STUDY ON THE STRENGTH DEVELOPMENT IN CEMENT STABILIZED SOFT CLAY

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Master of Engineering

By

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ABSTRACT

The inherent limitations of the conventional foundations lead to choose an alternative solution, namely, ground improvement technique for solving geotechnical problems. Shallow soil-cement stabilization and in-situ deep mixing technique (cement column) are widely used for soft ground improvement. Mixing of cement converts the existing soft ground into a composite media. The strength development of cement stabilized materials depends on various aspects such as water content, curing time, amount of cementing materials, temperature and type of soils. Hence, the understanding of the strength-deformation characteristics of induced cemented clay is necessary to reflect its behavior in the rational design of the composite ground.

In this study, the findings obtained from laboratory investigation on cement-stabilized clay are presented. Typical soft clay from the KUET campus, Khulna, the southwest region of Bangladesh is considered in this investigation. Ordinary Portland cement is used as a cementing agent. The cement was mixed thoroughly with the remolded clay at a percentage of 2.5%, 5%, 7.5%, 10%, 15%, 20%, 25%, 35% and 50% of the solid weight of soil. To have the same initial water content at all cases, soil-cement mixing was done at the liquid limit state of the clay. The soil-cement samples were wrapped properly so that additional water cannot be entered into the samples while kept under water for curing and also to prevent moisture evaporation till the designated rest period. Unconfined compression tests were conducted at a rest period of 0.25, 1, 3, 7, 14, 28 and 56 days to examine the development of strength deformation characteristics with time. The change of water content, unit weight, failure strain, compressive strength and stiffness was also examined at different cement content and rest period. A relationship is established among the cement content, rest period and unconfined compressive strength. Significant changes were also observed in other physical and mechanical properties. Finally, an empirical equation is proposed which can be used with a reasonable degree of accuracy for the estimation of compressive strength at an elapsed rest period for particular cement content.

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INTRODUCTION

1.1 General

In the south and Southeast Asian region, due to the increasing trend of urbanization and industrialization, marginal sites need to be utilized for the development of infrastructure facilities. Marginal sites in this region generally consist of very weak soil deposits. The civil engineering construction in such sites needs special attention in terms of Geotechnical engineering context. The inherent limitations of the conventional foundation lead to choose an alternative solution namely ground improvement technique for solving Geotechnical engineering problems in the marginal sites. Amongst the various ground improvement methods, shallow soil-cement stabilization and in-situ deep mixing technique (cement column) are widely used for soft ground improvement. Although, lime/cement mixing method has been used to improve the properties of soils near the ground surface since ancient times, deep stabilization of soft soils with lime and/or cement stabilized columns has been the subject of research in Sweden, Japan and other Countries in recent times (Bergado & Miura 1994). The modern application of this method for deep mixing of in-situ soils (in the form of lime or cement columns and/or walls) started in late 1970's in Japan (Terashi & Tanaka 1981, Kawasaki et al 1981 and Suzuki 1982).

In the recent years, construction industries and agencies of Bangladesh concentrated its attention towards invention of suitable substitute of bricks and therefore have decided to discourage the mass use of bricks where possible to protect the environment. In modern civil engineering practice, bricks have long before been substituted by various modern materials such as concrete blocks, sand-cement blocks and stabilized soil blocks etc. in Western Europe and other developed countries. But in countries like ours one of the main strategies of low cost construction should, no doubt, be the mobilization of mass use of easily available local and cheap building materials, structures and utilization of simple and local technology of construction. Soil is no doubt the cheapest, easily available and most simple material, which in our country is used either in the form of foundation base or as filling material. But modern construction technology has provided us with the scope of using soil as universal construction materials for use in building elements, road structures and similar construction by improving the properties of soil using different stabilizing/cementing agents such as cement, lime, bitumen, polymer etc. Soil-cement i.e. soil mixed with cement, is the most universal and cost effective kind of stabilized soil.

In the recent years the use of cement as a stabilizing agent to strengthening the soft soil both in the shallow and deep levels below the ground surface have been increased significantly. The improvement of the soft ground due to cement stabilization depends largely on the amount of strength developed in the cement-stabilized soils compared to its natural counterpart. Hence the understanding of the strength and deformation characteristics of induced cemented clay is necessary to reflect its behavior in the rational design of the composite ground. The strength development of cement stabilized materials depends on various aspects such as initial water content of soil, curing time or rest period, amount of cementing materials, temperature and other such other relevant factors. Some fundamental works in this direction were done at a significant level by Nagraj et al. (1990, 1996 & 1997) and Yamadera (1998 & 1999).

The subsoil condition in Khulna region i.e. south-west part of Bangladesh consists of recent alluvial deposits and organic composition and often creates problem to geotechnical engineers in designing economic foundations for strength and high compressibility (Alamgir et al. 2001) Ground improvement techniques have been adopted in this region to solve the geotechnical engineering problems economically. Shallow and deep stabilization of ambient clay media by cement admixture which is now readily available in Bangladesh, is promising ground improvement technique in this contrast. This study points out the effects of cement content and rest period i.e. after mixing elapsed time on the strength deformation characteristics of cement stabilized clay deposits depicted from laboratory investigations. The strength development in cement stabilized clay were examined by unconfined compression test at rest period of 0, 1, 3, 7, 14, 28 and 56 days for the cement content of 2.5%, 5.0%, 7.5%, 10.0%, 12.5%, 15.0%, 20.0%, 25.0%, 35.0%, and 50.0% of the solid weight of clay. Relationships are established among the cement content, rest period, unconfined compressive strength, stiffness and the failure strain. It is observed that the cement content increases the shear strength and stiffness of soil considerably. The rate of increase of soil strength can easily be determined at the particular cement content for the required rest period.

1.2 Background of this Study

Increased construction activities due to rapid urbanization and industrialization force the use of marginal sites. This necessitates resort to appropriate soft ground improvement methods to handle stability and settlement problems as accost effective counterpart of conventional foundation system. Soft ground is improved by lime or cement stabilization as one of the ground improvement techniques. It has been proved that this technique is effective for improving the bearing capacity or the stability of the ground, and it is reported that in recent years, the execution of ground improvement techniques is steadily increasing every year. There is still need score for understanding the mechanical characteristics of lime or cement stabilization to enhance the efficiency. It can be considered that in such a kind of stabilized material the cementation will invariably occur between soil and lime or cement. The alternative method of soft ground improvement, by admixturing soft clay in their in-situ state it self with cementing binders like lime and cement was developed simultaneously in 75's both in Sweden and Japan (Broms and Boman 1975, Kawasaki 1981 Okamura & Terashi 1975 and Saitoh et al. 1985). T.S. Nagaraj, N. Miura, A. Yamedra of Saga University, Japan and Y. Prakash of Indian Institute of Science, India also studied it combinedly in 1996. It was found by above researchers that stabilizing the soft or loose soil could significantly increase the supporting power of soil. Amongst the various ground improvement methods, shallow soil-cement stabilization and in-situ deep mixing technique (cement column) are widely used for soft ground improvement (Alamgir 1996). The modern application of this method for deep mixing of in-situ soils (in the form of lime or cement columns or walls) stated in late 1970's in Japan (Terashi & Tanaka 1981, Kawasaki et al. 1981 and Suzuki 1982). Recently published research works on stabilized soils also do not provide any comprehensive conclusion on the strength of stabilized soil. Moreover, conclusion has yet been accomplished on the strength deformation behaviour of stabilized Khulna soil, although some works conducted in the Department of Civil Engineering, Khulna University Engineering & Technology at undergraduate level. However, consideration the prospects of soil-cement stabilization as a ground improvement technique, it is necessary to evaluate the potential of such technique by using cement admixture, since this region has extensive deposition of very soft up to a great depth.

1.3 Objective of this study

The sub-soil in Khulna region consists of very soft soil up to a considerable depth and the bearing capacity is very low. The physical and mechanical properties of soft soils can often economically be improved by the use of admixtures. Therefore to improve the sub-soil conditions cement of different proportions are mixed with the natural soft soil and laboratory tests are performed to investigate the development of strength with deformation. The main objectives of this study are:

a. To find out the stress-strain behaviour of cement stabilized soil.

b. To find out the relationship between strength and deformation characteristics of stabilized soil with various proportion of cement content.

c. To observe the change of water content in the stabilized soil cement content and rest period.

d. To observe the strength development in stabilized soil with time and cement content.

e. To establish an empirical equation among the strength, percentage of cement content and rest period.

1.4 Organization of this Study

This dissertation is composed of five chapters. The outline and relations among these five chapters is shown in Figure 1.1. The first chapter forms the introduction of the study. The background and the objectives are presented in a comprehensive style. The ground improvement technique, soil-cement stabilization of is summarized in chapter two. The characteristics of soft clay, mechanism of soil-cement stabilization factors affecting soil cement stabilization are presented in brief. Present state of the art of the research and development in soil/cement stabilization technique is also highlighted here. Chapter there describes the materials and methods of this study in which the overall condition of materials, test scheme and the laboratory test method are described. In chapter four, the results and discussions are described elaborately. Typical representation of test result, empirical relationship, comparisons of test results are presented. Summary and conclusion of this study are presented in chapter five. Finally the recommendation for future study is also enclosed.

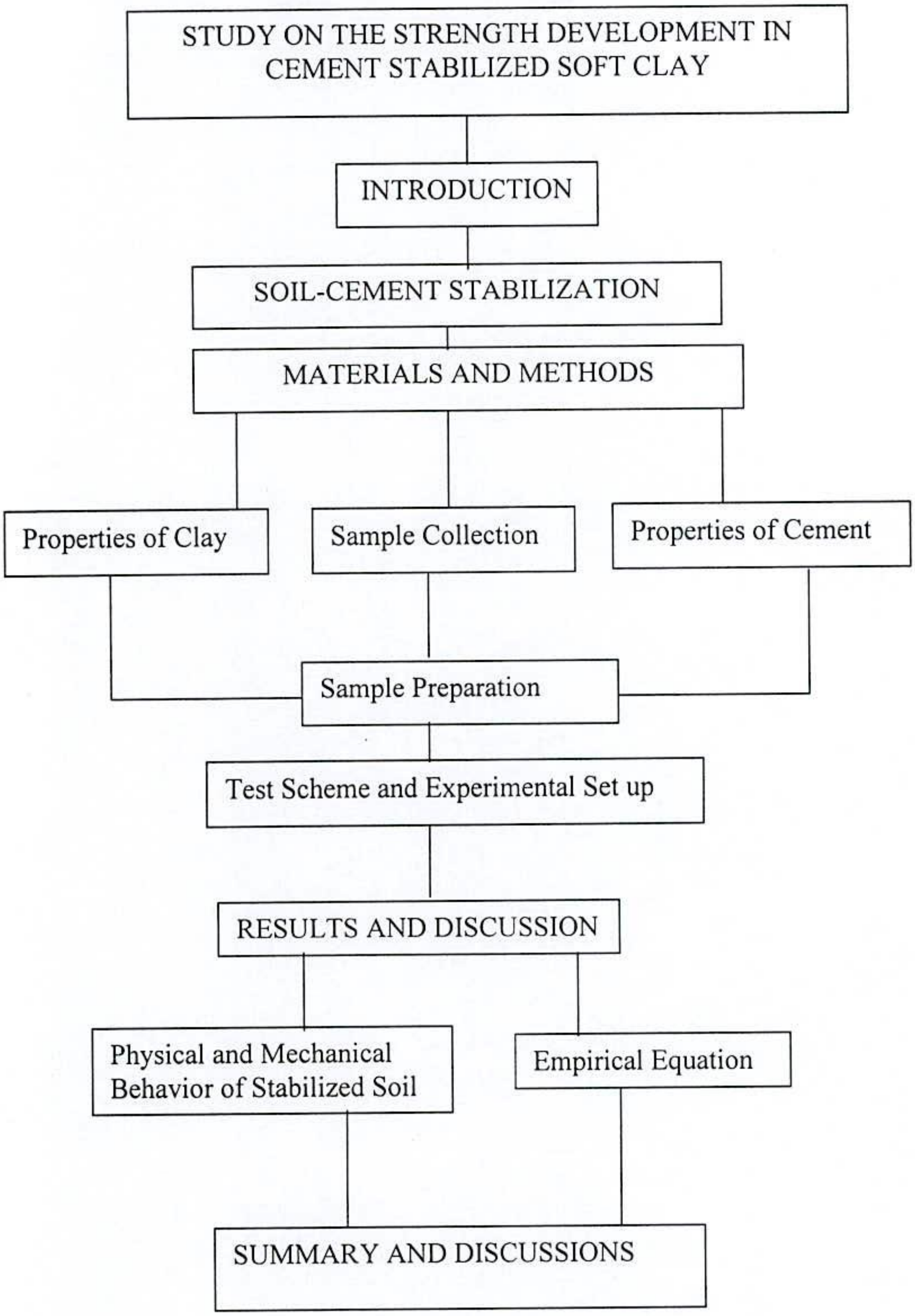


Figure 1.1 Diagram of the project outline.

CHAPTER TWO

SOIL-CEMENT STABILIZATION

2.1 General

The general properties of naturally cemented and induced cemented soil are discussed in this chapter. The strength developed mechanism of cement stabilized soils and the role of different factors on such strength developed are discussed in brief as reported in the available literature.

2.2 Cementation in Natural Clays

Clay can be explained by three chemical bonding processes such as mineral contact points between particles, exchange of cations and precipitation of cementing agents, as realized by Bjerrum (1967) for Norwegian clay. The third process leading to the development of additional strength in the clay due to the precipitation of cementing agents. The effect of precipitation is limited to strengthening of the links of the clay structure, the clay itself not otherwise being affected. In many clays there exist considerable quantities of solvable chemical agents such as organic matter, carbonates, gypsum, aluminum and ion iron compounds, which under certain conditions could precipitate and form chemically stable cements, crystalline or gels, possessing considerable strength. This implies that in untreated clay, the major part of additional resistance developed against deformation is the result of cementation. In natural soil, the cementation substances such as silica (SiO_2), carbonate ($CaCO_3$), organic matter, etc. create bonding effects among the particles of the soil structure.

Silica is produced by chemical sedimentation due to a change in P^H, and by some creatures such as radiolarian and diatoms. Carbonate is produced by a reaction of carbonic gas, change in P^H, evaporation of moisture, bio-chemical sedimentation of coral or lime-plant and by the dissolution of organic material (Tohno 1974). The significance of cementation effect on the geotechnical properties of natural clay is illustrate in Figure 2.1 (JGS 1997).

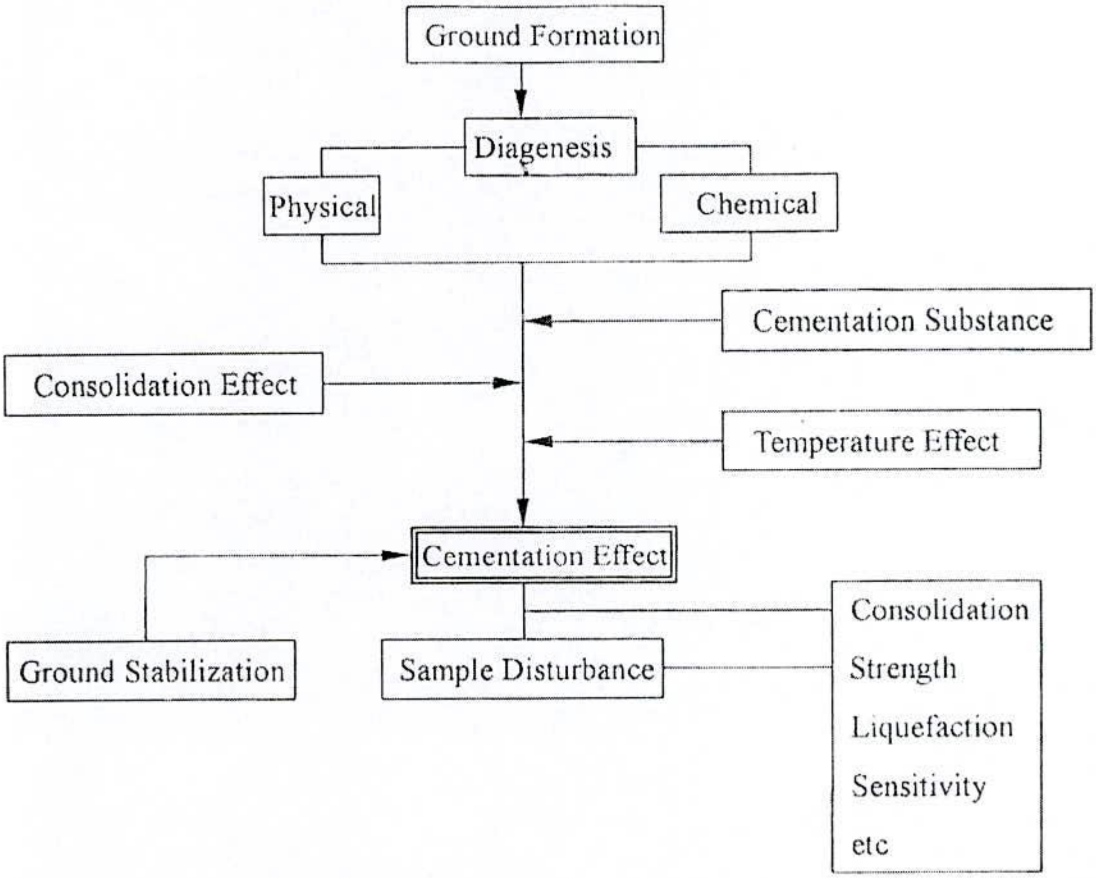


Figure 2.1 Significance of cementation effect on geotechnical engineering (JGS, 1997).

2.3 Induced Cementation in Clays

The natural bonding of soil can be changed many folds by induced cementation i.e. mixing the soil with the cement or lime. This additional bonding changes both the physical and mechanical properties of soil. This has considerable implications for ground improvement by shallow soil-cement stabilization or in-situ deep mixing. Generally mechanical properties of the soil are influenced by certain again effects.

Cementation is one of these again effects and the cementation substance creates a bonding effect among soil particles during a long geological period. It is known that soil affected by cementation effects demonstrates high pre-consolidation pressure and the strength after remolding decreases to a large extent. Cement columns are constructed in-situ by mechanically mixing cement with soft clay. The measure in strength and decrease in Compressibility of the soft clay result from the reaction of the clay with Cement through the process of ion exchange and flocculation and well as pozzolanic reaction.

2.4 Soil Stabilization

Soil is no doubt the cheapest and easily available most simple material which in our country is used either in the form of foundation base or as filling material. But modern construction technology has provided us with the scope of using soil as universal construction material for use in building elements, road structures etc. by improving the properties of soil using different stabilizers such as cement, lime, bitumen, polymer etc.

Mechanical properties of soil are influenced by certain aging effects. Cementation is one of these aging effects and the cementation substance crates a bonding effect among soil particles during a long period. It is known that soil affected by cementation effects demonstrates high pre-consolidation pressure, and the strength after remolding decreases to a large extent It is generally regarded that a soil particle dose not exist as a single unit and soil structure invariably consists of enclosed pores and structural units which are made up of groups of particles. This soil structure is a mass in which connectors exist between silts, sand and aggregates and different types of pores as shown in Figure 2.2. In natural soil, the cementation substances such as silica, carbonate, organic matter, etc. create bonding effects among the particles of the soil structures as shown in Figure 2.3. This additional bonding changes both the physical and mechanical properties of soil. This phenomena of soil can be enhanced many folds by induced cementation i.e. mixing the soil with the cement or lime This has considerable implications for ground improvement by shallow soil-cement stabilization or in-situ deep mixing. The microstructure of the natural soil is changed significantly due to its admixture with cement.

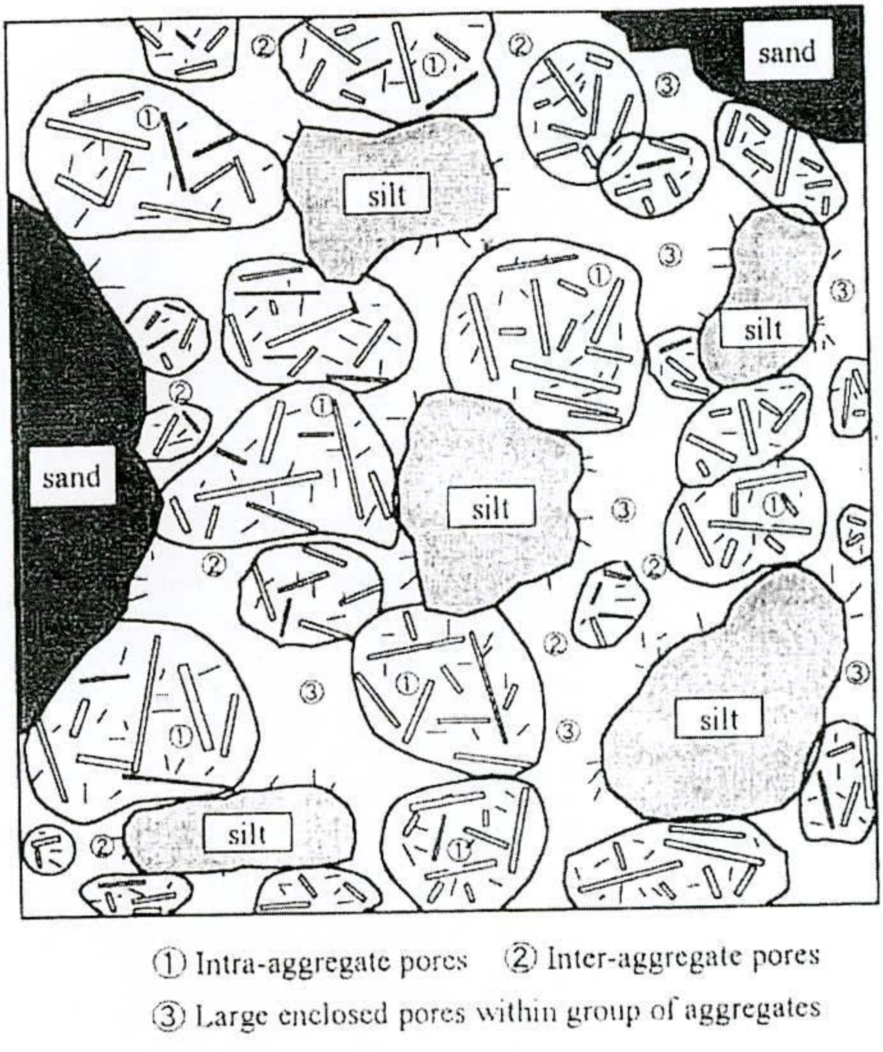


Figure 2.2 Microstructure of fine-grained soil (Nagaraj et al. 1990)

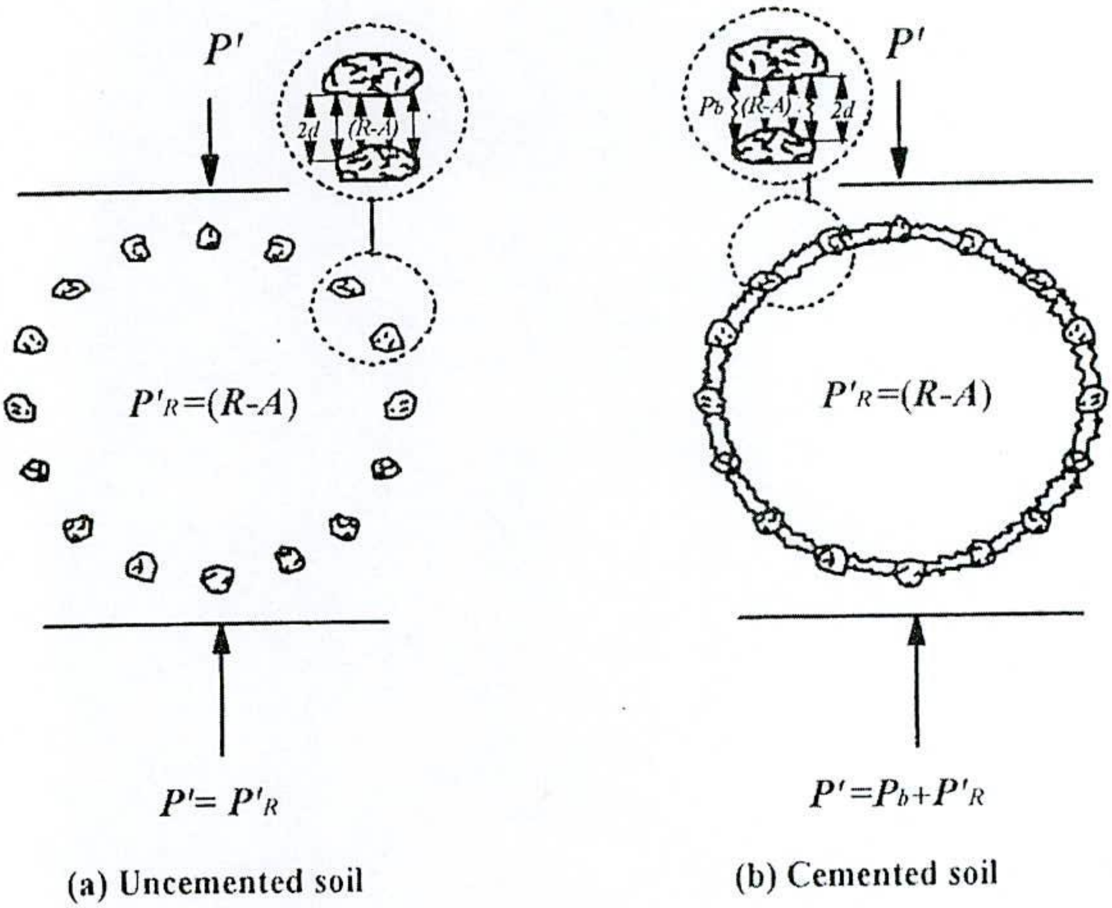


Figure 2.3 Possible microstructure for cemented soil (Nagraj et al., 1994)

2.5 Stabilization Agent

Generally certain aging effects influence mechanical properties of the soil. Cementation is one of these aging effects, and the cementation substance creates bonding effects among soil particles during a long geological period. It is known that soil affected by cementation effects demonstrates high pre-consolidation pressure and the strength after remolding decreases to a large extent. Other stabilizing agents are lime, bitumen, chemical, temperature (heating and cooling), geotextile and fabrics etc. These stabilizing agents also improve the properties of soil by stabilization. Chemical stabilization is generally more expensive than other types of stabilization.

2.6 Soil Cement Stabilization

Soil cement i.e. soil mixed with cement is the most universal kind of stabilized soil. It may also be termed as 'Soil Concrete', i.e. a special type of concrete composed of fine aggregate, binding element and water without any course aggregate. Stabilized soils thus may be used in construction works both in the form of soil and materials.

Clay can be explained by these chemical bonding processes such as mineral contact points between particles, exchange of cautions and precipitation of cementing agents, as realized by Bjerrum (1967) for Norwegian clay. The third process leading to the development of additional strength is the clay due to the precipitation of cementing agents. The effect of precipitation is limited to strengthening of the links of the clay structure, the clay is self not otherwise being affected. It many clays there exist considerable quantities of soluble chemical agents such as organic matter, carbonates, gypsum, aluminum and ion iron compounds, which under certain conditions could precipitate and form chemically stable cements, crystalline or gels, possessing considerable strength. This implies that is untreated clay, the major part of additional resistance developed against deformation is the result of cementation.

2.7 Mechanism of Soil-Cement Stabilization

The essential ingredients of Ordinary Portland Cement are lime, silica and alumina. All of these Compounds are abundant in nature as chalk (or lime stone) and clay (or shale). The process of manufacturing is basically simple, its main drawback being the need to raise the temperature of the raw material to about 1500^0C, which is enough to remove the structure water (water molecule which is part of the chemical composition for the raw material). The final powdered form products, which are compound of calcium silicates, calcium aluminates and smaller proportions of other compounds, are commonly referred as Portland cement. Four major constituents namely, tri-calcium silicate ($3CaO.\ SiO_2$), di-calcium silicate ($2\ CaO.\ SiO_2$), tetra-calcium aluminate ($3CaO.\ Al_2O_3$.) and tetra-calcium alumino-ferrite ($3CaO.$

Al_2O_3. Fe_2O_3) are the major strength-producing compounds. When the pore water of the soil encounters with the cement, hydration of the cement occurs rapidly and the subsequent major products (Primary Cementations) are hydrated calcium silicates ($C_2\ SH_x$, $C_3S_3H_x$), hydrated calcium aluminates ($C_3\ AH_x$, C_4AH_x), and hydrated lime $Ca(OH)_2$; where C. S. A. H. are the symbols used by cement scientists to designate calcium (CaO), silicate (SiO_2), aluminate (Al_2O_3), and water (H_2O), respectively. The first two hydration products just mentioned are the main cementation products formed while the hydrated lime is deposited as a separated crystalline solid phase. These cement particles bind the adjacent Cement grains to gather during hardening and to form a hardened skeleton matrix, which enclose unaltered soil particles. Furthermore, the hydration of cement subsequently enhances the rise of P^H value of pore water, which is caused by the dissociation of the hydrated lime. The soil silica and alumina, which are inherently acidic, are dissolved by the strong bases of cement compounds from the clay minerals and amorphous minerals on the surface of clay particle, in a manner similar to the reaction between a weak acid and a strong base. The reactions of tri-calcium silicate (C_3S), which is the most dominant constituent, stabilization, can be represented in the following qualitative equations and are shown in Figure 2.4.

Hydration: $C_3S + H_2O = C_3S_2H_x$ (Primary cementing products) + $Ca\ (OH_2)$ (Hydrated gel)

Hydrolysis: $Ca\ (OH)_2 = Ca^{++} + 2(OH)$.

Pozzolanic reactions:

With soil silica: $Ca^{++} + 2(OH)^- + SiO_2$ (soil silica) = CSH

(secondary cementing product)

With soil alumina: $Ca^{++} + 2(OH)^- + Al_2O_3$ (soil alumina) = CAH

(secondary cementing product)

When $P^H < 12.6$, then the following reaction occurs:

$C_3S_2H_x = C_3S_2H_x$ (hydrated gel) + Ca $(OH)_2$

In order to have additional bonding forces produced in the cement-clay mixture., the silicates and aluminates in the material must be soluble. The solubility of the clay mineral is affected by the impurities present, the crystalline degree of materials, the grain size, etc The cement hydration and the pozzolanic reaction can last for months, or even years, after the mixing; hence, the strength of cement-treated clay is expected to increase with time. Furthermore, the secondary cementing substance formed will enhance the bond strength between clay particles; hence, a subsequent increase in strength and durability of the soil can be expected.

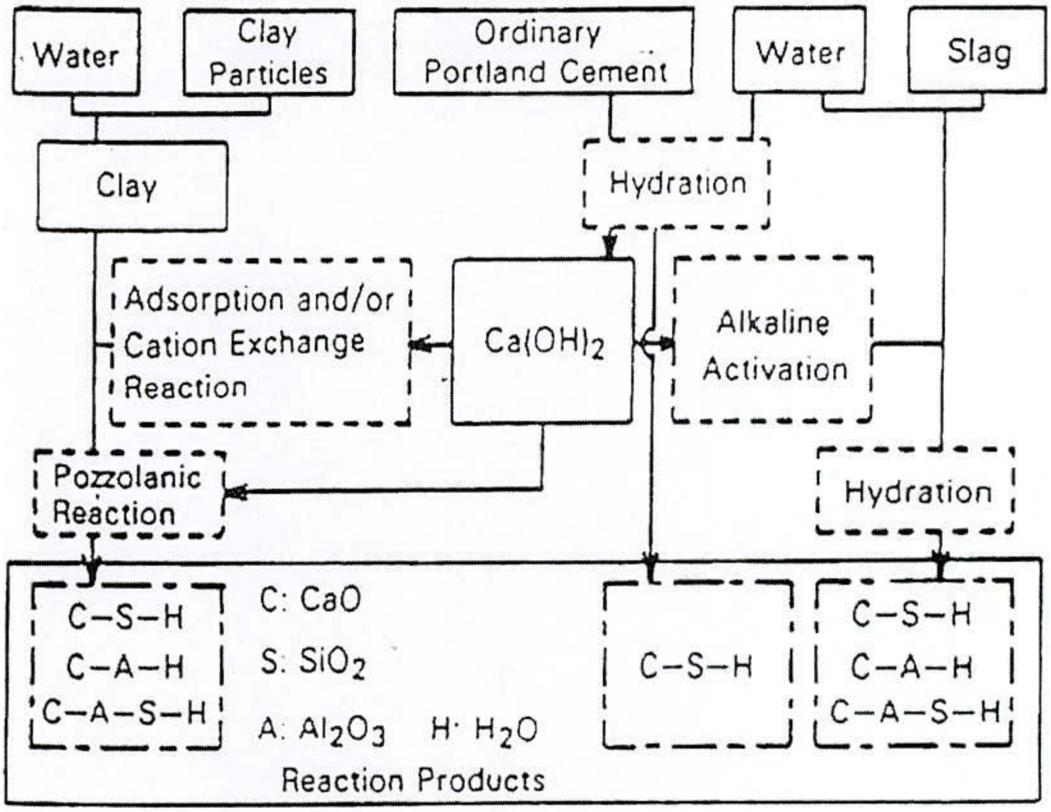


Figure 2.4 Chemical reactions between soil and hardening agents (Saitoh et al. 1985).

2.8 Strength Development in Cemented Soils

The shear strength component of the naturally cemented clays are composed of two stress components, such as the resistance due to the uncemented state and the resistance due to the cementation, as stated by Nagraj et al. (1994) shown in Figure 2.5 and expressed as

$$\tau = \tau_R + \tau_b$$

Where, τ is shear strength; τ_R is shear resistance in uncemented state and τ_b is shear resistance due to cementation.

In the above equation τ_R is due to the initial state resulting from physio-chemical interaction immediately after remolding or at any definite time and that of the recovery is due to the thixotropic characteristics of clay during its deposition. So the above equation can be modified as the following by neglecting the effect of volume change.

$$\tau = \tau_{Ri} + \tau_{Rt} + \tau_b$$

Here, τ_{Ri} is shear strength immediately after remolding; τ_{Rt} strength recovery due to thixotropy. The magnitude of these two components depends on clay minerals, water content and chemical composition. The components τ_{RT} and τ_b increase with geological time.

2.9 Stress-Strain Behavior of Cemented Soil

Nagaraj et al. (1994) state that the shearing resistance (q) of cemented soil is the sum of the shearing resistance of the soil contributed from the cemented (q_b) and uncemented (q_R) part and can be expressed by the following equation.

$$Q = q_R + q_b$$

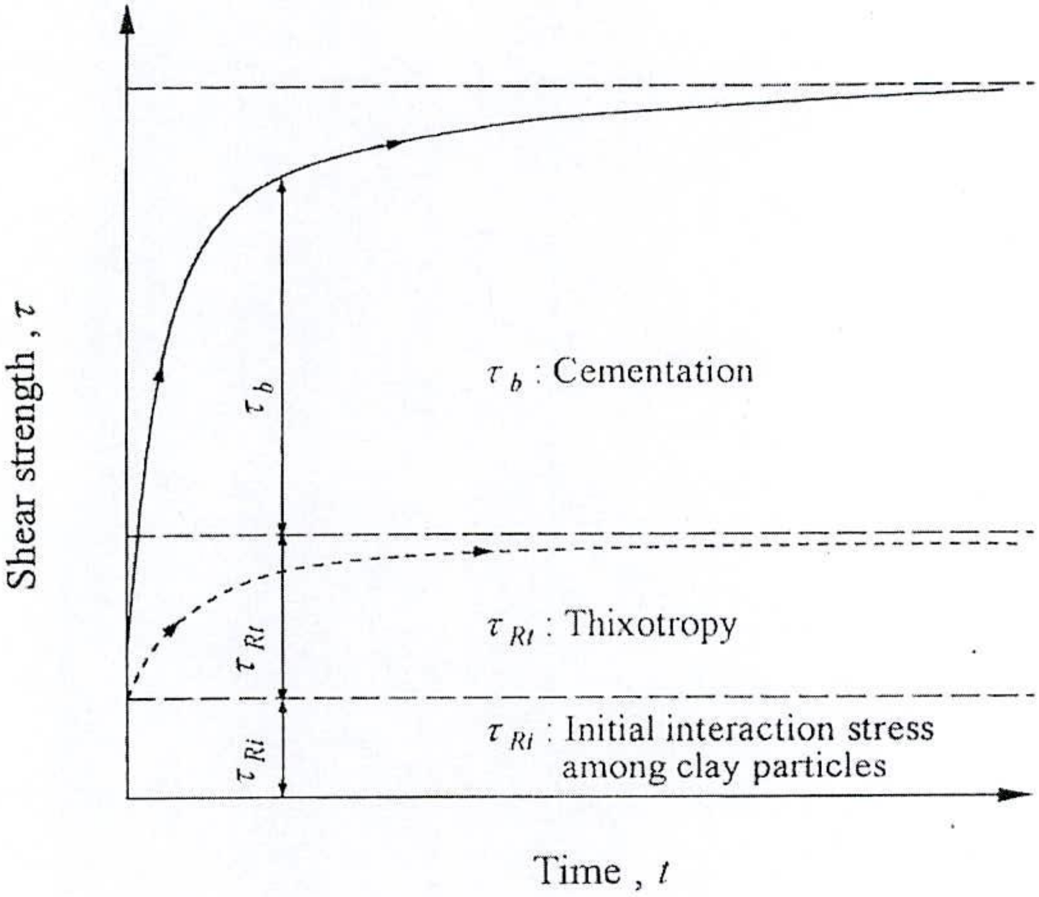


Figure 2.5 Illustration of shear strength component in typical clay (Yamadera 1999).

The Figure 2.6 demonstrate the stress –strain behavior of cemented soil in consideration shearing resistance component. The cementation substances may break after the peak at small strain with progress in shear, Thus the cementation component of resistance (q_b) Shaw a hardening behavior, At the last strain in shear, the uncemented stress component (q_R) dominates in the total resistance, since q_R shows hyperbolic with strain, as same as the behavior of normally consolidated uncemented soil, In addition, it was observed that the pore pressure of cemented soil at any stage of undrained shearing has the following three components:

$$u = u_R + u_b + q_b /3$$

Where u is the pore pressure component of cemented soil, u_R is due to the uncemented stress component of pore pressure corresponding to q_R, u_b is equal to the decrease in q_b caused by the breakdown of cementation substances and q_b /3 is equal to the increase in mean principal stress due to an increase in the deviator stress, q_b.

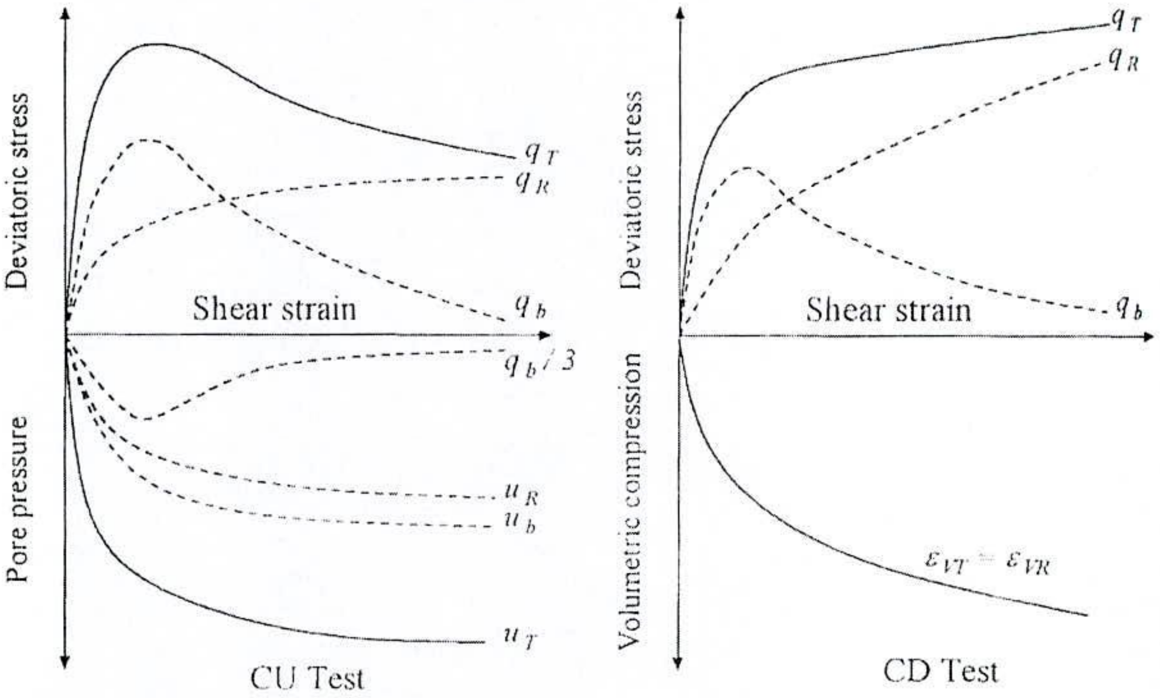


Figure 2.6 Cemented, uncemented and net components of shear strength with strains (Nagaraj et al., 1991).

2.10 Factors Affecting Soil-Cement Stabilization

The physical and mechanical properties of cement stabilized soils depend on several factors, mainly the properties of base materials and the environmental aspects. The strength development of cement stabilized materials depends on many such as type of soil, nature of cement stabilization, water content, cement content, rest period, temperature soil minerals and other such factors. In the following sections, brief descriptions are given on this important issue of soil cement stabilization.

2.10.1 Type of soil

The type of soil affects the consequent curing temperature of the stabilization soil in situation at different times after installation, hence, effects the behaviour of strength development. The effectiveness of cement and lime decreases with increasing water content and organic content. The improvement decreases generally with increasing water content and organic content. The improvement decreases generally with increasing plasticity index, and/or increasing activity of the clay. The increase in strength due to both lime and cement treatment in organic clay is often very low, and among them, cement is more effective than lime in stabilizing organic soils (Miura et al, 1987). Granular soils with sufficient fines are ideally suited for cement stabilization. Such soils can be easily pulverized silty & clayey soils can produce satisfactory soil-cement but those with a high clay-content are difficult to pulverize.

2.10.2 Nature of cementing agent

The type of cement is dictated by the distribution of the percentage amount of each forming compound. Since the reaction potential of the ions of the clay mineral depends on the reacting constituents of cement, then the resulting characteristics of the stabilized soil should also be dependent on the type of cement. Portland Cement is more available and cheaper in the market compared with other types that is why is more popularly used in soil stabilization.

2.10.3 Cement content

Generally, the higher the cement content, the greater the strength of the cement-treated clay (Broms, 1986 and Uddin et al, 1997). The actual quantity of cement required for a particular soil is ascertained by laboratory tests. Sometimes, the quantity of cement is determined according to the minimum unconfined compressive strength. As a rough guide, the cement content can be taken as 6% for sandy soils and 15% for clayey soils. High-early strength cement is more effective than ordinary Portland cement but is rarely used, as it is costlier.

2.10.4 Water content

Current studies on cement admixed clay revealed that the total amount of water present in the soil-cement paste affects significantly the strength development of the treated soil. The higher the clay water content, the lesser the strength for the same curing period (Miura et al 2001). Moreover, the higher the clay water content, the lesser the apparent pre-consolidation pressure (or one-dimensional yield stress) for the same cement content and curing period (Lorenzo, 2001). The micro-structural effects of water content in a cemented soil are shown in Figure 2.7.

2.10.5 Rest period

The strength of cement-treated soil will increase with increasing curing time (Uddin, 1997). The rate of strength development increase rapidly at the early stage of curing for cement treated clay around less than 30 days for cement content of 10% and beyond this time, generally, the rate of increase of strength will gradually decrease seemingly asymptotically. For cement-treated clay the curing time should be at least 30 days (Uddin, 1997). The micro-structural effects of rest period in a cemented soil are shown in Figure 2.7.

2.10.6 Soil minerals

Soils with property of higher pozzolanic reactivity, the strength characteristics of the resulting treated soil are governed by the strength behavior of the hardened cement bodies. While those having lower pozzolanic reactivity, the strength characteristics of the resulting treated soil is governed by the strength characteristics of the hardened soil bodies (Saitoh et al, 1985). If the improvement conditions are equal, then greater strength is expected from the soil with higher pozzolanic reactivity. Among the clayey soils, montmorillonitic and kaolinitic clayey soils were found to be offectiver pozzolanic agents are compared to illitic and chloritic clayey soils (Hilt and Davidson, 1960).

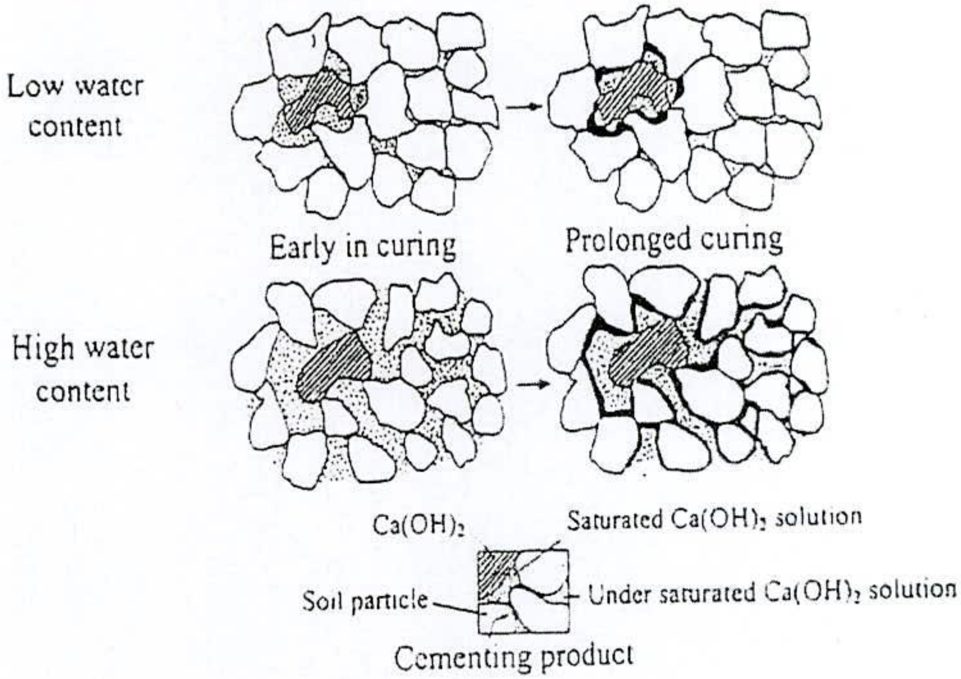


Figure 2.7 Physical conceptual model proposed for cement-stabilized clay.

2.10.7 Temperature

The increase of temperature of the treated soil enhances the solubility of the silicates and the aluminates in the soil, hence, it accelerates the pozzolanic reactions, with calcium ions and consequently, increases the rate of accomplishment of the strength gain of the treated soil.

Kawasaki et al. 1981 reported the noticeable effects of temperature on the development of strength in the cement stabilized marine clay for different rest period and cement content. The research findings revealed that the strength of cemented soil depends on cement content and as well as curing temperature. For the increase of temperature of 10 to 50°C, the unconfined compressive strength of cemented soil increases by 2.5 to 3 folds as the curing period elapsed from 1 to 28 days and cement content increases from 10 to 20%.

2.11 Application of Cement Stabilization

2.11.1 Shallow stabilization

Soil-cement stabilization has been commonly applied for improving the engineering performance of sub-grade, which enables a consequent reduction of the thickness of the base coarse for road construction. This type of surface stabilization usually involves mixing of the cement/lime with the borrow soils on the site, and then compacting at optimum moisture content. Lime has been favorably applied to cohesive soils while cement to cohesionless soils.

2.11.2 Deep stabilization

Deep Mixing Method (DMM), which was originally developed to improve soft ground ports and harbor structures, is now extended and popularly used in deep stabilization for foundations of buildings, storage tanks, and embankments. DMM column is manufactured by mixing the chemical agents, which is either in a form of slurry or powder of cement or lime, with in-situ soft soil rotating mixing blades, which is forwarded at an specified speed into the ground. The chemical agents are injected through a nozzle located near the mixing blades. The favorable applicability of soil-cement stabilization to shallow and deep ground improvement in soft ground environment over other ground improvement techniques have been thoroughly discussed by Kamon and Begado (1991). Wet Jet Mixing Method (WJMM), Dry Jet Mixing Method (DJMM) isy also the field application of deep stabilization. The wet jet mixing method differs from the currently employed deep mixing method in how the slurry of cement is introduced or mixed with the in-situ soil. While the diameter of the DMM, improved column is predefined and is dictated by the diameter of the rotating mixing blade, the WJM-improved column is not predefined and is dependent on the applied pressure of the jetted slurry and the relative packing of the in-situ soil. The Dry Jet Mixing Method differs by using dry powder of cement or quicklime from the WJMM, which uses slurry of cement. The powder form admixture is transported to the deep ground through a pipe with the aid of compressed air (under pressure of several hundred kPa) and mixed with the clay mechanically by rotating wings. Since no water is added into the ground so the effect on improvement is expected to be much higher than that of slurry method. The graphical illustration of the method is shown in Figure 2.9.

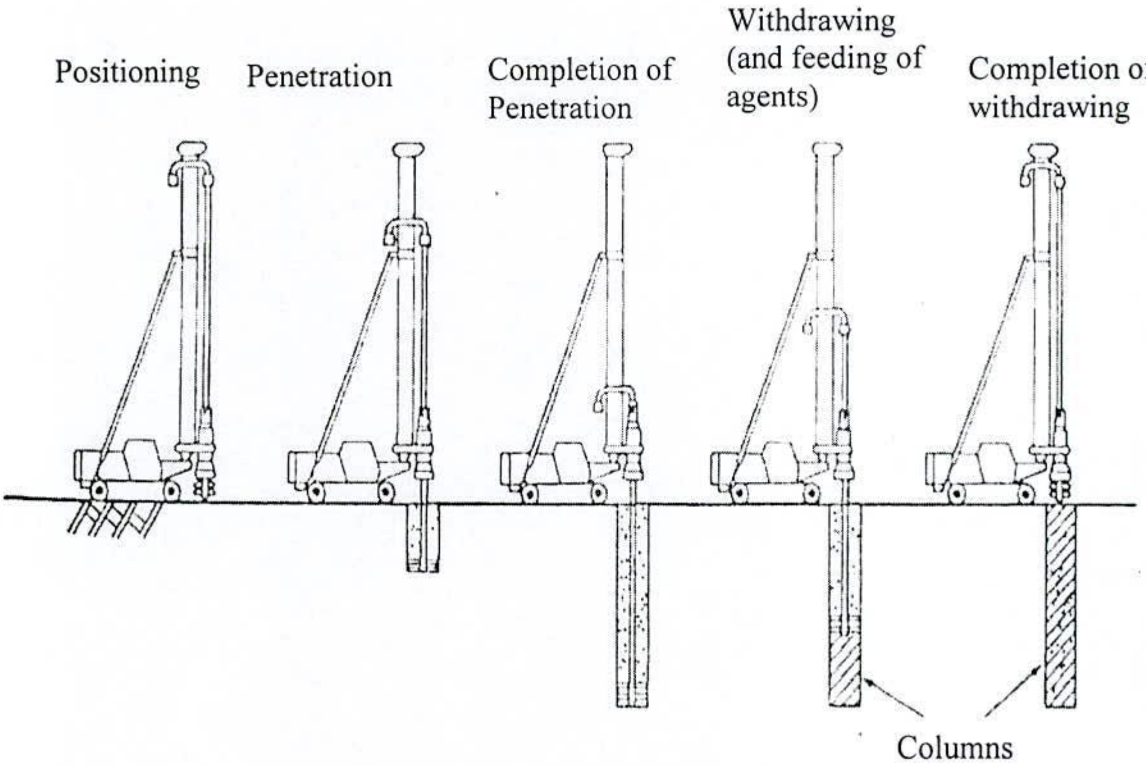


Figure 2.9 Construction sequence of deep mixing method of soil cement stabilization.

2.12 Environmental Effect

Ground improvement by soil – cement stabilization causes some environmental problems. However, in some cases this technique also uses in the remediation technique of ground contamination. The positive and negative environmental impacts are discussed briefly in the following articles.

2.12.1 Negative environmental impacts

Ground improvement by solidification had become more popular in the last decade. There are some environmental which we must avoid generating pollution during and after the operation of solidification techniques. The environmental problems caused by the used of ground stabilizers, such as alkaline leachate by the cement or lime stabilizer, and ground water contamination by the migration of grouting chemicals. Ground water Contamination by grouting chemicals is more serious. People who drank this contaminated water had severe health problems. This contamination triggered the establishment of strict governmental guidelines regarding the use of chemical grouting in Japan. The groundwater during execution of grouting must be low p^H 8.6. The environmental impact of DMM during Construction execution is considered to be minimal compared with the other improvement method.

2.12.2 Positive environmental impacts

The uncontrolled release of heavy metals and organic chemical substances to the subsurface has often resulted in widespread soil and ground water contamination. The remediation of the sites with contaminated ground should be performed as soon as possible. Solidification techniques have the potential to stabilize or treat soils to permit the safe closure and /or development of these sites.

Soil mixing techniques have increasingly been relied upon for the in situ remediation of contaminated soils. Depending on the application, large or small diameter (4 to 0.3 m) mixing augers can be used to inject cement, betonies and other stabilizers to modify soil properties and thereby rededicate contaminated soils and sludges. A major advantage of DMM is the capability to treat deep soils without excavation, shoring or dewatering, and thus the cost is relatively low and there is less exposure of wastes to the surface environment.

CHAPTER THREE

MATERIALS AND METHODS

3.1 GENERAL

A brief discussion about the methodology, materials used in this study, properties of base materials, collection and preparation of sample including method applied for testing specimens is described in this chapter. Investigation the strength development of cement stabilized clay with cement content and rest period was carried out by the conventional laboratory test. The unconfined compression tests were carried out in the laboratory.

3.2 Methodology

To preparation of cemented-soil in the laboratory within a short elapsed time is very difficult. Therefore, a mechanical study of cement or lime stabilized soil is occasionally carried out in the laboratory to understand the mechanical properties of cemented soil (Yamedra, 1999). As the cement is the most common cementing agent and has been used in Bangladesh for long time for stabilization, in this study the ordinary Portland cement is considered as the cementing agent. Stabilized soil sample is prepared in a conventional method and the mechanical properties of the sample was measured through unconfined compression test for different conditions in terms of cement content and rest period.

3.3 Materials used in this Study

A well-known brand of Ordinary Portland Cement of Bangladesh, namely, King brand of Meghna Cement Company was used as a Cementing agent for the preparation of samples. A typical soft clay sample collected from KUET, Campus located in the Khulna, southwest region of Bangladesh. Bulk of disturbed clay was collected from a depth of 5 feet from existing ground surface to avoid the top crust of clay layer and to get reasonably inorganic cohesive soils.

3.3.1 Properties of Cement

The physical properties of the cement obtained from routine laboratory test are given in Figure 3.1 and Table 3.1. In the routine laboratory tests, the normal consistency of the cement is obtained as 25.30% initial setting time as 1 hr 15 mins and the final setting time is 4 hrs. 5 mins. The fineness of the cement is 3.80%.

Figure 3.1 Sample of ordinary Portland cement used in this study.

Table 3. 1 Physical properties of the cementing agent used in this study.

Type of Cementing agent	Ordinary Portland Cement
Normal consistency	25.30%
Initial setting time	1 hour 15 mins
Final setting time	4 hour 5 mins
Fineness	3.80%

3.3.2 Properties of soil

The cement stabilized soil samples were prepared using a particular type of clayey soils collected from a location of KUET campus, Khulna. The general sub-soil profiles of KUET campus consist of fine-grained soil up to great depth. For this study soil sample was collected from a depth of 7.5 to 10 feet from the existing ground surface to have an inorganic cohesive soil sample free from roots vegetations, sufficient amount of disturbed samples were collected to prepare designated soil-cement samples. Routine laboratory tests were conducted for the characteristic of the base clay. The basic properties of this cohesive soil are given in Table 3.2 and its location in the plasticity chart is shown in Figure 3.2.

Table 3.2 Basic Properties of clay used in this study

Properties	Value
Natural water content (w)	33.25%
Liquid Limit (LL)	42.50%
Plastic Limit (PL)	25.67%
Plasticity Index (PI)	16.83
Specific Gravity (G_S)	2.73
Organic contents (OC)	3.15%
Unconfined compressive strength (q_u)	50 kPa

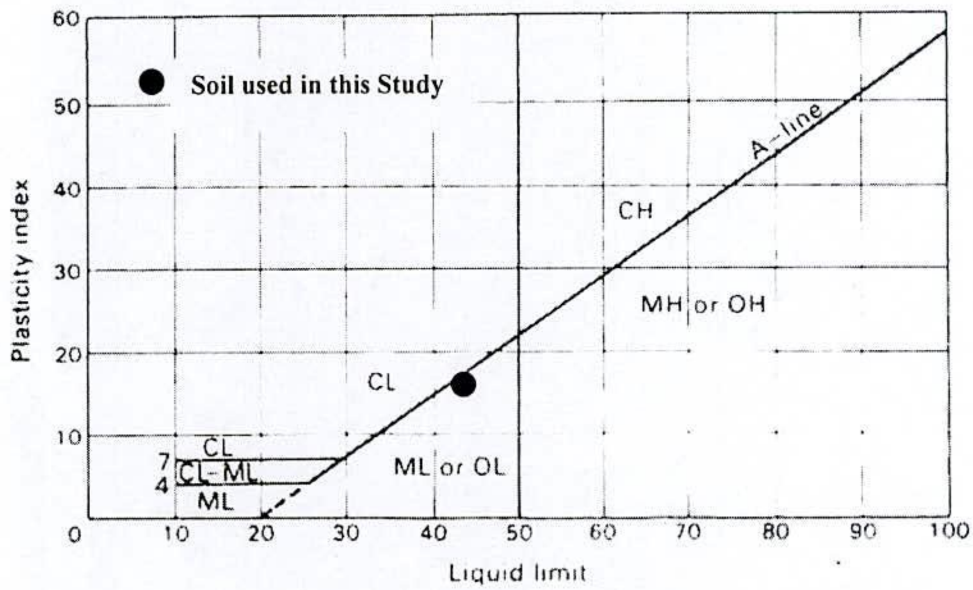


Figure 3.2 Showing the location of used soil sample in the Plasticity Chart.

3.3.3 Properties of used water

The properties of water used in this study were clear and free from harmful salts, alkalis, acids or organic matter. In general the potable water is also satisfactory for soil-cement stabilization. The water, which is supplied in the KUET campus from the water treatment plant, was used for sample preparation. The basic properties of water are given in Table 3.3.

Table 3.3 Basic Properties of used water

Properties	Value
P^H	8.12
Cl^-	407 mg/lit.
Fe	Nil
Colour	Nil
TDS	937 mg/lit.

3.4 Collection of Soil Samples

The soil samples were collected from the designated location and depth both in undisturbed and disturbed condition.

3.4.1 Collection of disturbed soil sample

Disturbed soil samples were collected from KUET campus, Khulna located in the south-west region of Bangladesh. Bulk amount of disturbed fine-grained soils were collected from a depth of 7.5 to 10 feet from existing ground surface to avoid the top crust of clay layer. The samples were carried to the Geotechnical Engineering Laboratory and preserved properly.

3.4.2 Collection of undisturbed sample

Undisturbed soil sample means that the sample in which the natural structure and properties remain preserved. To know the strength of natural soil undisturbed specimens are collected from the depth of 7.5 to 10 feet in the same location of undisturbed samples, by Shelby tube. After extrusion from the tube the specimens are trimmed into standard cylindrical shape of 35 mm. diameter and 70 mm. length.

3.5 Preparation of Test Sample

The test samples of soil-cement were prepared by mixing three ingredients soil powder, cement and water. In the following sections the employed process are discussed.

Before preparation of samples various index properties of the soil such as water content, liquid limit, plastic limit, specific gravity, organic contents etc. were determined.

3.5.1 Powder of base soil sample

Air dry soil powder free from any chuck of foreign materials was used as the main ingredients to prepare stabilized soil-cement specimen as shown in the Figure 3.3. The collected undisturbed samples were first brought to the laboratory and spreaded it over the floor to get air- dry soil samples. After drying, then soil chucks were broken and grinded by using wooden hammer as fine as possible without applying unnecessary pressure. The soil powder was passed through # 40 standard sieve to avoid the chuck. The soil ingredient used in all the tests was ensured to be as similar as possible. The water content of air-dry soil sample was measured at a range of 3%-5%.

Figure 3.3 Powder of air-dried base soil samples.

3.5.2 Initial water content

The percentage of water in terms of soil solid, at which soil powder is mixed with cement, is considered here as the initial water content. Initial water content is one of the important factors for the strength development of the treated soil. The higher the clay water contents the lesser the strength for the same curing period. Moreover, Water content in the soil-cement paste is one of the most important parameters, which is responsible for the development of strength in the sample. For a condition where the cement mixed with clay at the water content corresponding to its liquid limit or higher than that, the fabric is predefined (Nagaraj et al 1997). The cement particles from micro-pore drift towards the inter-aggregate spacing. Although the hydration mechanism is the same as above, since it is mainly to weld the fabric at these sites without altering the overall clay fabric, this suggested that the parameter responsible for the initial fabric becomes the dominant parameter. Since cement per site cannot be estimated from water-cement ratio considerations for different clays, water content at the liquid limit state appears to be an appropriate parameter for analysis of strength development due to cement mixing (Yamadra 1999). In this study the initial water content was 42.5%, which is the water content at the liquid limit of clayey soils used in this study.

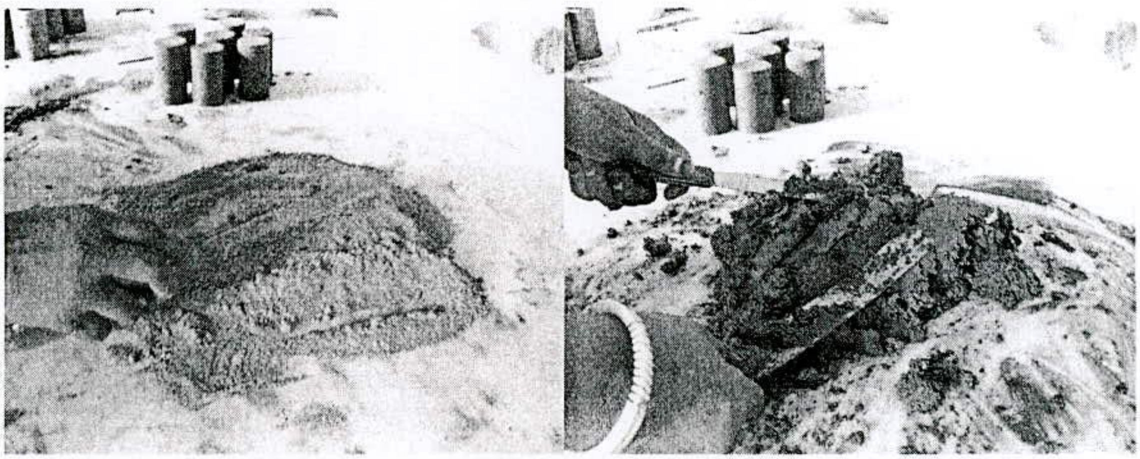


Figure 3.4 Mixing of soil and cement with water.

3.5.3 Mixing of soil, cement and water

Soil, cement and water in the designated ratio by weight were mixed manually by using hand. The mixing were done thoroughly to ensure uniformity in soil-cement mixture as shown in Figure 3.4. The mixing was performed in such a way so that no water can escape or loss. The amount of total mixing ingredients was kept almost same to ensure the similarity of the specimens. The mixing time is around 10 min. for a bulk of 5 kg samples, but proposed mixing was ensured during this period.

3.5.4 Preparation of test specimen

For the preparation of specimen the clay samples in powder form were mixed thoroughly with cement powder, then make paste and pour into the test specimen mold (as shown in Figures 3.5, 3.6 and 3.7) in the different cement ratios in the following steps:

i. At first, the required ingredients as per the predesignated soil-cement specimen have been weighted and kept separated from each other.

ii. In a laboratory porcelain bowl the weighted soil and cement were mixed thoroughly to have a uniform mixture.

iii. In the uniform mixture of soil and cement then added, which is equal to the water content at liquid limit state of soil.

iv. Then by thorough mixing naturally by a wooden smooth rod, the soil and cement with water, slurry or past was prepared which was free from lumps and other foreign particles.

v. The paste was then put into the plastic mold layer by layer fairly by the help of fingers by ensuring that no air voids were entrapped in to the soil sample.

vi. Soil-cement pastes then kept into the mold under air curing for six hours.

vii. Sample were then ejected from the mold by providing minimum pressure as possible.

viii. The specimens were then sufficiently wrapped by polythene so that water can not come in contact with the specimen.

ix. The wrapped specimens were then put into a water tank for curing up to the required rest period.

Figure 3.5 Pouring of soil-cement paste in the mold to make test specimen.

3.5.5 Curing of Specimen

As the hydration proceeds, both the physical and mechanical properties of soil-cement specimen changes due to formation of gel and other associated chemical changes. Proper environment is required for such positive changes. Since water is the major controlling parameter, the loss of water with elapsed time after formation of soil-cement specimen should be prevented. To ensure the no loss of water from the specimen after formation due to evaporation, the samples were kept in a water tub in the room temperature as shown in Figure 3.5. The samples were kept in such a way that no water could come in a contract with the specimen. The samples were removed from the tub at the designated rest period. This process is considered here curing, which is very similar to concrete. The time elapsed after the formation of soil-cement samples is termed as rest period.

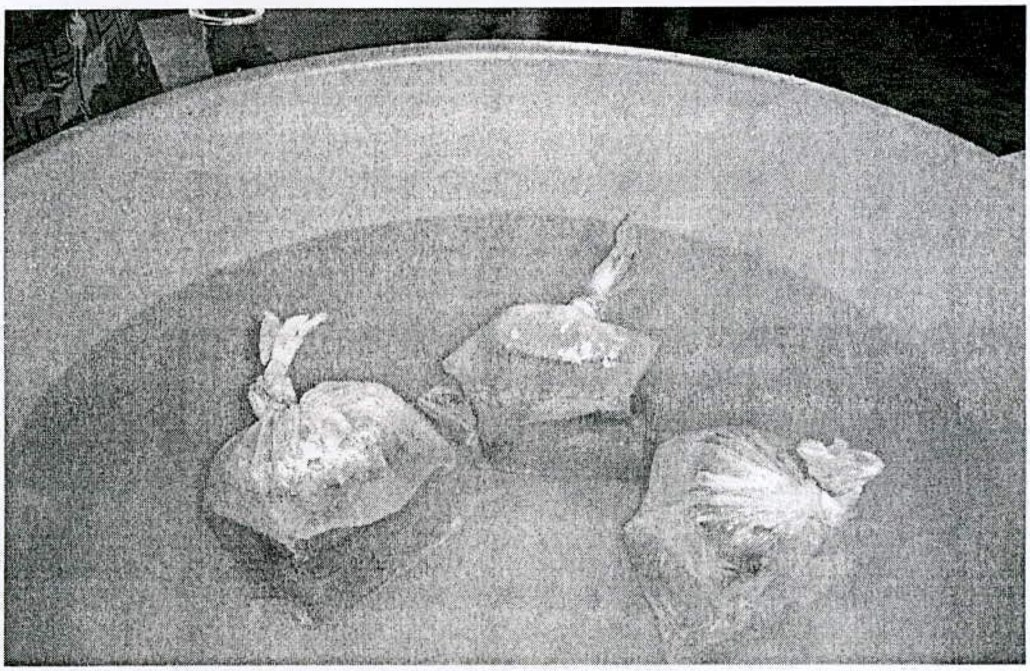


Figure 3.6 Curing of specimen under room temperature.

3.6 Test Programme

The changes of some physical and mechanical properties of soil-cement samples were evaluated by performing laboratory tests with the variation of cement content and rest periods. The cement content, considered as the percentage of soil, varies from 2.5% to 50% and rest period varies up to 56 days in a sequence as shown in the Table 3.4. As a result the total sample condition is 70 (=7x10) at which the required tests were performed. For each condition three (3) specimens were tested, in general as shown in Figure 3.7. If the variation of result within these three specimens are noticeable then a forth or fifth samples were tested, as required.

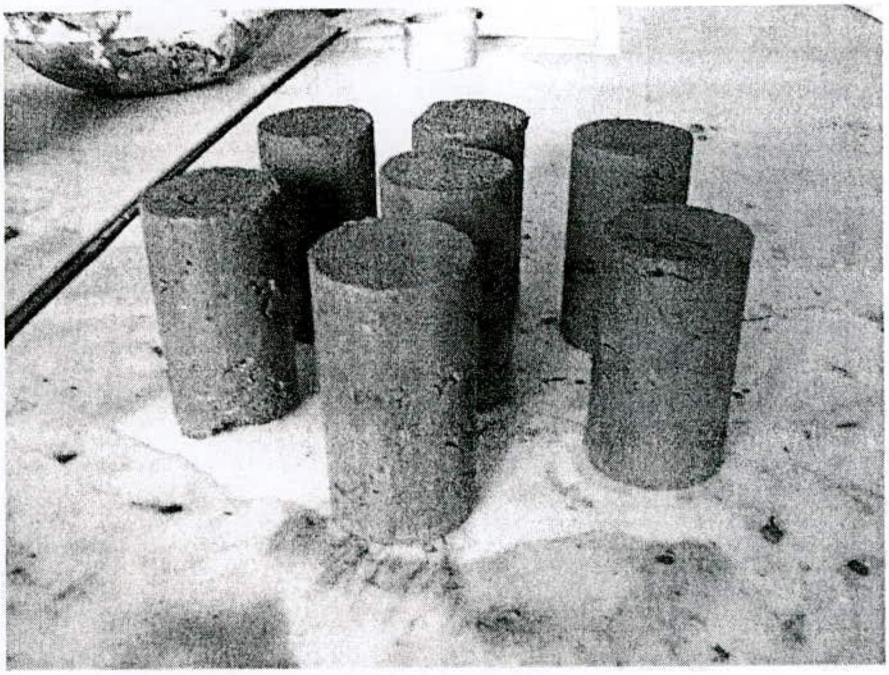


Figure 3.7 Test specimens

Table 3.4 Different conditions of test specimens

Rest Period	Cement as a percentage of soil									
(days)	2.5%	5.0%	7.5%	10%	12.5%	15%	20%	25%	35%	50%
<1	T1	T8	T15	T22	T29	T36	T43	T51	T57	T57
1	T2	T9	T16	T23	T30	T37	T44	T52	T58	T58
3	T3	T10	T17	T24	T31	T38	T45	T53	T59	T55
7	T4	T11	T18	T25	T32	T39	T46	T54	T60	T56
14	T5	T12	T19	T26	T33	T40	T47	T55	T61	T57
28	T6	T13	T20	T27	T34	T41	T48	T56	T62	T58
56	T7	T14	T21	T28	T35	T42	T49	T57	T63	T59

3.6.1 Change of water content

The changes of water contents of with rest period and cement content were measured for each test conditions. Water content was measured as the percentage of dry soil-cement samples. The dry condition was ensured by keeping the samples for 24 hours into the oven at a temperature more than 110^{0} C. A samples of 35mm diameter and 70mm height was used for their measurement.

3.6.2 Change of unit weight

The microstructures of disturbed fine-grained soils have changed significantly due to induced cementation. The unit weight of a soil-cement sample with the variation of cement content and rest period also changes with the rearrangement of microstructures. In this study the change of unit weight was also measured for each sample conditions. Standard laboratory procedure was used for the determination of of unit weight of each soil-cement samples.

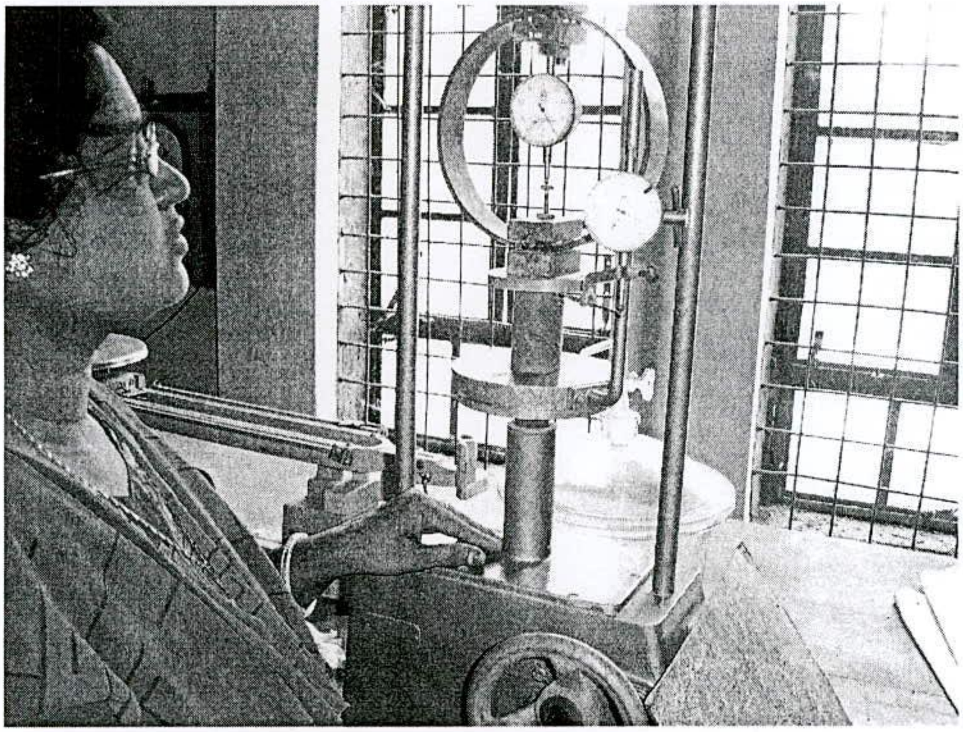


Figure 3.8 Unconfined compression test.

3.6.3 Development of strength

The strength development in soil-cement samples was measured in the laboratory by unconfined compression test for each condition. At last three (3) specimens of size 35mm diameter and 70mm height were tested for each condition. Standard test (ASTM D-2166) procedures were followed. The tests were performed at a strain rate of 1% deformation per minute. Except the samples tested for t<1 days and t = 1days, others samples were removed from the water tub and opened from the wrapped polythene just 1 hour before the test. The recorded data were then calculated and the deviator stress versus axial strain curves were plotted. From this curve the maximum deviator stress was considered as the unconfined compressive strength of the tested samples. However; the stress-strain curve up to the maximum limit of 20% axial strain was considered in case of deviator stress increased even after 20% strain.

3.6.4 Changes of stiffness

As the strength of cement stabilized soil changes will cement content and rest period, it is expected that the stiffness of soil-cement will also be changed. In this study the stiffness of soil-cement samples were quantified by the modules of elasticity (E_s) obtained from the stress-strain curve in the similar fashion of the determination of Young's modules as stated in Figure 3.9. For each soil-cement sample conditions, Es were determined from the deviator stress verses axial strain curves were plotted from unconfined compression test results.

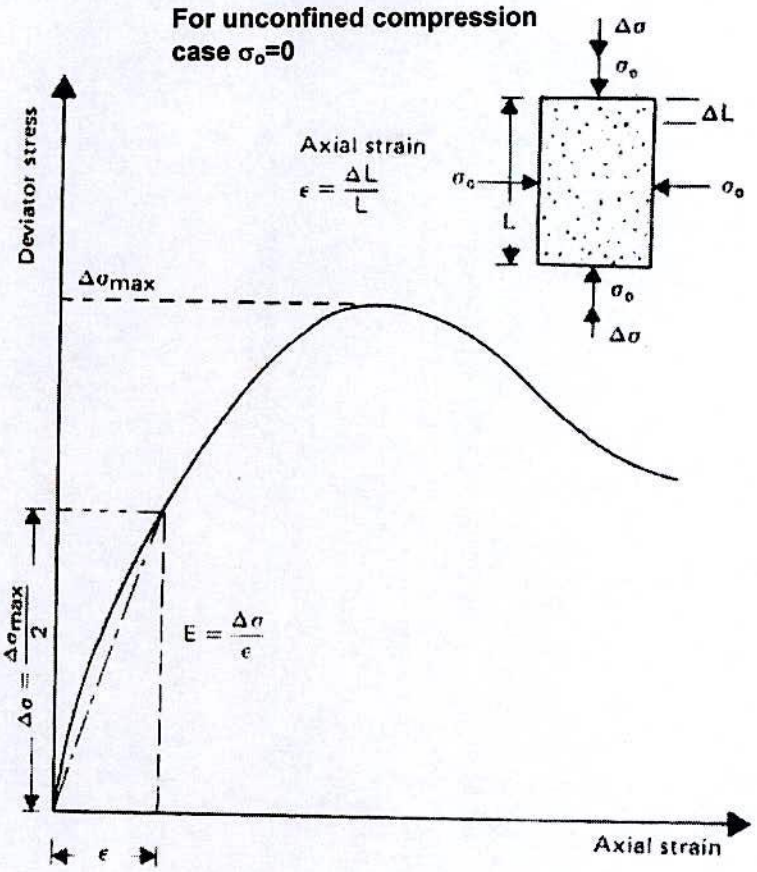


Figure 3.9 Determination of stiffness (Young's modulus) of cement-stabilized soil from unconfined compression test.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 General

This chapter presents the behaviour of cement stabilized soil samples with typical representation of laboratory test results for the change of cement content and rest period. The test results include changes of moisture content, unit weight, stress-strain behaviour, and axial strain at peak and failure strength, unconfined compressive strength and the stiffness. Empirical relationships among the cement content, rest period, unconfined compressive strength and stiffness of the cement-stabilized soil have been established based on the experimental results and hence presented in this chapter. Finally the relationship is examined with the test results.

4.2 Change of Moisture Content within Cement-Stabilized Soil

Laboratory investigation was conducted on the cement stabilized soil for changing the percentage of cement content and rest period i.e. the elapsed time after the preparation of samples. All the samples were prepared at the water content, equal to the liquid limit of the used cohesive soils. Due to cementation effects the mixing initial water content changes with time, however, these changes are also varied with the percentage of cement content. The result about this variation is shown in Table 4.1 and hence discussed in the following articles. Here results are presented for the variation of cement content from 2.5% to 50% and elapsed time after sample preparation i.e. rest period from 6 hours (0.25 days) to 56 days.

Table 4.1 Change of moisture content in cement-stabilized soil with the increase of cement content and rest period

Cement Content c_{sc}(%)	Moisture Content, w_{sc}(%) Rest Period, t_{sc} (days) 0.25	1.00	3.00	7.00	14.00	28.00	56.00
2.50	45.48	44.76	43.64	42.03	40.39	38.64	38.02
5.00	44.12	42.28	41.32	42.24	40.12	39.50	39.80
7.50	43.29	41.06	40.69	40.15	39.80	39.36	37.54
10.00	42.13	40.49	39.48	39.30	38.73	38.21	37.23
12.50	41.65	39.03	38.79	38.63	37.81	37.66	36.98
15.00	40.24	40.30	37.91	36.60	34.01	35.48	32.88
20.00	38.73	35.95	34.01	33.98	33.41	30.27	29.48
25.00	37.25	33.75	34.61	33.72	32.17	29.69	28.85
35.00	33.91	30.58	28.38	27.15	25.99	24.84	24.56
50.00	30.51	29.45	27.50	24.56	23.83	21.88	21.56

4.2.1 Variation of moisture with cement content

The change of moisture content of cement-stabilized soil with the increase of cement content is shown in Figure 4.1 in a presentation of moisture content, w_{sc}(%) versus cement content c_{sc} (%) diagram as measured for various rest period, t_{sc}(%). The figure shows that there is a general trend of the decrease of moisture content with the increase of cement content. As the value of c_{sc} increases, the differences of moisture content for the variation of rest period also increases. From the figure, it can be seen, for the increase of c_{sc} from 2.5% to 50%, the value of w_{sc} reduces from 42.03% to 24.56% at a rest period of 7 days. From this figure, it is also observed at t_{sc}=0.25 days, wsc varies from 45.48% to 30.51% and has a reduction of moisture content as 14.97%, while this reduction is 16.46% i.e. varies from 38.02% to 21.56% for t_{sc}=56 days, for the increase of c_{sc} from 2.5% to 50%. The trend of changing the moisture content is very much consistent with the properties of cement-stabilized soil. As the cement content increases, more water is required for hydration and cementation to form the gel.

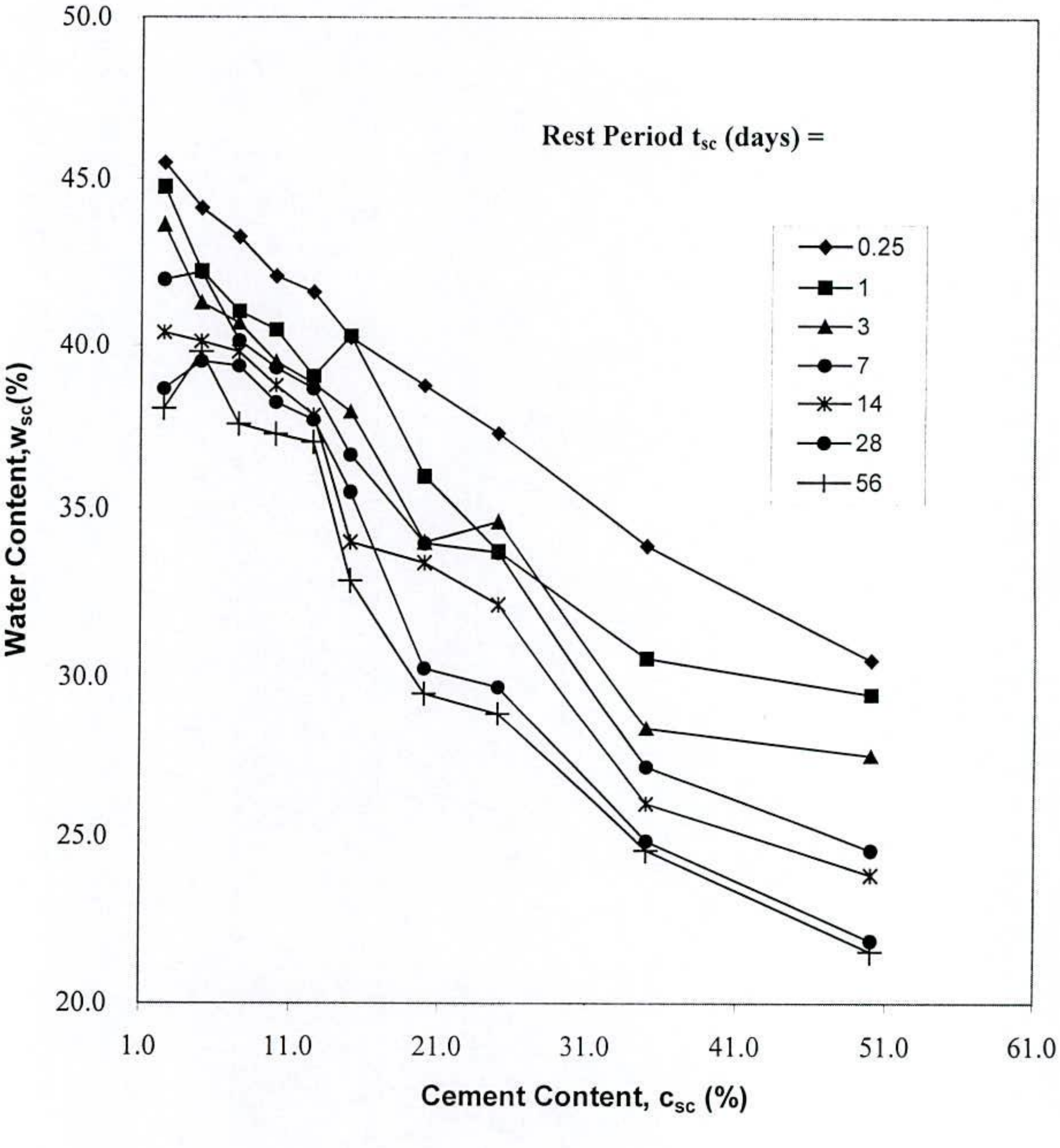


Figure 4.1 Reduction of moisture content in the cement-stabilized soil with the increase of cement content for different rest period.

4.2.2 Variation of moisture content with rest period

The variation of moisture content of the cement-stabilized soil with rest period is presented here in Figure 4.2 and hence discussed. The results are presented for the same ranges of variation of cement content (2.5% to 50%) and rest period (0.25 to 56 days) as described in the last section. From the figure it can be seen that the moisture content decreases as the rest period increase at difference cement content. The trend of changes is similar to those for cement content i.e. reduction of moisture content with t_{sc}, but here it is flatter than those of for the change of c_{sc}. From the figure, it can be seen, for the increase of t_{sc} from 0.25 to 56 days, the value of w_{sc} reduces from 42.13% to 37.23% at a cement content of 10%.

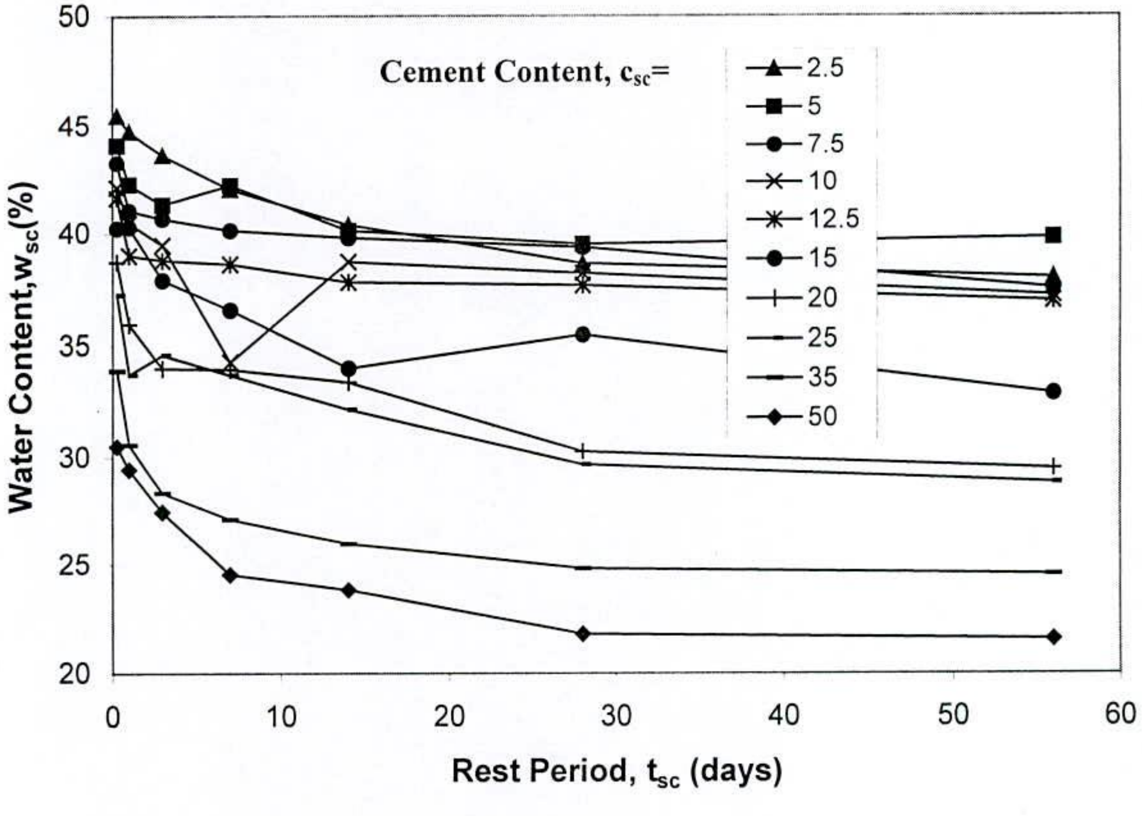


Figure 4.2 Reduction of moisture content in the cement-stabilized soil as the rest period increases for different cement content.

From this figure, it is also observed at c_{sc}=2.50%, w_{sc} varies from 45.48% to 38.02% and has a reduction of moisture content as 7.46%, while this reduction is 1.95% i.e. varies from 30.51% to 28.56% for c_{sc}=50% days, for the increase of t_{sc} from 0.25 to 56 days. The rate of decrease of moisture content with rest period is relatively lower than that of for the increase of cement content. The results reveals that as the rest period increase moisture content reduces at a comparatively steeper rate up to t_{sc}=28 days, after that the reduction in negligible, which is quite logical since most of the hydration within the cement-stabilized soil occur at the early stage of mixing.

4.3 Change of Unit Weight of Cement Stabilized Soils

The unit weight of any materials depends on the arrangements of atomic structure of the element and microstructure of the mass. Due to induced cementation the microstructures of the natural soil resulting to cement-stabilized soil are changed significantly. As a result the unit weight of the natural soil changes due to induced cementation. Again, the unit weight of a stabilized soil depends on the type and amount of the cementing agent and the period elapsed after mixing. The change of unit weight of cement-stabilized soil, γ_{sc} (gm/cm^3), as evaluated from this laboratory investigation by changing the cement content from 2.5% to 50% and the rest period from 0.25 to 56 days are presented in Table 4.2. The changes of unit weight with respect to cement content and the rest period are presented and hence discussed in the following sections.

Table 4.2 Change of unit weight in cement-stabilized soil with the increase of cement content and rest period

Unit Weight of Cement-stabilized Soil, γ_{sc}(gm/cm^3)							
Cement Content	**Rest Period, t_{sc} (days)**						
c_{sc}(%)	**0.25**	**1.00**	**3.00**	**7.00**	**14.00**	**28.00**	**56.00**
2.50	1.68	1.70	1.72	1.74	1.75	1.73	1.72
5.00	1.70	1.72	1.72	1.74	1.74	1.72	1.71
7.50	1.70	1.70	1.72	1.74	1.74	1.73	1.69
10.00	1.69	1.68	1.72	1.73	1.74	1.68	1.68
12.50	1.71	1.68	1.67	1.68	1.72	1.69	1.69
15.00	1.70	1.70	1.71	1.72	1.75	1.73	1.70
20.00	1.73	1.73	1.74	1.72	1.74	1.72	1.70
25.00	1.74	1.74	1.74	1.74	1.76	1.72	1.72
35.00	1.81	1.78	1.78	1.77	1.77	1.75	1.74
50.00	1.82	1.80	1.81	1.79	1.79	1.78	1.76

4.3.1 Variation of unit weight with cement content

The change of unit weight of cement-stabilized soil with the increase of cement content is shown in Figure 4.3 in a presentation of unit weight, γ_{sc}, versus cement content, c_{sc}, diagram as measured at rest period, t_{sc}. The figure shows that with some random variation at the lower amount of cement content, the unit weight slight decreases from its initial stage up to level of c_{sc}=12.50%, beyond this level on cement content, γ_{sc} increases almost linearly with c_{sc}. From the figure, it can be seen, for the increase of c_{sc} from 2.50% to 12.50%, the value of γ_{sc} reduces from 1.74 to 1.68 gm/cm^3 at a rest period of 7 days. But for the same rest period, for the increase of c_{sc} from 12.50% to 50%, the value of γ_{sc} increase from 1.68 to 1.79 gm/cm^3. From this figure, it is also observed at t_{sc}=0.25 days, γ_{sc} varies from 1.68 to 1.82 gm/cm^3 and has a overall increase of unit weight as 0.14gm/cm^3, while this reduction is 0.04% i.e. varies from 1.72 to 1.76gm/cm^3 for t_{sc}=56 days, for the increase of c_{sc} from 2.50% to 50%. The trend of changing the unit weight is very much consistent with the properties of cement-stabilized soil as expected to change with the increase of cement content. If the cement content goes up beyond a certain level, 12.50% in this instant, more close, connected and strongly bonded microstructures can be formed, as a result, the value of unit weight increases.

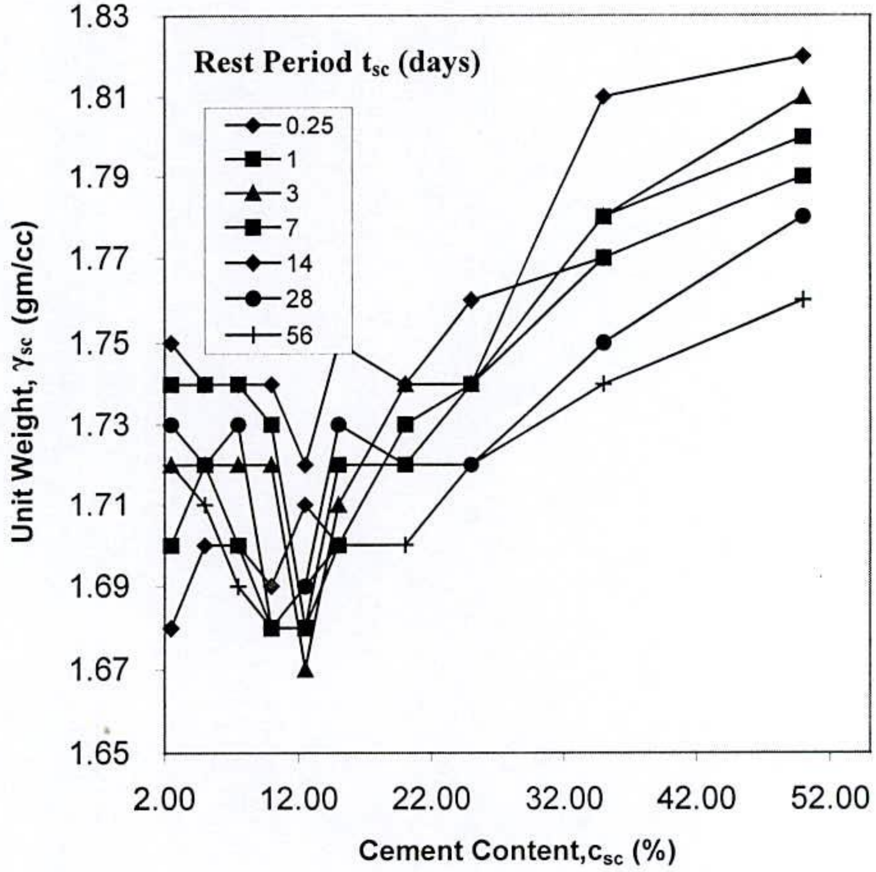


Figure 4.3 Changes of unit weight of cement-stabilized soil with the increase of cement content for different rest period.

4.3.2 Variation of unit weight with rest period

Unit weight of cement-stabilized soil changes with the increase of rest period for various cement content as obtained from the series laboratory experiments is shown in Figure 4.4 in a presentation of unit weight, γ_{sc}, versus rest period, t_{sc} diagram as obtained for different cement content, c_{sc}. The figure shows that as a general response, the unit weight of cement-stabilized soil increases from its initial stage till the rest period of t_{sc}=14days, beyond this period, γ_{sc} decreases almost linearly with c_{sc}. However, it is observed that for the higher value of cement content i.e. c_{sc}=35% and 50%, the value of γ_{sc} reduces with the increase of rest period. From the figure, it can be seen, for the increase of rest period, t_{sc} from 0.25 to 7.0 days, the value of γ_{sc} reduces from 1.71 to 1.68 gm/cm^3 at a cement content of 12.5%. But for the same cement content, for the increase of t_{sc} from 7 to 56 days, the value of γ_{sc} increase from 1.68 to 1.72 gm/cm^3. From this figure, it is also observed at c_{sc}=2.5%, γ_{sc} varies from 1.68 to 1.72 gm/cm^3 and has a overall increase of unit weight as 0.04gm/cm^3, while this reduction is 0.06% i.e. varies from 1.82 to 1.76gm/cm^3 for c_{sc}=50%, for the increase of t_{sc} from 0.25 to 56 days. The general decreasing trend of unit weight with t_{sc} is very much consistent with the properties of cement-stabilized soil as expected as the changing of microstructure with elapsed time after mixing. As the time increases, hydration occurs and due to the formation of gels, pore spaces increases in between the tightly connected grains, resulting the decreasing of unit weight.

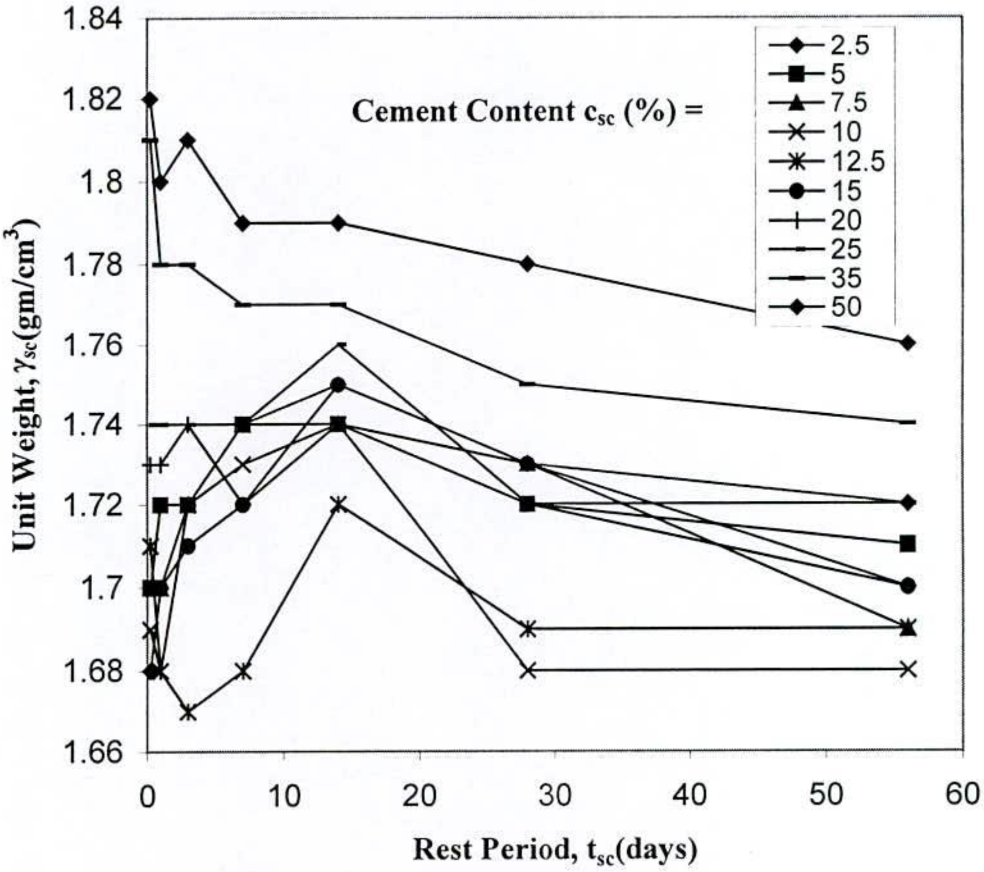
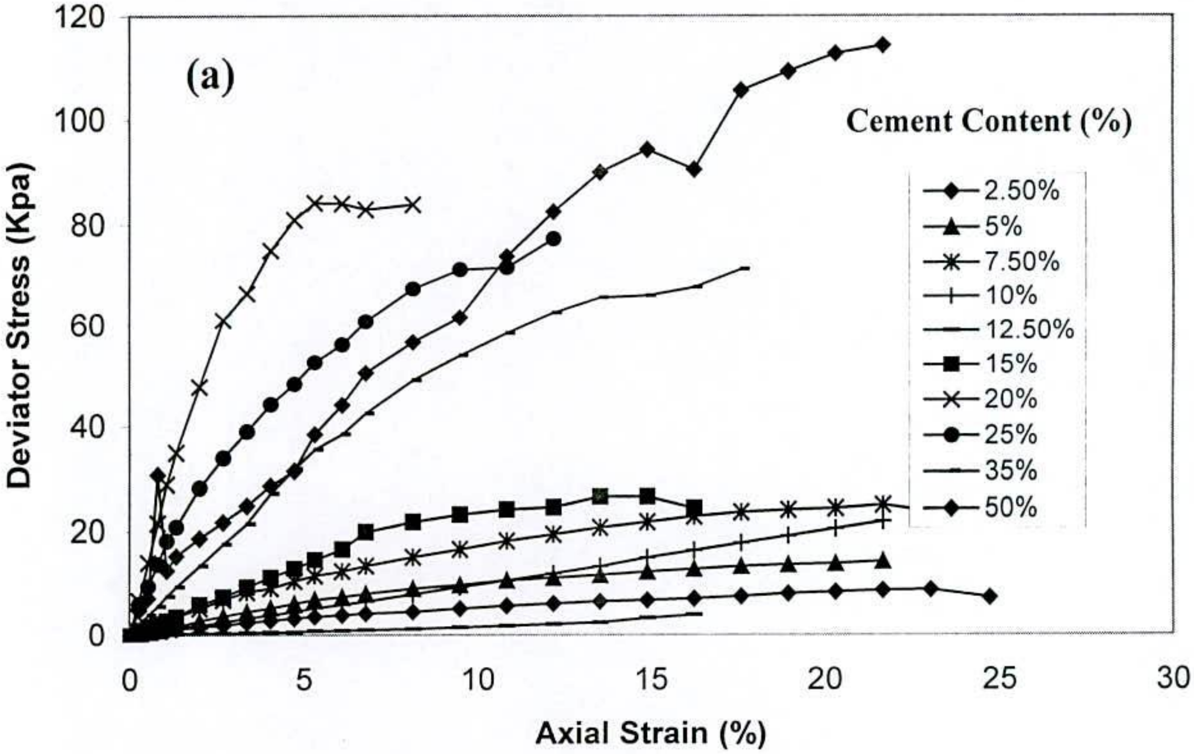
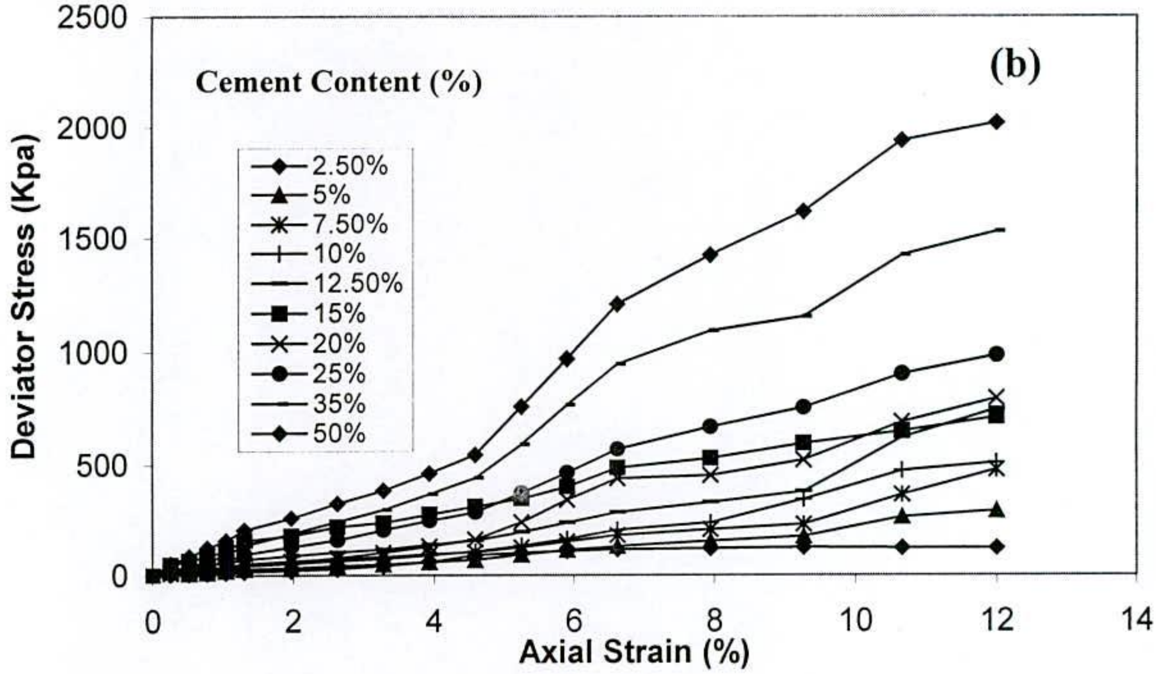


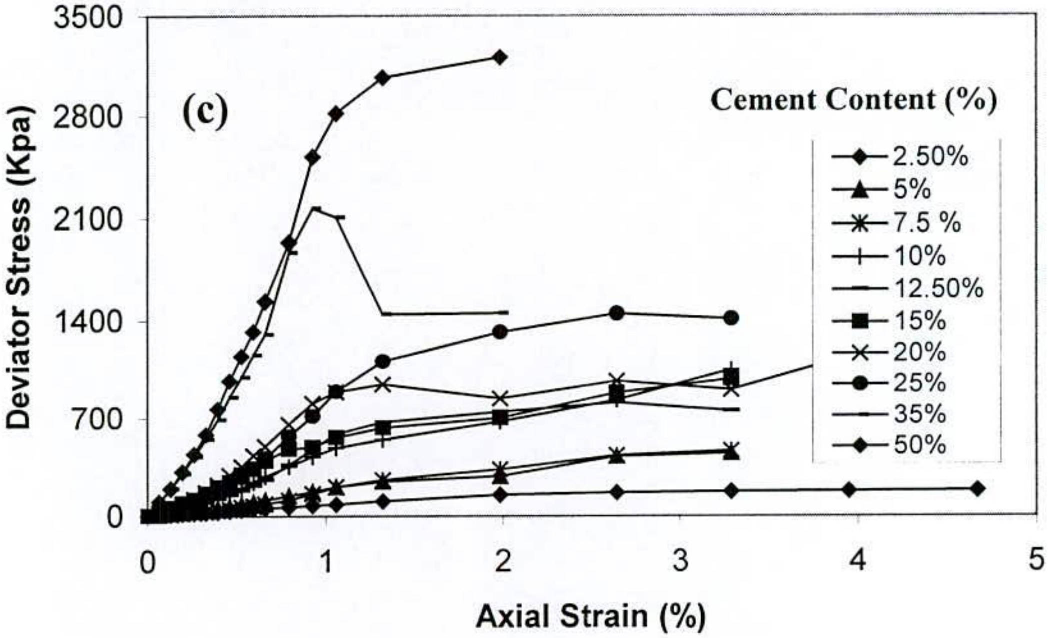
Figure 4.4 Changes of unit weight of cement-stabilized soil with the increase of rest period for different cement content

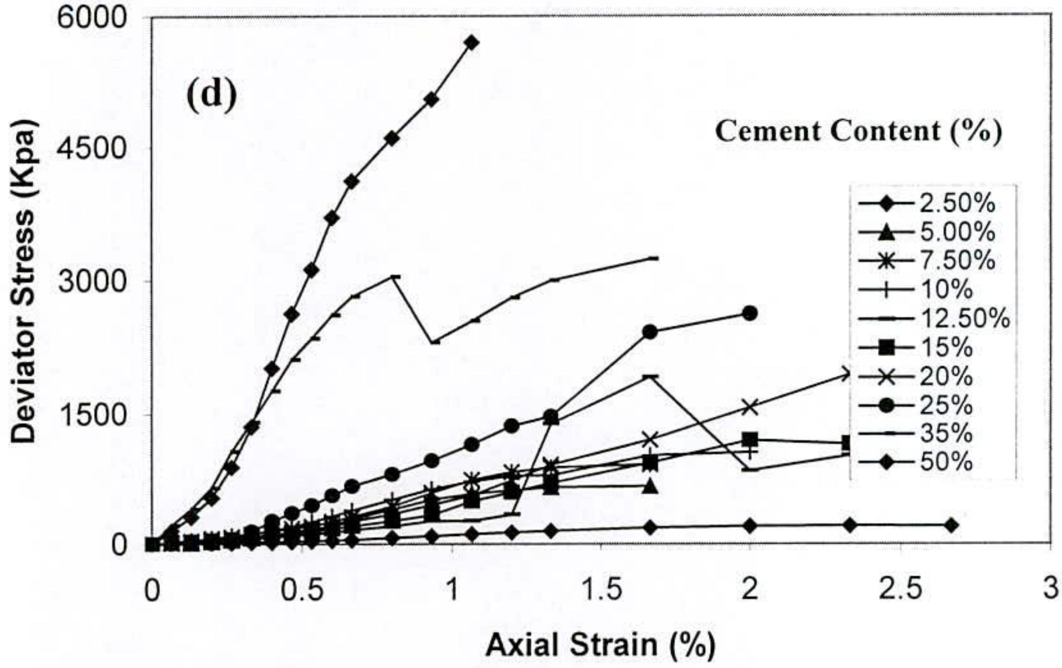
4.4 Typical Representation of Stress-Strain Behaviour of Cement-Stabilized Soil

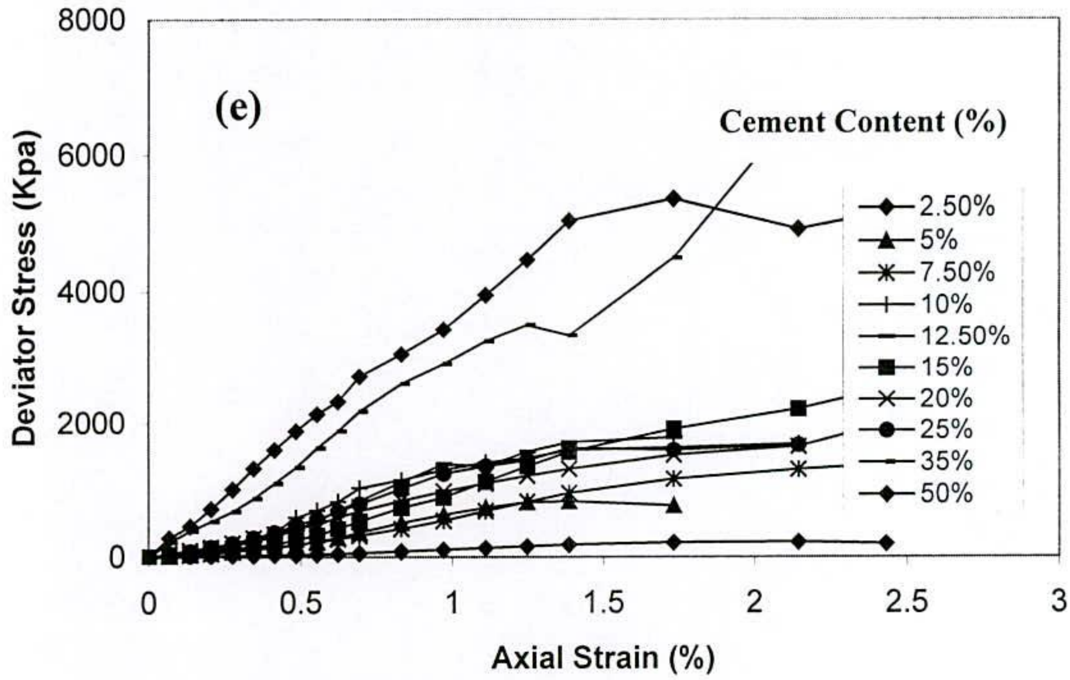
Stress-strain behaviour of cement-stabilized soil samples have been established by conducting unconfined compression test on the soil-cement specimen prepared at the cement content, c_{sc}, from 2.5 to 50% at the rest period, t_{sc}, of 0.25 to 56 days. The tests were performed on the specimen representing 70 conditions. All the evaluated stress-strain behaviour of cement-stabilized soils is then presented in the form of deviator stress ($\Delta\sigma$) versus axial strain (ε_a) diagram. Out of these 70 stress-strain diagrams, 6 typical stress strain diagram as presented in Figure 4.5 (a), (b), (c) & (d) for c_{sc}=2.5%, 10%, 25% and 50% for the variation of t_{sc} from 0.25 to 56 days and also in Figure 4.6 (a), (b), (c) and (d) for t_{sc}=0.25, 3, 14 and 56 days for the variation of c_{sc} from 2.5 to 50%. From the figures it can be seen that the stress is increasing with strain showing almost similar behavior of very soft to medium clay for the lower cement content and at earlier rest period and stiff to hard soil or rock behaviour at higher cement content and later rest period. The figures depict that in all the cases soil-cement samples show nonlinear stress-strain behaviour during shearing in unconfined compression tests. As a general trend of stress-strain behaviour of the cement-stabilized soil, it can also be seen from all the figures that as the cement content increases, the stress-strain curve stays above than the relatively lower cement content, similarly, as the rest period increases, the stress-strain curve stays above than the relatively lower rest period.

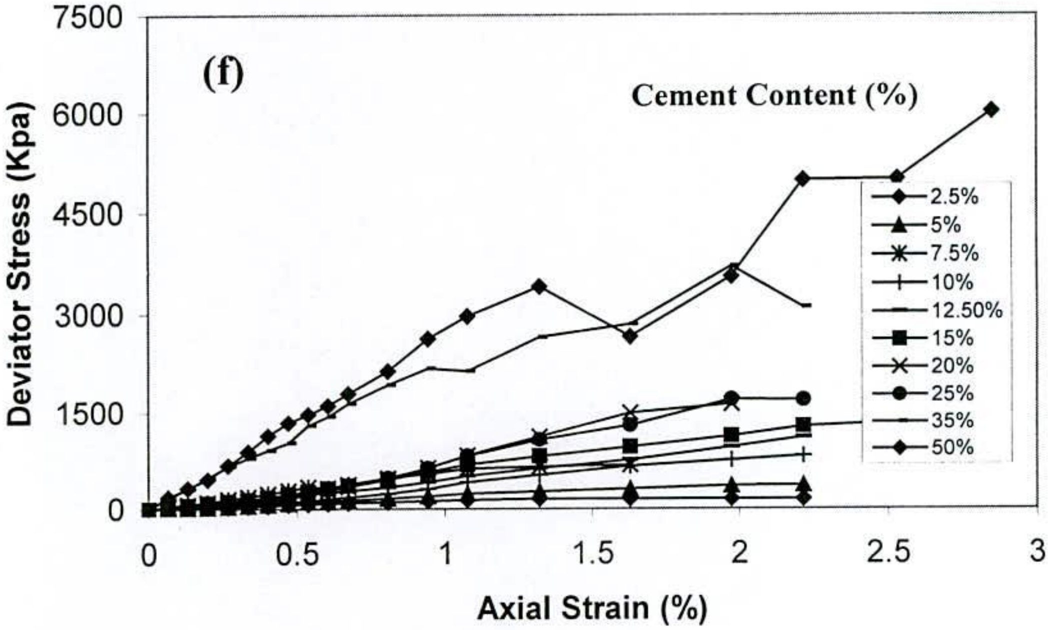



(b)
Cement Content (%)
2.50%
5%
7.50%
10%
12.50%
15%
20%
25%
35%
50%
Deviator Stress (Kpa)
Axial Strain (%)


(c)
Cement Content (%)
2.50%
5%
7.5 %
10%
12.50%
15%
20%
25%
35%
50%
Deviator Stress (Kpa)
Axial Strain (%)


(d)
Cement Content (%)
Deviator Stress (Kpa)
Axial Strain (%)
6000
4500
3000
1500
0
0
0.5
1
1.5
2
2.5
3
2.50%
5.00%
7.50%
10%
12.50%
15%
20%
25%
35%
50%


(e)
Cement Content (%)
Deviator Stress (Kpa)
Axial Strain (%)
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
3
2.50%
5%
7.50%
10%
12.50%
15%
20%
25%
35%
50%



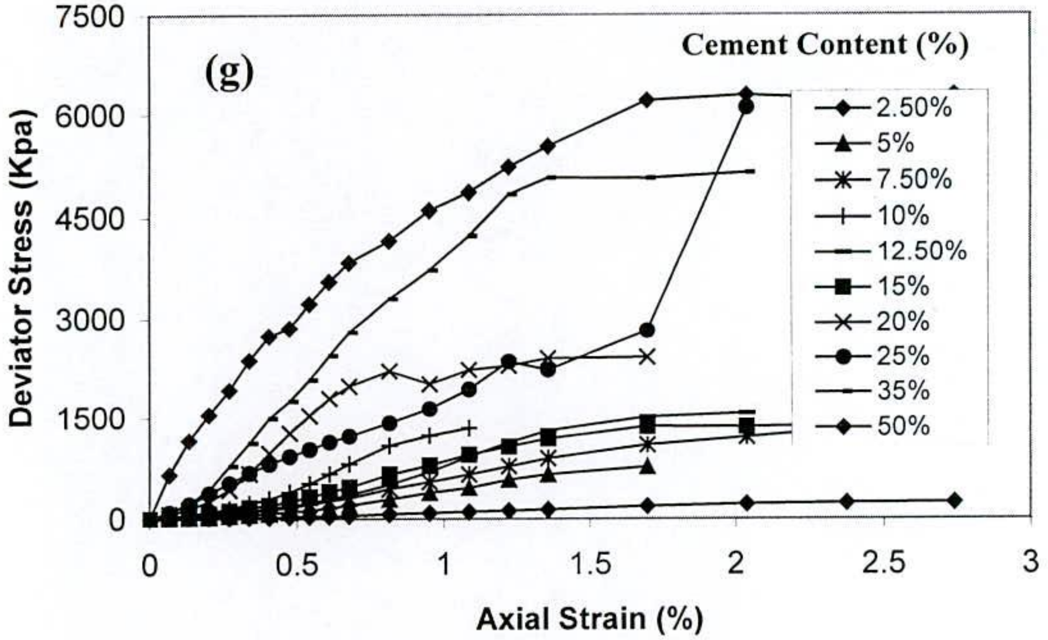
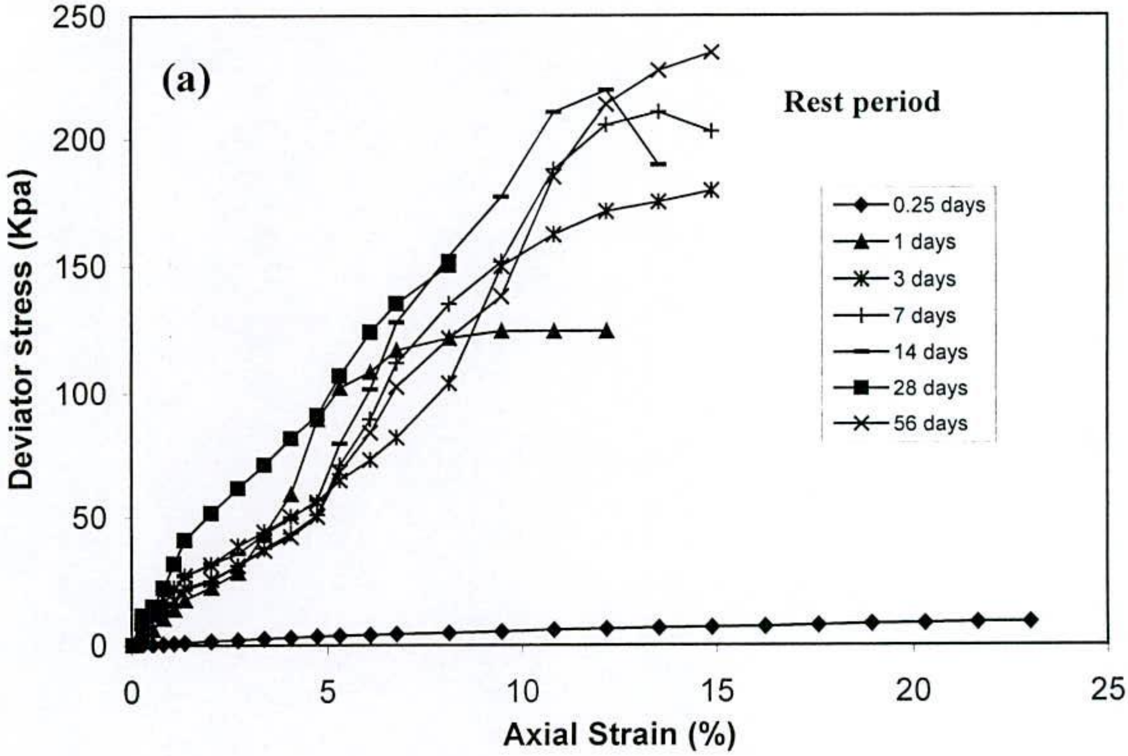
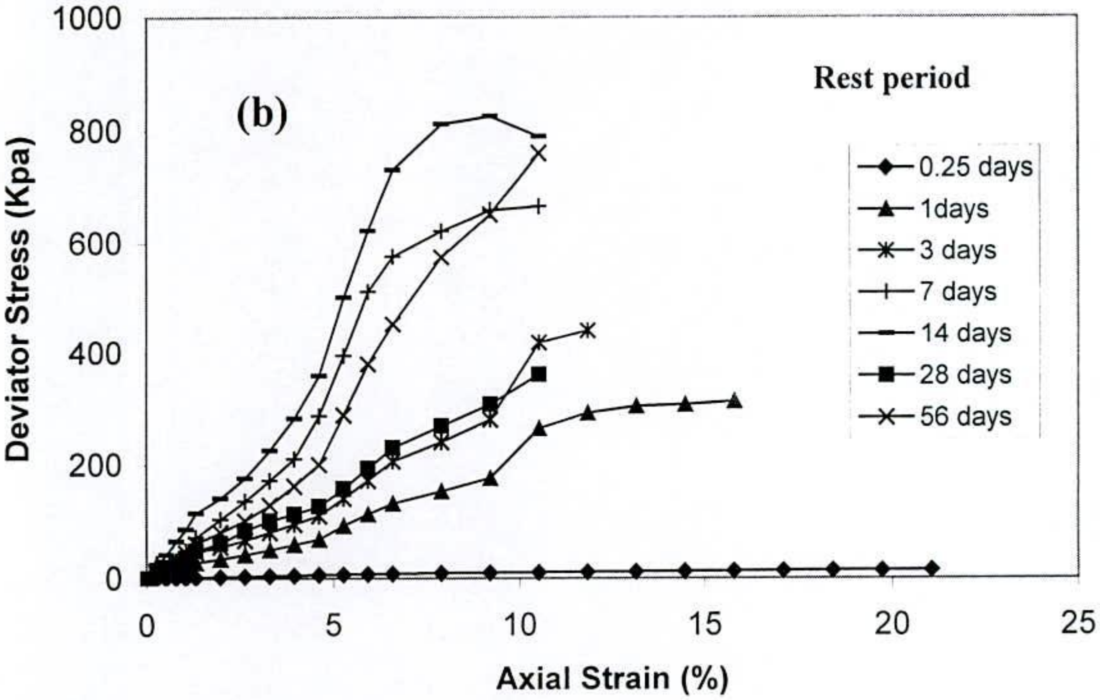
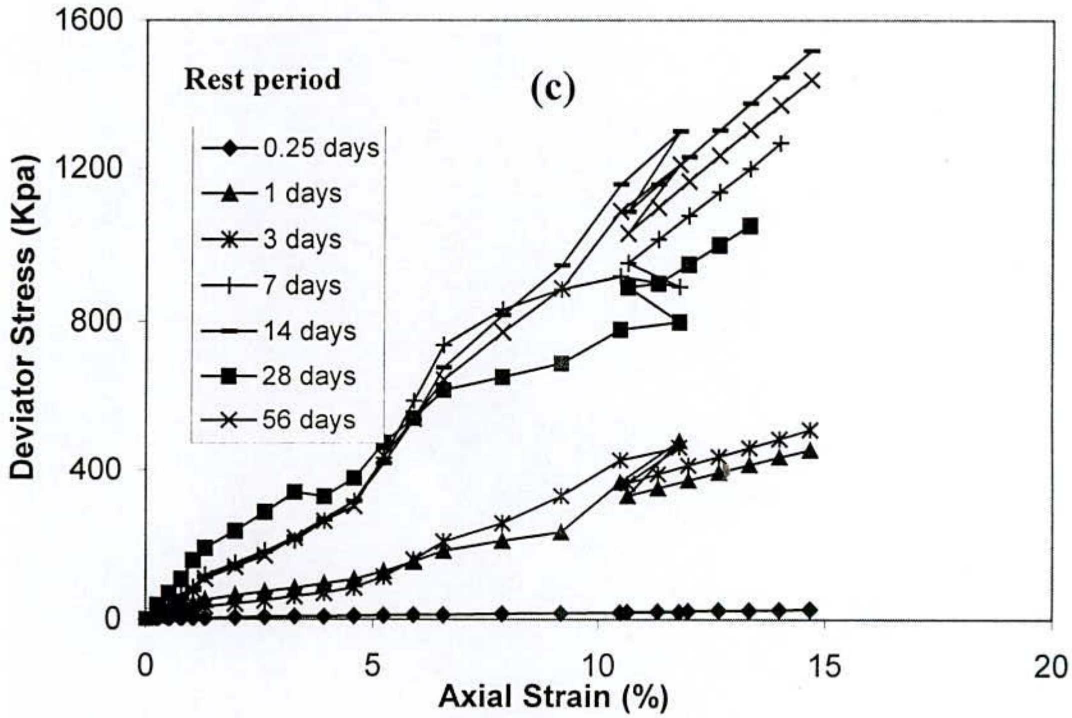
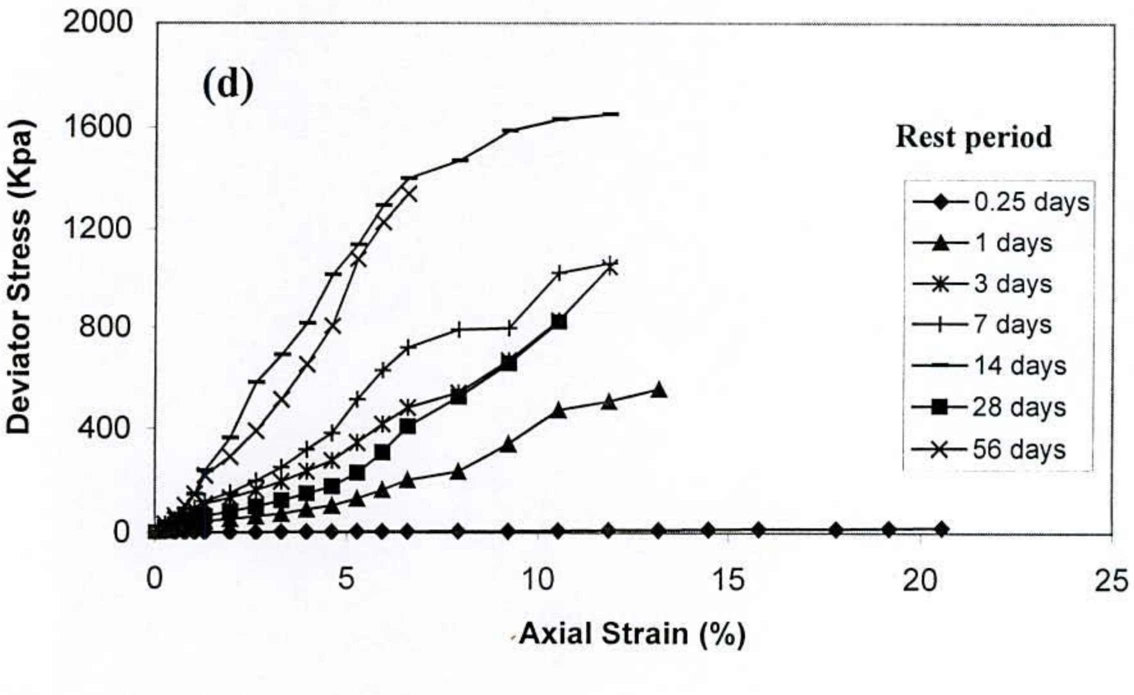


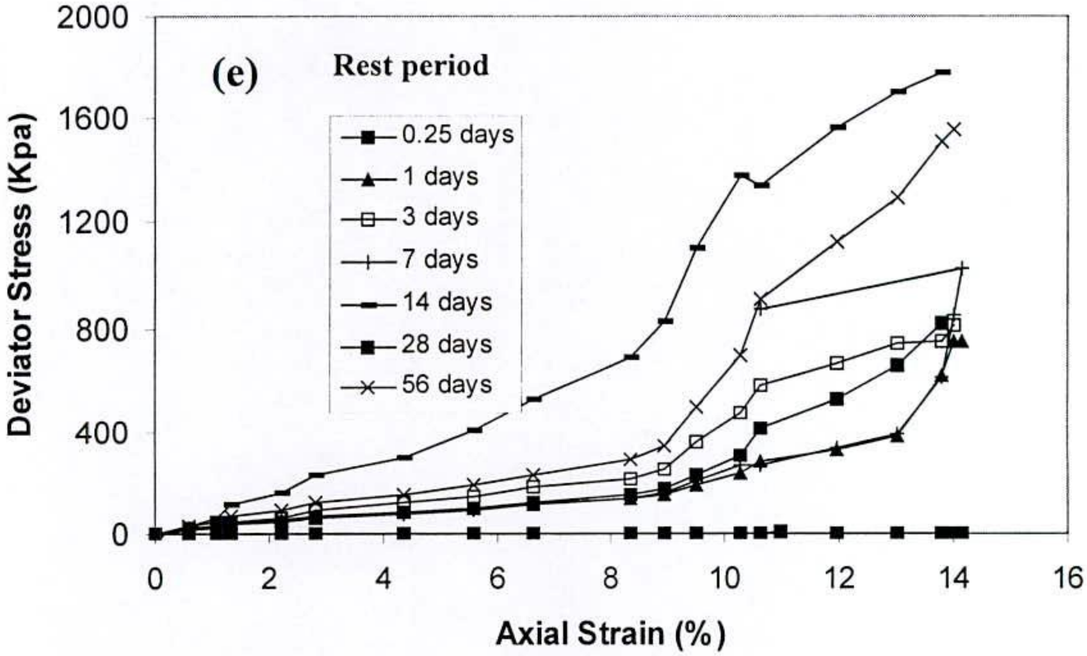
Figure 4.5 Stress-strain behaviour of cement-stabilized soil for the rest periods of (a) 0.25, (b) 1.0, (c) 3.0, (d) 7.0, (e) 14, (f) 28 and (g) 56days for the variation of cement content from 2.5% - 50%.

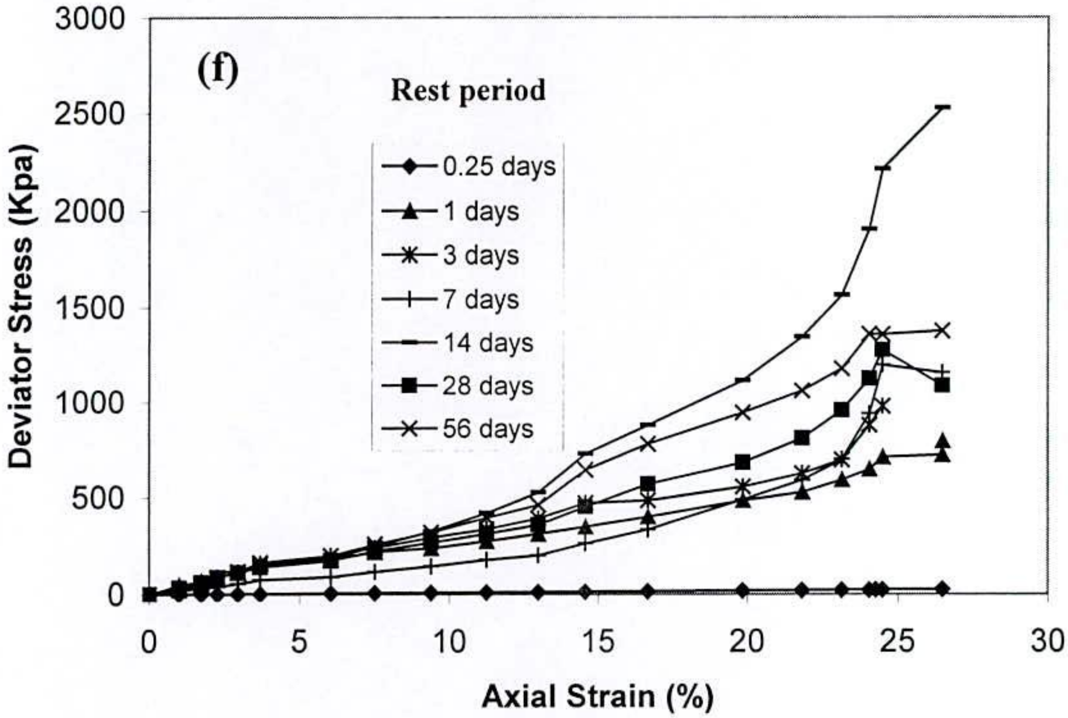

(a)
Rest period
0.25 days
1 days
3 days
7 days
14 days
28 days
56 days
Deviator stress (Kpa)
Axial Strain (%)
0
50
100
150
200
250
0
5
10
15
20
25

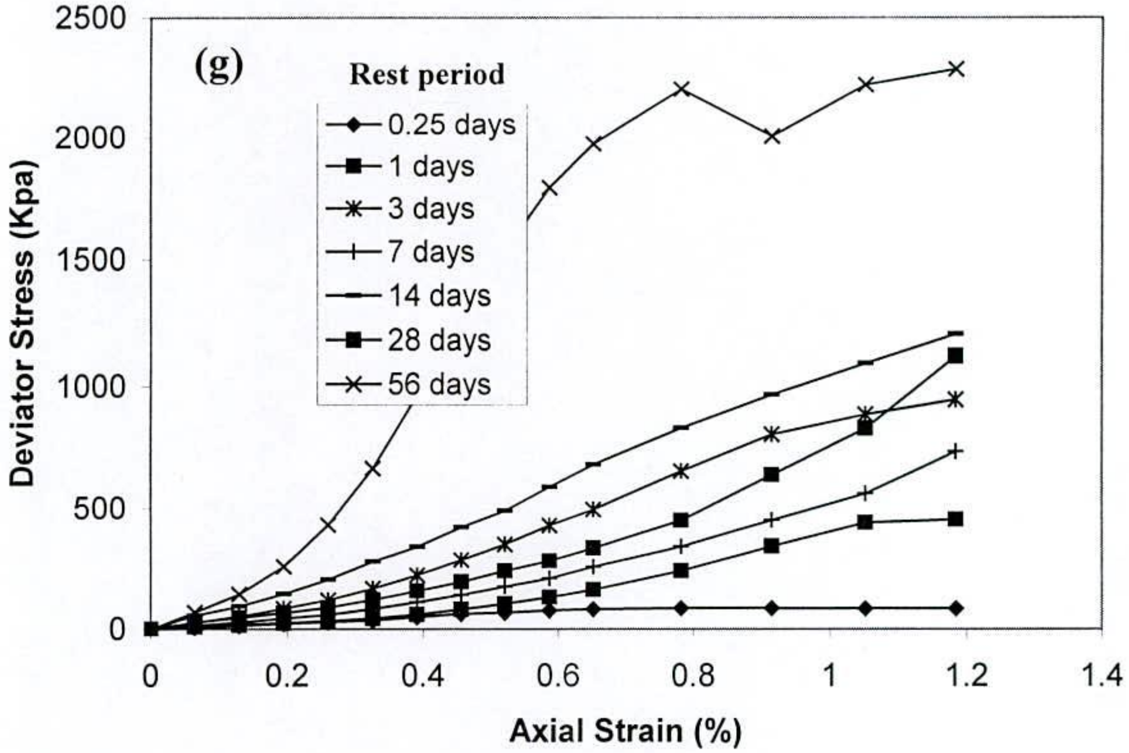

(b)
Rest period
0.25 days
1days
3 days
7 days
14 days
28 days
56 days
Deviator Stress (Kpa)
Axial Strain (%)
0
200
400
600
800
1000
0
5
10
15
20
25


1600
1200
800
400
0
Deviator Stress (Kpa)
Rest period
(c)
0.25 days
1 days
3 days
7 days
14 days
28 days
56 days
0
5
10
15
20
Axial Strain (%)

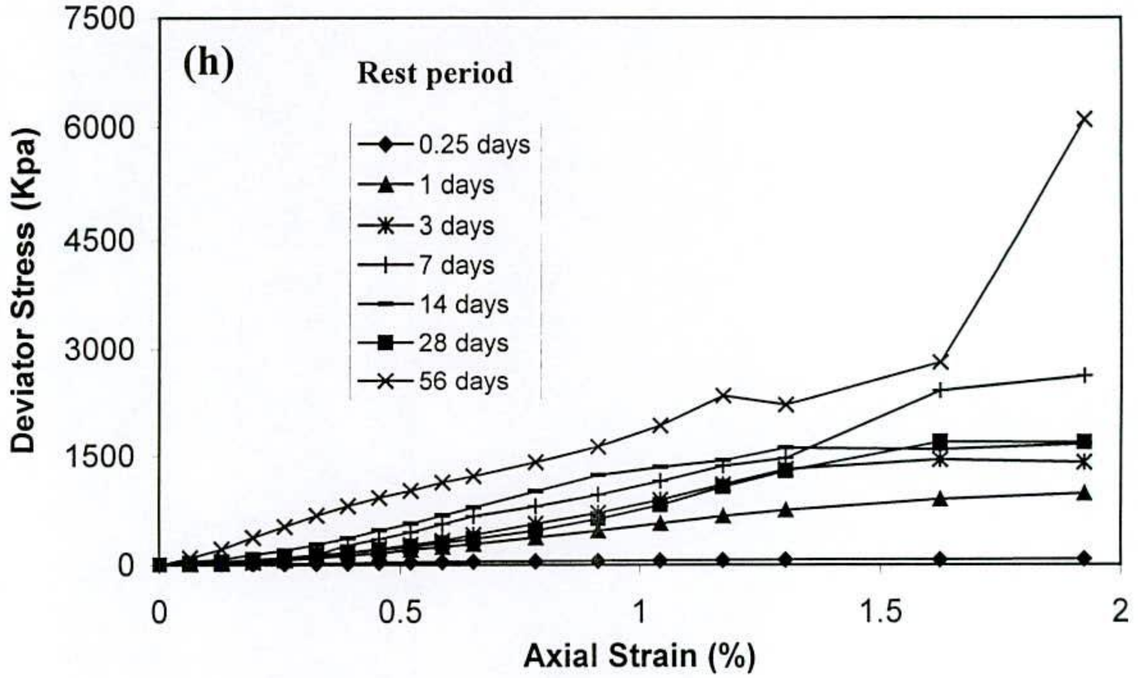

2000
1600
1200
800
400
0
Deviator Stress (Kpa)
(d)
Rest period
0.25 days
1 days
3 days
7 days
14 days
28 days
56 days
0
5
10
15
20
25
Axial Strain (%)


(e)
Rest period
0.25 days
1 days
3 days
7 days
14 days
28 days
56 days
Deviator Stress (Kpa)
Axial Strain (%)

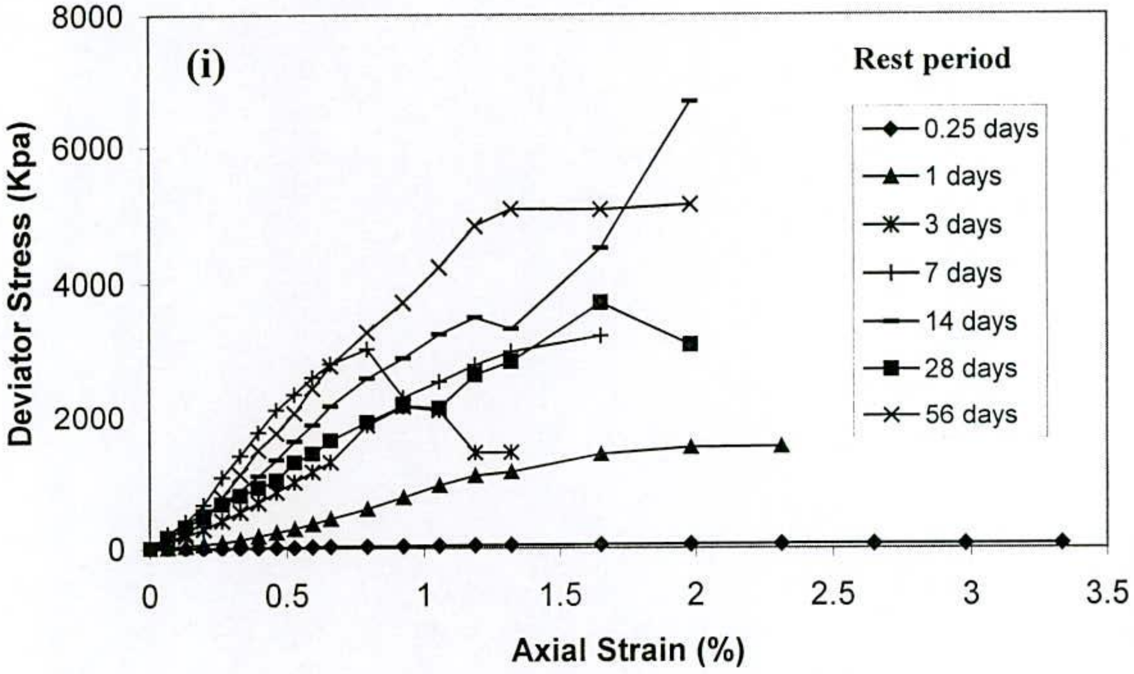

(f)
Rest period
0.25 days
1 days
3 days
7 days
14 days
28 days
56 days
Deviator Stress (Kpa)
Axial Strain (%)



(g)
Rest period
0.25 days
1 days
3 days
7 days
14 days
28 days
56 days
Deviator Stress (Kpa)
Axial Strain (%)
2500
2000
1500
1000
500
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4



(h)
Rest period
0.25 days
1 days
3 days
7 days
14 days
28 days
56 days
Deviator Stress (Kpa)
Axial Strain (%)
7500
6000
4500
3000
1500
0
0
0.5
1
1.5
2



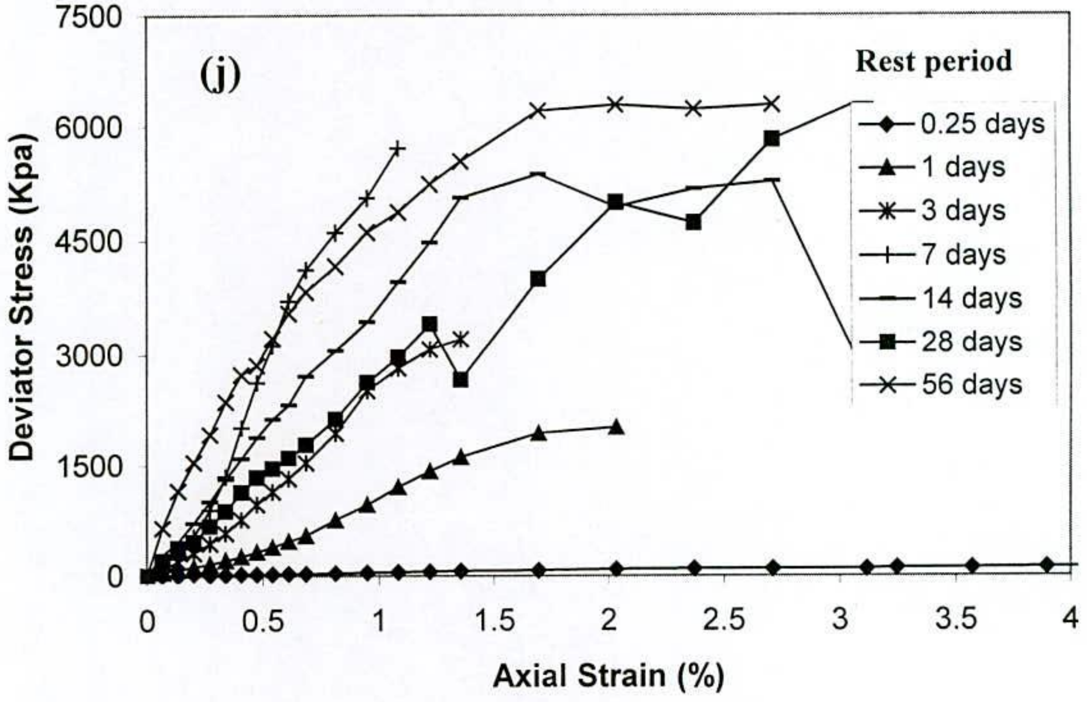


Figure 4.6 Stress-strain behaviour of cement-stabilized soil for the Cement contents of (a) 2.5, (b) 5.0, (c) 7.5 (d) 10, (e) 12.5, (f) 15, (g) 20, (h) 25, (i) 35, and (j) 50% for the variation of rest period from 0.25 to 56 days.

4.5 Change of Axial Strain at failure

The stress-strain behaviour of natural soil has changed due to its stabilization be cement admixture. This behaviour again also changes with the amount of cement content, rest period and other associated factors. As the stress-strain behaviour changes due to induced cementation, the magnitude failure strain also will be changed. For the addition of cement admixture and the elapsed of rest period, the microstructure has changed, which resulting the changes of magnitudes of strain at the failure strength of cement-stabilized soil. The change of failure strain of cement-stabilized soil, ε_{sc}(%), as evaluated from this laboratory investigation by changing the cement content from 2.5% to 50% and the rest period from 0.25 to 56days are presented in Table 4.3. The changes of failure strain with respect to cement content and the rest period are presented and hence discussed in the following sections.

Table 4.3 Change of axial strain at failure in the cement-stabilized soil with the increase of cement content and rest period

Axial Strain at Failure Strength, ε_{sc}(%)										
Rest Period, t_{sc} (days)	**Cement content c_{sc}(%)**									
	2.5	**5**	**7.5**	**10**	**12.5**	**15**	**20**	**25**	**35**	**50**
0.25	23.92	21.06	20.97	17.63	16.08	3.21	0.96	1.63	2.87	3.38
1	8.99	3.53	2.39	2.42	2.17	2.32	2.55	2.5	2.07	1.66
3	3.74	2.68	2.2	2.21	1.65	1.71	1.94	1.75	1.1	1.32
7	1.32	1.54	1.21	1.97	1.85	2.05	1.63	1.9	1.86	2.02
14	2.56	1.52	1.52	1.44	2.41	1.99	2.27	1.72	1.37	1.03
28	2.5	1.5	2.75	1.04	1.88	1.94	1.05	1.59	1.63	1.71
56	2.09	1.4	3.17	1.68	1.41	2.11	2.15	1.27	1.58	2.5

4.5.1 Change of axial strain with cement content

Figure 4.7 shows the changes of failure of cement-stabilized soil with the increase of cement content presented in a failure strain, ε_{sc}, versus cement content, c_{sc}, diagram as measured as rest period, t_{sc}, increases. The figure shows that with some random variation, not noticeable in true sense, as a general trend, the failure strain decreases with increase of cement content and the variation of failure strain with the increase of cement content is insignificant. However, for a rest period, t_{sc}=0.25 days i.e. just immediately after the formation of cement-stabilized soil, the failure strain dropped sharply at the increase of c_{sc}. In this case, the value of ε_{sc} has reduced from 23.92% to 16.08% for the changes of c_{sc} from 2.5% to 12.5% and from 16.08 % to 3.38% for the changes of c_{sc} from 12.5% to 50%. From the figure, it can be seen, for the increase of c_{sc} from 2.50% to 50%, the value of ε_{sc} reduces from 2.56 to 1.03% at a rest period of 14 days. From this figure, it is also observed that for the variation of c_{sc}=2.5% to 50%, ε_{sc} varies from 3.74 to 1.03% for any increase of rest period from t_{sc}=3 to 56 days. The result depicts the failure strain almost in typical small range after 3 days for any changes of cement content, which reflects the genuinely the behaviour of cement-stabilized soil.

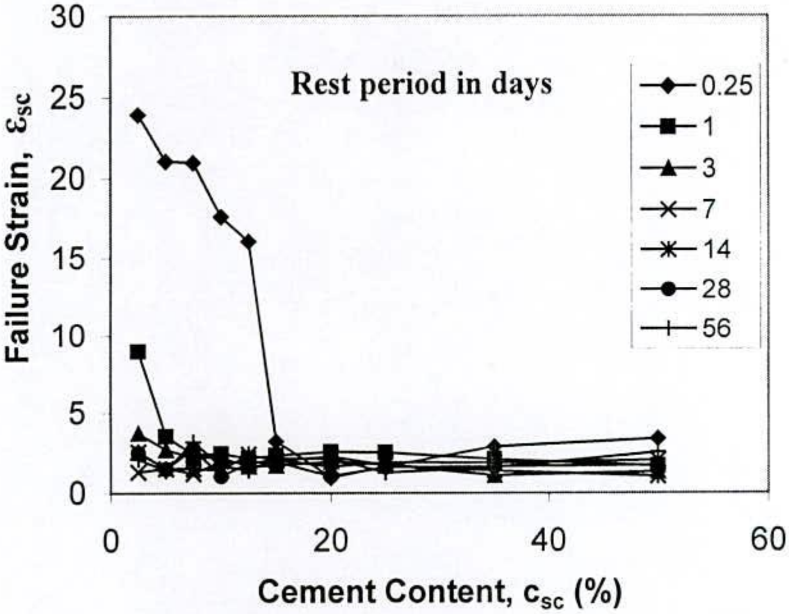


Figure 4.7 Changes of failure strain of cement-stabilized soil with the increase of cement content for different rest period.

4.5.1 Change of axial strain with cement content

Figure 4.7 shows the changes of failure of cement-stabilized soil with the increase of cement content presented in a failure strain, ε_{sc}, versus cement content, c_{sc}, diagram as measured as rest period, t_{sc}, increases. The figure shows that with some random variation, not noticeable in true sense, as a general trend, the failure strain decreases with increase of cement content and the variation of failure strain with the increase of cement content is insignificant. However, for a rest period, t_{sc}=0.25 days i.e. just immediately after the formation of cement-stabilized soil, the failure strain dropped sharply at the increase of c_{sc}. In this case, the value of ε_{sc} has reduced from 23.92% to 16.08% for the changes of c_{sc} from 2.5% to 12.5% and from 16.08 % to 3.38% for the changes of c_{sc} from 12.5% to 50%. From the figure, it can be seen, for the increase of c_{sc} from 2.50% to 50%, the value of ε_{sc} reduces from 2.56 to 1.03% at a rest period of 14 days. From this figure, it is also observed that for the variation of c_{sc}=2.5% to 50%, ε_{sc} varies from 3.74 to 1.03% for any increase of rest period from t_{sc}=3 to 56 days. The result depicts the failure strain almost in typical small range after 3 days for any changes of cement content, which reflects the genuinely the behaviour of cement-stabilized soil.

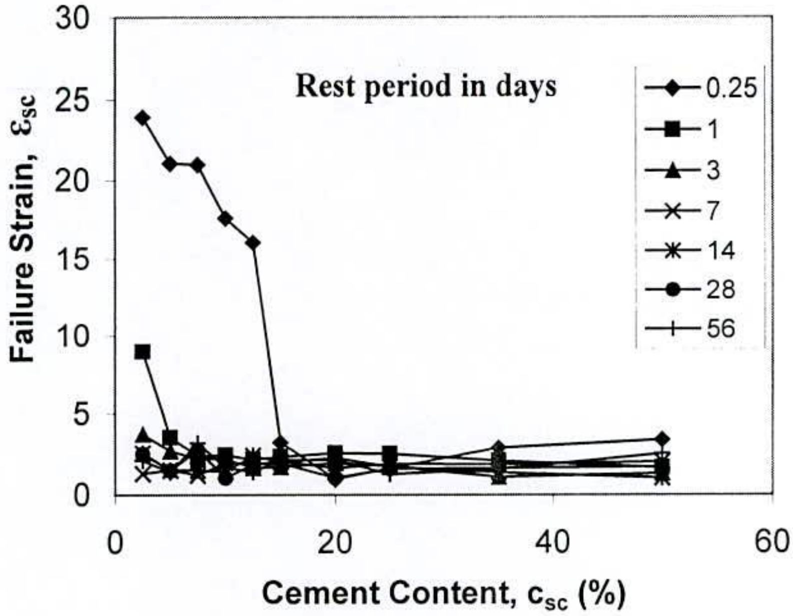


Figure 4.7 Changes of failure strain of cement-stabilized soil with the increase of cement content for different rest period.

4.5.2 Change of axial strain with rest period

Figure 4.8 shows the changes of failure of cement-stabilized soil with the increase of rest period presented in a failure strain, ε_{sc}, versus rest period, t_{sc}, diagram as measured as different cement content, c_{sc}. The figure shows that with some random variation, not noticeable in true sense, as a general trend, the failure strain decreases sharply with increase of rest period from 0.25 to 3 days despite the percent of cement content and the variation failure strain with the increase of rest period is insignificant and can be treated as unchanged. Although small changes are observed here, which may occur due the difference of simple preparation, which was done manually in the laboratory. However, for a rest period, c_{sc}=2.5%, the failure strain dropped sharply at the increase of rest period. In this case, the value of ε_{sc} has dropped sharply from 23.93% to 3.74% for the changes of t_{sc} from 0.25 to 3 days and from 3.74% to 2.09% for the changes of t_{sc} from 3 to 56 days. From the figure, it can be seen, for the increase of t_{sc} from 3 to 56 days, the value of ε_{sc} reduces from 3.74 to 1.03% for the variation of c_{sc}=2.5% to 50%.

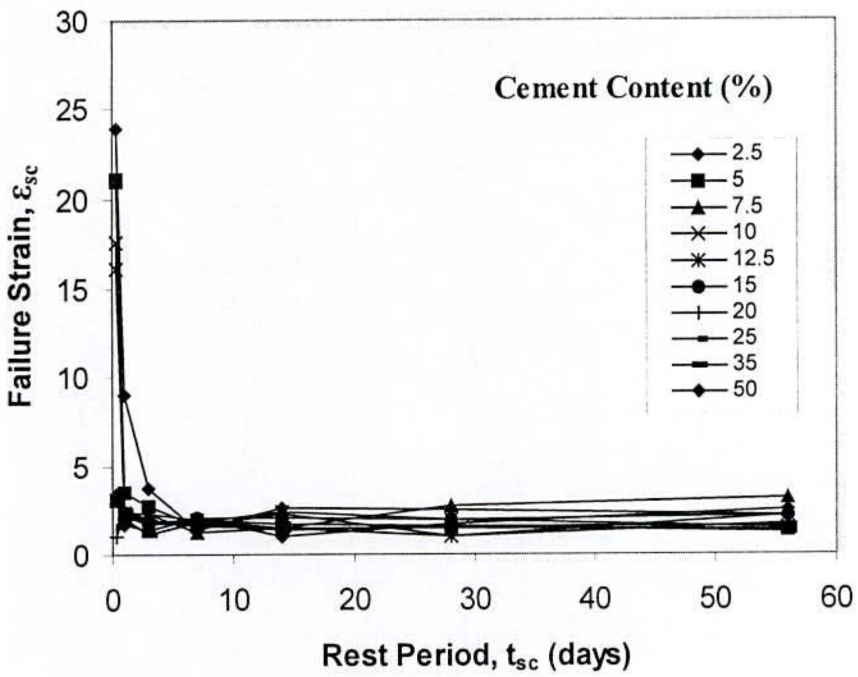


Figure 4.8 Changes of failure strain of cement-stabilized soil with the increase of rest period for different cement content.

4.6 Strength Development in Cement-Stabilized Soil

Cement stabilization reduces the size of double layer and thereby increasing the attraction between the clay particles which leading to a flocculated structure. Furthermore, the silica and alumina in the clay mineral react with the calcium silicates and calcium aluminate hydrates to form a cementing gel. All these reactions changes the mechanical behaviour of soil-cement sample which have been reflected genuinely in the test results as presented in Table 4.4 showing the development of compressive strength, q_{sc}, in the cement-stabilized soils for the changes of cement content and rest period. The compressive strength of cement-stabilized soil as measured in the unconfined compression test equipment on a specimen similar size of soil specimen, for the variation of cement content from c_{sc}=2.5% to 50% and elapsed rest period of t_{sc}=0.25 to 56 days. The change of compressive strength obtained for the increase of cement content and rest period is discussed in the following sections.

Table 4.4 Change of compressive strength in the cement-stabilized soil with the increase of cement content and rest period

Compressive Strength of Cement-stabilized Soil, q_{sc} (kPa)										
Rest Period, t_{sc} (days)	Cement content c_{sc}(%)									
	2.5	5.0	7.5	10.0	12.5	15.0	20.0	25.0	35.0	50.0
0.25	8.43	13.90	24.31	24.45	24.48	24.58	87.10	74.01	68.72	101.23
1	124.00	304.16	415.40	550.48	773.08	747.05	874.56	1042.14	1534.27	1878.30
3	174.00	440.76	445.51	830.45	855.80	981.01	1295.94	1459.88	2213.51	3209.68
7	150.28	338.99	619.65	823.75	1181.82	1302.79	1630.69	1817.60	3733.71	6229.71
14	210.63	653.64	911.16	922.17	1057.65	1229.15	1881.70	2424.38	3815.06	5285.62
28	234.98	767.31	1402.38	1178.83	1522.72	1509.02	2469.77	3240.28	5558.19	5428.11
56	225.70	843.83	1535.39	1696.34	1853.27	2314.97	1703.85	1715.09	4994.66	5677.52

4.6.1 Change of compressive strength with cement content

The development of strength, q_{sc}, with cement content, c_{sc}, is described here in Figure 4.9 in the presentation of q_{sc} versus c_{sc} diagram for different t_{sc}. From this figure, it can be seen that the value of q_{sc} increases clearly for the increase of cement content from 2.5% to 50%. This phenomenon holds true for any rest period of t_{sc}=0.25 to 56 days considered in this study. At a rest period of t_{sc}=0.25 days, q_{sc} increases from 8.43 to 101.23 kPa for the increase of c_{sc} from 2.5% to 50%, while this value increase from 225.70 to 5677.52 kPa for the increase of c_{sc} from 2.5% to 50% at a rest period of t_{sc}=56 days. Again at t_{sc} =28 days, qsc increases from 235 to 5428 kpa for the increment of c_{sc} from 2.5% to 50%. The figure depicts that the maximum increase of compressive strength of cement-stabilized soil (maximum is obtained as q_{sc}=6229 kPa for c_{sc}=50% and t_{sc}=56 days) is more than 100 times than that of the unconfined compressive strength of the natural soil (q_u=50 kPa). From this figure it is also observed that for the increased of c_{sc} by 20 times, the value of q_{sc} has increased from 10 to 40 folds. The intensity of strength development also varies with cement contents. However, it is found that the strength increases almost linearly with the increase of cement content for all the rest period. The development of compressive strength as obtained here quite with the agreement of the phenomena of strength development of soil due to induced cementation.

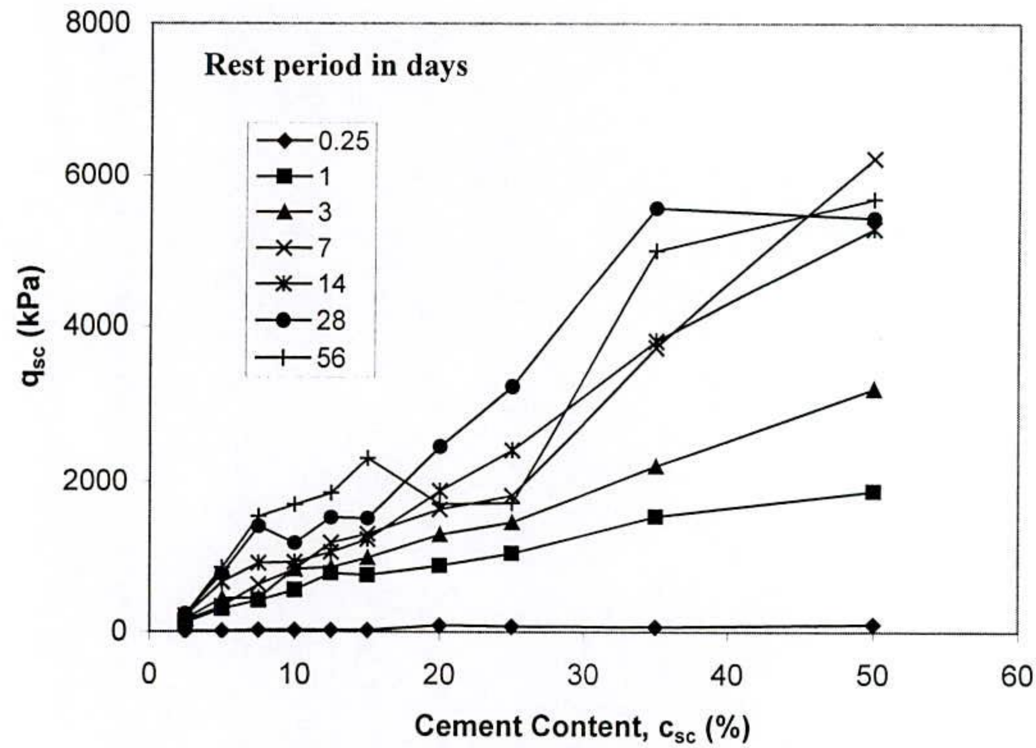


Figure 4.9 Development of compressive strength in the cement-stabilized soil with the increase of cement content and for different rest period.

4.6.2 Change of compressive strength with rest period

The development of compressive strength in the cement-stabilized soils for the elapsed of rest period, t_{sc} = 0.25 to 56 days, for different cement content, c_{sc}=2.5 to 50%, is presented here in Figure 4.10 in q_{sc} versus t_{sc} diagram at different c_{sc}. This figure depicts that the strength of cement-stabilized clay remains in increasing trend even after 56 days of sample preparation for the case of lower percentage of c_{sc} i.e. up to 15%, beyond this cement content i.e. c_{sc} more than 15%, q_{sc} increases with the increase of rest period, t_{sc}, up to 28 days, beyond which q_{sc} decreases slightly. This figure shows that for c_{sc} = 2.5, 20 and 50%, the value of qsc increase from 8.43 to 225.7 kPa, 87.10 to 1703.85 kPa and 101.23 to 5677.52 kPa, respectively, for the elapsed of rest period, t_{sc} from 0.25 to 56 days. This figure also shows that even after six hours of sample preparation, soil cement paste already gained some strength; at t_{sc}=0.25 days, the q_{sc} becomes 8.0 to 101 kPa for the increase of c_{sc} from 2.5% to 50%, which is also greater than the unconfined compressive strength of natural soil, q_u=50 kPa. From these two figures, it can observed that the strength gained in soil-cement sample for various cement content varies from 65 to 96% in the first 28 days compared with that of obtained in 56 days.

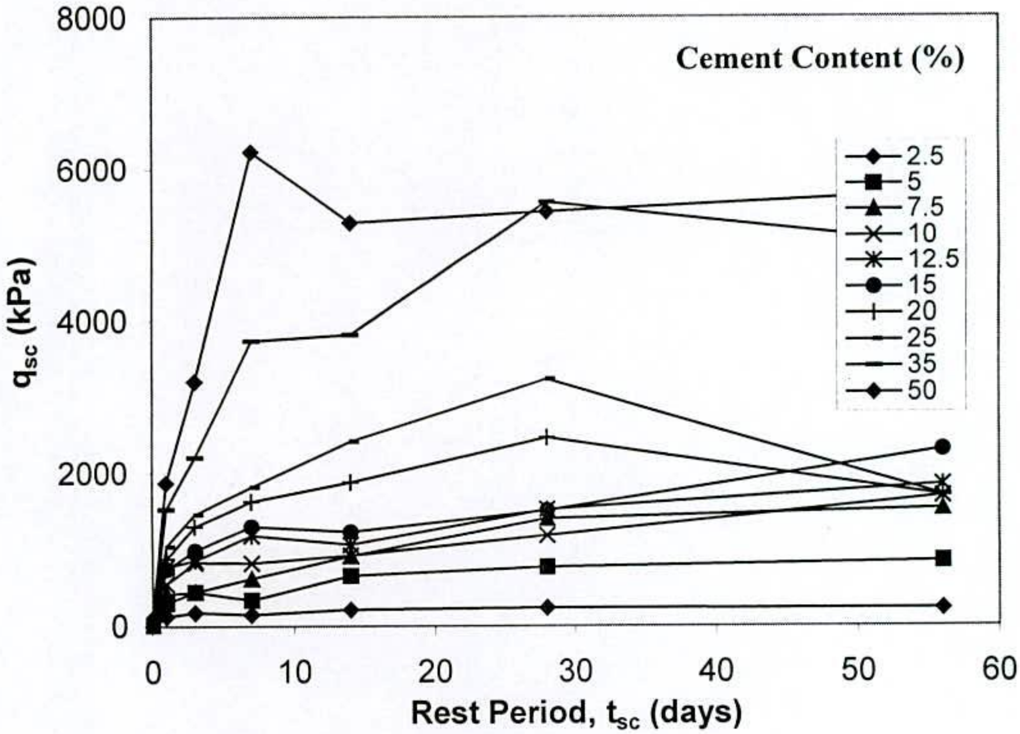


Figure 4.10 Development of compressive strength in the cement-stabilized soil with the increase of rest period and for different cement contents.

4.7 Change of Stiffness of Cement-Stabilized Soil

As the cementation proceeds, the microstructure of cement-stabilized soil changes depending on the several controlling factors. So the stiffness of the stabilized soil changes for the amount of cement content mixed with natural clays and the rest period elapsed after the preparation of sample. The changes of the stiffness of cement-stabilized soil, expressed here as Young's modulus, E_{sc}, for the variation of cement content, c_{sc} from 2.5 to 50% and rest period, t_{sc}, from 0.25 to 56 days are presented in Table 4.5. The evaluation method of Esc from the stress-strain curve of cement-stabilized soil is presented earlier in Chapter 3. In this study Esc is determined as the secant modulus from zero up to the half of the maximum deviator stress. However, it is evident that the value of Esc determined in unconfined compression test and unconsolidated Undrained triaxial test are generally low (D' Appolonia et al,1971). The change of stiffness of cement-stabilized soil for the increase of cement content and rest period are discussed in the following sections.

Table 4.5 Change of stiffness in the cement-stabilized soil with the increase of cement content and rest period

Stiffness of Cement-stabilized Soils, E_{sc} (kPa)										
Rest Period, t_{sc} (days)	Cement content c_{sc}(%)									
	2.5	5.0	7.5	10.0	12.5	15.0	20.0	25.0	35.0	50.0
0.25	63	129	211	320	213	2000	12571	7500	4375	4462
1	1696	12600	17778	20896	30408	43373	34615	50980	82813	109677
3	7965	18333	30940	46875	52500	53846	77711	78804	196078	223958
7	13393	21034	58621	40291	66129	64563	78947	81604	246324	257317
14	10185	46000	58750	62651	59735	50169	67516	107143	466667	561224
28	10085	42308	61207	110164	87222	83523	283721	424242	433065	807692
56	11089	56667	64583	136508	116883	106897	102000	121429	172857	398571

4.7.1 Variation of stiffness of cement-stabilized soil with cement content

The changes of the stiffness, E_{sc}, of cement-stabilized soil with cement content, c_{sc}, are described here in Figure 4.11 in the presentation of E_{sc} versus c_{sc} diagram for different t_{sc}. It can be seen in this figure that the value of E_{sc} increases very significantly for the increase of cement content from 2.5% to 50%. This phenomenon holds true for any rest period of t_{sc}=0.25 to 56 days considered in this study, despite some inconformity as observed. The inconformity may occur due to the lack of uniformity during sample preparation from the prepared paste, which was done manually. At rest periods of t_{sc}=0.25, 7 and 56days, E_{sc} increases from 63 to 4462kPa, 13,393 to 2,57,371kPa and 11,089 to 3,98,571kPa, respectively, for the increase of c_{sc} from 2.5% to 50%. The figure depicts that the maximum increase of stiffness of cement-stabilized soil is obtained as E_{sc}=8,07,692kPa for c_{sc}=50% and t_{sc}=28days. From this figure it is also observed that for the increased of c_{sc} by 20 times, the value of E_{sc} has increased from 25 to 80 folds. The intensity of strength development also varies with cement contents. From the figure, it can be commented that the development of the stiffness of cement-stabilized soil is obtained here is quite expected and found to be with the in agreement the behaviour of stabilized soil.

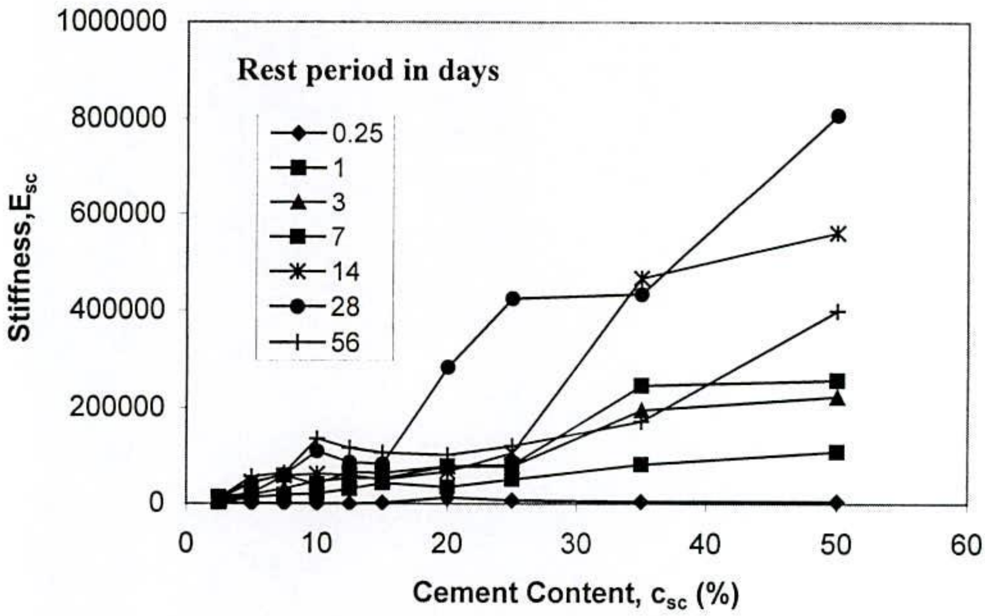


Figure 4.11 Variation of stiffness of cement-stabilized soil with the increase of cement contents for different rest period.

4.7.2 Variation of stiffness of cement-stabilized soil with time

The stiffness of the cement-stabilized soils as changes for the proceeds of rest period, t_{sc} = 0.25 to 56 days, for different cement content, c_{sc}=2.5 to 50%, is presented here in Figure 4.12 in E_{sc} versus t_{sc} diagram at different c_{sc}. This figure depicts that the stiffness of cement-stabilized clay remains in increasing trend even after 56 days of sample preparation for the case of lower percentage of c_{sc} i.e. up to 15%, beyond this cement content i.e. c_{sc} more than 15%, E_{sc} increases with the increase of rest period, t_{sc}, up to 28 days, beyond this rest period E_{sc} decreases markedly. This figure shows that for c_{sc}=2.5, 20 and 50%, the value of Esc increase from 63 to 11,089 kPa, 2,000 to 1,06,897 kPa and 4,462 to 3,98,571 kPa, respectively, for the elapsed of rest period, t_{sc} from 0.25 to 56days. This figure also shows that even after just immediately after the sample preparation, soil cement paste already gained some stiffness, which is also greater than that of the natural soil. From this figure it can also be seen that higher percent cement content, the stiffness of stabilized soil decreases from a highest value after rest period crosses 28 days.

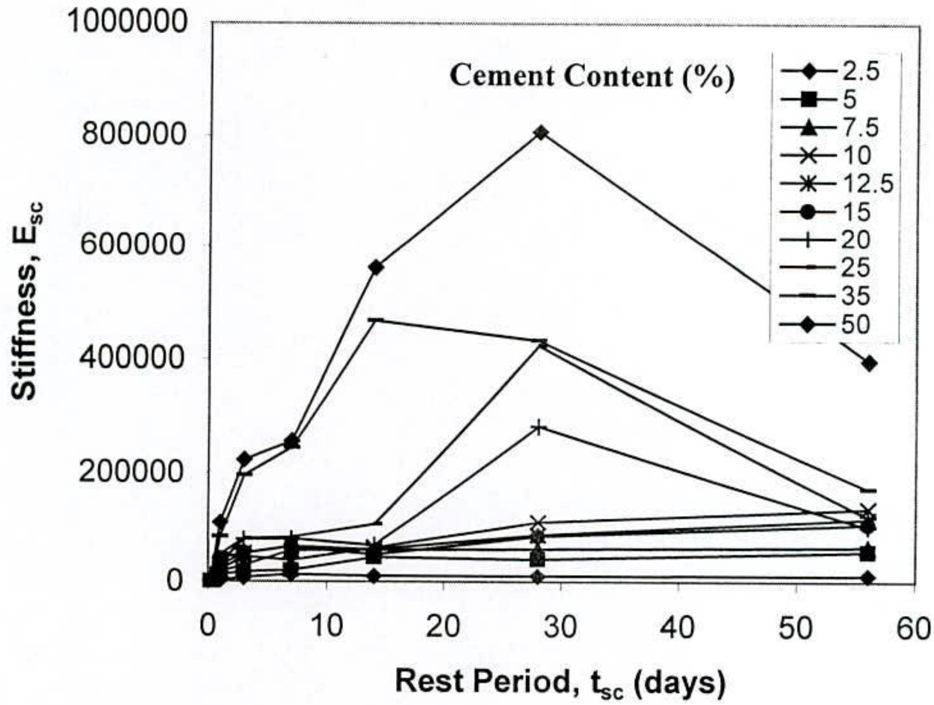


Figure 4.12 Variation of stiffness of cement-stabilized soil with the increase of rest period and for different cement content.

4.8 Empirical Relationships

An empirical equation based on the experimental data is suggested here to predict the compressive strength of cement-stabilized soil having the variables of cement content and rest period. This empirical relationship is established by representing a hyperbolic equation (konder 1963) of a series of curves of q_{sc} versus c_{sc} for the variation of t_{sc}. Figure 4.13 shows the presentation of the variation of compressive strength of cement-stabilized soil in the q_{sc}/c_{sc} versus t_{sc} curve as obtained for the increment of c_{sc}, which a hyperbolic representation of q_{sc} versus t_{sc} curves as presented in Figure 4.10. This hyperbolic representation can be expressed in the following linear equation, which is valid for $2.5\% \leq c_{sc} \leq 50\%$ and $0.25 \leq t_{sc} \leq 56$ days.

$$q_{sc} = c_{sc} [a_{sc}+b_{sc}t_{sc}]$$

Where,

q_{sc} = compressive strength of cement-stabilized soil

c_{sc} = cement content in percent

t_{sc} = rest period of cement-stabilized clay in days

a_{sc} = constant having the value of 70

b_{sc} = constant having the value of 1.6

This equation can be used to predict the strength of cement-stabilized clay for cement content at any rest period for the specific type of clay and cement considered in this study. This equation also limited to the cement content ranges from 2.5% to 50% and the rest period from 0 to 56 days. To suggest a more general empirical equation, more investigation should be carried out by changing other important parameters such as cement type, clay type, initial mixing water content. However, this empirical equation can be used with a reasonable degree of accuracy. For example, considering a case of having c_{sc}=10%, t_{sc}=14 days, the predicted q_{sc} using the above proposed empirical equation is predicted as 1080 kPa. In this investigation, the experimental value for this case is measured as 922 kPa, which is very close to the predicted value.

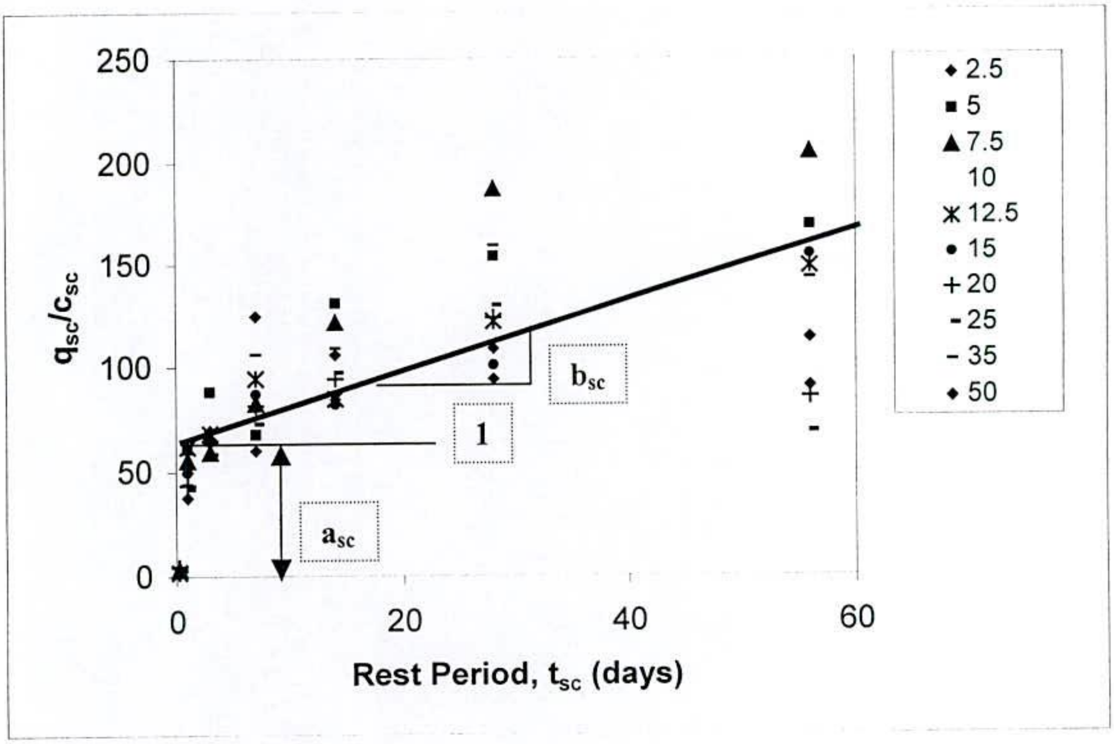


Figure 4.13 Development of empirical equation among the compressive strength, cement content and rest period of a cement-stabilized soil.

4.9 Verification of Proposed Empirical Equation

The empirical equation proposed in this study in the previous article based on the performed laboratory experiments is hereby verified here with the experimental results reported by Kawasaki et al. 1981. The experimental results were reported for the cement content as 20%, rest period up to 60 days and the ordinary Portland cement as the cementing agent. The comparison is given in Figure 4.14. It is observed that the variation is negligible from the practical point of view. So, it can be concluded that the proposed empirical equation can be used by the practicing engineers with a reasonable degree of accuracy for the estimation of unconfined compressive strength at any rest period for particular cement content, as considered in this study.

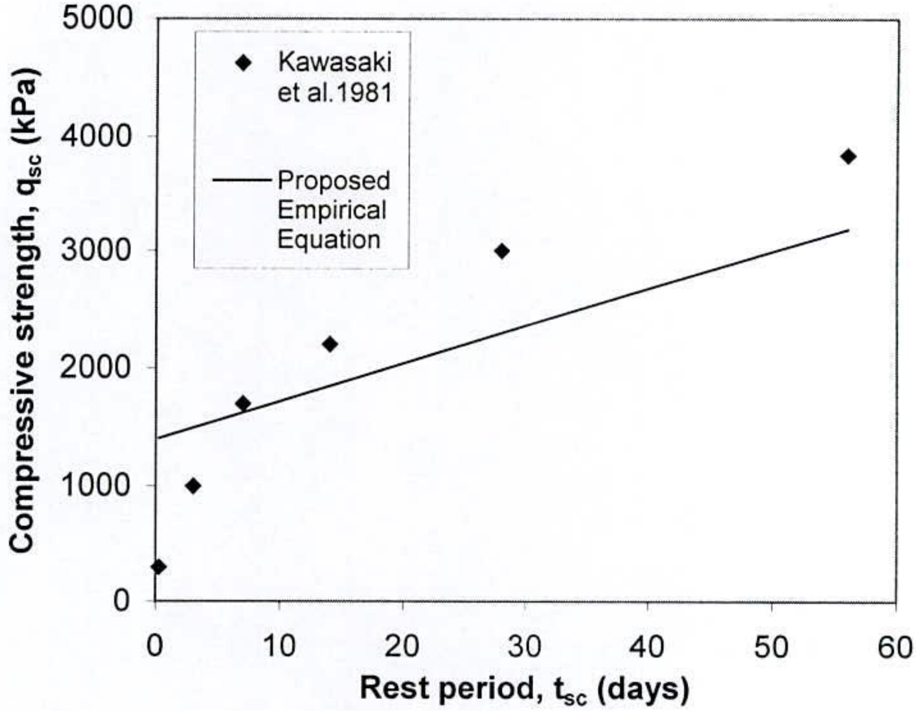


Figure 4.14 Verification of the proposed empirical equation.

4.10 Application of this Research Outcome

In the recent years, soil stabilization has become one of the most effective and economical ground improvement techniques since the physical and mechanical properties of soils, ranges from fine-grained to coarse-grained can be improved economically up to the desired level by the use of admixture. Among the admixtures, Portland cement has earned popularity as an admixture for both the shallow and deep stabilization. Case study shows that the cement content usually varies in the range of 5 to 14% by the weight of soil considering economical aspects. However, research shows that the strength of cement-stabilized soil increases with the increase of cement content and the strength increases with the increase of elapsed time after mixing.

As the strength of cement-stabilized soils depends on cement content and elapsed time, cost and time are the two most important controlling factors, which the practicing engineers have been facing in the field while selecting cement content for particular project. Usually trials are used for the selection of cement content. In this study based on the rigorous laboratory testing for the wide range of conditions, cement content and rest period vary from 2.5 to 50% and 0.25 to 56 days, respectively, an empirical equation verified with test results is proposed. Practicing engineers can use this proposed empirical equation to estimate the cement content required to improve the ground up to the desired strength at particular rest period. It helps for a quick estimation of the ground improvement cost.

CHAPTER FIVE

SUMMARY AND CONCLUSION

5.1 Summary

In this study the physical and mechanical characteristics of cement stabilized soft fine-grained soil was investigated through a series of laboratory tests. Typical soft clay was collected from KUET campus located at Khulna south –west region of Bangladesh. The base soil was collected from a depth of 7.5 to 10 feet from the existing ground surface to avoid the top crest of clay layer. The base soil has the liquid limit =42.5%, plasticity index =16.83, natural moisture content =33.25%, Undrained shear strength is 50 kPa. Ordinary Portland cement of initial setting time as 1 hour 15 mins., final setting time as4 hours 5 mins., normal consistency as 25.30% and fineness as 3.80% had been used as a admixture for stabilization. The air dried clay samples were mixed thorough with cement powder in ten different cement content, which are 2.5%, 5.0%, 7.5%, 10%, 12.5%, 15%, 20%, 25%, 35%, 50% of the dry mass of clay. The mixing of cement with clay was done at the water content of the liquid limit of base clay. The mixing was done properly to get a uniform mixture of soil cement and to prepare a uniform paste free from lumps and other foreign particles. The soil cement paste was then pour in to the cylindrical plastic mould having 35mm diameter and 70mm height fairly by the help of fingers so that no air voids entrapped into the soil sample. After six hour the specimen removed taken out from the cylindrical mould and it was tightly wrapped in vinyl bags to prevent the loss of moisture from the cement-stabilized soil due to evaporation. After 24 hours, the wrapped specimens were placed under water in the room temperature until testing at the designated rest period. To obtained the strength deformation behavior of soil cement samples unconfined compression tests were done for all specimens at each percentage of cement content for the test periods of 0.25, 1, 3, 7, 14, 28 and 56 days. There are total seventy test conditions of samples for tests. In each test three specimens were tested and the average values are taken. Besides the stress-strain data, water cement ratio and unit weight of soil cement samples were measured during testing for the variation of cement content and rest period. Stress- strain curves are then plotted from test data. From the curves the compressive strength (q_{sc}) and initial tangent modulus (E_{sc}) were determined. After finding all the data, the necessary graphs are drawn showing the change of water content with time and cement content and stiffness of stabilized soil with time and cement content. Water content is found to vary significantly with time. The obtained strength of stabilized soil increased significantly. The strength of cement stabilized clay increased with increasing cement content & rest period except few variations. Stiffness of stabilized soil also increased with time. Finally an empirical relationship is suggested to evaluate the strength of stabilized soil for any cement content at any rest period.

5.2 Conclusion

Based on this study the following conclusions can be made:

i. The study reveals that cement can be considered as one of the most common, reliable and cost effective admixture for both shallow and deep soil stabilization.

ii. The microstructure of soil is being changed significantly due to the induced cementation which observed from the change of moisture content, unit weight, compressive strength and the stiffness of cement stabilized soil

iii. The moisture content of cement stabilized soil decreases with the increase of cement content and rest period.

iv. The unit weight of cements stabilized soil also changes, showing a decreasing with the increase of cement content and rest period. However no distinct trend was depicted.

v. The stress-strain diagram shows the behaviour similar to that of soil at lower cement content and rest period but it shows the beheviour of hard material such as very hard clay or rock at higher cement content and rest period.

vi. The failure strain of the cement stabilized soil decreases with the increase of cement content and rest period.

vii. The unconfined compressive strength of natural cohesive soil increases significant due to cement stabilization.

viii. The strength of cement stabilized clay largely depends on cement content mixed with soil and the rest period.

ix. The stiffness of cement stabilized soil measured in terms of Young' s modulus increases almost linearly with the increase of cement content but for the rest period, stiffness increases up to certain rest period, beyond this the stiffness decreases.

x. The proposed empirical equation can be used for the prediction of the compressive strength of cement stabilized soil for the cement content ranges from 2.5% to 50% and the rest period 0.25 to 56 days.

xi. Finally it can be concluded that the present study contributes significantly to understand the beheviour of cement-stabilized soil for mixing ordinary Portland cement with the fine-grained soils.

5.3 Recommendations For Future Research

Based on this study, the following recommendations for future research can be made:

i. More investigation on cement stabilized soil such as change of microstructure; porosity and permeability can be done in future to understand the behaviour of soil-cement explicitly.

ii. The observation of compressibility properties of cement stabilized soil performed in oedometer or triaxial tests can be interesting areas for future research work.

iii. Strength Development needs to be observed for more rest period as the strength was found to be increasing even after 56 days, in this study.

iv. Investigation should be carried out in future by varying the initial water content to observe the effect of initial water content in the strength development process.

v. Effects of organic contents on the strength development of cement stabilized soil will be an interesting future since a significant layer of Khulna sub-soil consisting organic soils.

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