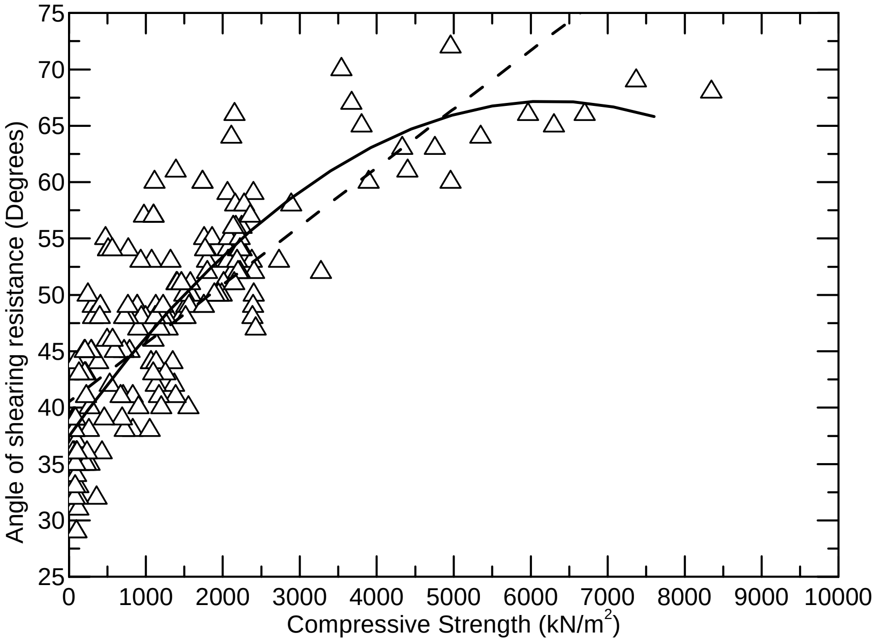


Fig. 4.124 Relation between compressive strength and angle of internal friction

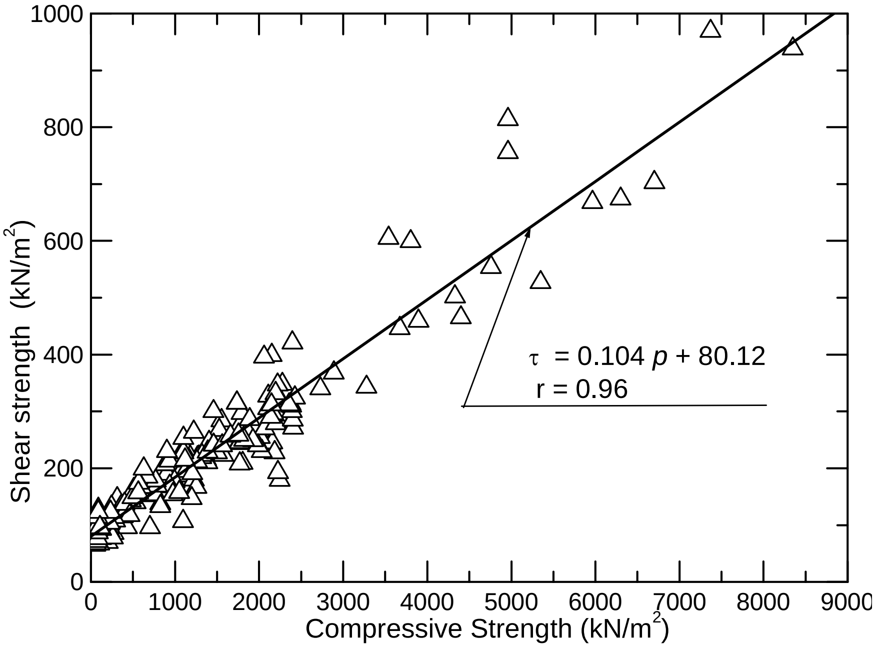


Fig. 4.125 Relation between Compressive strength and Shear Strength of Grouted samples

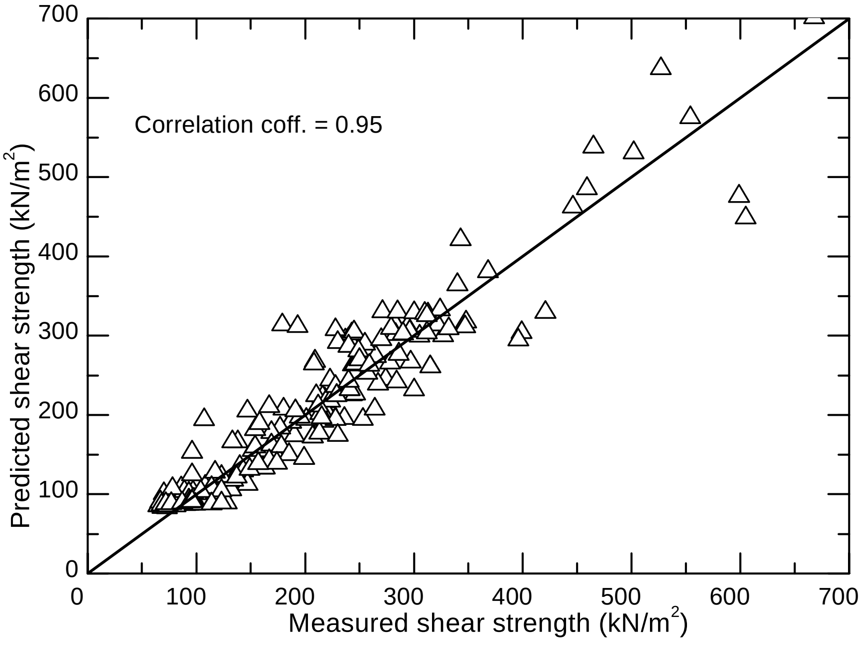


Fig. 4.126 comparison between Measured and Predicted Shear Strength of Grouted samples

Hence a simple test such as compressive strength will be sufficient to predict the shear strength of the grouted soil. Thus the relationship developed between the shear strength and the compressive strength can be advantageously used to estimate the strength of the grouted soil in the field.

Chapter 5

STUDIES ON CEMENT GROUTED SAND BEDS

Contents

5.1 Introduction

In particulate grouts, the limit of injectability is decided from the groutability ratio (ratio of D_{15} of the soil formation to d_{85} of the grout material), in addition to its initial fluidity, while in Newtonian fine grouts these limits are mainly a function of their initial viscosity and gel time. The groutability ratio reveals that the size of the grout particle and the size of opening or pore space of the mass to be grouted should be in such a proportion that blockage and filtering of the grout can be minimized.

In order that grouting results be good, it is evident that the injector has to choose the grout most suitable to the problem (viscosity, setting time, strength), but it is also necessary to know how to distribute it in the soil. For this, it is necessary to make a correct choice of: (i) grout hole equipment (ii) distance between grout holes (iii) length of injection passes (iv) number of grouting phases and (v) grouting pressure and pumping rate (Shroff, 2009).

5.2 Design and fabrication of the grouting set up

For the purpose of assessing the groutability and for conducting model studies in the grouted bed in the laboratory, a grouting set up had to be designed and fabricated. A grouting setup normally requires a grout chamber with agitator, an air compressor, a regulating valve and a grouting nozzle. The grout chamber fabricated is a barrel type cylindrical drum of 50 litre capacity (0.30 m dia & 0.75 m height) placed vertically with an axial shaft fitted with blades as shown in Figure 5.1(a).The shaft is connected to a motor mounted on a bracket. The cement water slurry is fed through an opening provided for grout inlet and is thoroughly mixed by the rotation of the blades. The compressed air is allowed to enter through the pressure inlet pipe from the air compressor and can be regulated by a pressure regulating valve. The pressure relief valve controls the injection pressure to the predetermined values and the measurement of the injection pressure can be made with the help of the pressure gauge attached to the grout chamber. The graduated perspex tube connected to the grout chamber gives an idea about the quantity of grout pumped into the medium. A photograph of the grout chamber is shown in Fig.5.1 (b).

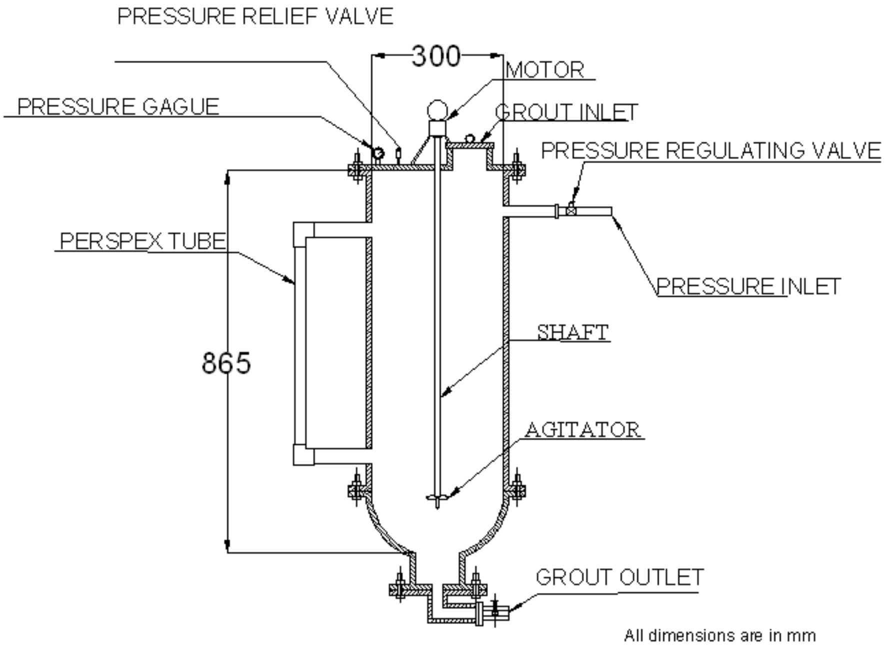
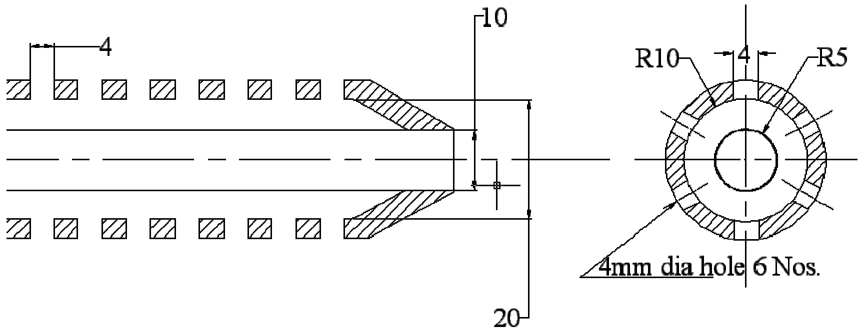


Fig. 5.1 (a) Section of grout chamber

Fig.5.1 (b) Grout chamber

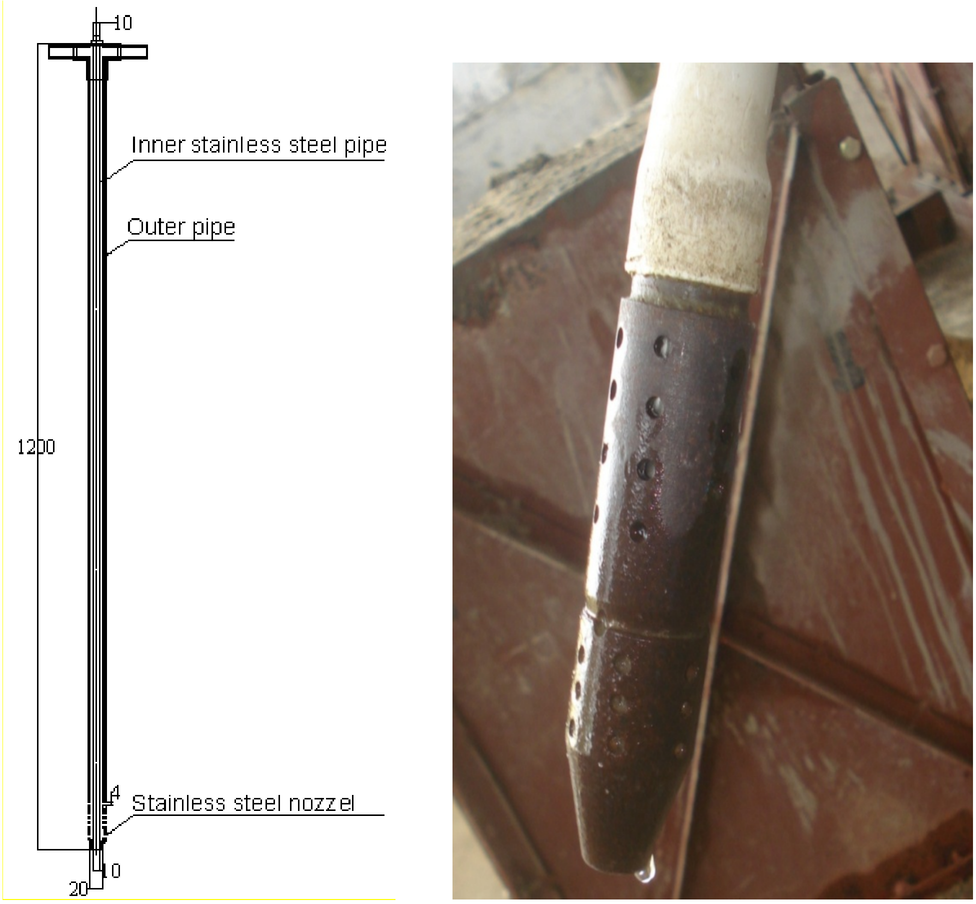
The grouting nozzle consists of an inner pipe passing through an outer pipe as shown in Figure 5.2 (a). The inner pipe is made of thin stainless steel tube of 10 mm diameter flush with the outer pipe and open at the bottom. The outer pipe is made of PVC having inner diameter 20 mm, the lower end is provided with a stainless steel nozzle and the end tapered for easy penetration of the nozzle. The stainless steel nozzle is provided with 24 numbers of 4 mm diameter holes through which the grout flows to the sand bed. A cross-section of the nozzle is shown in figure 5.2 (b). Fig.5.2 (c) shows the photograph of the grouting nozzle. A water jet under pressure through the inner stainless tube facilitates the penetration of the nozzle into the grouted medium. The grout flows through the annular space between the outer and inner pipe and discharges through the nozzle holes into the sand medium to be grouted.

Figure 5.3 shows a schematic diagram of the grouting setup. The grout slurry is poured into the chamber through the inlet and when switched ON the motor agitates the grout, which rotates the blades attached to the shaft. To get sufficient pumping pressure for the grout slurry, compressed air was pumped into the chamber by opening the valve V1. Control of the pumping pressure of grout slurry can be done by regulating the valve V2. Opening the valves V3, V4, and V5 and simultaneously closing the water inlet valve and water jet valve permits the flow of the grout into the annular space between the outer and inner pipe and then into the medium to be grouted through the holes provided in the nozzle. Flow of the grout in the vertical direction can be obtained by opening the valve V6 and closing the valve V5. After the grouting operation, the grout pipe and nozzle can be cleaned with the help of the water jet and water inlet. Fig 5.4 shows a photograph of the grouting set up.



(b) Cross-section

All dimensions are in mm



(a) Longitudinal section **(c) Photograph**

Fig. 5.2 Grouting nozzle

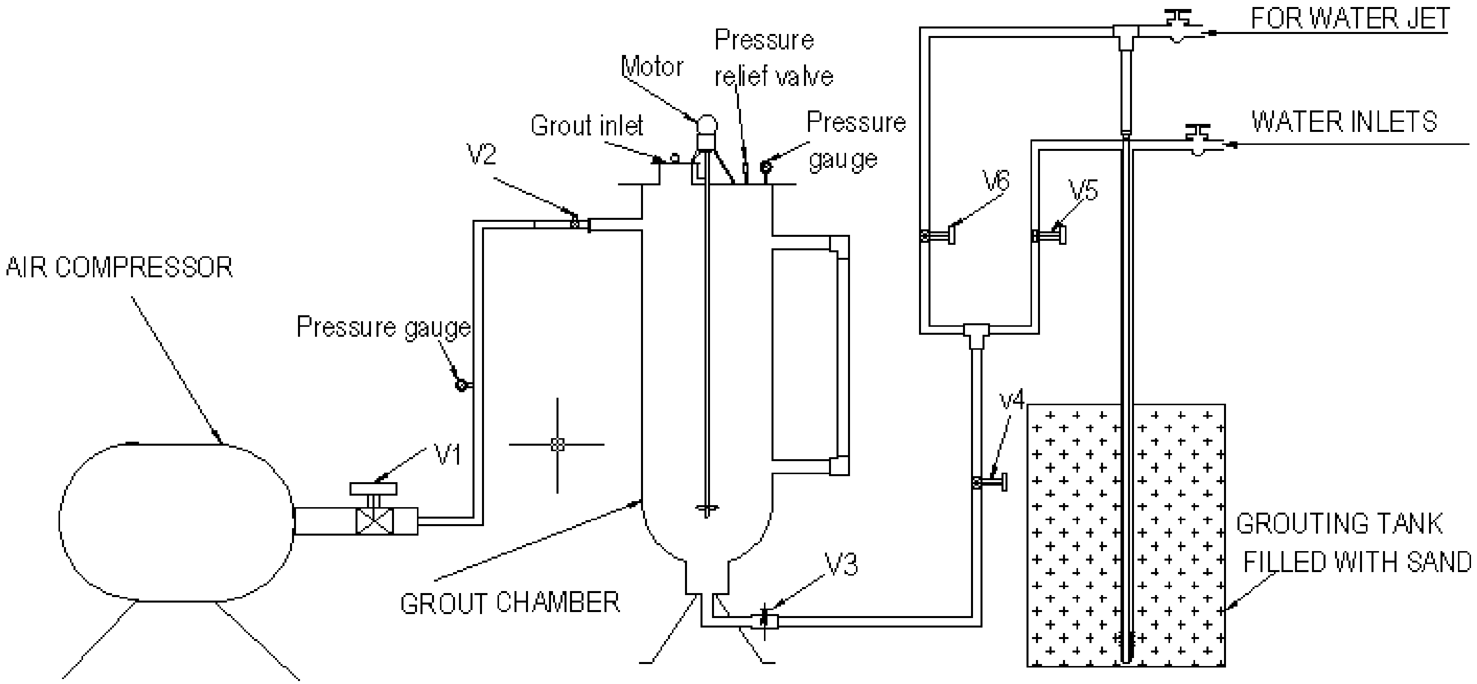


Fig: 5.3 Schematic diagram of the grouting setup

Fig. 5.4 Grouting set up

5.3 Grouting of sand beds

Detachable steel tanks of 0.45 m x 0.45 m x 0.60 m and 1 m x1 m x 0.60 m were used for the laboratory studies. The tanks were assembled in the proper position and the bottom of the grouting nozzle was kept on the sand bed at a distance of 5cm from the bottom of the tank. The sand bed was prepared in the tank at a unit weight of 13.1 kN/m^3 (loosest state). Cement grout was prepared by adding 10 % (by weight of sand + cement) of water and was poured into the grout chamber. While preparing the grout, the viscosity was measured using Mash funnel ensuring that the viscosity was within the pumpable limits. The grout so prepared was pumped into the sand medium by maintaining the pressure at 5 kg/cm^2. When pumping of around $^1/_3$ rd of the quantity of the grout was over, the nozzle attached to the pipes was lifted slowly and kept at $^1/_3$ rd the height from the bottom. The process was repeated till another $^1/_3$ rd quantity of the grout got pumped into the medium. Again the nozzle was lifted and kept at $^2/_3$ rd height from bottom of the tank for pumping the final $^1/_3$ rd quantity of the grout into the sand medium. Throughout the period of the pumping, the agitator was kept working in order to avoid the settling of cement.

After this the nozzle was completely withdrawn from the sand and cleaned with water jet. The hole left in the sand bed which was already full with cement slurry was filled with dry sand. Figs 5.5(a), 5.5(b) and 5.6 show the grouting process in progress and the grouted sand. These grouted beds were kept in humid conditions for curing. After 7 days of curing, load tests were conducted on these grouted beds, dimensions of the cross section at different depths were taken and representative samples were taken at different depths and at different radial distances.

5.4 Grouting efficiency from cross section dimensions

A preliminary idea about the grouting efficiency can be obtained from the cross section area of the actual grouted medium at different depths. For this purpose, the side walls of the tank were removed so that the dimensions of various cross sections of the intact grouted mass at different depths could be taken.

Fig. 5.5 (a) Grouting process in small tank in progress

Fig. 5.5(b). Grouting process in large tank in progress

Fig. 5.6 Grouted sand bed

5.4 .1 Cement alone

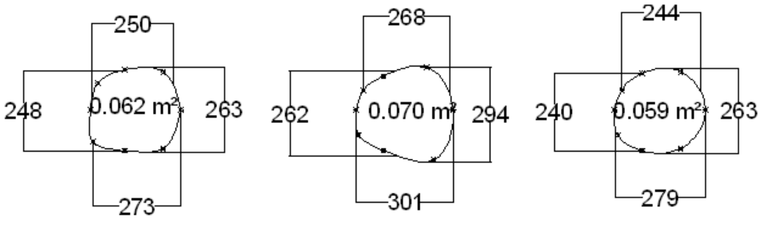
Cement grout should be sufficiently fluid enough to allow efficient pumping or injection and sufficiently stable to resist displacement and erosion after the injection. The principal variables affecting the properties of cement grout are water : cement ratio and rate of bleeding along with subsequent plasticity and ultimate strength of the grout.

Grouting of the sand bed was done with cement contents of 2, 4, & 6 % by the weight of sand, the initial water content being 10 % (by weight of sand + cement). In order to get a quantitative idea about the lateral flow of the grout, the cross sectional dimensions were measured at different depths - 100, 200, 300, 400, 500 and 600 mm from the top of the grouted bed. Fig 5.7 shows the cross sectional area of medium sand grouted with 2 % cement (water cement ratio of 4.3) at different depths. It can be seen that the area of cross section increases with the increase in the depth. A three dimensional view of the resultant grouted mass is shown in Fig.5.7 (vii).

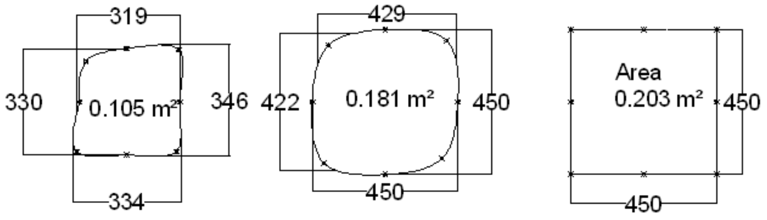
The cross sectional area of medium sand grouted with 4 % of cement (water cement ratio of 2.2) at different depths are shown in figure 5.8. The cross section area is almost constant through out the depth of grouting shown in the three dimensional view (Fig.5.8 (vii)).

Fig 5.9 shows the cross section of medium sand grouted with 6 % of cement (water cement ratio of 1.4) at different depths. It is seen that cross sectional area increases with increase in the depth of grouting which is also clear from the three dimensional view (Fig. 5.9 (vii)).

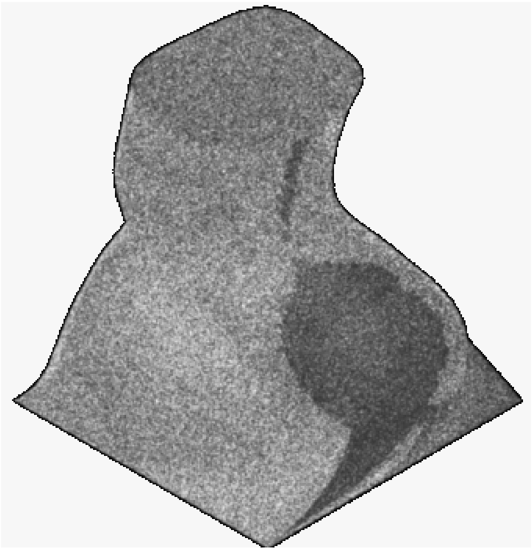
A comparison of cross sectional area of grouted samples with 2, 4 and 6 % cement at different depths is presented in the form of a column chart in Fig. 5.10 (a). It can be seen that the effective cross section area of the mass grouted with 4 % cement is maximum at all depths. This is more clear from Fig. 5.10 (b) which gives the volumes of these grouted masses calculated based on these measurements. A volume as high as 78 % of the original volume was obtained in the case of grout with 4 % cement, whereas it was only 45 % and 53 % in the case of 2 % and 6 % cement grouts respectively.



(i) Depth 100mm (ii) Depth 200mm (iii) Depth 300mm

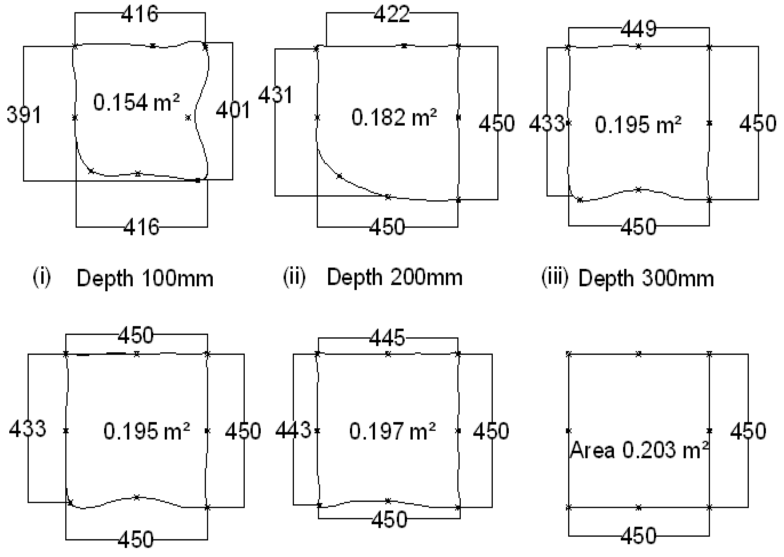


(iv) Depth 400mm (v) Depth 500mm (vi) Depth 600mm



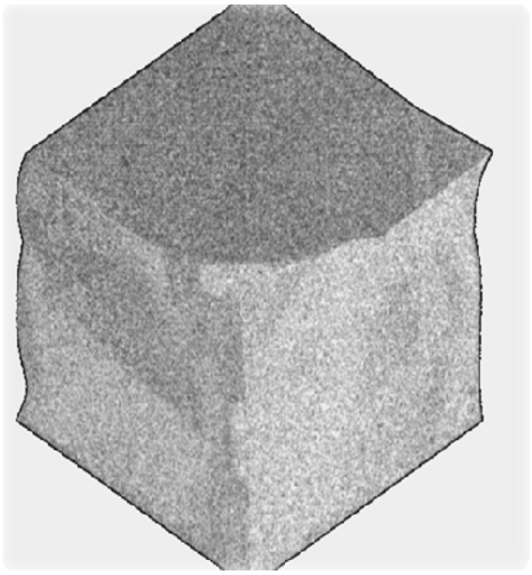
(vii) Three dimensional view

Fig 5.7 Cross sections of 2 % cement grouted medium sand



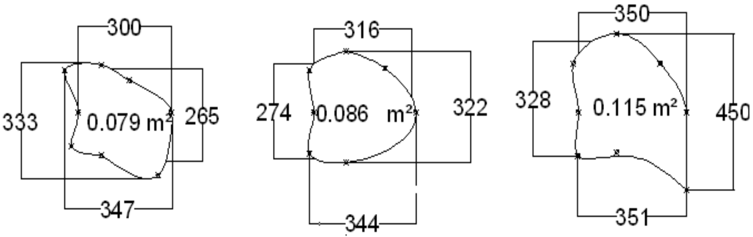
(i) Depth 100mm (ii) Depth 200mm (iii) Depth 300mm

(iv) Depth 400mm (v) Depth 500mm (vi) Depth 600mm

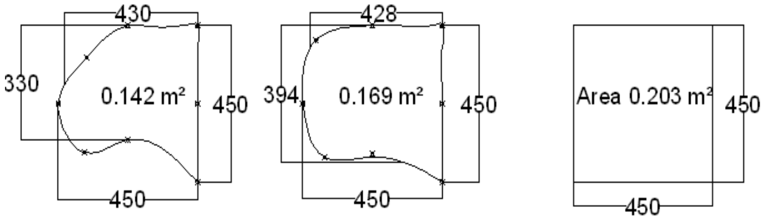


(vii) Three dimensional view

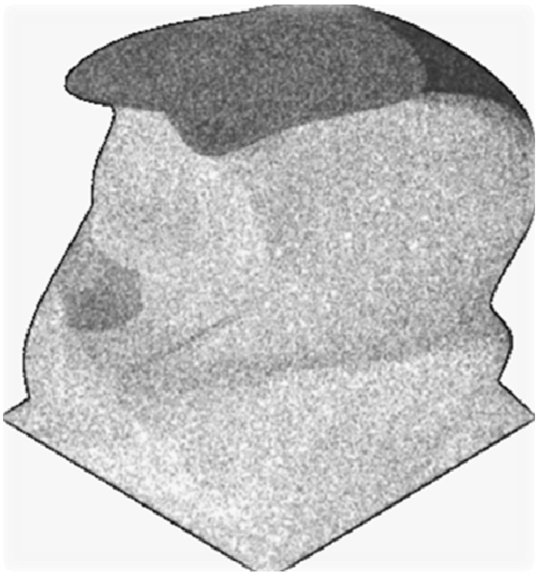
Fig 5.8.Cross sections of 4 % cement grouted medium sand



(i) Depth 100mm (ii) Depth 200mm (iii) Depth 300mm



(iv) Depth 400mm (v) Depth 500mm (vi) Depth 600mm



(vii) Three dimensional view

Fig 5.9 Cross sections of 6 % cement grouted medium sand

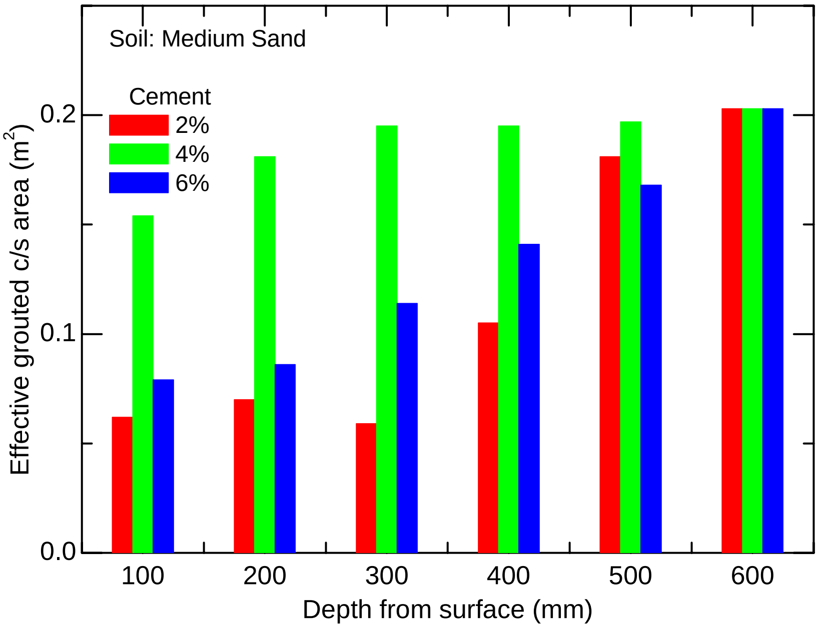


Fig. 5.10 (a) Comparison of cross section areas of grouted samples at different depths

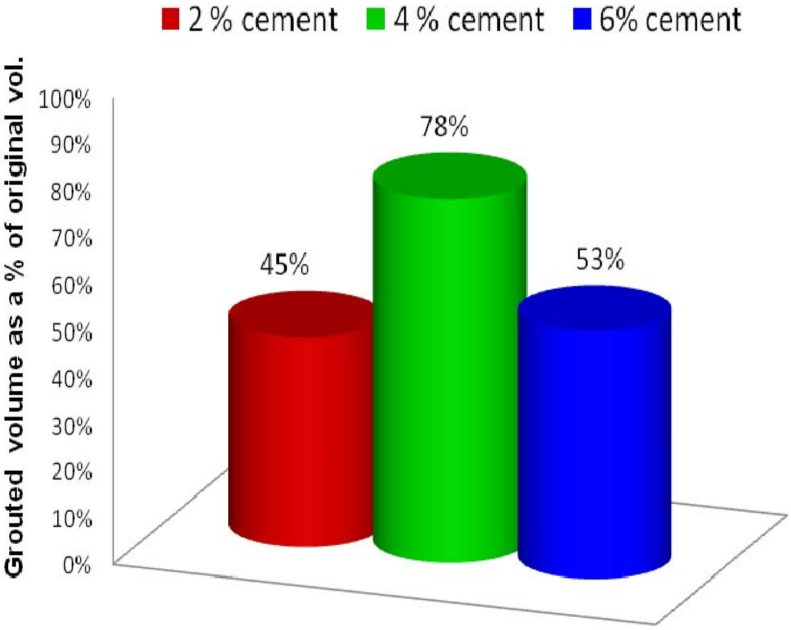


Fig. 5.10 (b) Comparison of volume of grouted samples at different % cement

The cross sectional areas of coarse sand grouted with 2, 4, and 6 % cement at different depths are shown in Fig. 5.11. It can be seen that the sample grouted with 4 % cement indicate a slight increase in effective grouted gross cross sectional area compared with 2 % and 6 % cement. Fig 5.12 shows the three dimensional views of these coarse sand specimens grouted with 2, 4 and 6 % cement.

A comparison of effective grouted cross sectional area of medium and coarse sand is presented in Fig. 5.13. The effective grouted cross sectional area is more upto a depth of 400 mm for medium sand, but it over taken by coarse sand at 500 mm depth. Eventhough the effective c/s is much more at shallow depth in medium sand, there is not much difference in total effective c/s area.

Fig. 5.14 shows the effective c/s area of medium and coarse sand grouted with 4 % cement. It can be seen that cross sectional of medium sand is much significant compared to coarse sand at this cement percentage.

The effective c/s area of medium and coarse sand grouted with 6 % cement is shown in Fig. 5.15. At a depth of upto 400 mm the medium sand shows significant increase in c/s area than coarse sand. Eventhough the same amount of cement is used in both cases, the total grouted volume of medium sand is more significant than coarse sand. In both cases of medium and coarse sand, 4 % cement is more effective than 2 and 6 % cement.

The effectiveness of the three cement grouts – 2 %, 4 % and 6 % in medium sand and coarse sand were compared in terms of the effective grouted cross section area at different depths and are presented in Figs 5.13, 5.14 and 5.15. It can be seen that these cement grouts are more effective in grouting medium sand.

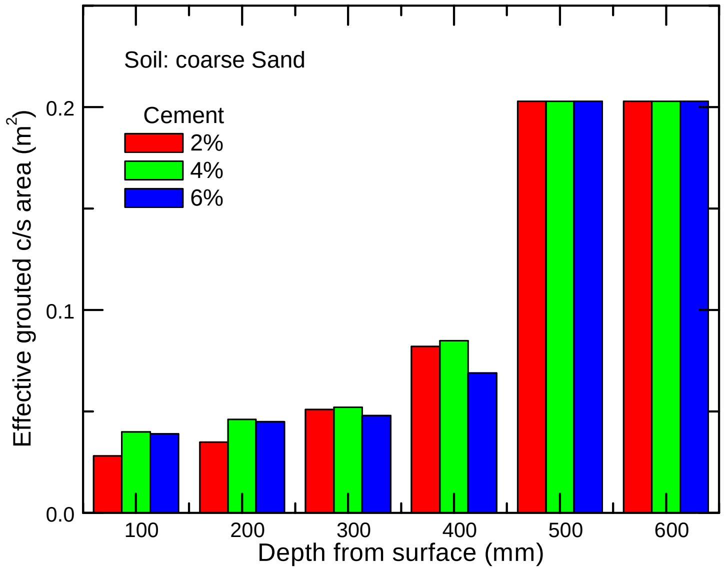
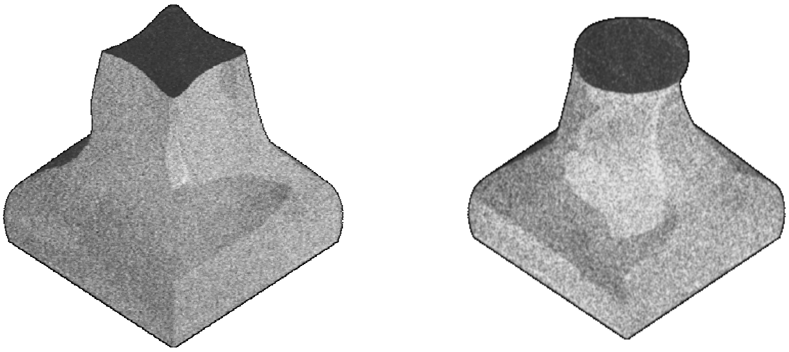
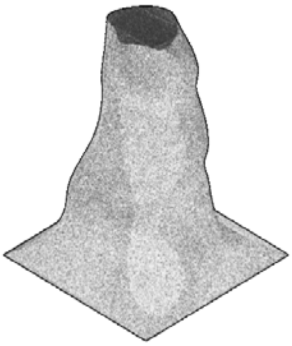


Fig. 5.11 Comparison of cross section areas of grouted samples at different depths



(i) Coarse sand grouted with 2% cement

(ii) Coarse sand grouted with 4% cement



(iii) Coarse sand grouted with 6% cement

Fig.5.12 Three Dimensional views

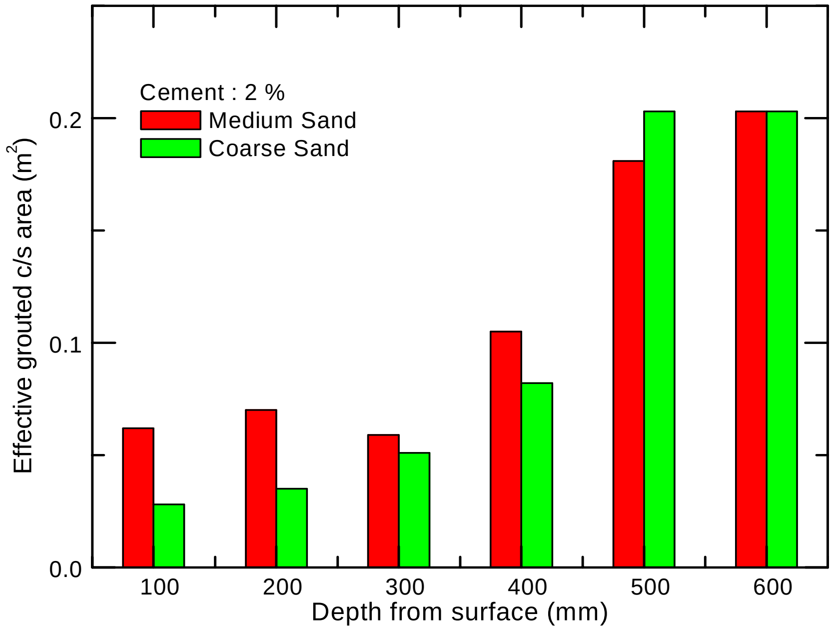


Fig. 5.13 Comparison of cross section areas of grouted medium & coarse sand

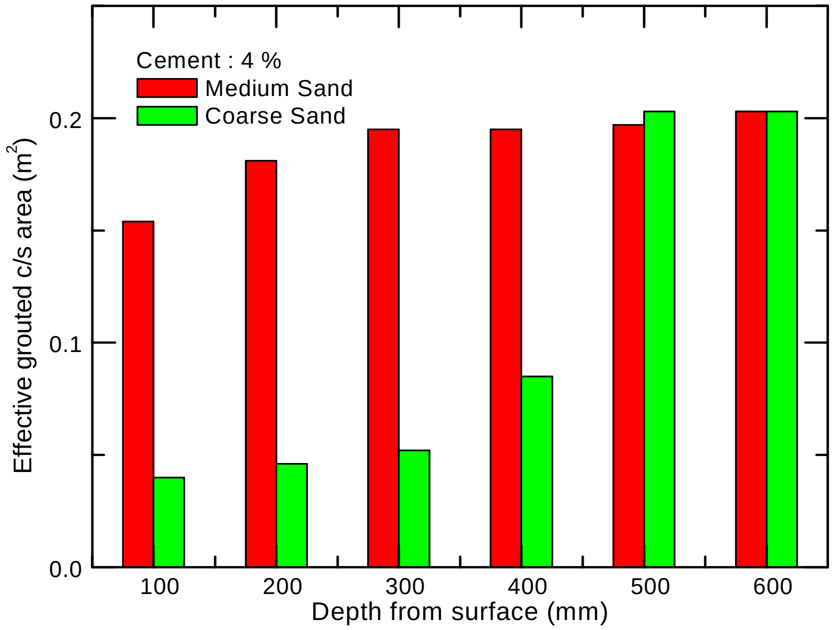


Fig. 5.14 Comparison of cross section areas of grouted medium & coarse sand

5.4.2 Cement with admixtures

The earlier results show that the lateral flow of the grout is very poor in the case of 6 % cement compared to 4 % cement. This may be due to the low stability and viscosity of the 6 % cement grout. The effectiveness of antibleeders and fluidisers in increasing the stability and viscosity of cement grouts have already been established. Hence studies were made in this direction to verify whether the antibleeders and fluidiser could enhance the lateral flow of the cement grout.

The addition of cement to bentonite results in a suspension which has interesting synergistic properties and has been widely used as permeation grout. Depending on the amounts of cement, bentonite and water, grouts will have different properties. Burgin (1979) and Deere (1982) observed a striking influence on viscosity of cement grout by an addition of a small percentage of bentonite. They observed significant increase in Marsh funnel viscosity. Small amounts of bentonite appear to be preferable, sufficient to reduce sedimentation and bleeding but not so great as to impair significantly the pump ability and penetrability. John (1982) suggested that fluidizing agents may be added to reduce the viscosity of the grout.

De Paoli (1992) investigated the fundamental observation on cement based traditional materials that in order to improve the mix permeability it is necessary to increase its stability under pressure, thereby reducing water loss and filter cake growth.

The admixtures used in the present study to make the grout more stable include bentonite and aluminium sulphate (antibleeders) and detergent (fluidiser). Figs. 5.16 (a) & 5.16 (b) show the effect of bentonite (5, 10 & 15 % by weight of cement) and detergent (0.05 % by weight of cement) when used along with 6 % cement in grouting medium sand. Similarly the effect of 2 % aluminium sulphate and 0.05 % detergent when used along with the same 6 % cement in grouting medium sand is shown in Fig. 5.17. It can be seen from the figures that the effective grouted cross sectional area is not increased by the use of either bentonite or aluminium sulphate. In other words, the admixtures do not play any significant role in improving the grouted volume of medium sand.

But these admixtures can influence the efficiency of the grout, when grouting is done in coarse sand. Figs 5.18 (a) and 5.18 (b) clearly bring out this. The column chart shown as Fig. 5.18 (a) clearly gives the increase in the effective grouted cross section area when a combination of different percentages of bentonite and 0.05 % detergent were used along with the cement grout. It can be seen that the best results are produced by the combination of 15 % bentonite and 0.05 % detergent along with the 6 % cement grout. Fig. 5.18 (b) which shows the increase in grouted volume on using these admixtures along with 6 % cement, in grouting coarse sand, underlines the above statement. Some typical photographs of grouted samples are shown in fig.5.19.

5.5 Grouting efficiency from actual cement contents.

The flow of grouts in the pore space of the soil or any discontinuity of rock is resisted by the drag at the interface between the grains and the fluid. For soils that are not uniformly graded, useful estimates of the grout penetrated to the soils are required. Generally the monitoring and efficiency of grouting is observed by the flow - rate versus pressure which depends upon the porosity of the soil to be grouted.

The efficiency of grouting mainly depends upon the penetration of cement grout through the pores of sand. Therefore cement content determination is very much necessary to assess the quantity of lateral flow of the grout into the soil mass, For this purpose, samples were collected from various points in the cured grouted mass.

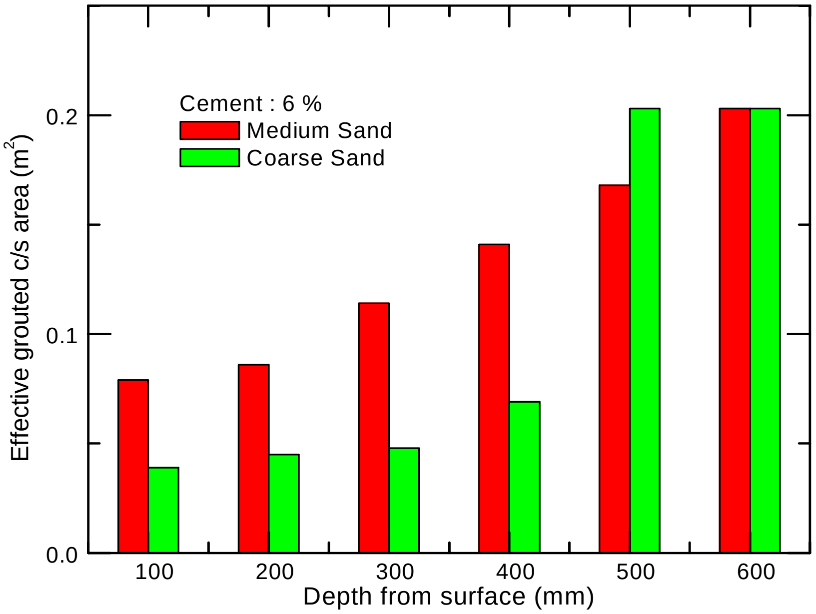


Fig. 5.15 Comparison of cross section areas of grouted medium & coarse sand

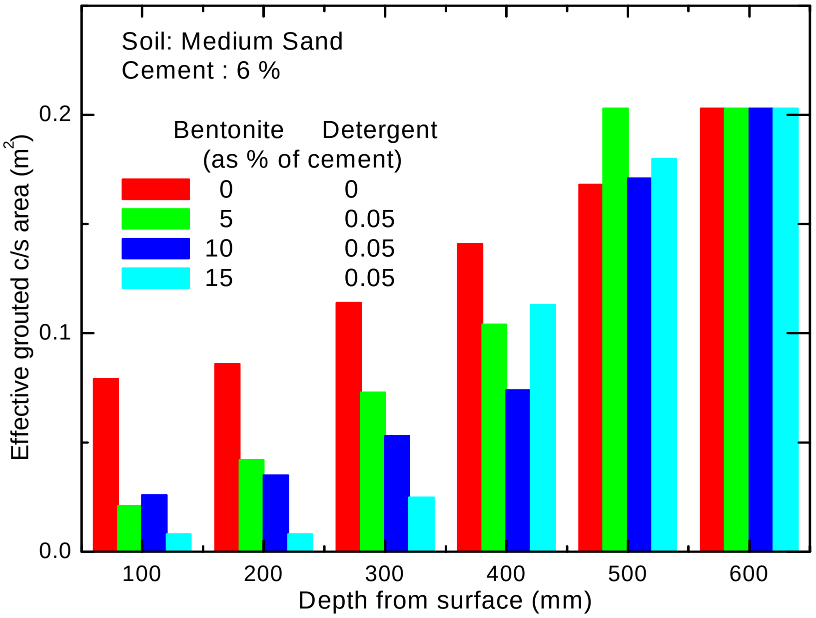


Fig. 5.16 (a) Effect of antibleeder & fluidiser on the flow of grout

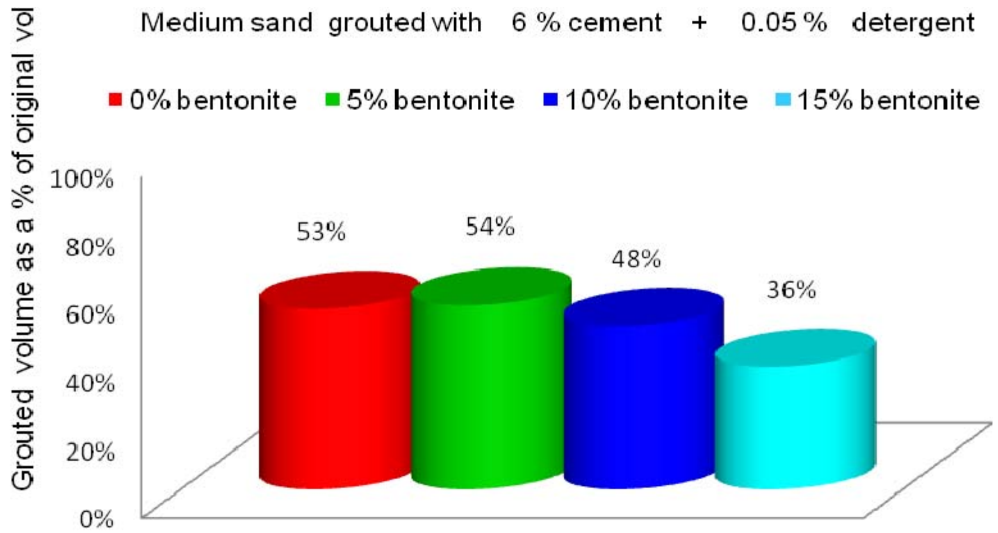


Fig. 5.16 (b) Influence of % bentonite on the grouted volume

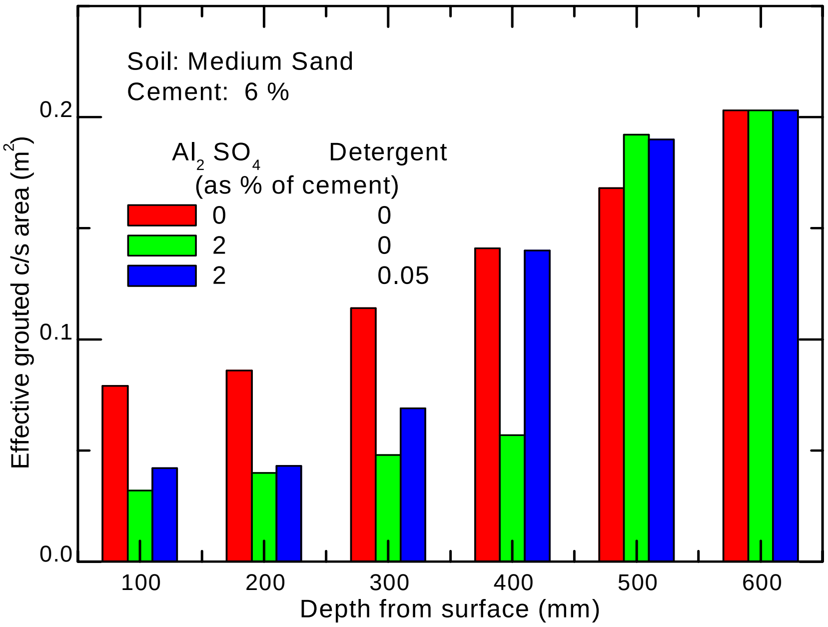


Fig. 5.17 Effect of antibleeder & fluidiser on the flow of grout

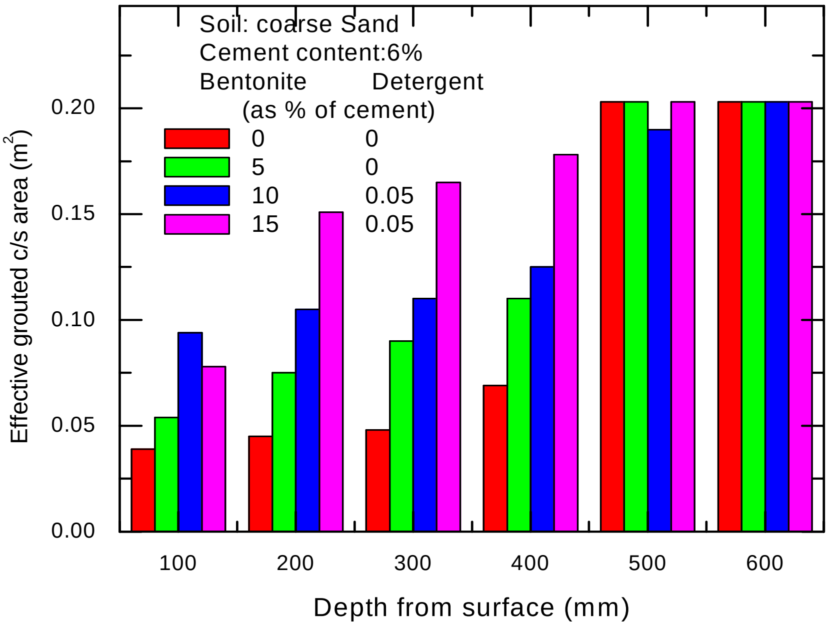


Fig. 5.18 (a) Effect of antibleeder & fluidiser on the flow of grout

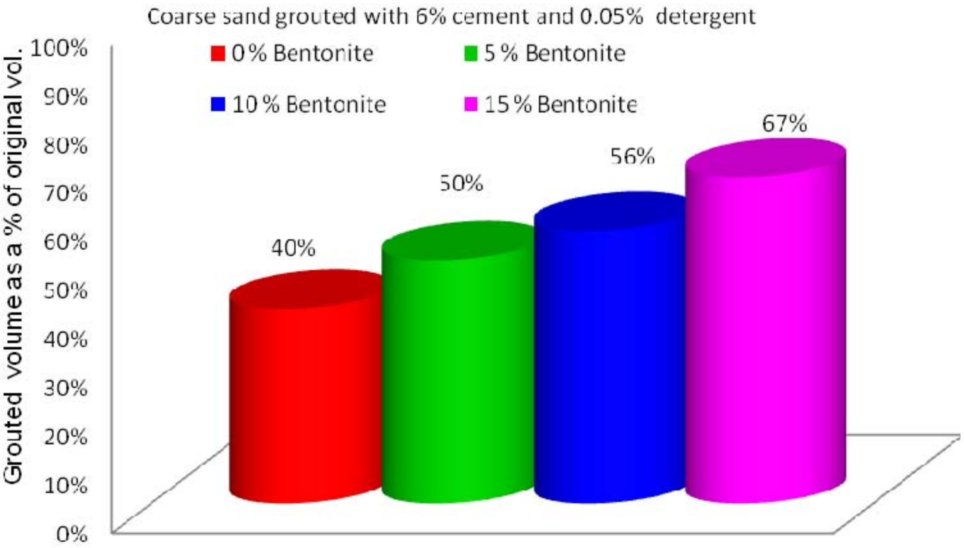
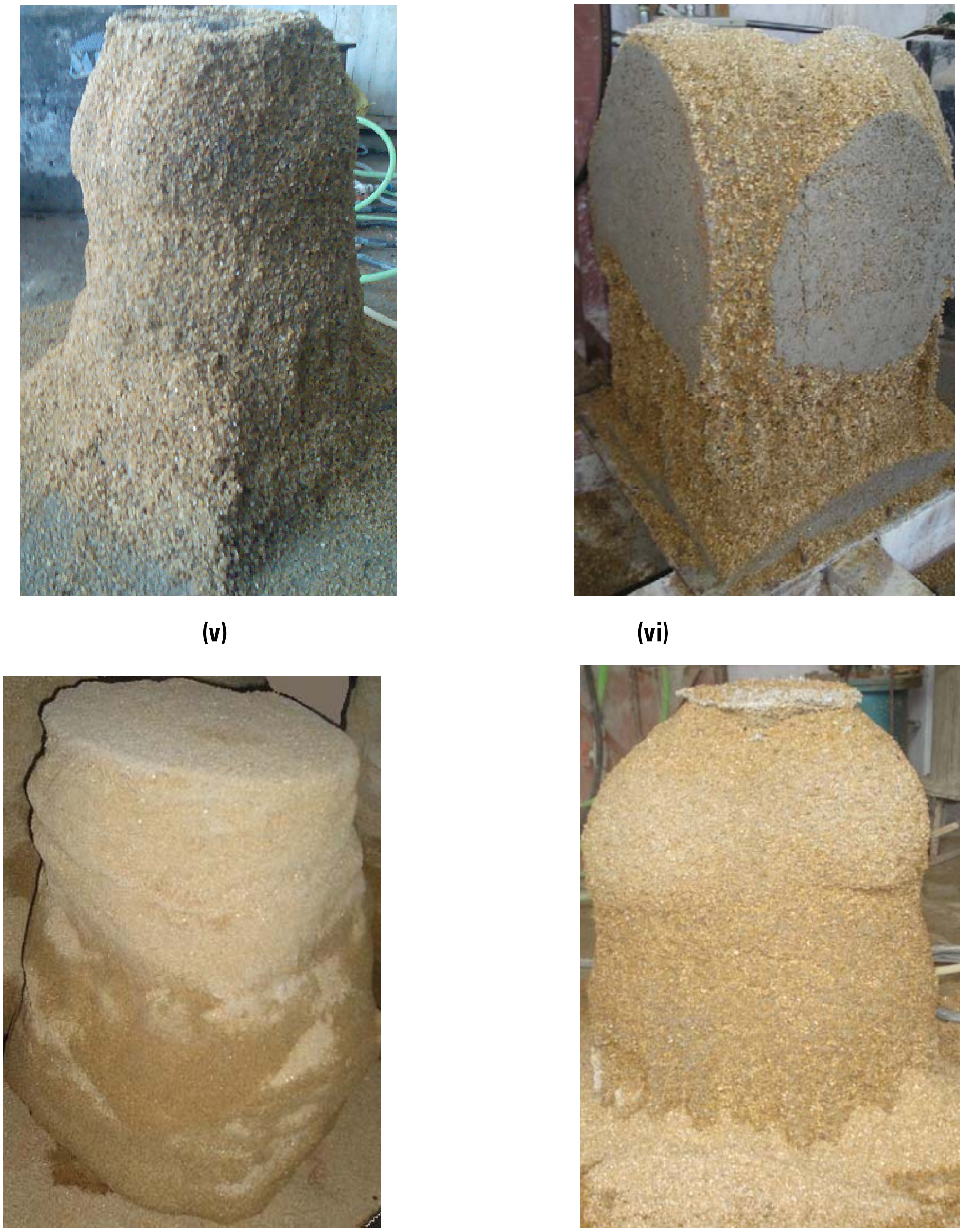


Fig. 5.18 (b) Influence of % bentonite on the grouted volume

(i) **(ii)**

(iii) **(iv)**

Fig. 5.19 (a) Typical photographs of grouted samples



(v) **(vi)**

(vii) **(viii)**

Fig. 5.19 (b) Typical photographs of grouted samples

5.5.1 Cement content determination

As mentioned above, the grouting efficiency can be estimated by determining the cement content of freshly grouted samples or hardened samples as per the procedure (explained in section 3.4.3) given in ASTM Standards (D: 806-00) “Standard test method for cement content of hardened soil- cement mixtures”.

The sand bed prepared as explained in 5.3 at a unit weight of 13.1 kN/m^3 was grouted using 2, 4 or 6 % cement and kept under humid conditions for curing for a period of 28 days. Samples from different depths and from different radial distances were cut from this grouted mass for the determination of cement content.

Fig.5. 20 shows the variation of the cement content with radial distance from the centre of grout hole at various depths of 200, 300, 400, 500 and 600 mm from the top of the grouted bed. 2 % cement (w/c ratio of 4.3) was used for grouting this bed of medium sand. As one would expect, the distribution of cement is not uniform with maximum cement content around the grout hole and it gradually decrease with distance from the centre of the hole. At the centre, eventhough the cement content is very high (5 to 8), it reduces to around 1.5 % as the distance increases to 20 cm. The pattern of this variation in cement content remains the same irrespective of the depth. The same results are also plotted in Fig. 5.21 in the form of a column chart which gives a better representation of this variation.

The variation of cement content with travel distance of grout in the case of 4 % cement (w/c. ratio of 2.2) at different depths are presented in Fig. 5.22. In this case also the samples were taken from distances of 0, 6, 12 and 22 cm from the centre of the grout hole. Compared to the earlier case the cement content obtained at various depths at the same radial distance do not vary much. Also the higher cement contents obtained at farther distances and the higher grouted volume (Fig. 5.8) indicates the better efficiency of the 4 % cement grout in medium sand.

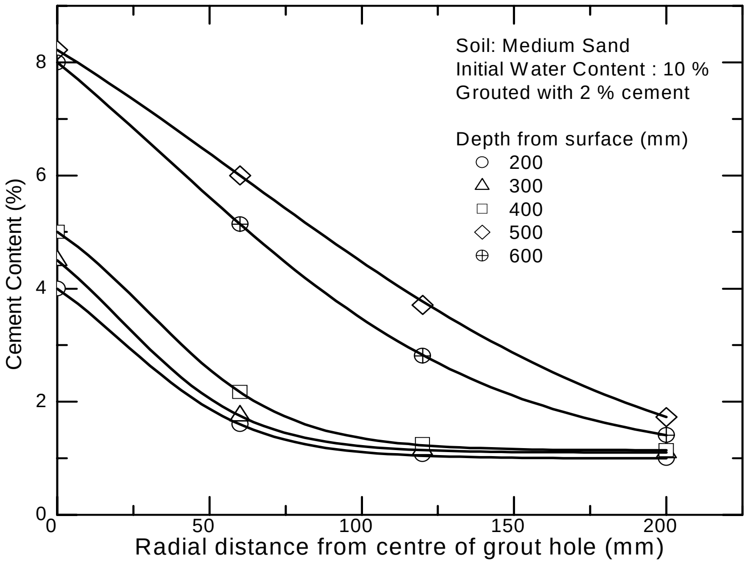


Fig.5. 20 Variation of cement content with travel distance of the grout

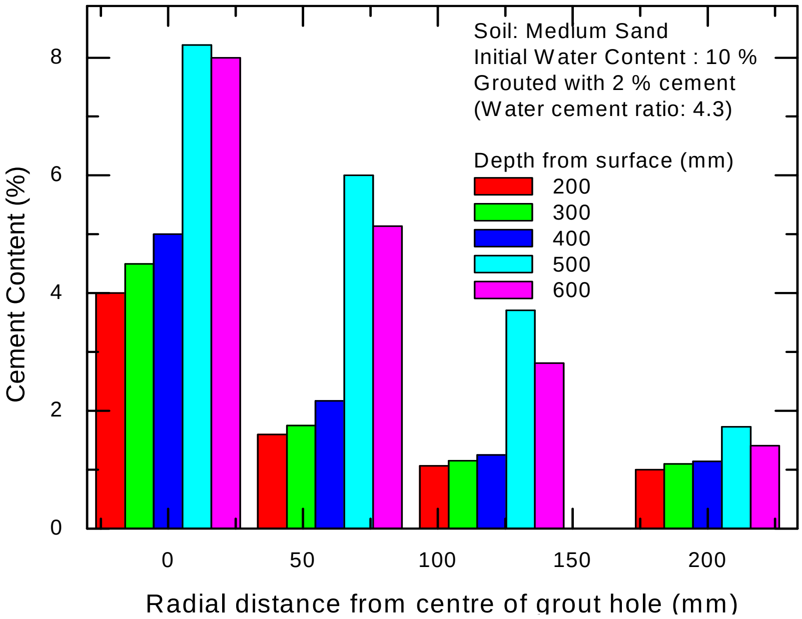


Fig.5. 21 Variation of cement content with travel distance of the grout

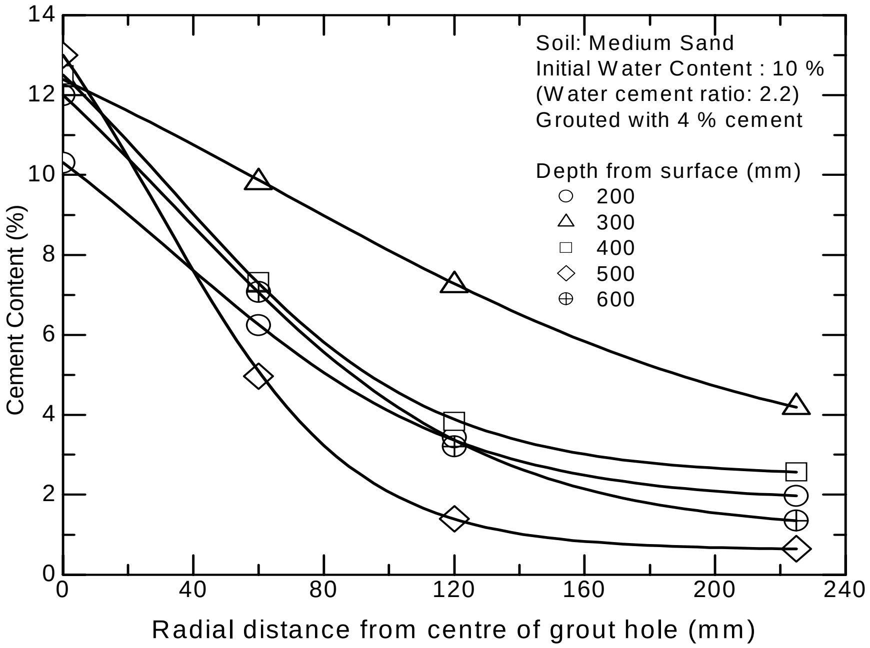


Fig.5. 22 Variation of cement content with travel distance of the grout

Fig.5.23 shows the variations in cement content at different depths and at different radial distances when the medium sand is grouted with 6 % cement (w/c = 1.5). The very high cement content (of the order of 10 -17 %) at the centre indicate the poor flow of the grout in the lateral direction, which is also substantiated by very small cement contents away from the grout hole.

A comparison of the flow of the grout in the lateral direction when the medium sand is grouted with cement 2, 4 & 6 % cement grouts at depths 300, 400 & 600 mm from the surface are given in Figs 5.24, 5.25 & 5.26 respectively. It can be seen that 4 % cement grout is more effective from the cement content and is more economical.

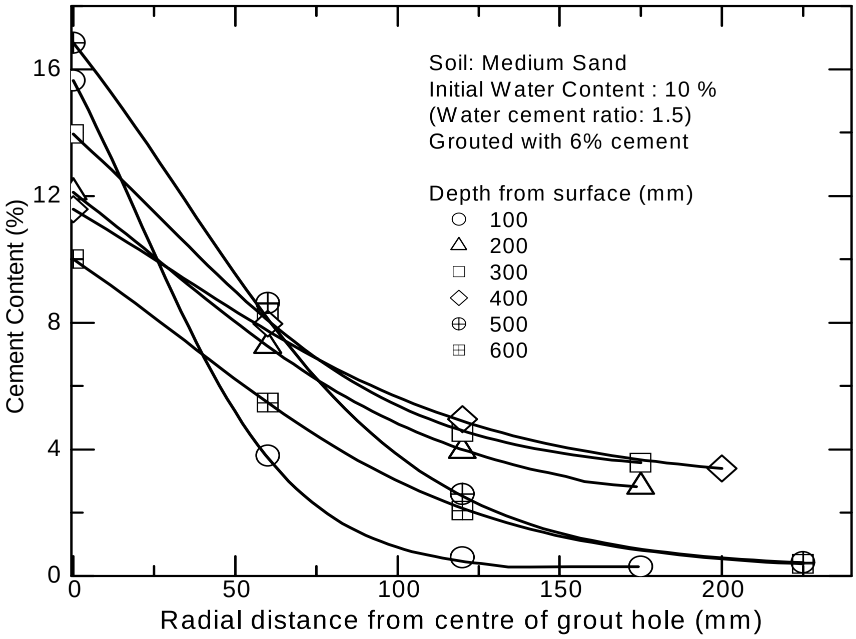


Fig.5. 23 Variation of cement content with travel distance of the grout

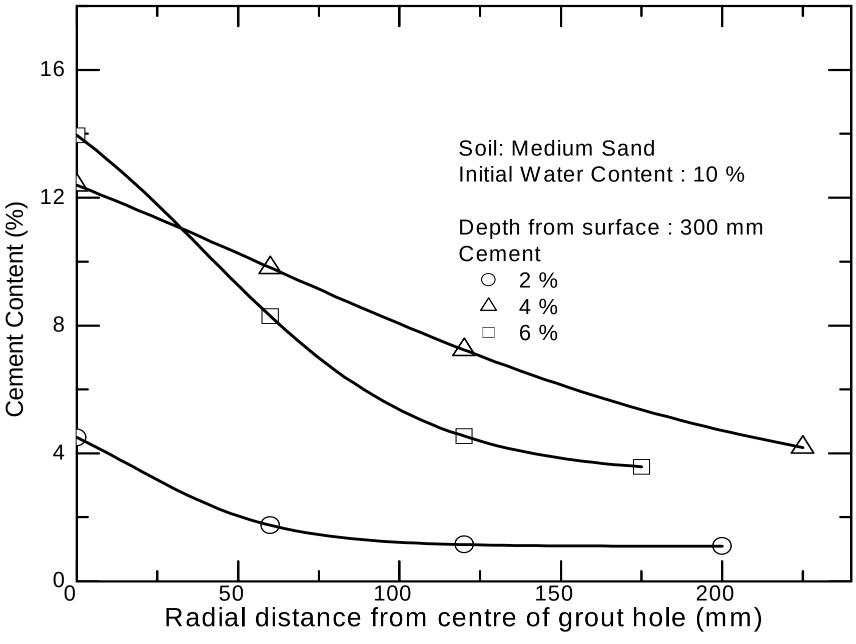


Fig.5. 24 Variation of cement content with travel distance of the grout

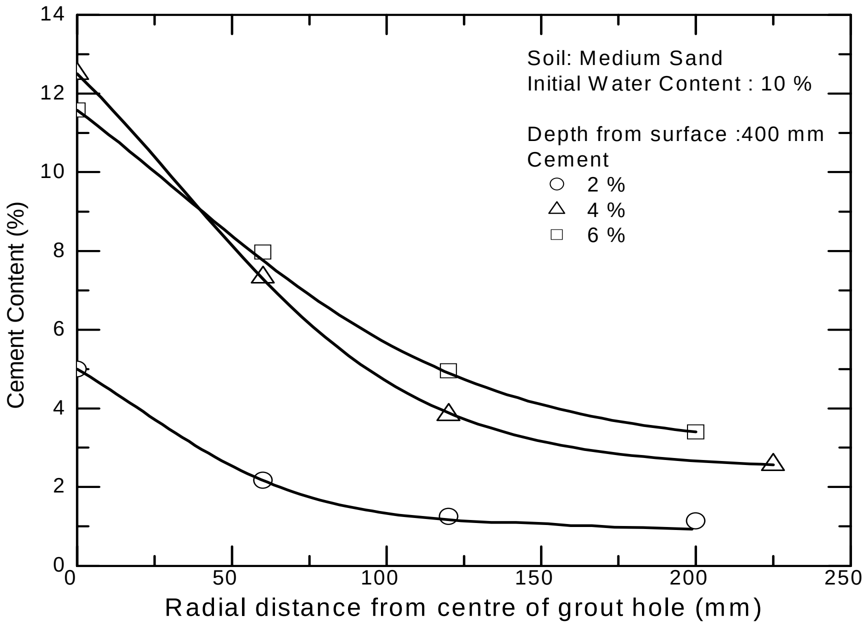


Fig.5. 25 Variation of cement content with travel distance of the grout

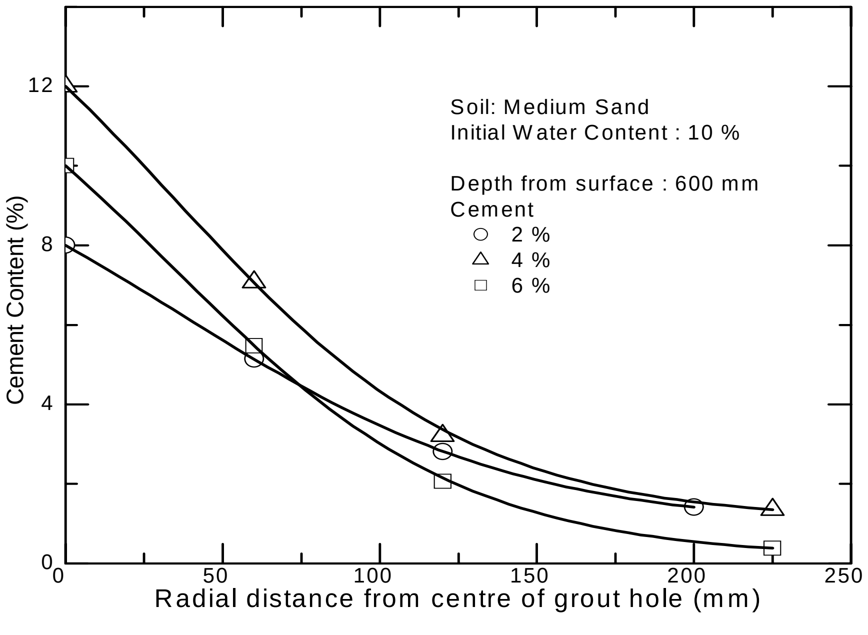


Fig.5. 26 Variation of cement content with travel distance of the grout

Fig.5.27 presents the results of the cement content determined at different depths and at different radial distances when the medium sand is grouted with 6 % cement along with admixtures. The admixtures used in this case were bentonite (antibleeder - 5 % by weight of cement) and detergent (fluidiser - 0.05 % by weight of cement). Similarly the effect of the combination of admixtures – aluminium sulphate (antibleeder – 2 % by weight of cement) and detergent on the 6 % cement grout in improving the lateral flow is given in Fig 5.28. Fig. 5.29 compares the effect of these admixtures with that of the grout without any admixture. It is clear from the figure that these admixtures can certainly enhance the lateral flow. Further it can be seen that aluminium sulphate performs better as an antibleeder compared to bentonite, when used along with cement grout.

The results of cement contents at different depths and at different radial distances, determined when coarse sand is grouted with different grouts ie, 2, 4 and 6 % cement are presented in Figs. 5.30, 5.31 and 5.32 respectively. Fig. 5.30 gives a clear indication that

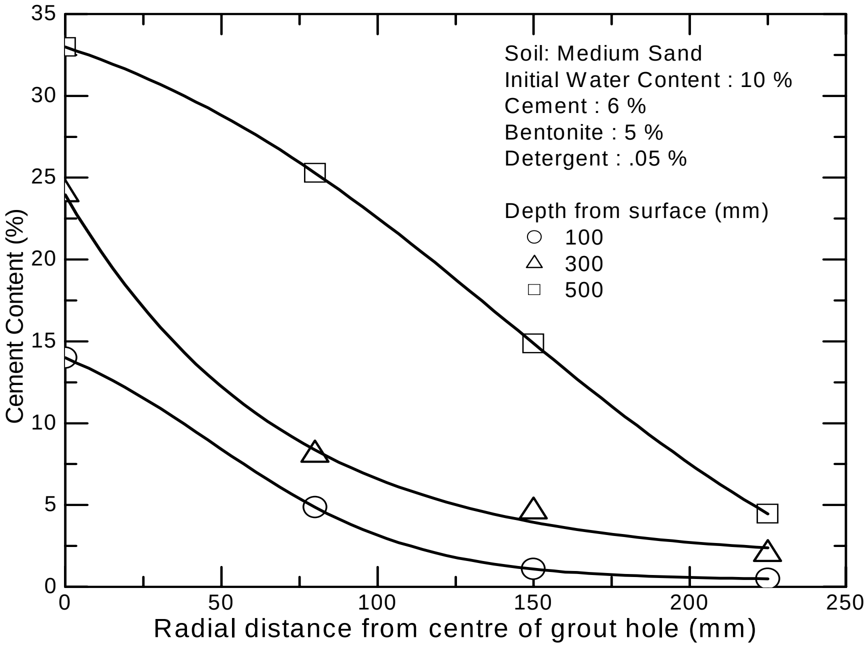


Fig.5. 27 Variation of cement content with travel distance of the grout

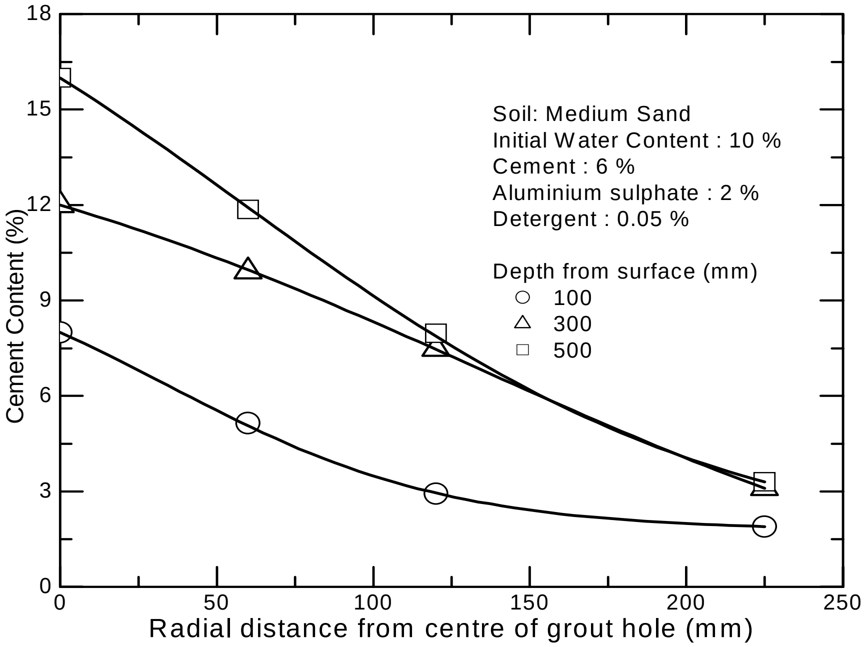


Fig.5. 28 Variation of cement content with travel distance of the grout

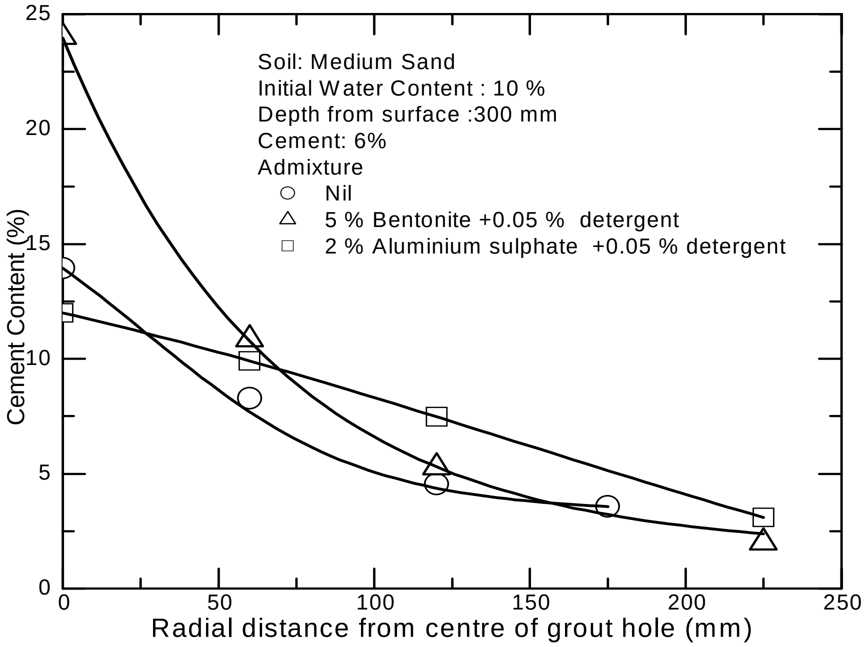


Fig.5. 29 Variation of cement content with travel distance of the grout

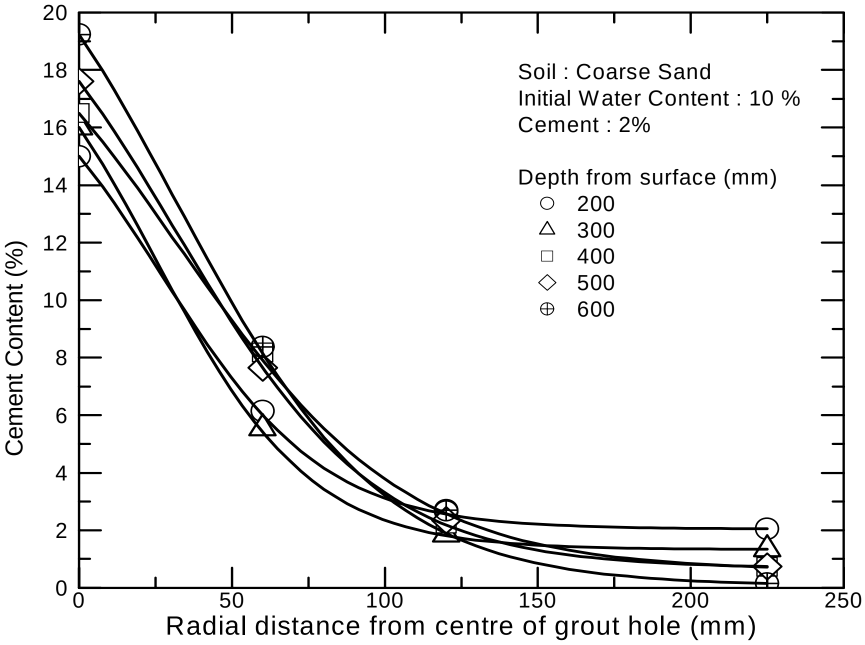


Fig.5. 30 Variation of cement content with travel distance of the grout

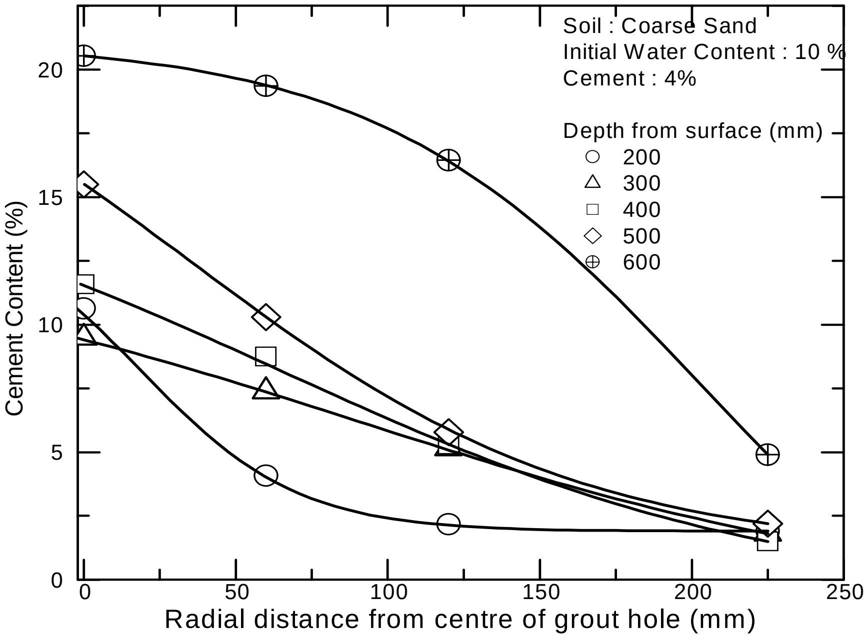


Fig.5. 31 Variation of cement content with travel distance of the grout

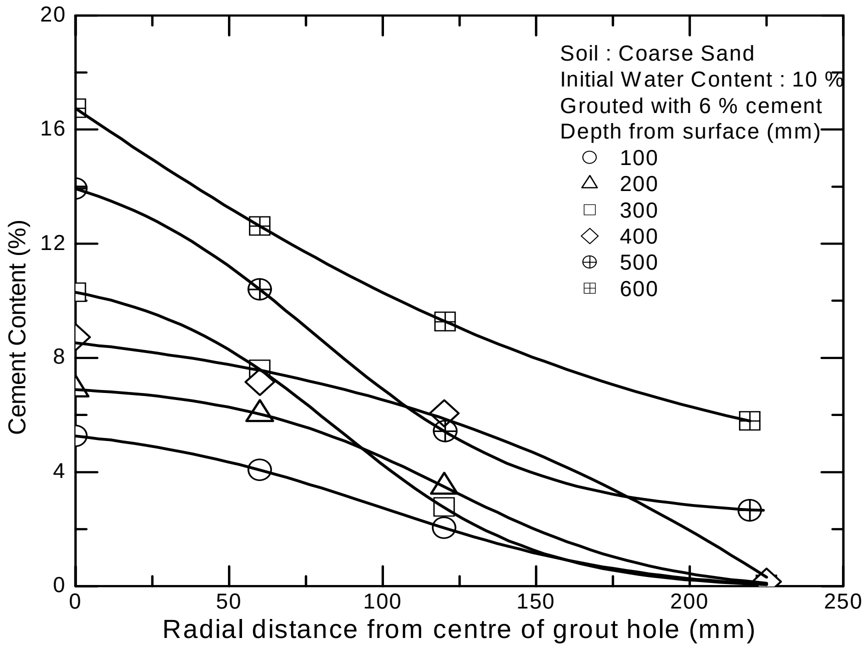


Fig.5. 32 Variation of cement content with travel distance of the grout

2 % cement is not at all effective; where as the flow of grout is better in the case of 4 % and 6 % cement grouts, even without the use of any admixtures. A comparison of the effect of these three cement contents at a particular depth i.e. 300 mm is presented in Fig. 5.33. It can be seen that, similar to the case of medium sand, 4 % cement is more effective in grouting the coarse sand also.

Figures 5.18 and its discussion clearly brings out the effect of admixtures in improving the lateral flow of the grout in coarse sand. Since the combination of 15 % bentonite and 0.05 % detergent was found the most effective, cement contents were determined by taking samples at different depths and at different radial distance from the coarse sand grouted with 6 % cement along with these admixtures. The results presented in Fig. 5.34 clearly shows the improvement in the grout efficiency in reaching farthest places. The much higher cement content ($\simeq$ 4 %) at these points is an indication of a more or less uniform and effective lateral flow of this grout in coarse sand.

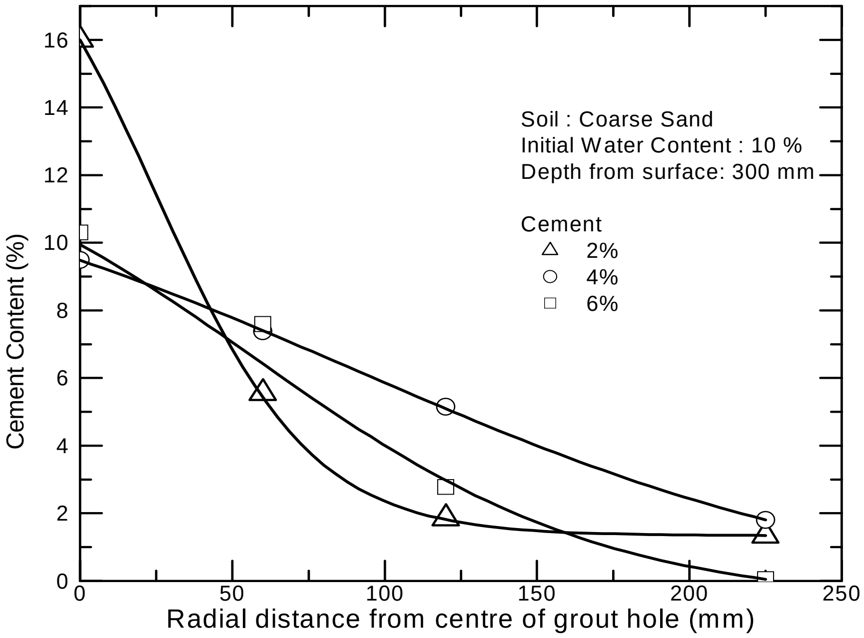


Fig.5. 33 Variation of cement content with travel distance of the grout

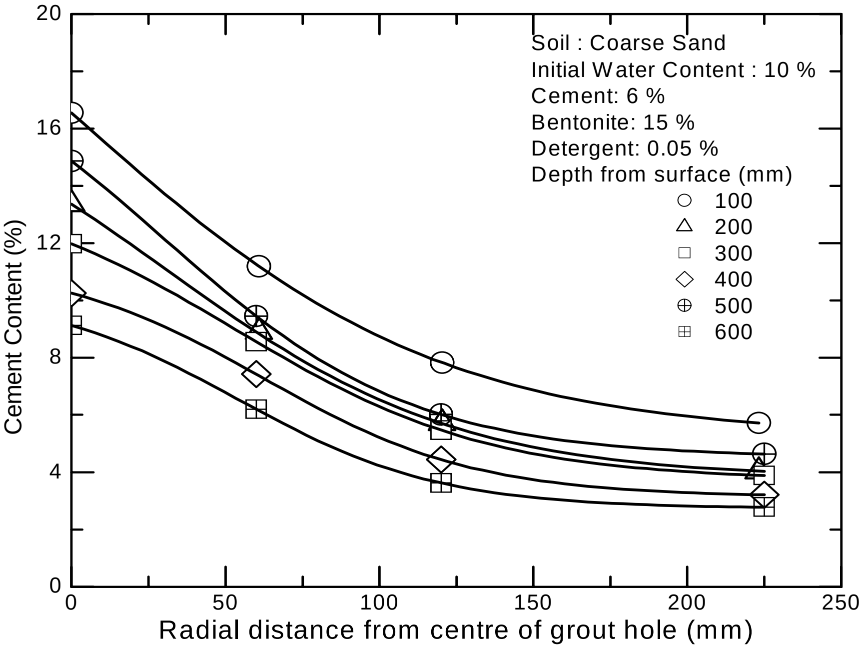


Fig.5. 34 Variation of cement content with travel distance of the grout

5.6 Grouting efficiency from load tests

The results and discussions in the previous sections show that the grouting efficiency can be assessed reasonably well from the effective grouted cross section area and also by the determination of cement contents at different radial distances. But it was felt that a more realistic picture could be obtained if load tests were conducted on these grouted sand beds.

Load – settlement characteristics of grouted sand was studied by conducting load tests in tanks of size 1 m x 1 m x 0.6 m. The sand was filled in the tank at the loosest state (unit weight -13.1kN/m^3). Grout was injected in to the sand bed using different percentages of cement with or without admixtures. The top 100 mm of the sand bed was removed and the grouted bed was kept in humid conditions for curing for a period of 28 days. The cured sand bed was loaded through a plate 20 cm x 20 cm with the help of a hydraulic jack. The loading setup is shown in Fig. 5.35.

Fig. 5.36 shows the load settlement curves in the case of medium sand grouted with 2, 4 & 6 % cement along with that for ungrouted sand. 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. When the sand at loosest state was grouted with 2% cement, the ultimate stress became 380 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. In case of sand grouted with 6% cement, the ultimate stress was 830 kN/m^2, which is 35 times the value of that of the sand at loosest state.

The load settlement curves of coarse sand grouted with 2, 4 and 6 % cement at the loosest state, is shown in Fig. 5.37. It can be seen from the plots that the ultimate stress at the loosest state (unit weight 14 kN/m^3) is only 16.9 kN/m^2. Maximum compaction yielded a unit weight of 16.2 kN/m^3 and the corresponding ultimate stress was 301 kN/m^2. It is interesting to note that for the grout with 2 % cement at loosest density, the ultimate stress was only 220 kN/m^2 against 301 kN/m^2 for the ungrouted sand at densest state. The ultimate loads for 4 % and 6 % cement grouted coarse sand was 989 kN/m^2 and 1023 kN/m^2 respectively. ie, 4 % and 6 % cement grout yield almost the same strength, which is around 60 times that of the ungrouted coarse sand at the loosest state.

A comparison in the strength behaviour between medium sand and coarse sand when grouted with 4% cement is given in Fig 5.38. The strength of the grouted coarse sand is much higher when the deformations are small and it exhibits a brittle type failure. But the load carrying capacity of the grouted medium sand exceeds that of the coarse sand at higher settlements.

Fig 5.39 shows the increase in strength of the medium and coarse sand with the increase in cement content in the grout. In the case of grouted medium sand, the increase in strength is at a steady rate, where as for grouted coarse sand, the rate of increase in strength is quite high as the cement content is increased from 2 to 4 %. Further, in the case of coarse sand, minimum cement content is required for the grouting to be effective. This may be due to the increased pore space available in the case of coarse sand compared to medium sand.

Fig. 5.35 Loading set up

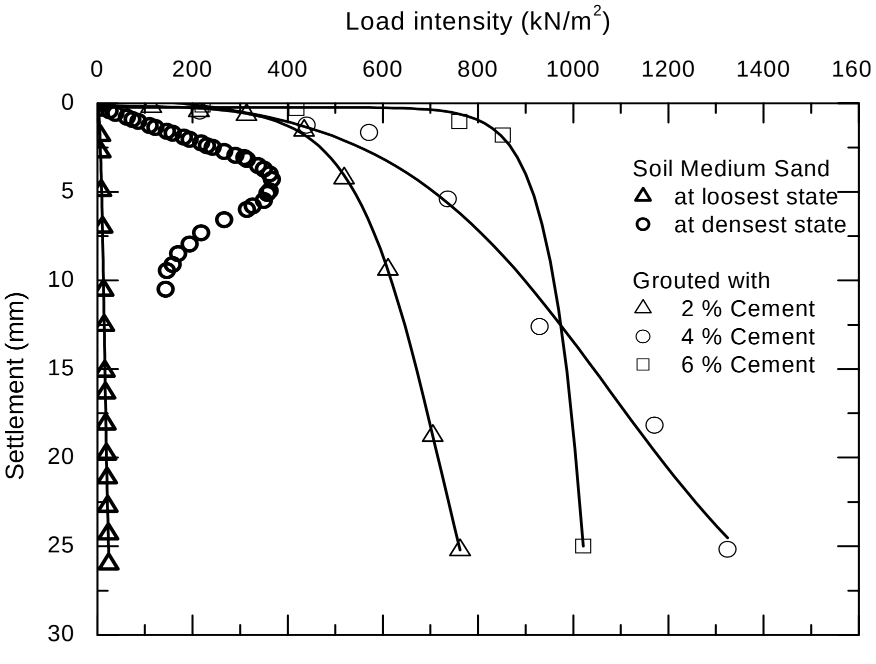


Fig. 5.36 Load settlement curves for grouted sand bed (medium sand)

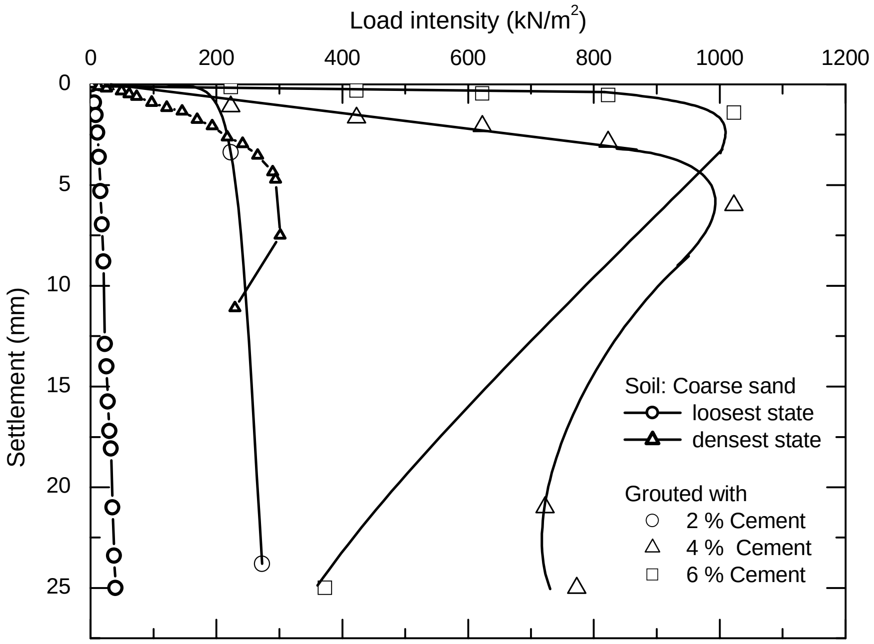


Fig. 5.37 Load settlement curves for grouted sand bed (coarse sand)

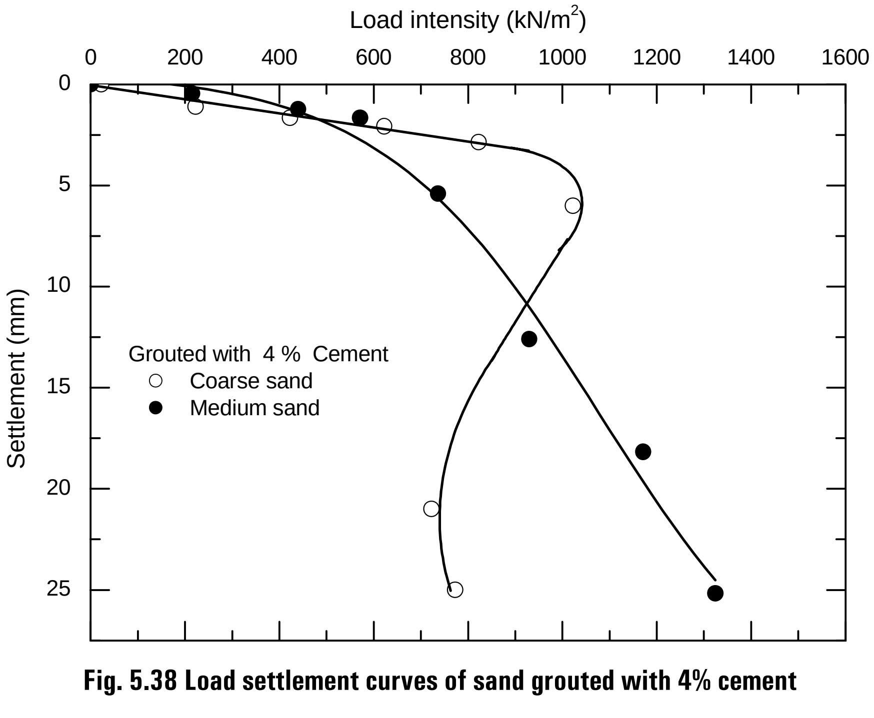


Fig. 5.38 Load settlement curves of sand grouted with 4% cement

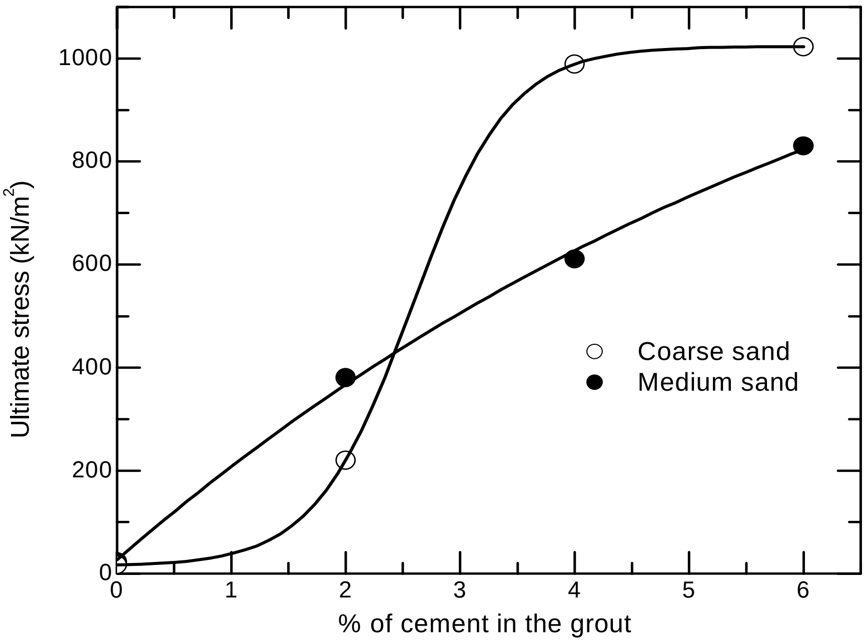


Fig. 5.39 Variation of ultimate stress of grouted sand with % of cement in the grout

Cement – bentonite mixes are very common in grouting practice. Cement, when used alone is susceptible to bleeding or segregation to a high degree which affects the pumping operation seriously. Many authors (Shroff and Shah, 1992; Lovely et al. 1994 & 1997) recommended the addition of small percentages of bentonite to solve this problem, which helps to increase the stability and travel distance of the cement grout.

Load test was conducted on the medium sand bed grouted with 6 % cement along with the admixtures. The admixtures used are bentonite (5 % by weight of cement, which was found to be the optimum dosage as given in Fig 5.16) and detergent (0.05 % by weight of cement). The results from the load test are plotted in Fig 5.40 which also gives the load- settlement curve for 6% cement without any admixtures. Eventhough there is a slight reduction (around

20 %) in strength, the admixtures make the grouted sand bed to be more ductile, thus eliminating the chances of a sudden failure of foundations.

The tremendous improvement in the lateral flow of the grout when admixtures were used along with 6% cement in the case of coarse sand was discussed in sections 5.4 and 5.5. In order to verify whether the same effect is reflected in the strength behaviour also, load test was conducted on coarse sand grouted with 6 % cement along with the admixtures – 15 % bentonite and 0.05 % detergent, and the results are presented in Fig 5.41. In this case, in addition to making the sand bed more ductile, the admixtures help to increase the load carrying capacity (twice the strength compared to the sand bed grouted without admixtures). This can be attributed to the increased lateral flow of the grout when admixtures are used along with cement in grouting coarse sand beds, which is more clear from Fig 5.42.

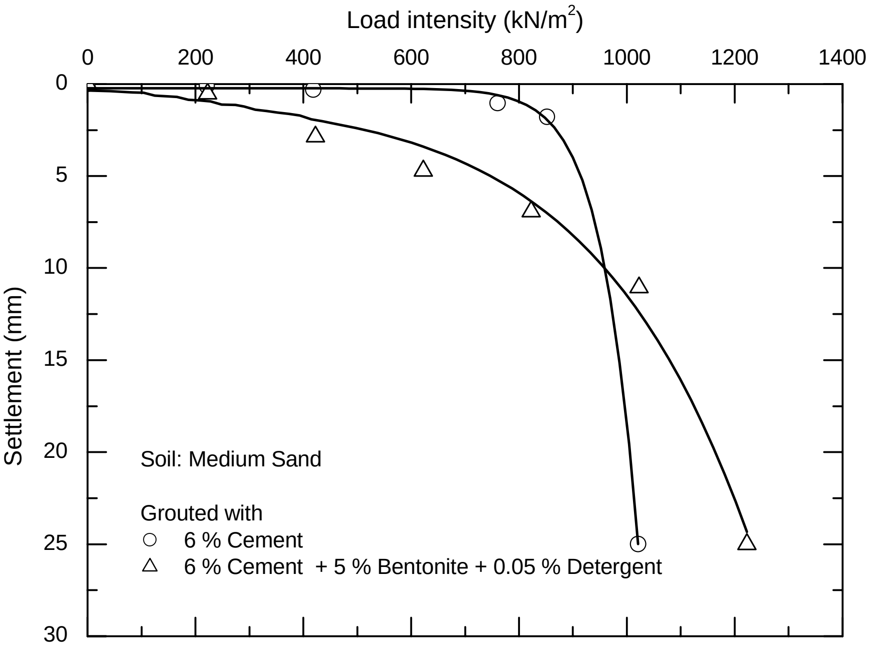


Fig. 5.40 Effect of admixtures on the load – settlement behaviour (medium sand)

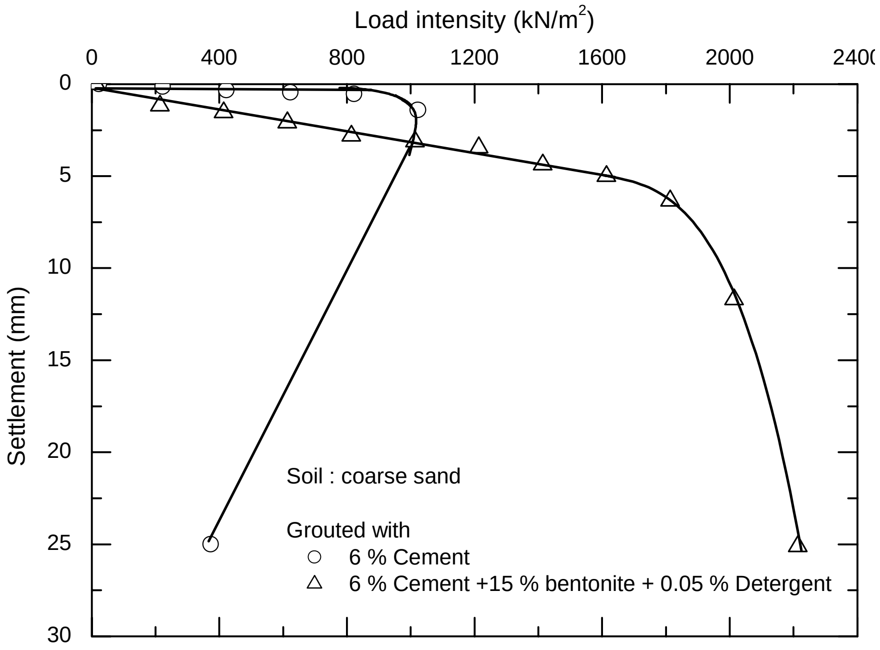


Fig. 5.41 Effect of admixtures on the load settlement behaviour (coarse sand)

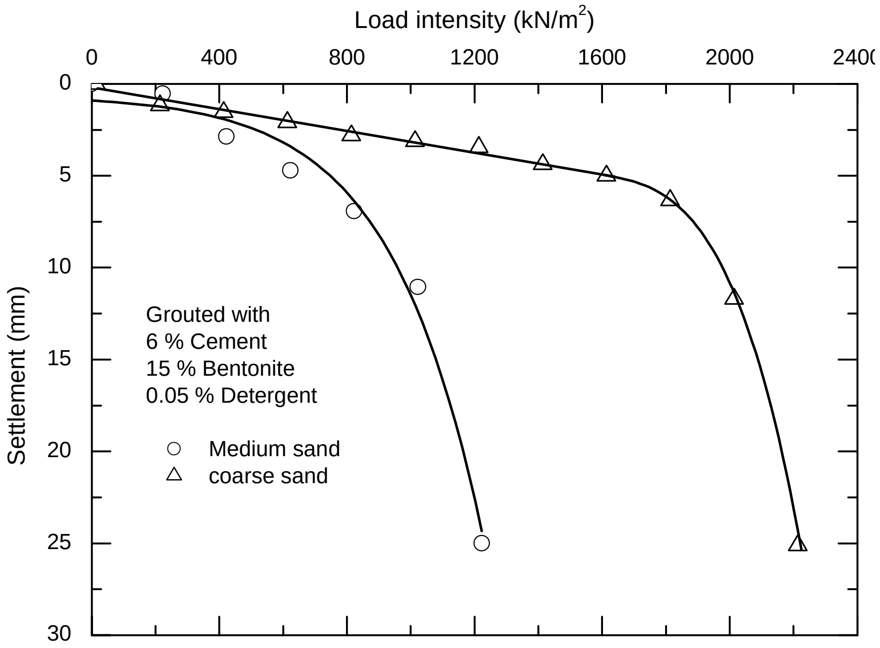


Fig. 5.42 comparison of the effect of admixtures in medium and coarse sand

Investigations were made to study the load carrying capacity of cement grouted beds in the ideal condition; i.e. what would have been the strength, had the grout been uniformly spread over the entire volume of the soil mass. For this purpose medium sand was uniformly mixed with different percentages of cement (2, 4 and 6 % by weight of sand) and water (10 % by weight of sand + cement) and filled in such a way that the initial unit weight of medium sand alone was 13.1 kN/m^3 (corresponding to the loosest state). After curing under humid conditions for 28 days, load test was conducted following the same procedure, the results of which are presented in Fig 5.43. As expected, there is a phenomenal increase in strength with percentage of cement.

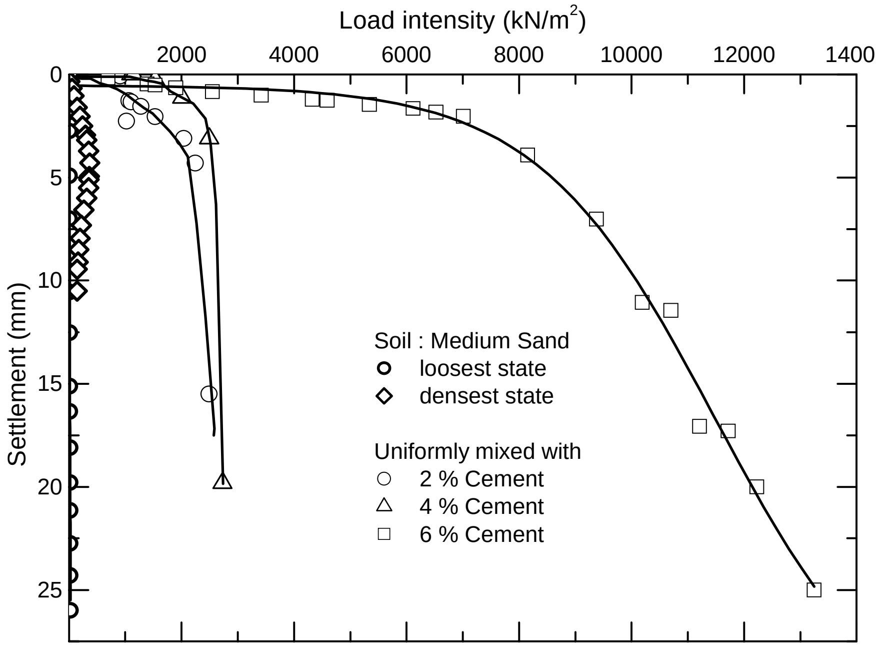


Fig. 5.43 Load settlement curves of cement treated medium sand (uniformly mixed)

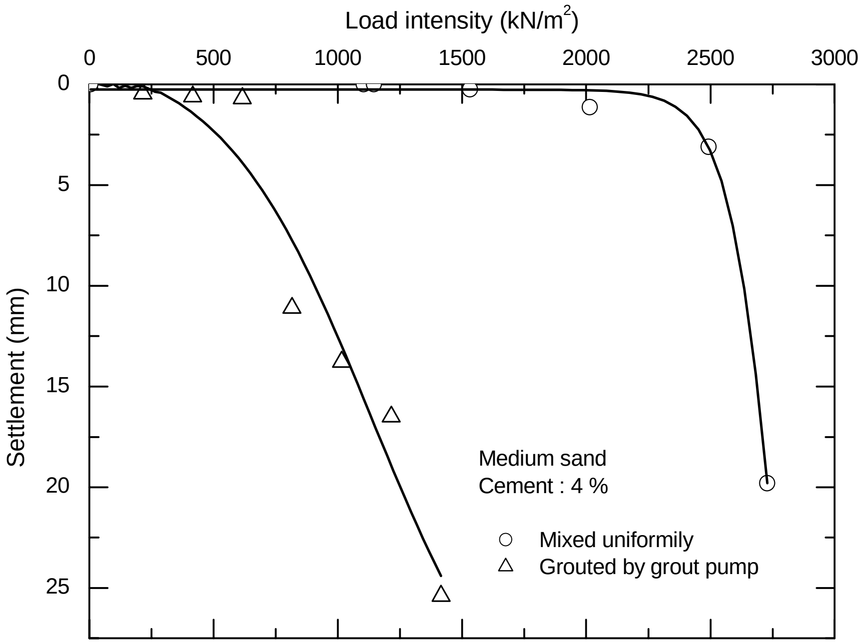


Fig. 5.44 Comparison of load settlement behaviour of cement grouted and uniformly mixed sand beds

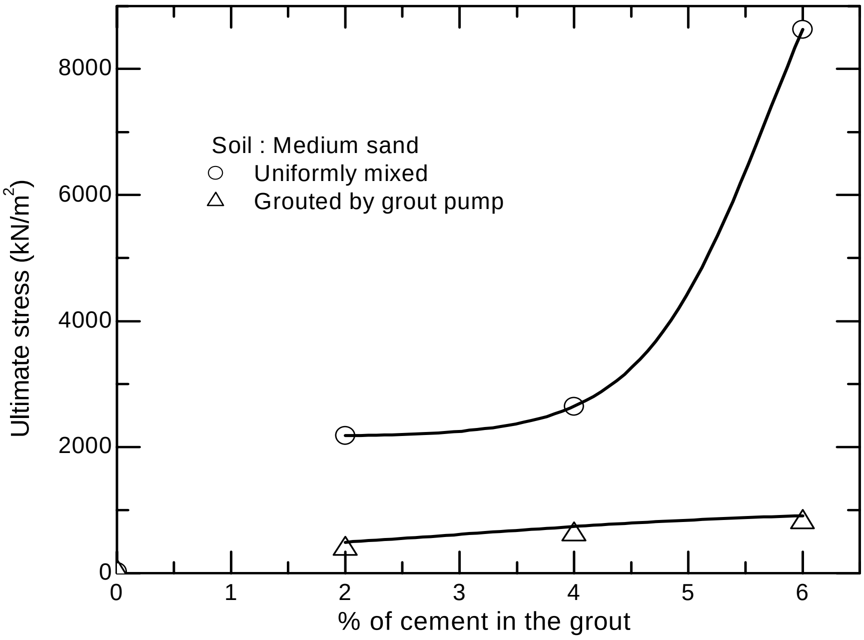


Fig. 5.45 Variation of ultimate stress of grouted sand with % of cement

A comparison in strength of the medium sand beds grouted with cement (grout pumped through grout pump) without any admixtures, with that of the uniformly mixed medium sand beds is given in Figs 5.44 and 5.45. It can be seen that grouting by grout pump could yield only one-third the load carrying capacity of that of the uniformly mixed bed, for a cement content of 4 %. This figure along with Fig. 5.45 stress the need for developing proper grouting tools and methods for making the grouting process more efficient so that the foundation design can be made more economical.

Chapter 6

PERMEABILITY STUDIES ON THE GROUTED SOIL

Contents

6.1 Introduction

The effectiveness of grouting to improve the strength characteristics of loose sandy soils has already been established with the help of experimental results in Chapters 4 and 5. Grouting is normally undertaken to reduce the permeability of rock or soil formations and this process is used extensively in the construction of hydraulic structures such as dams, power houses, tunnels and in a wide variety of special cases. Various materials such as cement, sand, silt, clay, bentonite, chemicals etc. are used, depending upon the need and purpose of grouting and the nature of formations to be grouted. Eventhough the application of this grouting technique to reduce the permeability of rock formations has been reported in literature, no serious attempts are reported about the effective use of this technique to reduce the permeability of soil formations. The results of experimental investigations carried out in this direction are presented in this chapter.

The results obtained from permeability tests conducted on different graded sand fractions such as fine, medium and coarse sand at a dry unit weight of 14.5 kN/m^3 is given in Table 6.1. As one would expect, the permeability increases with increase in grain size of soil particles.

Table 6.1. Coefficient of permeability of different sand fractions

Sl. no.	Soil type	Size range (mm)	Permeability (m/sec)
1	Fine sand	0.075 – 0.425	0.54×10^{-4}
2	Medium sand	0.42 5 – 2.0	1.86×10^{-4}
3	Coarse sand	2 .0 – 4.75	2.69×10^{-4}

The technology of grouting now plays an important role in all the fields of foundation engineering such as seepage control in rock and soil under dams, advancing tunnels, cut off walls etc. in the evaluation of safety of any dam, problems connected with excessive leaching and seepage. Seepage not only causes loss of valuable water stored in the reservoir, but also poses problems by its existence through piping. Control of seepage through the dam foundation and minimizing exit gradient on the downstream, play key roles in the analysis and design of dams. When transit or utility tunnels are to be placed beneath the water table and the soils encountered have permeability greater than approximately 1 x 10^{-5} m/s, water inflow can be expected. Along with this water inflow, soil can be eroded into the tunnel, resulting in piping collapses and adverse surface settlements. Remedial and rehabilitation measures for arresting excess leaching and seepage mainly involve controlling the permeability of the soil strata by means of grouting.

Kenai et al.(2006) investigated the effect of compaction methods on mechanical properties and durability of cement stabilized soil. According to them the reduction in permeability could be attributed to the reduction of large pores by the cement particles and cement hydration products. Thus the treatment of soil with cement could lead to a better mechanical strength, lower permeability and hence better durability.

6.2 Cement as the grout material

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

In order to determine the effect of cement in reducing the permeability of the sand medium, permeability tests were conducted on specimens prepared in the permeability mould. For preparing the samples, medium sand (unit weight 14.5 kN/m^3) was mixed with different percentages of cement in the dry condition. Then 10 % (by weight of sand – cement mixture) water was added to the mixture, mixed well and filled in the mould for conducting the permeability test.

Figure 6.1 shows the effect of cement content on permeability of sandy soil treated with cement, at different curing periods. As one would expect, the permeability decreases with increase in the percentage of cement. The reduction in permeability is only marginal in case of specimens cured for 7 & 14 days, whereas the reduction is substantial as the curing period is increased to 28 days. Similarly increased use of cement (beyond 10%) can influence the permeability at higher curing periods only. The reduction in permeability with respect to the cement content and curing period is more clear in Fig. 6.2. It can be seen that the permeability got reduced by 1/7400 in the case of 25% cement and cured for 28 days. When cement alone was added to the medium sand, the cement hydrates and occupied the voids of sand thereby decreasing the interconnectivity of soil voids by blocking the potential flow paths.

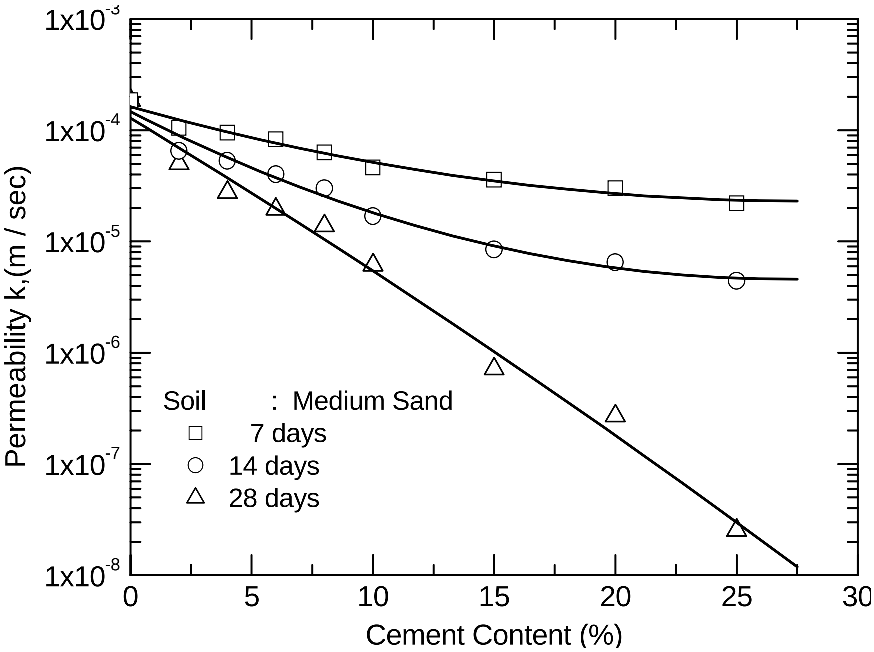


Fig.6.1 Effect of cement content on permeability of cement treated sand

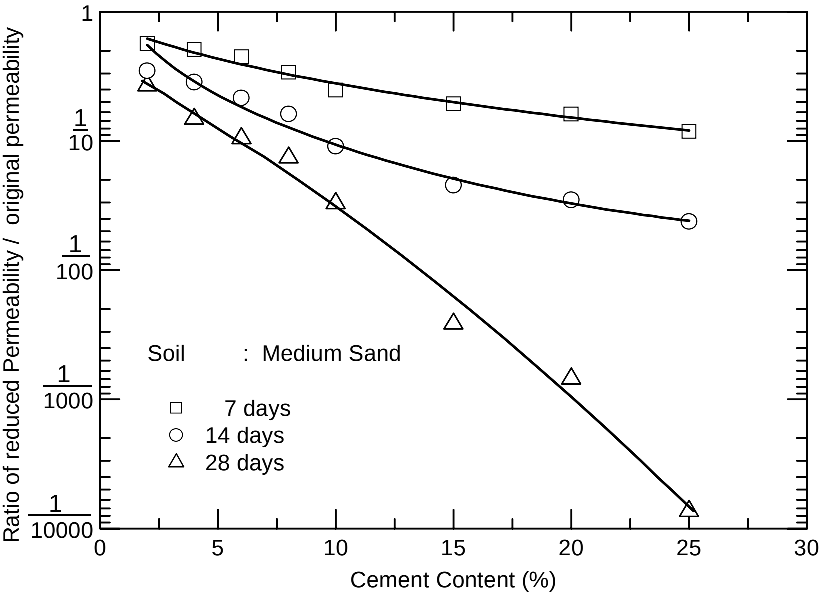


Fig.6.2 Reduction in permeability with cement content

The permeability and strength of grouted sand is strongly influenced by the method of grouting because different mechanisms govern the deposition and packing of cement particles within the pores 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 pore spaces of the grouted sand (Schwarz and Krizek, 1994).

Fig.6.3 shows the effect of curing period on permeability of cement treated sand having different cement contents 4, 10 and 25 %. It can be also be seen that eventhough the permeability decreases with elapsed time, it becomes almost constant beyond 15 days of curing period for lower cement contents (i.e. 4 % and 10 %), but at higher contents (e.g. 25 %), the permeability goes on reducing drastically even after 15 days. Hence one can presume that reduction in permeability is directly related to the hydration of cement. The reduction in the permeability with reduction in the size of particles of the mixture (sand + cement) is quite clear from Fig.6.4 which is a plot between the effective size D_{10} of the

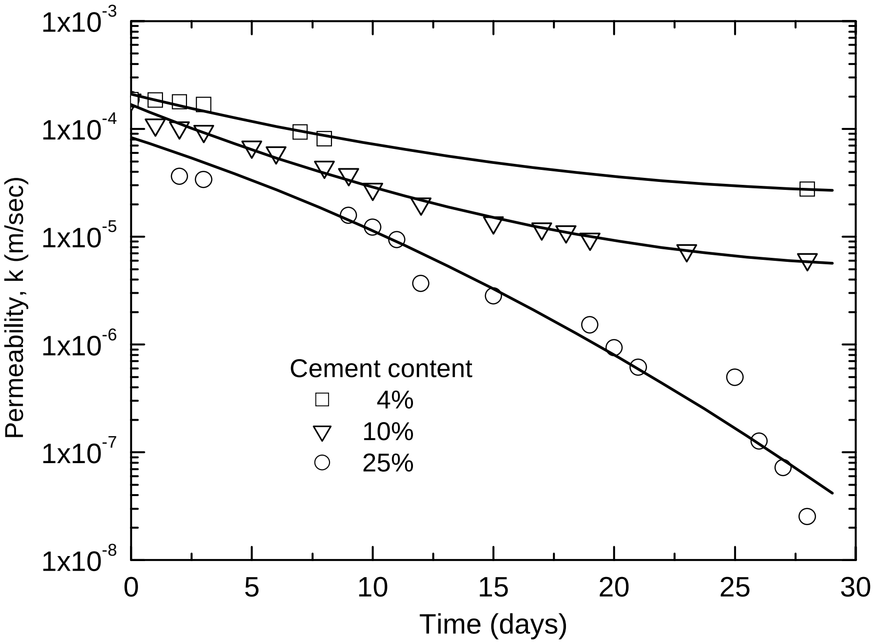


Fig.6.3 Effect of curing time on permeability of cement treated sand

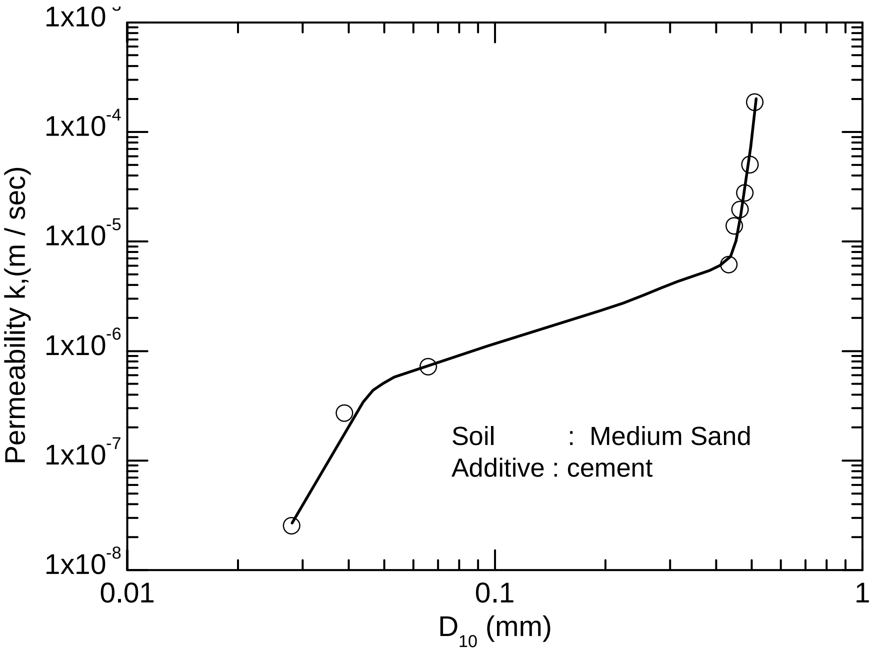


Fig.6.4 Effect of effective size of particles on the permeability of cement treated sand

sand - cement mixture and the corresponding permeability. Similarly, the addition of cement (process taking place in cement grouting) will cause a reduction in the void ratio and consequently the permeability. The plot between the void ratios ‘e’ and the coefficient of permeability ‘k’ (Fig. 6.5) illustrates the reduction in permeability accompanied by the reduction in void ratio.

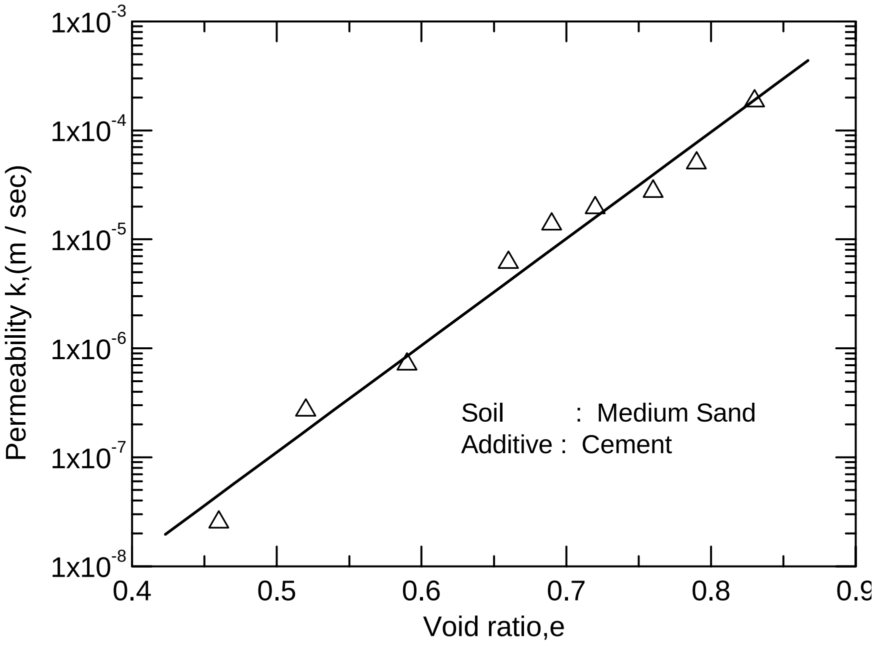


Fig. 6.5 Plot between void ratio and permeability of sandy soil treated with cement

6.3 Cement with admixtures

In most of the cases, the primary aim of grouting is to reduce or cut off seepage through sandy subsoil by making it impermeable by deposition of fine materials in pore spaces with grouting. The sand layers may be uniform mass of either very fine or coarse grains or it can also be a well graded media. The hydraulic conductivity of sand beds can be reduced by injecting fine materials (10 % cement + bentonite) into the interspaces of the formation (Lovely, 1998).

A soil bentonite mix is a three phase material of solids, water and air. Besides their different densities, the two components of the solid phase have different properties and must be considered separately. The bentonite particles have a very high specific surface (5 - 12 × 10^4 m^2/kg) which allows them to retain a portion of water that displays inability to flow as freely as the remaining water in the pore space (Chapuis 1990). Fig.6. 6 presents the results of permeability tests conducted on medium sand treated with two different percentages – 4 % and 10 %. The different percentages of bentonite (0.2 to 1.5 % by wt. of the sand + cement mixture) was added and the permeability tests were conducted after a curing period of 15 days, as per the procedure discussed in section 3.4.3. It is clear that there is a phenomenal reduction in the permeability due to the addition of this admixture, i.e., bentonite. Another interesting observation is that, eventhough the permeability goes on decreasing with % of bentonite, at higher % of bentonite (e.g. 1.5 %), the permeability corresponding to 4 % cement and 10 % cement yield almost the same value.

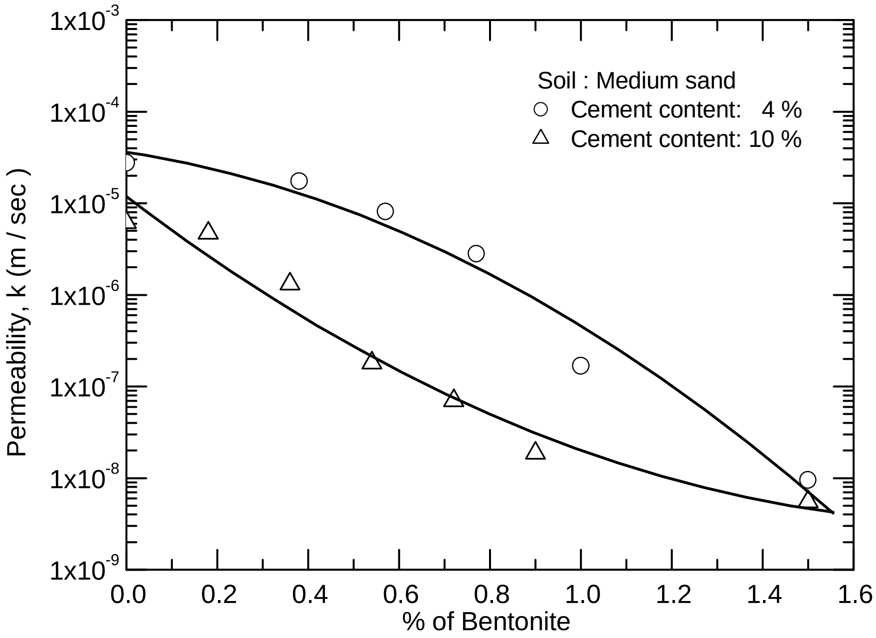


Fig. 6.6 Effect of bentonite on permeability of sandy soil treated with cement

This result can be advantageously used in field applications such as construction of subsurface check dams. i.e. by increasing the percentage of bentonite by a small amount, one can get a saving in the quality of cement to achieve the same permeability, thereby reducing the cost substantially.

6.4 Locally available clay

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 (Terzaghi et al., 1996).

The reduction in the coefficient of permeability, at constant void ratio, from kaolinite to illite to smectite is largely the result of a reduction in the size of individual flow channels and an increase in the tortuosity of the flow paths (Mesri and Olson, 1971).

Eventhough bentonite clay can be used for reducing the permeability of sandy soils, the availability of bentonite is confined to certain regions. Hence investigations were done to check whether the locally available clay could be used in place of bentonite to reduce the cost factor involved.

Cochin marine clay collected from a location in Elamkulam (properties given in table 3.3) in the Greater Cochin area was mixed with medium sand in different percentages and the permeability was measured.

The results are presented in Fig. 6.7. It can be seen that unlike cement (Fig. 6.1) where the permeability goes on reducing with cement content, the reduction in permeability with increase in the percentage of clay is marginal, upto a clay percentage of around 15 %. Thereafter, there is a drastic reduction in permeability with percentage of clay. Experiments were also conducted on other sand fractions- i.e. fine and coarse. Different percentages of clay were mixed with these sand fractions and the permeability tests were conducted. The results of tests on these sand fractions are also given in Fig. 6.7.

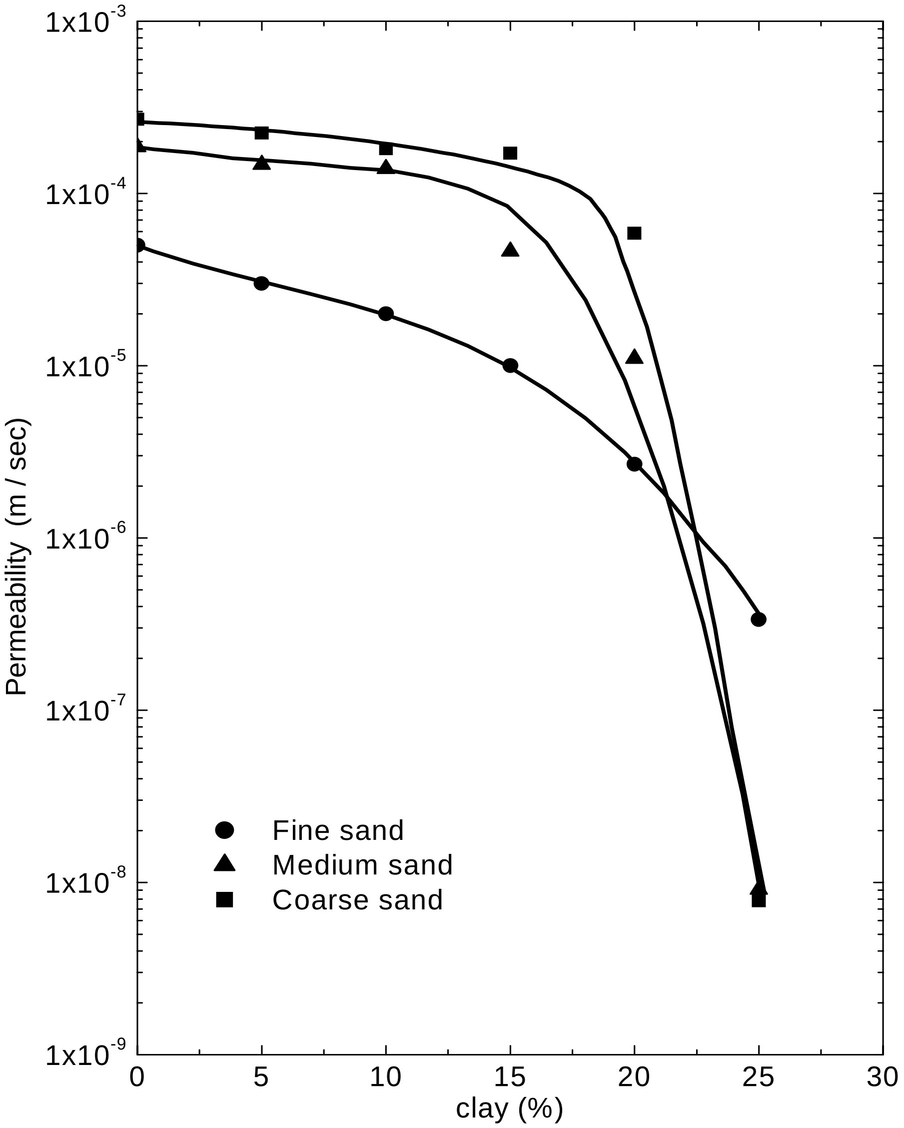


Fig.6.7 Effect of percentage of clay on Permeability

Eventhough the permeability decreases with increase in clay percent in all the three cases, the variation in the permeability in case of fine sand and coarse sand are not in the same pattern. In the case of fine sand, there is a gradual reduction in the ‘k’ value and the lowest permeability that could be attained is only 3.4 x 10^{-7} m/ sec, even at a very high clay content of 25 %. In contrast to this, there is no significant reduction in the permeability in case of coarse sand mixed with clay (upto around 17%), but the value suddenly drops beyond a clay content of 20 % and a very low permeability of the order of 7.8 x 10^{-9} m/ sec can be achieved for a clay content of 25 %. The permeability value for medium and coarse sand mixed with 25 % clay is only 1/40th of that of the fine sand with the same amount of clay. Hence, if grouting can be performed with a high percentage of clay, more reduction in permeability can be attained in case of coarser fractions of sand.

In the above set of experiments, the same amount of clay (5, 10, 15, 20 & 25 %) was mixed with all the three fractions of sand, the initial unit weight being 14.5 kN/ m^3. Hence the void ratios of the specimens having the same clay content remain the same. The void ratio in each case and the corresponding permeability values for all the three fractions of sand are tabulated in Table 6.2. The wide variations in permeability for the three sand fractions having the same void ratio are quite clear from the table. In other words, we can get the same permeability for different sand fractions, eventhough their void ratios are different. For example, fine sand without any clay (void ratio = 0.83) and coarse sand having 20 % clay (void ratio = 0.52) yield almost the same value of permeability.

Table 6.2 Effect of void ratio on permeability of sandy soil with clay

Sl. No.	% of clay	Void ratio	Coefficient of permeability k (m/sec) for		
			Fine sand	Medium sand	Coarse sand
1	0	0.83	5.0×10^{-5}	1.86×10^{-4}	2.69×10^{-4}
2	5	0.74	3.0×10^{-5}	1.47×10^{-4}	2.24×10^{-4}
3	10	0.66	2.0×10^{-5}	1.39×10^{-4}	1.81×10^{-4}
4	15	0.59	1.0×10^{-5}	4.6×10^{-5}	1.71×10^{-4}
5	20	0.52	2.67×10^{-6}	1.1×10^{-5}	5.87×10^{-5}
6	25	0.46	3.36×10^{-7}	9.1×10^{-9}	7.8×10^{-9}

The above fact is also brought out by the figure 6.8, which is a plot between the effective size (D_{10}) of the particles in the specimen and the permeability. Eventhough the permeability is almost constant for all the soil fractions at higher values of D_{10}, it varies widely as the value of D_{10} decreases.

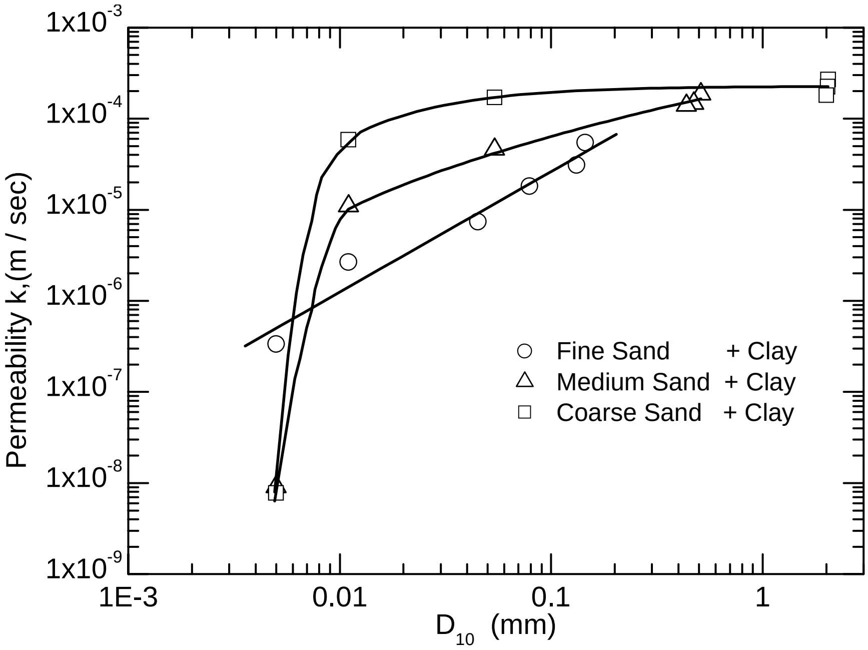


Fig.6.8 Effect of Permeability with grain size D_{10}

6.5 Bentonite

Bentonite clay, which is also used as an antibleeder along with cement grout was tried in order to reduce the permeability of the sand. Samples for permeability test were prepared by mixing medium sand (unit weight 14.5 kN/ m^3) and bentonite powder (in the dry condition) at different percentages and filling the mixture in the moulds. The results obtained from the permeability tests are given in Fig. 6.9. It can be seen from the figure that the permeability reduces drastically as the percentages of the bentonite increases. The figure also gives a comparison of the performance of bentonite in relation to the locally available clay and cement. The effectiveness of bentonite in relation to Cochin marine clay and cement in reducing the permeability of a sand medium is quite clear from this figure.

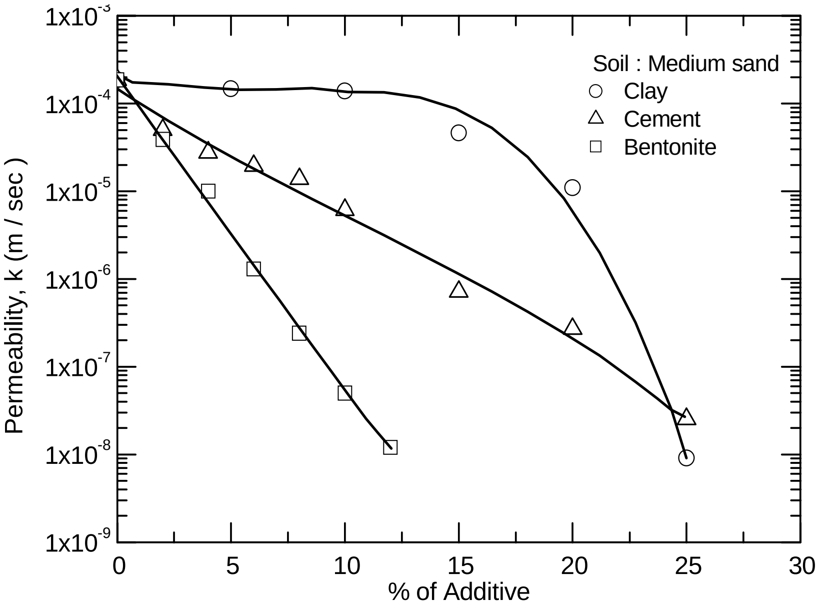


Fig.6.9 Effect of Permeability with additives

6.6 Locally available clay along with cement/ lime

The improvement in strength characteristics of the locally available clay (Cochin marine clay) on treatment with lime or cement has been clearly brought

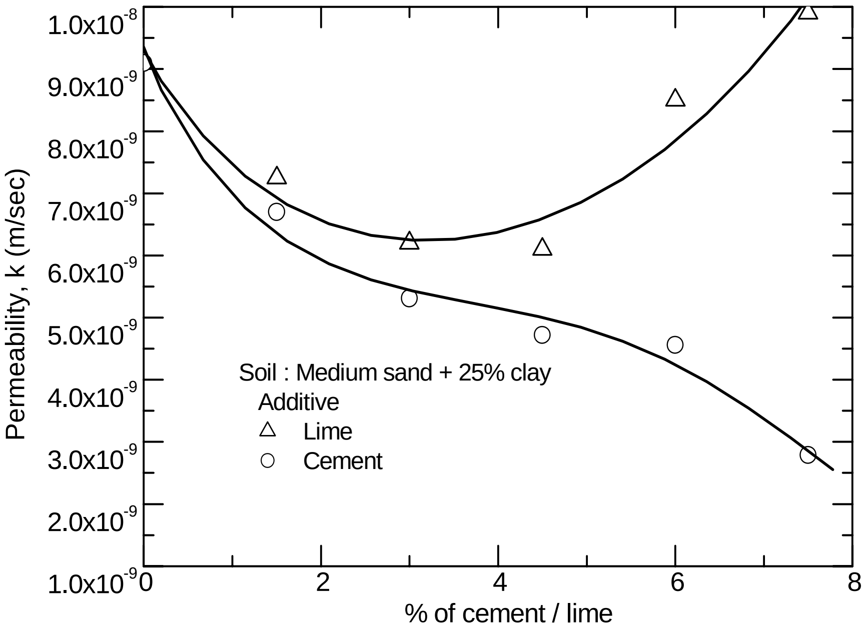


Fig. 6.10 Effect of additives on permeability of sandy soil treated with clay

out by Jose et al. (1987) and Abraham (1993). But the effect on permeability when this clay is treated with these additives has not been studied. Experiments were conducted in this direction by conducting permeability tests on the samples prepared by mixing medium sand and 25 % Cochin marine clay treated with different percentages (by dry weight of clay) of cement or lime and cured for 15 days, in order to explore the possibility of getting further reduction in the permeability. The results are presented in Fig. 6.10. Eventhough smaller percentages of lime cause a reduction in permeability, it becomes more permeable as the lime content increases. But the treatment with cement causes a reduction in the permeability, the effect of which is more pronounced at higher percentages of cement. Hence the permeability of a sand medium can be reduced to any extent by the use of a proper combination of locally available clay and cement.

Chapter 7

SUMMARY AND CONCLUSIONS

Contents

7.1 Introduction

There has been a rapid development in the field of civil engineering requiring selection of site from considerations other than soil quality alone. This results in the need to make use of sites with very low bearing capacity/strength also, such as loose sandy soils. This investigation examines the scope of improving granular soils of low strength with cement grouting. Results on systematic studies carried out on strength of cement grouted sand medium from the view point of bearing capacity are scanty. Based on the experimental investigations and test results, the following conclusions are made.

7.2 Strength improvement on densification

Investigations carried out to assess the improvement in the load carrying capacity of sand beds on densification through vibration techniques gave the following conclusions.

- The load carrying capacity of the sand medium depends not only on the density but also on the gradation and the load carrying capacity of finer fractions, is always higher compared to the coarser fractions irrespective of the density. This can be attributed to the increased contact area between the particles, in the case of finer fractions.
- Maximum densification improves the load carrying capacity of the sand at the loosest state by 16 times and even that would not be sufficient to serve as the bed for shallow foundations in the case of multistoreyed buildings.

7.3 Improvement of shear strength on grouting

The present investigations mainly focused at studies on the strength behaviour of these loose sandy soils when grouted with different materials such as cement with or without admixtures, lime etc. Grouted sand present the general characteristic of cemented soils and can be considered as an intermediate material between soil and concrete (Dano et al. 2004). The review of published experimental results related to grouted sand (Schwarz and Krizek 1994; Zebovitz et al.1989) reveals a large discrepancy in the results due to a wide variety of parameters related to the soil (grain size distribution, density specific area, etc), the grout (nature, type, particle size distribution etc) and the injection conditions (rate of discharge, grout pressure, injection procedure etc).

The conclusions drawn from the results of a series of direct shear tests, conducted on samples prepared (by hand mixing) with different grouting materials are given below.

7.3.1 Grouted with cement alone

- The shear strength of the loose sandy soil steadily increases with increase in cement content and also with curing period, for all sand fractions.
- The rate of increase in shear strength is very high at higher percentages of cement than at lower percentages in the case of all the sand fractions.
- Eventhough specimens of medium sand give higher shear strength than coarse sand specimens at lower cement contents; the coarse sand specimens register higher strength as the cement content increases.
- The influence of the increased initial water content of the grout is to decrease the shear strength of the grouted sand and the effect is more pronounced at higher cement contents.
- Shear strength of the grouted sand increases with increase in normal pressure. The stress–strain response exhibits a linear relationship prior to the peak, for all cement contents and the value of shear strength steadily increases with increase in cement content.

7.3.2 Grouted with cement and admixtures

Several admixtures are used along with the cement grout to improve the various properties of grout suspensions. The effects of these admixtures on the strength of grouted sand were not studied previously. The following conclusions are made related to the shear strength of loose sand grouted with cement along with these admixtures.

- The effect of accelerators (Calcium chloride & 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. Among the two accelerators studied, the performance of calcium chloride is better, compared to sodium silicate with regard to shear strength.
- 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 increases at lower percentage of triethanolamine and a marginal reduction is noticed as the percentage of this salt increases. Comparing the two retarders, triethanolamine gives much higher shear strength even at lower percentages and hence can be considered as a better retarder.
- The shear strength increases upto the optimum dosage (0.05 %) of detergent (fluidiser), thereafter the value is found to decrease.
- The use of optimum dosage (below 0.02 %) of aluminium powder (expander) increases the shear strength of the grouted sand.
- 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. The addition of bentonite (which is also an antibleeder) to the cement grout causes a reduction (approx. 15 %) in shear strength.

7.3.3 Grouted with lime

- The shear strength of the loose sandy soil increases with increase in lime content and curing period, but this increase is negligible compared to the tremendous increase in shear strength when cement is used as the grout material.

7.4 Shear strength parameters

The effect of grouting on the shear strength parameters ‘*c*’ and ‘Ø’ are studied in detail and the following conclusions made.

7.4.1 Grouted with cement alone

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 influence of the initial water content of the cement grout is very significant in the case of values of *c* and with Ø. While the value of *c* drastically reduces with increase in i.w.c., the effect on Ø- value is just opposite. i.e. the value of Ø goes on increasing with increase in the initial water content of the grout, except in the case of fine sand.

7.4.2 Grouted with cement and admixtures

- Among the two accelerators tried, the reduction in Ø- value is more with the addition of Calcium Chloride compared to Sodium Silicate but the greater increase in cohesion intercept results in increased shear strength.

- The use of triethanolamine as a retarder causes only a marginal reduction in Ø- value which is compensated by the increase in cohesion intercept. The addition of even a very small percentage of tartaric acid (around 0.5%) brings down the Ø- value by 10 %, but the same amount of reduction is experienced only at high percentages (8 to 10%) of triethanolamine. Hence these results also confirm that one has to be very careful in the use of tartaric acid as a retarder along with cement grouts.
- The use of optimum dosage (0.05 %) of the detergent (fluidiser) will not adversely affect the values of the shear strength parameters.
- Unlike other admixtures, the addition of aluminium powder increases the Ø- value of the cement grouted sand. The use of optimum dosage (0.005 %) will also not adversely affect the cohesion intercept.
- Eventhough there is a marginal decrease in cohesion initially (at around 2%), increase in percentage of aluminium sulphate increases the cohesion intercept and the effect of curing period also significantly in the case of aluminium sulphate.
- A comparison between the effects of the two antibleeders i.e., aluminium sulphate and bentonite on the cohesion intercept shows that the effect of aluminium sulphate is to increase the cohesion whereas bentonite causes a slight reduction in the value of cohesion intercept. But the Ø- value after an initial reduction, increases with increase in percentages of these two admixtures.

7.4.3 Grouted with lime

- When lime is used as a grouting material the cohesion intercept increases with increase in lime content and curing period, but decreases with increase in the initial water content.
- The Ø value remains more or less constant at the initial stages, but the value increases at higher lime contents (beyond 15%). Another interesting observation is that in the case of lime also, the value of Ø increases with increase in water content, which is not in line with the variation of *c* value.
- The marginal improvement in the values of the shear strength parameters compared to the tremendous improvement when the loose sandy soil is grouted with lime and cement respectively, confirms the superiority of cement over lime in grouting granular beds.

7.5 Compressive strength

Determination of shear strength through direct shear test is a time consuming process and at higher cement contents it is very difficult to conduct this test till the failure at lower normal loads occurs. It is also difficult to collect three to four identical samples after grouting. Compressive strength tests were done on the grouted samples with the objective of arriving at some simple correlation between the compressive strength and the shear strength of grouted samples, since this test is very simple and can be done very accurately, irrespective of the cement content. The conclusions drawn from the test results are,

- Compressive strength goes on increasing with increase in percentage of cement content and curing period. Also, as in the case of shear strength, the compressive strength also decreases with increase in initial water content.

- The compressive strength increases with increase in cement content for all the three sand fractions – i.e. fine, medium and coarse sand. Eventhough the coarse fraction shows less strength than the fine & medium sand at lower cement contents, it overtakes the other two, as the cement content increases (beyond 15%).
- A comparison between the performance of calcium chloride and sodium silicate (accelerators) on the compressive strength shows that calcium chloride is preferred over sodium silicate as an admixture, along with cement grout.
- Among the retarders, the reduction in strength is much less in the case of triethanolamine compared to tartaric acid. Further the property of triethanolamine in reducing the viscosity of cement grouts can be taken advantage of in using this as an admixture along with cement grout.
- Use of aluminium powder (expander) in cement grouts does not affect the compressive strength.
- The effect of both the antibleeders - aluminium sulphate and bentonite - on the compressive strength of cement grouted sand is almost the same. Eventhough there is an initial reduction in strength at smaller percentages, it picks up strength as the percentage increases. Hence, both these admixtures can be used as antibleeders along with cement grouts without adversely affecting the compressive strength.

7.6 Relation between compressive strength and shear strength

Attempts to correlate the results from compressive strength and shear strength tests yield the following very useful relationships.

- Correlation between the cohesion intercept *c* and compressive strength *p* of the grouted soils gives an excellent straight line relationship with a high correlation coefficient of 0.95 as,

$$c = 0.079\,p - 2.21$$

- The relationship between the angle of shearing resistance Ø and the compressive strength *p* is a non linear one and the equation is

$$Ø = 37.52 + 0.009\,p - 7.58\,E^{-7}\,p^{2}\ ,$$

with a correlation coefficient of 0.83

- The relationship between shear strength and compressive strength *p* is given by the following equation.

$$\tau = 0.104\,p + 80.12\ ,$$

with a high correlation coeff. of 0.96

7.7 Studies on cement grouted sand beds

In order to simulate the grouting process in the field, model tests were conducted on sand beds prepared in steel tanks in the laboratory. For this purpose, a grouting set up was designed and fabricated. The grouting nozzle was designed so as facilitate the flow of the grout smoothly both in the vertical and lateral directions. The following conclusions were drawn from the results of the model studies conducted using this set up developed in order to study the grouting efficiency.

7.7.1 Grouting efficiency from cross section dimensions

- A comparison of cross sectional area of grouted mass (medium sand) with 2, 4 and 6 % cement shows that the effective cross section area of the mass grouted with 4 % cement is maximum at all depths. A grouted volume as high as 78 % of the original volume was obtained in the case of 4 % cement grout, whereas it was only 45 % and 53 % in the case of 2 % and 6 % cement grouts respectively.
- In the case of coarse sand also, grouting with 4% cement gave the maximum areas of cross section, which is less than that of medium sand.
- Use of admixtures in cement grout does not enhance the cross section area of medium sand.
- The admixtures used play an important role in increasing the cross section areas of the grouted mass, in the case of coarse sand. 15 % bentonite and 0.05 % detergent (by weight of cement) prove to be very effective along with 6 % cement grout in coarse sand.

7.7.2 Grouting efficiency from actual cement contents

The efficiency of grouting mainly depends upon the penetration of cement grout through the pores of sand. The following conclusions are drawn from the results of cement contents determined by chemical analysis on samples from the grouted mass, in order to assess the quantity of lateral flow of grout into the soil mass.

- 4 % cement grout is more effective in medium sand and coarse sand compared to 2 % and 6 %, while considering the travel distance of the grout and the cement contents at various points in the grouted mass.

- Use of admixtures enhances the lateral flow in the case of both medium & coarse sand. Aluminium sulphate performs better as an antibleeder compared to bentonite, when used along with cement grout, in the case of medium sand.
- A combination of 15 % bentonite and 0.05 % detergent along with 6 % cement grout was found to be very effective in the case of coarse sand.

7.7.3 Grouting efficiency from load tests

The results of a series of load tests conducted on the grouted sand beds gave the following conclusions

- A comparison in the strength behaviour between medium sand and coarse sand when grouted with 4% cement shows that the strength of the grouted coarse sand is much higher and it exhibits a brittle type failure.
- For coarse sand, a minimum cement content is required for the grouting to be effective. This may be due to the increased pore space available in the case of coarse sand compared to medium sand.
- Eventhough there is a slight reduction (around 20%) in strength in medium sand, the admixtures make the grouted sand bed to be more ductile, thus eliminating the chances of a sudden failure of foundations.
- In the case of coarse sand, the admixtures help to increase the load carrying capacity (twice the strength compared to the sand bed grouted without admixtures). This can be attributed to the increased lateral flow of the grout when admixtures are used along with cement in grouting coarse sand bed

- A comparison in strength of the medium sand beds grouted with cement (grout pumped through grout pump) with that of the uniformly mixed sand beds (ideal condition) stresses the need for developing more appropriate grouting tools and methods for making the grouting process more efficient so that the foundation design can be made more economical.

7.8 Permeability studies on the grouted soil

The following conclusions are drawn from the results of permeability tests conducted on sand samples prepared with different grouting materials.

- The permeability goes on reducing with increase in cement content.
- The effect of the curing period is to decrease the permeability of cement grouted sand. But at lower cement contents, the permeability remains more or less constant beyond a curing period of 15 days.
- The permeability got reduced by 1/7400th in the case of medium sand grouted with 25% cement and cured for 28 days.
- Addition of small percentages of bentonite along with cement grout drastically reduces the permeability. A substantial reduction in cost can be achieved by reducing the cement content and slightly increasing the corresponding bentonite content to obtain a particular value of permeability.
- Locally available clay (Cochin marine clay) is found to be very effective in reducing the permeability of sand beds. With higher percentages of clay, greater permeability reduction is achieved in coarse sand fractions.

- Among the various grouting materials tried, bentonite is found to be the most effective in reducing the permeability of granular beds.
- The effect of cement is more pronounced, compared to lime, when used along with clay in reducing the permeability of sandy beds. The permeability of a sand medium can be reduced to any extent by the use of a proper combination of locally available clay and cement.

Thus the present study undoubtedly proves the effectiveness of using grouting as an efficient technique in improving the foundation beds of loose sandy soils.

REFERENCES

1. Abraham, B. M.(1993). “A study of the strength and compressibility characteristics of Cochin marine clays.” *Ph.D thesis* School of Engg. Cochin University of Science and Technology, Kochi.
2. Acar, Y. B. and El-Tahir, A. E. (1986). “Low strain dynamic properties of artificially cemented sand.” *J. Geotech. Engrg.*, 112(11), 1001–1015.
3. Agarwal, K. B. and Pramod Kumar. (1981). “Settlement of shallow foundations in collapsible granular soil.” *Sym. On Engrg. Behavior of coarse grained soils, boulders and rocks,-Geomech-81,* Vol.1, 163-168.
4. Aiban, S. A. (1994). “A study of sand stabilization in eastern Saudi-Arabia.” *Elsevier science bv, Enginering Geology.,* 38, 65-79
5. Akbulut, S. and Saglamer,A. (2002). “Estimating the groutability of granular soila: a new approach.” *Tunnelling and underground space technology*,Elsevier Science Ltd. 17, 371-380.
6. Al-Awad, M.N.J., (2002), Simple correlation to evaluate Mohr-Coulomb failure criterion using uniaxial compressive strength, J. King Saud Univ., Vol. 14 Eng. Sci.(1), pp 137-145, Riyadh

7. Anagnostopoulos, C. A. (2007). “Cement-clay grout modified with acrylic resin or methyl methacrylate ester: physical and mechanical properties.” *Const. and Building materials* Elsevier 21(2) 252-257.
8. Ansary, M. A., Siddique, A., Siddique, M. S. A., and Ali, M. H. (1998) “Sterss – strain - strength and stiffness characteristics of rock samples from maddhapara, Bangladesh.” *Conf. on the Geotechnics of Hard Soils-Soft Rocks*, Evangelista & Picarelli (eds) Balkema, Rotterdam. 3-14
9. Arenzana, L., Krizek, R. J., and Pepper, S. F. (1989). “Injection of dilute microfine cement suspensions fine sands.” *12th Int. Conf. on Soil MEch. And Foundation Engrg*, Brazil, 18/2, 131-1334.
10. Ata, A., and Vipulanandan, C. (1998). ‘‘Cohesive and adhesive properties of silicate grout on grouted-sand behavior.’’ *J. Geotech. and Geoenvir. Engrg.*, ASCE, 124(1), 38–44.
11. Ata, A., and Vipulanandan, C. (1999) “Factors affecting mechanical and creep properties of silicate-grouted sand.” *J. Geotech. Geoenviron. Eng.*, 125 (10), 868–876.
12. Axelsson, M. and Gustsfson, G. (2006). “A robust method to determine the shear strength of cement-based injection grouts in the field.” *Tunnelling and underground space technology,* 21(5), 499-503.
13. Baig, S., Picornell, M. and Nazarian,S. (1997). “Low strain shear moduli of cemented sands.” *J. Geotech. and Geoenvir. Engrg.*, ASCE, 123(6), 540–545.
14. Bement.R.A.P and Selby.A.R;(1997) “compaction of granular soils by uniform vibration equivalent to vibrodriving of piles” *Geotechnical and geological engineering,* 15,p 121-143

15. Boulanger, R. and Hayden, R. F. (1995). “Aspect of compaction grouting of liquefiable soil.” *J. Geotech. and Geoenvir. Engrg.*, ASCE, 121(12), 844–855.
16. Bussey, W .H. (1973). “Suspension grouts and their injection.” *Bulletin of the Association of Engineering Geologists* Vol.X, No. 4, 313-323.
17. Chapuis, R. P. (1990). “Sand-bentonite liners: predicting permeability from laboratory tests.” *J. can. Geotech., 47-57.*
18. Chattopadhya,B.C., and Saha,S. (1981). “Effect of grain size of cohesionless soil on its shear strength characteristics.” *Sym. On Engrg. Behavior of coarse grained soils, boulders and rocks,-Geomech-81,* Vol.2, 291-297.
19. Clarke, W.J., Royal, M.D. and Helal, M. (1992) Ultrafine cement tests and dam test grouting, *Proc. Of the conf. on Grouting, Soil Improvement and Geosynthetics, New Orleans. Edited by Roy, H. Borden, Robert, D. Holtz and Ilan Juran.* ASCE. New York, 1. 626-638.
20. Clough, G. W., Sitar, N., Bachus, R. C. and Rad, N. S. (1981), “Cemented sands under static loading”, *Journal of Geotechnical Engineering.Div.*, ASCE, Vol. 107,No. GT6, 799-817
21. Consoli, C. N., Foppa, D., Festugato, L., and Heineck, K. S. (2007). “Key parameters for strength control of artificially cemented soils.” *J.Geotech. and Geoenvir. Engrg.,* ASCE, 133(2), 197-205.
22. Consoli, C. N., Prietto,. P. D. M. and Ulbrich, L. A. (1998). ‘Influence of fiber and cement addition on behavior of sandy soil.” *J.Geotech. and Geoenvir. Engrg.,* ASCE, 124(12), 1211-1214.
23. D2487-10
24. D806-00 Standard test method for cement content of hardened soil cement mixtures, ASTM

25. Dano, C., Hicher, P.Y. and Tailliez, S. (2004). "Engineering properties of grouted sands." *J.Geotech. and Geoenvir. Engrg.*, ASCE, 130(3), 328-338.
26. Das, B. M., Yen, S. C. and Dass, R. N. (1995). "Brazilian tensile strength test of lightly cemented sand." *Can.Geotech. J.* 32, 166-171.
27. Datye, K. R. (1961) "Clay and chemical grouting." *J. the Institution of Engineers, Poona center,* Vol. III, 1-22.
28. De Paoli, B., Bosco, B., Granata, R. and Bruce, D.A. (1992) Fundamental observations on cement based grouts (1) Traditional materials, *Proc. Of Conf. on Grouting in Geotechnical Engineering,* New Orleans, Louisiana Edited by Roy H. Borden, Robert D, Holtz and Ilan Juran, ASCE, New York, 474- 485.
29. Deere, D.U. (1982) Cement – Bentonite grouting for dams, *Proc. Of Conf. on Grouting in Geotechnical Engineering,* New Orleans Edited by Wallace Hayward Baker, ASCE, New York, 279- 300.
30. Desmukh,A.M.(1978). "Stabilization of Idikki arch dam foundation." *Indian Geotechnical J.,*8(2),81-90.
31. Eklund, D. and Stille, H. (2007). "Penetrability due to filtration tendency of cement-based grouts." *Tunnelling and Underground Space Technology.* (Press).
32. Ellis, G.W. (1986), Dynamic consolidation of fly ash, *Proc. Intl. Symposium on Environmental Geotechnology,* Pennsylvania, pp. 543- 564
33. Elston, J. P. (1958). "Cement and clay grouting of foundations suggested specifications for pressure grouting." *J. Soil Mech. And Found. Div.* ASCE, SM-1, 1548-1-27.

34. Forssblad, L. (1965), Investigation of impact on a ground surface, *Acta Polytechnica Scandinavian Civil Engineering and Building Construction*,series No. 43
35. Glory. J., Abraham, B. M., Jose, B. T., and Paul, B. (2001). “Improvement of bearing capacity of sandy soils by grouting, *IGC 2001*, The New Millennium Conference 14-16 Dec, 2001 Indore (MP).
36. Haeri, S. M., Hamidi, A., Hosseini, S. M. and Asghari, E. (2006). “Effect of cement type on the mechanical behavior of a gravely sand.” *Geotech. and Geological. Engrg.,* 24, 335-360.
37. Heh, K.S. (1990). Dynamic Compaction of sand, *Phd dissertation, Polytechnic University, Brooklyn*,NY,December.
38. Hsieh, H. S.,Wang, C. C. and Ou, C. Y. (2003). “Use of jet grouting to limit diaphragm wall displacement of a deep excavation.” *J.Geotech. and Geoenvir. Engrg.,* ASCE, 129(2), 146-157.
39. Huang, J. T., and Airey, D. W. (1998). “Properties of artificially cemented carbonate sand.” *J. Geotech. Geoenviron. Eng.*, 124(6), 492–499.
40. Huang, Z., Chen, M. and Chen, X. (2003). “A developed technology for wet-ground fine cement slurry with its applications.” *Cement and Concrete Research,* 33, 729-732.
41. Ibragimov. M. N, “Soil stabilization with cement grouts”, (2005) *Soil mechanics and foundation engineering*, Vol.42 No. 2, 67-72.
42. Ibrahim, I. A., Elsersy, H. H. and Abadir, M. F. (2004). “The use of thermal analysis in the approximate determination of the cement content in concrete.” *J. thermal analysis and calorimetry.*, 76, 713-718.
43. IS 1498 : 1970 Classification and identification of soils for general engineering purposes

44. IS 1892 : 1979 Code of practice for subsurface investigations for foundations
45. IS 269 : 1989 Specification for 33 grade Ordinary Portland cement
46. IS 2720 : Part 5 : 1985 Method of Test for Soils - Part 5 : Determination of Liquid and Plastic Limit
47. IS 4031 : Part 2 : 1999 Methods of physical tests for hydraulic cement: Part 2 Determination of fineness by specific surface by Blaine air permeability method
48. IS 4031 : Part 4 : 1988 Methods of physical tests for hydraulic cement: Part 4 Determination of consistency of standard cement paste
49. IS 4332 : Part VII : 1973 Methods of Test for Stabilized Soils - Part VII : Determination of Cement Content of Cement Stabilized Soils
50. IS: 4999 (1991) *Recommendations for grouting of pervious soils.* Bureau of Indian Standards.
51. IS: 516 (1959) *Determination of compressive strength flexural strength and modulus of elasticity of cement concrete.* Bureau of Indian Standards.
52. Ismail, M. A., Joer, H. A., Sim, W. H., and Randolph, M. F. (2002). “Effect of cement type on shear behavior of cemented calcareous soil.” *J. Geotech. Geoenviron. Eng.*, 128(6), 520–529.
53. John, A.A (1982) Cement Grouting practice – U S Army Crops of Engineers *Conf. on Grouting in Geotechnical Engineering,* New Orleans Edited by Wallace Hayward Baker, ASCE, New York.
54. Jose, B. T., Lovely, K. M., Sridharan, A. and Abraham, B. M. (2000). “Effect of admixtures on the behavior of cement grouts.” *Proc. Of the Indian Geotech. Con-2000.* 229-232.

55. Jose, B. T., Sridharan, A. and Abraham, B. M. (1987). “Engineering Properties of Cochin Marine Clays and its Stabilisation with Lime”, *IX South East Asian Region Conference*, Bangkok, 115-126.
56. Kaniraj, S.R., and Havanagi, V.G. (2001). “Behavior of cement-stabilized fiber- reinforced fly ash- soil mixtures.” *J.Geotech. and Geoenvir. Engrg.,* ASCE, 127(7), 574-584.
57. Kenai, S., Bahar, R. and Benazzoug, M. (2006). “Experimental analysis of the effect of some compaction methods on mechanical properties and durability of cement stabilized soil.” *J. Mater. Sci.* 41, 6956-6964.
58. King, J. C. and Bush, E. G. W. (1961). “Symposium on Grouting : Grouting of granular materials.” J. *Soil Mech. And Founds.* ASCE Divi. SM2, 1-17
59. Karol, R. H (1982) “Seepage control with chemical grouts”. *Proc. Of the conf. on Grouting in Geotechnical Engrg.,* New Orleans, Edited by Wallace Hayward Baker, ASCE, New York.
60. Lade, P. V. and Overton, D. D. (1989). “Cementation effects in frictional materials.” *J.Geotech. Engrg.*, ASCE, 115(10), 1373-1387.
61. Lirer,S., Flora, A., Evangelista, A., Verdolotti, L., Lavorgna, M. and Iannace, S. (2006). “Permeation grouting of a fine-grained pyroclastic soils”. *Ground Improvement*, Thomas Telford, 10, No. 4, 135–145
62. Little D.N and Yusuf .F.A.M.S (2001), Engineering properties of lime treated sub-grades for mechanistic pavement design / analysis, National lime association mixture design and testing protocol (MDTP), 2001.
63. Littlejohn, G.S. (1982). Design of cement based grouts. *Proc. Of Conf. on Grouting in Geotech. Engrg.,* New Orleans, Edited by Wallace Hayward Baker, ASCE, New York. 35- 48.

64. Lorenzo, G. A. and Bergado, D. T. (2004). “Fundamental parameters of cement-admixed clay-new approach.” *J.Geotech. and Geoenvir. Engrg.*, ASCE, 130 (10), 1042-1050.
65. Lovely, K. M. (1998). “A study on the properties of grouting and control of permeability of grouted media. *Ph.D thesis* School of Engg. Cochin University of Science and Technology, Kochi.
66. Lovely, K. M., Jose, B. T., Sridharan, A. and Abraham, B. M. (1994). “Measurement and control of viscosity of bentonite grouts.” *Proc. Of the Indian Geotech. Con.,*Warrangal. 257-260.
67. Lovely, K. M., Jose, B. T., Sridharan, A. and Abraham, B. M. (1997).“Utilization of volume change behavior of bentonite grouts to increase grouting efficiency.” *Proc. Of the Indian Geotech. Con.,*Vadodara,Gujarat,India. Vol.1 261-264.
68. Lovely.K.M, (1998). Effect of admixtures on the behaviour of cement grouts.” *Indian Geotech. Con.* New Delhi.
69. Lovely.K.M, Jose.B.T, Sridharan.A and Abraham.B.M (1998) “Effect of admixtures on the properties of cement-bentonite grouts”*2nd Internal Con. on Ground Improvement Techniques, Singapore.*
70. Lowe, J. and Standford, T.C. (1982). Special grouting at Tarbela dam project. *Proc. Of Conf. on Grouting in Geotech. Engrg.*, New Orleans, Edited by Wallace Hayward Baker, ASCE, New York. 152- 171.
71. Maalej. Y., Dormieux. L., Canou. J. and Dupla. J. C. (2007). “Strength of a granular medium reinforced by cement grouting”. *C.R. Mecanique*, Elsevier, 335, 87-92.
72. Markou, I. N. and Atmatzidis, D. K. (2002). “Properties and performance of a pulverized fly ash grout.” *J. of Geotechnical and Geoenvironmental Engineering*, Vol. 128, No. 8 682-691.

73. Massarsch,K.R., and Fellenius,.B.H. (2002). "Vibratory compaction of coarse- grained soils." *Can.Geotech. j.* 39(3) 695-709.
74. Mehta, P. K. and Monteiro, P. J. M. ( ) "Concrete microstructure, properties and materials." *Indian Concrete Institute.* Chennai.
75. Mesri, G and Olson, R. E., (1971) Mechanisms controlling the permeability of clays *Clays and Clay Minerals,* Vol. 19, pp. 151-158. Pergamon Press. Printed in Great Britain.
76. Miller, E. A. and Roycroft, G. a. (2004). "Compaction grouting test program for liquefaction control." *J. Geotech. and Geoenvir. Engrg.*, ASCE, 130(4), 355–361.
77. Mori, A., and Tamura, M. (1986). "Effect of dilatancy on permeability in sands stabilized by chemical grout." *Soils and Foundations."* 26(1), 96-104.
78. Nash. K. L. (1953). "The shearing resistance of a fine closely graded sand"; *Proc. Of the third International conference on soil mechanics and foundation Engineering*, session 2/17; 160-164
79. Nonveiller, E. (1989). "Grouting- theory and practice." *Elsevier publishing company*, New YorK.
80. Ozgurel, H. G. and Vipulanandan, C. (2005). "Effect of grain size and distribution on permeability and mechanical behavior of acrylamide grouted sand." *J. Geotech. and Geoenvir. Engrg.*, ASCE, 131(12), 1457–1465.
81. Pandian, N. S., Nagaraj, T. S. and Raju, P. S. R. N. (1995). "Pearmeability and compressibility behavour of bentonite-sand/soil mixes." *Geotechnical testing journal.*, 18(1), 86-93.

82. Ping, Y., Zhen-bin, P., Yi-qun, T., Wen-xiang, P. and Zhong-ming,H. (2008). “Penetration grouting reinforcement of sandy gravel.” *J.Cent.South. univ. Technol.* 15;280-284.
83. Poran,C.J., and Heh,K.S., and Rodriguz,J.A. (1992). “Impact behavior of sand.” *Soils and foundations,* 32(4), 81-92.
84. Ribay, E. D., Maigre, I. D., Cabrillac, R. and Gouvenot, D. (2006). “Factors affecting the creep behavior of grouted sand.” *J. Geotech. and Geoenvir. Engrg.*, ASCE, 132(4), 488–500.
85. Schnaid, F., Prietto, P. D. M., and Consoli, N. C. (2001). “Characterization of cemented sand in triaxial compression.” *J. Geotech. Geoenviron. Eng.*, 127(10), 857–868.
86. Schwarz, L. G. and Krizek, R. J. (1992) “Effect of mixing on rheological properties of microfine cement grouts.” *Proc. Of the conf. on Grouting, Soil Improvement and Geosynthetics, New Orleans. Edited by Roy, H. Borden, Robert, D. Holtz and Ilan Juran.* ASCE. New York, 512-525.
87. Schwarz, L. G., and Krizek, R. J. (1994). ‘‘Effect of preparation technique on permeability and strength of cement-grouted sand.’’ *Geotech. Test. J.,* 17(4), 434–443.
88. Shroff,A.V. (2009), Development in design and executive in grouting practice, *31st IGS annual lecture at IGC-2009,* Guntur.
89. Shroff,A.V. and Shah,D. L. (1992). Grouting technology in tunnelling and dam construction. Oxford and IBH publishing Company, New Delhi.
90. Sinroja, J. M., Joshi, N. H. and Shroff, A. V.(2006). “Ground improvement technique using microfine slag cement grouts” *IGC 2006*,14-16 December 2006, Chennai, p 661-664

91. Terzaghi. K., Peck. R. B. and Mesri. G. (1996). " Soil mechanics in engineering practice." John Wiley & Sons. Singapore., INC Newyork.
92. Uppot, J. O. and Stephenson, R. W. (1989). "Permeability of clay under organic permeants." *J.Geotech.. Engrg.*, ASCE, 130(10), 115-131.
93. Vadivel, R. (2006). "Ground improvement using jet grout pile for tunneling in soft marine clay." *Proc. Of the Indian Geotech. Con.*,Chennai, 905-908.
94. Vipulanandan, C. and Orgurel, H. G. (2009). "Simplified relationships for particle size diatribution and permeation groutability limits for soils." *J.Geotech. and Geoenvir. Engrg.*, ASCE.
95. Yilmaz. D., Babuccu. F., Batmaz. S. and Kavruk. F. (2008). " Liquefaction analysis and soil improvement in beydag dam." *Geotech. Geol. Eng.*, 26: 211-224
96. Yoon, S. and Farsakh, M. A. (2009). "Laboratory investigation on the strength characteristics of cement-sand as base material." *Geotech. Engr., KSCE J. of Civil Engrg.*, 13(1), 15-22.
97. Zebovitz, S., Krizek, R. J. and Atmatzidis, D. K. (1989) Injection of Fine Sands with Very Fine Cement Grout, Journal of Geotechnical Engineering, 115(12), 1717-1733.

PUBLICATIONS

Publications based on the research works

Papers in Journals

1. Improvement of strength of loose sandy soils by grouting. *Journal of Ground improvement*, Thomas Telford, London, (*Communicated).*
2. Effect of water content of grout on strength of grouted soils. *Journal of Civil Engineering Research & Practice,* Ghana. *(Communicated).*

Papers in conferences

1. Improvement of strength parameters of loose sandy soils by grouting. *Indian Geotechnical Conference-2008 Bangalore.*
2. Influence of admixtures on strength of cement grouted soils. *Indian Geotechnical Conference-2009 Guntur*
3. Improvement of strength parameters of loose sandy soils by lime grouting. *International conference on advances in materials and techniques in civil engineering (ICAMAT- 2010).*