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Laboratory Study on Cement Admixed Marine Clay in Deep Mixing

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Abstract - Large tracts of Marine deposits are encountered along the coastal line of several countries all over the world. These deposits are generally low strength and undergo large settlements due to their high compressible behaviour. Due to these inherent undesirable engineering characteristics, geotechnical engineers have always been confronted with not only the apparent but also subtle problems in providing the most appropriate shallow and deep ground improvement techniques so as to meet the engineering requirements necessary for the design and construction of associated infrastructure facilities. Ground improvement by cement stabilization can be broadly divided into shallow stabilization and deep stabilization.

The fundamental parameters such as after-curing void ratio (e_{ot}) and cement content (A_w) have been found sufficient to characterize the strength and compressibility of cement-admixed clay at high water contents. From analyses performed on the results of unconfined compression tests, the ratio e_{ot}/A_whas been proven to combine together the influences of clay water content, cement content, and curing time on the strength of cement-admixed clay. The value of e_{ot}reflects, primarily, the clay water content and, secondarily, the cement content and the curing time. The after-curing unit weight, after-curing water content, and after-curing specific gravity were incorporated in an empirical relationship of e_{ot}.

1. INTRODUCTION

A. Outline Of The Project

Marine clay is a type of soft clay found in coastal areas that swell upon wetting and shrink upon drying. Initially the index and engineering properties of marine clay will be finding out by conducting various laboratory tests on the sample. The remolded clay samples were mixed with slurry of cement in different water-cement ratio. Mixing was done thoroughly to until a uniform, homogeneous clay– water–cement paste was attained. The Specimens are prepared as mould and keeping in the desiccators for curing. After curing UCS test will be conducting to examine the compressive strength of marine clay. This thesis work proposes a new approach of characterizing the strength and compressibility behavior of cement admixed clay. The essential role of after-curing void ratio (e_{ot}) and the cement content (A_w) will be emphasized.

B. General

Marine soils are among the most problematic soils in civil engineering practices. Most of the heavy engineering structures like Docks, Harbors etc. are taken foundation under marine clay. Marine clay is a type of soft clay deposits, which are inherently very low in strength and very high in compressibility, are widespread in coastal and lowland regions of the world. Due to these inherent undesirable engineering characteristics, geotechnical engineers have always been confronted with not only the apparent but also subtle problems in providing the most appropriate shallow and deep ground improvement techniques so as to meet the engineering requirements necessary for the design and construction of associated infrastructure facilities. Also, the scarcity of land following rapid developments in cities prompted engineers to increase the height of buildings, to elevate roadways, to construct subways, etc., which aggravate the related problems.

In recent years, the scale of design and construction of infrastructure in natural soft ground has increased tremendously as a result of extensive urbanization and industrialization. Soil strengthening is required in many land reclamation projects. The desired properties of the improved soil are increased strength, reduced compressibility, and appropriate permeability to solve stability, settlement, ground water, and other environmental-related problems.

C. Need for the study

A number of laboratory tests to study the engineering characteristics inherent to cement-stabilized clay have been conducted earlier. Most of these previous researchers utilized cement content (A_w) and curing time as controlled parameters in their study of the behavior of cement-admixed clay. The recent study "*Clay–Water/Cement Ratio Identity for Cement Admixed Soft Clays"* of Miura et al. (2001), demonstrated that the engineering behavior of cement-admixed clay is also affected by the clay water content (C_w) present in the clay-cement paste. Consequently, a new parameter, called total clay water content to cement content ratio (C_w/A_w), was proposed, stressing that such a parameter is a prime factor governing the engineering behavior of cement-admixed clay. This parameter, however, does not account for the effect of curing time; it accounts for only the initial condition of mixing, but not the final condition of the cured treated soil. Thus it is imperative to know the state of the treated soil just before it is subjected to loading, i.e., its after-curing condition. To account for the effect of curing time, clay water content, and cement content, Since the after curing void ratio would reflect the total clay water content, cement content, and curing time, obviously the effect of curing time had been included. These parameters will be assessed based on the results of unconfined compression tests and one-dimensional compression tests of cement admixed clay, with the base clay remolded at water contents equal to and up to twice its liquid limit. By principle, the initial void ratio is one of the basic parameters required in defining the initial state of soil.

D. Types of marine clays

Class A: The problems associated with soil include unsuitable slopes, land slippage, high shrink and swell poor foundation support and high water table conditions.

Class B: These primarily have wetness and drainage problems that can addressed on the construction planes.

E. Characteristics of marine soils

The marine deposits generally found in Northern Great Plains, during monsoon, undergo heave, lose density and become slushy when more water is available. Conversely, during summer, the soil desiccates, shrink, gain density and become very hard. Details of the marine clay have been presented by Tan (1983) and Yong et al. (1990), amongst others, and are only summarized briefly herein. The marine clay is the main constituent of the Kallang Formation, which covers much of the coastal plains and immediate offshore areas. This formation consists mainly of recent deposits of marine, alluvial, littoral and estuarine origins. This formation covers about one quarter of Singapore Island (Pitts 1992). The thickness of the marine clay stratum is usually between 10 and 15 m, but, in some instances, it can be thicker than 40 m. As this marine clay covers many of the deeply incised river valleys, Islands etc.

In areas where the marine clay deposit is thick, it is usually present in two layers, typically referred to as the upper and lower marine clay. These two layers are separated by a stiffer intermediate layer, which is widely considered to be the desiccated crust of the lower marine clay. Pitts (1992) suggested that the lower marine clay was deposited sometime between 12,000 to 18,000 years ago, at the end of the Pleistocene period. Between 10,000 and 12,000 years ago, the sea level dropped as a result of the Little Ice Age and it was hypothesized that this caused the top part of the lower marine clay to be exposed, desiccated and weathered. The upper marine clay is a holocene deposit that was deposited after the last Ice Age and is usually thought to be younger than 10,000 years. Between the two marine clay layers, the upper marine clay is often distinguished by its higher liquid limit and plasticity index. The clay used in this study comes from the upper marine clay layer. The upper marine clay is often classified as an inorganic clay of high plasticity, with the weight of organic matter in the marine clay usually ranging from 5 to 8% of the mass of solids.

F. Mineralogical Composition

The mineralogical composition of clay particles (-2µ fraction) depends up on the parent rock and its crystal structure. Usually clay minerals are hydrous aluminum silicates in crystalline form with one or more members of small group of other minerals such as magnesium or iron and include some alkalis and alkaline earths some times.
The structure of natural soils has been examined by numerous researchers (Lerouiel and Vaughan 1990; Burland 1990; Nagaraj et al. 1998; Liu and Carter 1999). However, natural soil structures are often formed by solute deposition at interparticle contacts, charge deficiencies, and vander Waal forces (Mitchell 1992), rather than by hydration and pozzolanic reactions.

G. Techniques for identification

Some of popular techniques adopted to identify; and determine the quanta of constituent minerals are

- Differential thermal analysis (D.T.A)
- X-Ray diffraction
- Chemical analysis
- Electron microscope resolution

H.Types of Clay Minerals

Basically, clay minerals can be grouped in to three main types

- Kaolinites
- Illites
- Montmorillonites

I. Clay mineral structures

Clay minerals consists essentially two basic building blocks, namely, the silica tetrahedron (sio_2) and the alumina octahedron (AL $(OH)_3$).

A silica tetrahedron consists of a central silicon atom surrounded by four oxygen atoms arranged at the apexes of the equilateral triangles. A number of such tetrahedral combine to form a sheet, which is silica sheet. In the silica sheet, single oxygen atoms project above the central plane of silicon atoms. The sheet is schematically represented by trapezium. The other structural element, namely, the hydrated alumina Ion; the form of an octahedral crystal has an alumina atom at the center with oxygen or hydroxyl ions arranged above and below it. A sheet form of aluminum hydroxide is called gibbsite. The sheet is schematically represented by a rectangle.

2. DAMAGE CAUSED BY MARINE CLAYS

2.1 Shallow footings

The most common problems in marine clay areas are failures in shear strength and excessive settlements. During dry and shrinking period soil losses moisture, causing a gap under the footings. The structures settle, usually in an uneven fashion, resulting in broken footings, cracked masonry walls. Deeply rooted vegetation such as trees often contribute to the problem. Trees draw water from soil through many small roots that extended below and well beyond the farthest reaching branches, drying out the soil and causing shrinkage. Tree roots can extend well underneath a house and its foundation. Many of the structures with settlement problems have relatively shallow foundations. Foundations that have settled during dry periods will often return to near the original position after rainfall replenishes the soil moisture causing the soils to swell again. After several cycles, however, the rebound of the foundation may be progressively less, resulting in larger and larger cracks.

2.2 Deep Footings

Due to seasonal variation GWT fluctuates. This leads to instability of the deep foundation. This causes shear failure and excessive settlements.

2.3 Basement walls

Damage to foundation walls often occurs when Marine Clays are placed as a backfill against basement walls. While this practice is now expressly prohibited the Fairfax country, it was a common procedure in houses built before 1975, and may still occur today where the builder is uninformed or careless. Damage from the pressure of swelling clays in backfill occurs after several yearly cycles of shrinking and swelling before the detrimental effects of the soils are revealed. Surface water can also accumulate against basement walls where the backfill has settled, increasing the soil moisture and swelling pressure of the soil.

2.4 Landslides

Landslides are common in landscaped yards and undeveloped areas; however damage to structures from landslides can be dramatic. Slope failures, which usually occur during wet periods of the year, have jeopardized buildings and made yards unusable. Where houses are involved in landslides, movement is usually very slow (fraction of an inch per year) and can be corrected. Most of the slides are less than one or two feet in depth and can be corrected by flattering the slope or replacing the clays with suitable soil materials. Deeper landslides have occasionally occurred, requiring stabilization measures. Slides, Shallow or Deep can damage underground utilities, such as gas, water and sewer service.

3. STABILIZATION OF SOFT CLAYS

Soil stabilization is a process of improving the engineering properties of the soil and making it more suitable. The process may include the blending of soils to achieve a desired gradation or the mixing of commercially available additives that may alter the gradation, texture or plasticity or act as a binder for cementation of the soil. Soil stabilization is used to reduce the permeability, compressibility of the soil mass in earth structures to increase its shear strength. Soil stabilization is required to increase the bearing capacity of the foundation soils. The principles of soil stabilization are used for controlling the grading of the soils.

3.1 Methods of soil stabilization

In recent years, the scale of design and construction of infrastructure in natural soft ground has increased tremendously as a result of extensive urbanization and industrialization. Soil strengthening is required in many land reclamation projects. The desired properties of the improved soil are increased strength, reduced compressibility, and appropriate permeability to solve stability, settlement, ground water, and other environmental-related problems.

Soft clay formations, especially those with high in situ water contents, are susceptible to large settlements and possess low shear strength unless they are naturally cemented. Precompression of such deposits with geodrains can prevent this large settlement and thus enhance shear strength. But this mode of attacking the problem often requires more time than is practically available. An alternative to this is cementation of the soft clay with supplementary cementing materials such as lime and cement. Such admixtures impart resistance to compression and develop adequate shear strength during time periods typically much less than those required by precompression.

The most commonly used methods of stabilization are

- Cement stabilization
- Lime stabilization
- Stabilization by grouting
- Chemical stabilization
- Bituminous stabilization
- By geotextiles and fibers
- Mechanical stabilization
- Thermal stabilization
- Salt stabilization
- Electrical stabilization

3.2 Cement stabilization

One of the ground improvement schemes that has been adapted is chemical stabilization using cement or lime. Cement is often used as an additive to improve the strength and stiffness of soft clayey soils. In Asia, however, the use of cement has permanently been outpacing the use of lime, not only because cement is abundant and cheaper but also because cement is more effective than lime (Broms 1984).

Ground improvement by cement stabilization can be broadly divided into

1. Shallow stabilization and
2. Deep stabilization.

Shallow stabilization, which can be considered as "low water content mixing" includes stabilization of subgrade for roadways, airfields, and other similar structures. Deep stabilization, on the other hand, includes the deep mixing method (DMM) using either slurries or powder of lime or cement to form columns of improved soil in the ground. In-situ deep mixing was introduced in 1975 as a viable means to place columnar inclusions in the soil. This improved column of soil will act as reinforcement or as a pile, transferring the load to its surface (skin) and to its base. The methods of mixing generally applied in the installation of deep mixing piles are either mechanical mixing or high pressure jet mixing/grouting (Kamon and Bergado 1991; Porbaha 1998). In the mechanical mixing method, the chemical admixtures are mixed into the soil by mixing blades; while in the jet mixing method, the chemical admixtures are mixed into the soil through jets of water or slurries of admixtures. The jet mixing method would normally produce higher water content cement admixed clay than the mechanical mixing method. Besides, the soft clay deposit normally has high water content. High water content cement-admixed clay is defined as those clay–cement mixtures having total clay water content (inclusive of water from cement slurry) of at least the liquid limit of the base clay (Lorenzo and Bergado 2004).

3.3 Deep Mixing Method (DMM)

Deep mixing method (DMM) has become a general term to describe a variety of soil mixing techniques to improve soils in-situ. The Federal Highway Administration has suggested the these techniques can be classified based on 1) method of additive injection (i.e. wet or dry injection), 2) method by which additive is mixed (i.e. rotary/mechanical energy or by high pressure jet, and 3) the location of the mixing tool (i.e. near the end of the drilling rods or along a portion of the drilling rods).

The application of the DMM for the construction of excavation support systems primarily uses a wet injection method where a typical cement based grout is used as a drilling fluid and as a binder to form a solidified column(s) of soil-cement. Figure 1 shows three common DMM techniques: Deep Soil Mixing (DSM), Shallow Soil Mixing (SSM) and jet grouting. The DSM method utilizes a series of overlapping augers and mechanical mixing shafts. The SSM method uses a single mechanical mixing auger located at the end of the drilling tool (Kelly bar). Jet grouting can be considered a type of soil mixing which utilizes high velocity, 28 to 42 MPa (4,000 to 6,000 psi) backpressure, jets to hydraulically shear the soil and blend a cement grout to form a soil-cement column. Three basic jet grouting systems are available. These systems are: single phase (grout injection only), dual phase (grout + air injection) and triple phase (water + air injection, followed by grout injection).

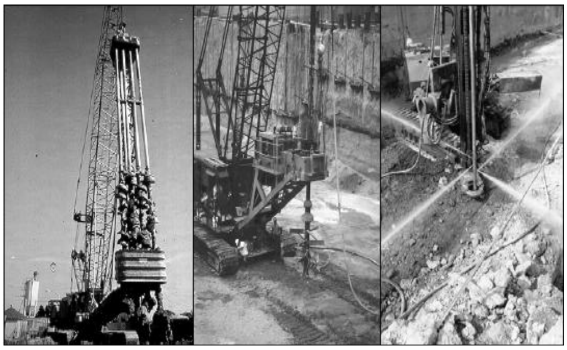

Fig 3.1: Wet Deep Mixing Methods: DSM, SSM and Jet Grouting

3.4 Jet grouting

Jet grouting is a method to construct in underground a column shaped solid substance by cutting and mixing in-situ soil material with a cement grout injected at a very high velocity and pressure. It is generally used tom strengthen and stabilize very soft soils like Marine clay and Alluvial soils for development purpose. This get grouting layer can be used for several purposes depending on the particular construction requirements. Thus it is widely used in Singapore and all over the world.

Over the years jet grouting technology has made great development. From early invention of single tube to double tube and triple tube system. These improvements have created big soilcreate column size as big as 0.2m diameter. However, in Japan, there is a new successful breakthrough on jet grouting research which can achieve up to 5m diameter; they called it "Super jet".

3.5 Jet grouting systems

There are three traditional jet grouting systems. Selection of the most appropriate system is generally a function of the in situ soil, the application, and the physical characteristics of soilcrete required for that application. However, any system can be used for almost any application providing that the right design and operating procedures are used.

3.5.1 Single Rod Jet Grouting (Soilcrete S)
Grout is pumped through the rod and exits the horizontal nozzles in the monitor with a high velocity, approximately 200 m/sec. This energy causes the erosion of the ground and the placement and mixing of grout in the soil. Single rod jet grouting is generally less effective soils.

3.5.2 Double Rod Jet Grouting (Soilcrete D)
A two-phase internal rod system is employed for the separate supply of grout and air down to different, concentric nozzles. Grout is used for eroding and mixing

with the soil. The air shrouds the grout jet and increases erosion efficiency. The double rod system is more effective in cohesive soils than the single rod system.

3.5.3 Triple Rod Jet Grouting (Soilcrete T)

Grout, air and water are pumped through different lines to the monitor. High velocity coaxial air and water form the erosion medium. Grout emerges at a lower velocity from separate nozzles below the erosion jet. This somewhat separates the erosion process from the grouting process and yields a higher quality soilcrete. Triple-rod jet grouting is the most effective system for cohesive soils.

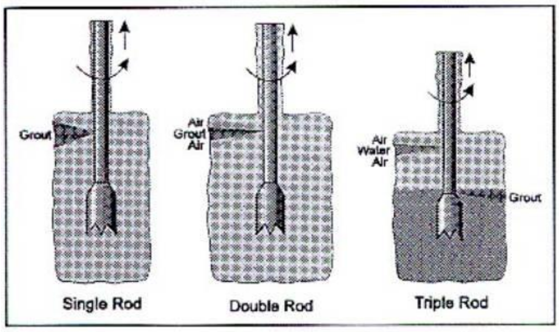

Fig 3.2: Jet Grouting Systems

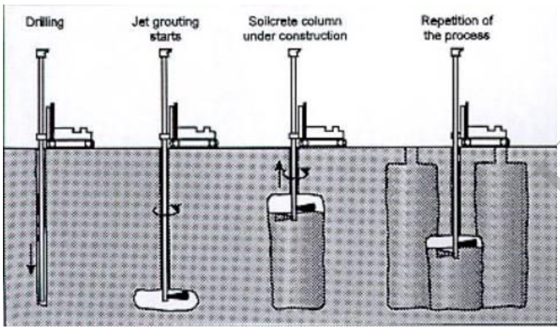

Fig3.3: Jet Grout Process

4. MECHANISM INVOLVED IN CEMENT STABILIZATION

Improvement of the properties of cement-treated soil has been attributed to the soil cement reaction (Mitchell 1981), which produces primary and secondary cementitious materials in the soil–cement matrix (Kezdi 1979; Schaefer et al. 1997; Cokca 2001). When the pore water of the soil encounters with the cement, a number of reactions takes place. While some of them are immediate and some others are long-term reactions, which are time and temperature dependent. The basic mechanisms have been identified.

- Hydration
- Flocculation
- Pozzolonoc reaction
- Carbonation

5. EXPERIMENTAL STUDY

5.1 GENERAL

An experimental investigation was undertaken to study the Index and Engineering properties of Marine clays stabilized with cement in Deep Mixing Method. Finally, to obtain empirical relations from the laboratory test results which are to be useful in soil-cement stabilization in Deep Mixing Method.

5.2 MATERIALS USED

5.2.1 Marine Clay

The base clay used in this thesis work is collected at a depth of 15m below the Ground level near Royapuram Port, Chennai District of Tamilnadu.

The physical and Engineering properties are summarized in Table 2.1 & 2.2. The liquid limit is about 61% and the natural water content varies from 76 to 84%. The specific gravity, *Gs*, and the initial void ratio, e_o, are 2.69 and 2.31, respectively. The undrained shear strength, *Su*, as obtained from unconfined compression test is 15.9 kPa.

5.2.2 Cement

To stabilize the marine soil and to study its properties after stabilization by Wet Mixing Method Type I Portland cement was utilized. The properties are summarized in Table 2.3.

6. TESTS CONDUCTED FOR THE THESIS WORK

The following tests were conducted on Marine clay to carry out this Thesis work

- Grain size distribution
- Specific gravity
- Atterberg limits
- Compaction test
- Unconfined compression strength test

7. EXOERIMENTAL PROCEDURE

7.1 Method of Cement-Admixed Clay Preparation

The clay samples utilized in unconfined compression test were remolded to water contents ranging from the liquid limit up to twice the liquid limit, and they were mixed with cement slurry with water–cement ratio (W/C) of 0.6. Type I Portland cement was utilized. The remolding water content (w*) is hereinafter defined as the water content of the remolded clay prior to the addition of cement slurry. The purpose of varying the remolding water contents is to simulate the actual condition of soil–cement column installation using the DMM with slurry of cement (e.g., Yang 1997). Prior to the introduction of cement slurry, the natural soil is subjected to remolding and mixing with the associated addition of water, which increased the water content of the natural soil. The remolded clay samples were mixed with slurry of cement so as to obtain cement contents of 5, 10, 15, and 20%. Mixing was done thoroughly to until a uniform, homogeneous clay– water–cement paste was attained.

7.2 Specimen Preparation and Testing

Due to the high workability of the clay–water–cement paste, each specimen for the UC test was made by pushing the paste into the 38 mm diameter by 76 mm height detachable metallic moulds. The inside of the moulds are coated with oil before pushing the soil-cement paste into them. This is because of to prevent loss of moisture and to remove the specimen easily from the mould. Pushing was done to remove air bubbles. The molded paste was allowed to protrude out from the other end of the mold to check the occurrence of any “honeycomb” structure. Pushing was continued until the surface of the protruding specimen was uniform and smooth. The density of each specimen with the same mixing condition was monitored and kept constant. After initial setting time the specimen was removed from the mould t
hen the specimen was wrapped in polythene covers and tied them to prevent any loss of moisture and then was placed in desiccators having a maintained ambient temperature of 25°C and humidity of 97%. The UC tests utilized three curing periods of 7, 14, and 28 days. After curing, the specimen was removed from the polythene covers and then was subjected to testing following the procedures given as per IS Standards.

The overall cement admixed clay preparation for the entire testing program for UC tests consisted of 5, 10, 15, and 20% cement contents and each cement content was in combination with remolding water contents of 60, 80, and 100% were performed.

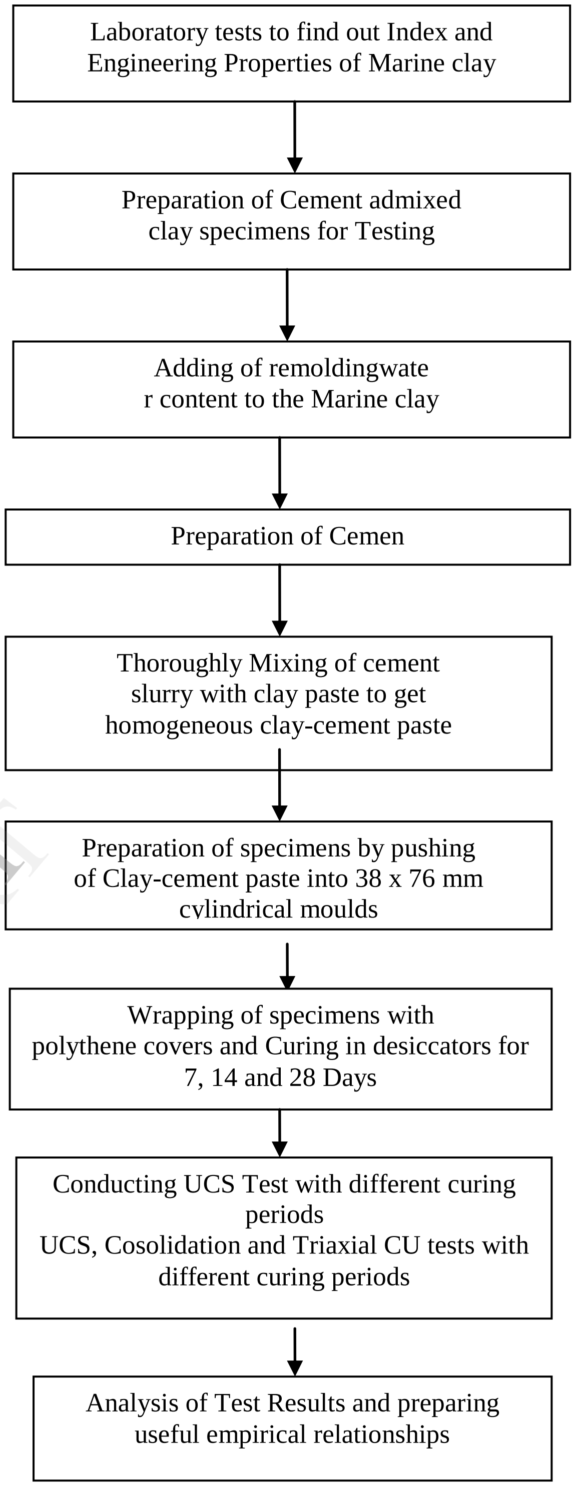

Figure 7.1: Study Methodology

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Table7.1: Index Properties of Marine Clay

Sl.NO.	TYPE OF TEST	PROPERTY
1	Grain Size Distribution Percentage	
	Gravel (>4.75mm) %	0
	Sand (4.75-2mm) %	4
	Silt (0.075-0.002mm) %	43
	Clay (<0.002mm) %	53
2	Atterberg Limits	
	Liquid limit (%)	61
	Plastic limit (%)	24
	Plasticity Index (%)	37

Table 7.2: Engineering Properties of Marine Clay

Sl.No.	TYPE OF TEST	PROPERTY
1	IS Classification	CH
2	Specific Gravity	2.69
3	UCS (kpa)	15.9
4	Max. Dry density at OMC = 21.4%	12.65

Table 7.3 Specification of Type I Ordinary Portland Cement
Used in the Study

Sl.No.	Physical Properties	Characteristic
1	Specific gravity ,*Gs*	3.17
2	Bulk density (g/cm^3)	1.02
3	Fineness–Blanie fineness (cm2/mg)	3170

Fig7.2: Homogeneous clay-Cement with Cement slurry paste after mixingof w/c ratio = 0.6

Fig 7.3: Preparation of mould

Fig 7.4: Preparation of cement admixed clay specimen

Fig 7.5: Curing of soil-cement Specimens in Desiccators

Figure 7.6: Unconfined compression Strength test set-up

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Fig 7.7: Failure Specimen @
higher water content
higher cement content

8. RESULTS AND DISCUSSION

8.1 GENERAL

All the experimental work results obtained are summarized in the following sections for the purpose of analysis. The various Index and Engineering properties are analyzed for the influence of cement stabilization of Marine clay by wet mixing in Deep Mixing Method.

8.2 DISCUSSION OF RESULTS

8.2.1 After-curing water content

The plot of after-curing unit water content (w_t) versus cement content at varying magnitudes of remolding water contents and curing times is shown in Fig. 3.1. The remolding water contents of 60, 80, and 100%; cement contents of 5, 10, 15, and 20%; and curing times of 7, 14, and 28 days were the main conditions set out during the specimen preparation. The after-curing water content decreased significantly with increasing cement content, and it also decreased slightly with curing time. As expected, the higher the remolding water content, the higher the after-curing water content of the cured treated sample. The reason why the after-curing water content decreased with increasing cement content is the increased amount of water reduction due to the hydration process of cement. Also, as the cement content as well as curing time increased, the increasing amount of cementing products resulting from the pozzolanic reaction eventually increased the weight of soil solids per unit volume. Thus, the after-curing water content consequently decreased.

Table 8.1. After curing W.C of cement admixed sample

Clay W.C (%)	Cement Content (%)	After curing water content (%)		
		7 Days	14 Days	28 Days
60	5	57.18	55.636	54.97
60	10	55.13	54.92	53.16
60	15	51.85	51.04	50.02
60	20	47.63	46.78	43.1
80	5	73.8	71.44	69.89
80	10	67.55	66.34	65.3
80	15	62.37	61.05	58.87
80	20	58.05	57.12	55.04
100	5	88.46	84.98	82.56
100	10	84.25	81.85	79.43
100	15	78.07	71.89	70.69
100	20	71.81	69.09	67.91

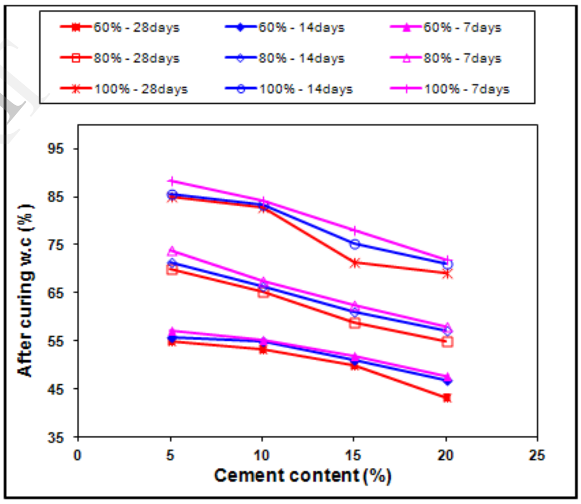

Fig 8.1: After curing W.C of cement admixed sample

8.2.2 After-curing unit weight

The plot of after-curing unit weight (γ_t) versus cement content at varying magnitudes of remolding water contents and curing times is shown in Fig. 3.2. The unit weight increased with increasing cement content and slightly increased with curing time. As expected, the higher the remolding water content, the lower the unit weight of the cured treated sample. For certain remolding water content, the conceivable reason why the unit weight increased with increasing cement content could be attributed to the increasing amount of cementing products being formed, which eventually increased the amount of soil solids per unit volume. Conversely, for certain cement content, the reason why the unit weight decreased with increasing remolding water content could be attributed to the subsequent increase of the volume of soil voids per unit volume of treated soil.

Table 8.2. After curing unit weight of cement admixed sample

Clay W.C (%)	Cement Content (%)	After curing water content (%)		
		7 Days	14 Days	28 Days
60	5	19.95	19.98	20.05
60	10	19.99	20.14	20.18
60	15	20.28	20.32	20.39
60	20	20.4	20.52	20.58
80	5	18.55	18.62	18.69
80	10	18.74	18.79	18.88
80	15	19	19.15	19.26
80	20	19.62	19.67	19.75
100	5	17.9	18	18.09
100	10	18.12	18.2	18.29
100	15	18.49	18.55	18.63
100	20	18.89	19.01	19.12

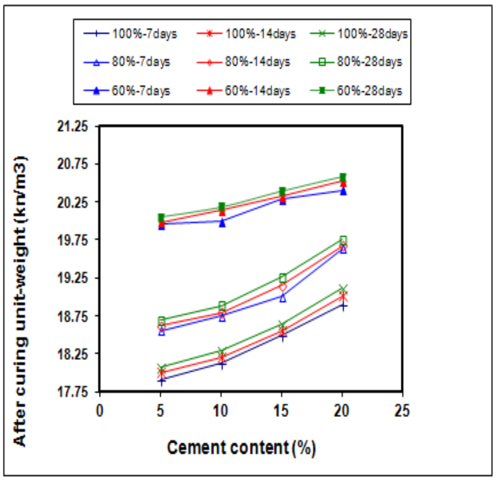

Figure 8.2: After curing unit weight of cement admixed sample

8.2.3 Unconfined Compression Strength behavior

The results of unconfined compression tests of samples cured at 7, 14, and 28 days are presented in Figs. 3.3(a–c), respectively and the values are shown in Table 3.3. In these plots, the symbols with the same shape correspond to specimens with the same cement content, and the same color of the solid line corresponds to same remolding water. The unconfined compression strength, q_u, increased with increasing cement content and curing time which agrees with the results of previous research. The increase in strength with cement content is attributed mainly to the cement hydration that leads to the dissociation of calcium ions which eventually react with soil silica and soil alumina leading to the formation of pozzolanic products. These pozzolanic products bound together the clay particles or clusters of clay particles (or clay minerals), and created a new bonded, stronger matrix of soil. Furthermore, since the process of cement hydration and the consequent pozzolanic reaction can last for months, or even years, after the mixing (provided enough water is available), the strength of treated soil is expected to increase with time.

For a certain cement content and curing time, the strength decreased with increasing remolding water content [From Figs. 3.3(a–c)], but only within the range of remolding water contents being used. Further work revealed that for remolding water content that is below the liquid limit of the base clay, the strength developed is lower than that of samples remolded at about the liquid limit. Fig. 3.4(a & b) shows the unconfined compression strengths of 10% & 20% cement content respectively, with curing times varied from 7 to 28 days and remolding water content (ω*) varied from 60 to 100%. Thus the relationship of strength and remolding water content is deemed applicable only to treated samples with water contents during the time of mixing equal to or greater than the liquid limit of the base clay. Therefore the remolding water content, the cement content, and the curing time have affected, interdependently, the strength development of cement-stabilized clay. In addition, to account for the water from the slurry of cement, a term called total clay water content (*Cw*) is adapted. This idea is similar to the concept adapted in concrete technology as discussed by Miura et al. (2001). The total clay water content, *Cw*, can be expressed by the relation

$$Cw = \omega^* + W/C\ (A_w) \rightarrow (1)$$

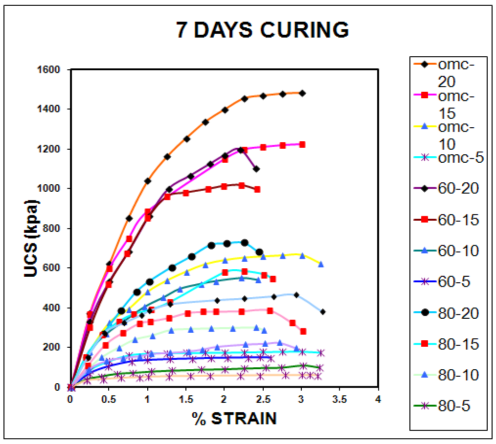

Fig 8.3(a): Stress-strain curves from UCS test (7 Days curing)

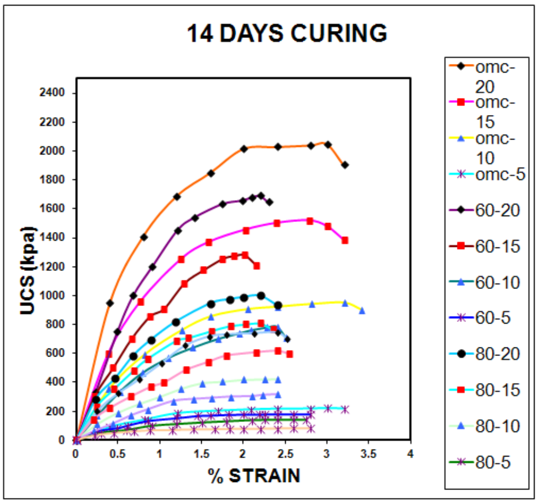

Fig8.3(b): Stress-strain curves from UCS test (14 Days curing)

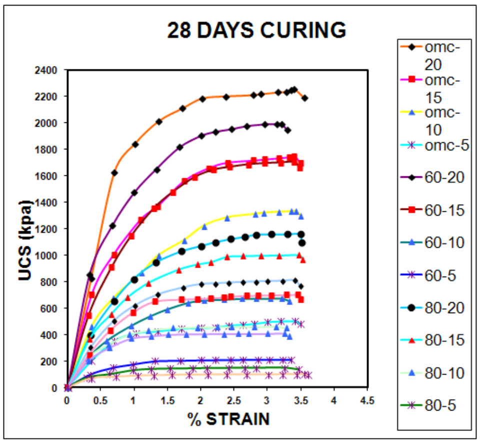

Fig 8.3(c): Stress-strain curves from UCS test (28 Days curing)

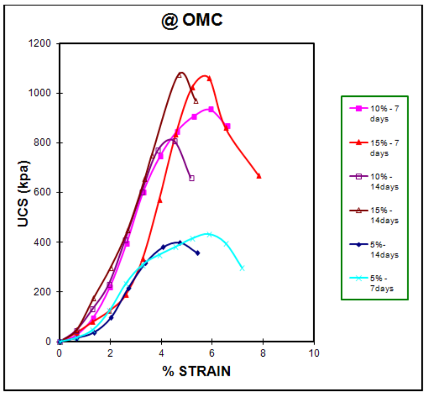

Fig 8.3(d): Stress-strain curves from UCS test (At OMC)

Table 8.3 Stress-strain curves from UCS tests

Remolding water content (%)	Cement Content (%)	7 Days curing		14 Days curing		28 Days curing	
		% Strain	UCS(kpa)	% Strain	UCS(kpa)	% Strain	UCS(kpa)
100	5	3.2	60	2.8	80.1	3.55	100
80	5	3.23	100	2.75	139.5	3.47	136
60	5	2.6	149	2.8	181	3.35	210.5
21.4	5	3.25	175.6	3.2	216.9	3.41	501.1
100	10	2.93	198.5	2.4	315.96	3.25	409.8
80	10	2.51	288	2.4	424.5	3.28	450
60	10	2.43	541	2.4	786	3.33	657
21.4	10	3.25	623.1	3.2	950.5	3.42	1333.3
100	15	3.01	285.8	2.55	598.5	3.45	700.8
80	15	2.62	545.98	2.2	808.8	3.47	1001.2
60	15	2.42	998.1	2.01	1281.1	3.4	1702.6
21.4	15	3	1224.25	2.78	1519.8	3.4	1749.5
100	20	3.27	381.2	2.52	702.8	3.41	808.8
80	20	2.44	685	2.2	1000	3.49	1159.8
60	20	2.41	110	2.2	1692	3.21	1991.5
21.4	20	3	1482.5	3	2050.2	3.4	2255.6

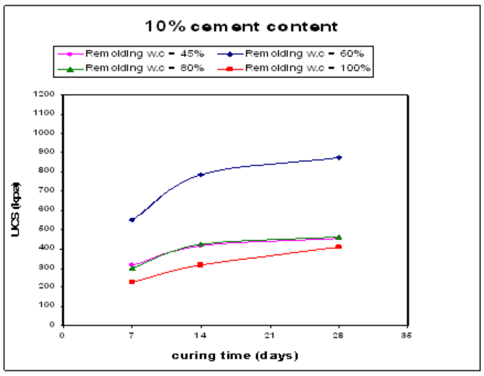

Fig 8.4(a): Effect of remolding water content on the UCS (10% cement)

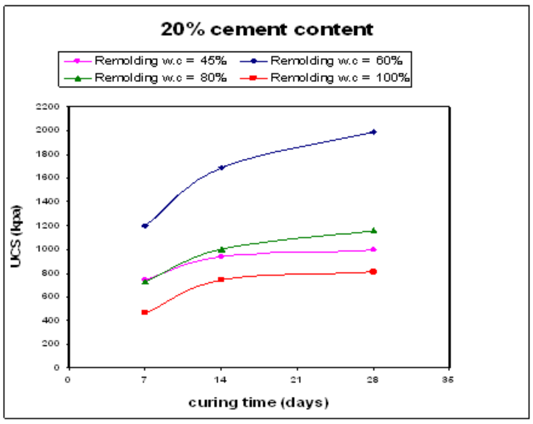

Fig 8.4(b): Effect of remolding water content on the UCS (20% cement)

9. INTERPRETATION OF RESULTS

9.1 Assessment of After-Curing Void Ratio (e_{ot}) and Cement Content (A_w) on q_u

The plot of unconfined compression strength, q_u, against ratio of total clay water content to cement contents C_w/A_w is shown in Fig. 3.5 where, q_u reasonably follows a function of C_w/A_wat certain curing time, even though the data scatter is quite high. The parameter C_w/A_whas been demonstrated previously by Miura et al. (2001) to generalize the strength development at a certain curing period, curing method, type of cement, etc. of cement-admixed clay. Both $C_w$and$A_w$are initial conditions of mixing, not after-curing conditions of the cured treated soil. The after-curing void ratio, e_{ot}, which takes into account, primarily, the effect of total clay water content and, secondarily, the effects of cement content and curing time, was adapted in this thesis work to supersede the $C_w$parameter. Since the initial state which reflects the failure strength at a certain shearing process of cured cement-admixed clay is dependent on curing time as well as cement content and total clay water content present in the clay water- cement paste, it is logical to utilize a parameter that combines together the effects of these factors. Besides, the e_{ot}parameter is essentially required in defining the initial state of the cured treated soil prior to any loading application.

9.2 DETERMINATION OF AFTER-CURING VOID RATIO, e_{ot}

Three physical properties of treated soil, namely: aftercuring unit weight (γ_t), after-curing water content (W_t), and aftercuring specific gravity (G_{st}), are necessary in order to obtain its after-curing void ratio, *eot*. These three parameters can be measured in the laboratory. Based on the analyses of the results, the methods of normalizing these parameters were obtained. The following sections explain in Empirical relationship method.

9.2.1 Empirical relationship of after-curing void ratio

Lorenzo and Bergado based on field observations given the empirical relationship to find out After-curing specific, G_{st} gravity of cement admixed soils is as follows:
$G_{st} = G_o\,(1 - A_w/100)^{0.0807} \rightarrow$ (2)
By substituting the expression of G_o and A_w from Eqs. (2), respectively, by substituting the expression of γ_w, γ_t ,wt, and G_{st} to Eq. (3), the empirical relationship of after-curing void ratio, e_{ot}, can be obtained as follows:

$$e_{ot} = \frac{(1+wt)G_{st} \times \gamma_w}{\gamma_t} - 1 \rightarrow \quad (3)$$

Fig. 3.5 shows the unconfined compression strength, q_u, against ratio of total clay water content to cement contents (C_w/A_w)

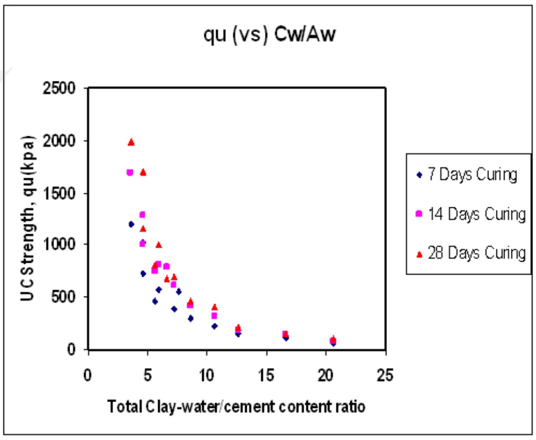

Fig 9.1: Unconfined compression strength q_u vs. C_w/A_w ratio

After curing Unit Wt. Y_t	After-curing w.c (%)	After Curing Spec. gravity G_{st}	Y_w	e_{ot}	e_{ot}/A_w
20.05	54.97	2.661	10	1.057	8.4
20.18	53.16	2.675	10	1.03	15.6
20.39	50.02	2.68	10	0.972	21.1
20.58	43.1	2.682	10	0.865	24
18.69	69.89	2.651	10	1.41	8.5
18.88	65.3	2.671	10	1.338	15.6
19.26	58.87	2.677	10	1.208	20.4
19.75	55.04	2.68	10	1.104	24
18.07	84.99	2.64	10	1.703	8.3
18.29	82.84	2.666	10	1.665	15.7
18.63	71.38	2.674	10	1.46	20.1
19.11	69.06	2.678	10	1.369	24.4

Table 9.1. Calculation of Ratio of After-curing void ratio to cement content

Remolding water content %	C_w/A_w	A_w (%)	C_w %	t (days)	G_o
60	5	12.6	63	28	2.69
60	10	6.6	66	28	2.69
60	15	4.6	69	28	2.69
60	20	3.6	72	28	2.69
80	5	16.6	83	28	2.69
80	10	8.6	86	28	2.69
80	15	5.93	89	28	2.69
80	20	4.6	92	28	2.69
100	5	20.6	103	28	2.69
100	10	10.6	106	28	2.69
100	15	7.27	109	28	2.69
100	20	5.6	112	28	2.69

10. CONCLUSIONS

From the results of laboratory tests conducted on Marine clay-cement samples the following conclusions are to be drawn.

- The e_{ot}/A_w ratio influences of clay water content, cement content, and curing time on the strength of cement-admixed clay. The magnitude of e_{ot} reflects,
  - Primarily, the effect of clay water content
  - Secondarily, the cement content and the curing time.
- If the clay water content increased while maintaining the cement content constant, the after-curing void ratio increased and the strength decreased.
- If the cement content increased while fixing the clay water content, the after-curing void ratio decreased and the strength increased.
- Finally, the parameters consisting of the after-curing void ratio e_{ot} and cement content A_w have been proven to be sufficient to characterize the strength of cement-admixed clay at higher water content.
- Therefore the strength is expected to increase with a increasing value of the e_{ot} /A_w ratio.

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