THESIS

STABILIZATION OF SEABED DREDGED MATERIAL FOR LANDFILL LINERS

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GRADUATE SCHOOL, KASETSART UNIVERSITY

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THESIS APPROVAL

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THESIS

STABILIZATION OF SEABED DREDGED MATERIAL
FOR LANDFILL LINERS

PRAKIT KAEWKAOROP

A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
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As concerning beneficial aspects, this research focused on the utilization of seabed dredged materials based on geo-environmental engineering viewpoint. The seabed dredged materials were in slurry state with extremely high water content. Therefore, this research proposed a combination concept of mechanical modification via continuous pre-loading and chemical stabilization to improve their major properties. The onsite and laboratory dewatering processes followed with cement stabilization techniques were successfully applied. In this study, initial water content of 110-140 % provided suitable water for hydration and workability.

For chemical stabilization, cement could be used effectively to improve properties of the seabed dredged materials. The required properties for sanitary landfill liners such as strength and permeability could be obtained. It was found that unconfined compressive strengths were influenced by not only the cement content but also the initial water content before mixing. In order to meet the requirement, the recommended w/c ratio should be within the range of 5.5- 6.5.

Using cement and silica fume as stabilizer, the strength characteristic curves were similar to those of cement stabilization. It was found that approximately 10% cement replacement by silica fume markedly affected the strength development, especially for the early curing time. The volumetric shrinkages could be lowered to approximately 9-12%. In addition, coefficients of permeability had trends to decrease slightly lower than those of cement stabilization. The results from XRD analysis showed that calcium silicate hydrate (CSH) and Ettringite were main reaction products which contributed to strength development. Due to formation of reaction products, the microstructures markedly changed and seemed to agree with results obtained from strength test and XRD analysis.

Student's signature   Thesis Advisor's signature   15 / Feb / 2007

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February 2007

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF FIGURES (Cont'd)

LIST OF FIGURES (Cont'd)

LIST OF FIGURES (Cont'd)

STABILIZATION OF SEABED DREDGED MATERIAL FOR LANDFILL LINERS

INTRODUCTION

General

With the huge quantities of dredged material created during dredging operations, the dredged materials are usually placed hydraulically into disposal areas in a slurry state. Due to the lack of available land in the densely populated metropolitan area, some of this dredged material has been dumped in the ocean at the designated disposal site, called the Mud Dump Site, where adverse effects on municipal water supply, shellfish beds, and fishing areas, wildlife or recreational areas are unacceptable.

There are many research programs in USA that determined environmental impacts of dredged material disposal. Utilization of dredged materials by considering such materials as a beneficial resource can mitigate adverse effects on the environments of both land and the ocean. Beneficial uses appear to be unlimited. Over 1,300 cases of beneficial uses have been documented (U.S. Army Corps of Engineers, 1987). Because natural dredged material's properties have extremely high water content and very low strength, seabed dredged materials are usually not geotechnical aspects. Therefore stabilization techniques are required to improve seabed dredged materials to achieve aspect.

Rapid increase of population affects directly to solid waste quantity and disposal of wastes using appropriate methods. Since wastes have to be filled in sanitary landfill on large appropriate areas, selected materials are necessary to be placed as liners in order to prevent problems due to contamination of underground water (John Zammit, P.E., 1984). In addition the amount of material dredged each year continues to rise not only in other countries but also in Thailand. Therefore, it is interesting application if dredged materials can be used as construction materials such as sanitary landfill liners.

This research focused on utilization of seabed dredged materials created during dredging operations as sanitary landfill liners, based on geo-environmental engineering viewpoint.

Statement of Problems

Some dredged materials are unsuitable to be used in construction, since they have such extremely high water content and low strength, therefore, stabilization of such dredged materials are needed prior to each application.

In this study, mechanical modification and chemical stabilization using cement and some pozzolanic admixtures, are proposed to improve the materials in order to achieve the recommended behaviors for the sanitary landfill liners; to support solid waste, to protect leakage of leachate and to protect groundwater from being contaminated, based on the geo-environmental engineering viewpoint.

Targets for soil stabilization are as follow;

- Shear strength must be good enough to support solid waste and mechanical equipment, strength at 28 days should be greater than 200 kN/m^2 or 2 kg/cm^2 as measured by the unconfined compression test.
- The coefficient of permeability must be lower than $1x10^{-7}$cm/sec for life cycle of 20 years.
- Durability tests are performed using linear shrinkage tests in accordance with BS 1377.

Therefore, it is important to control the soil liners with low hydraulic conductivity and shrinkage potential and adequate required shear strength.

Objectives

The main objectives of this study are:

1. To identify seabed dredged materials which are suitable for landfill liner.
2. To find a suitable and simple technique to modify properties of a dredged material, i.e.; to reduce an extremely high moisture content, for further stabilization.
3. To improve a pre-treated material by using cement and some pozzolanic materials, focusing on the dredged material properties for uses as liners in sanitary landfills.
4. To observe the reaction products and changes in microstructures of the treated dredged materials.

Scopes of Study

The seabed dredged material was obtained from the Gulf of Thailand, Samutprakan Province. The study consisted of laboratory tests on the improvement of dredged material based on the viewpoint of geo-environmental engineering.

1. In this study, dewatering technique was proposed in order to determine ranges of optimum mixing water content prior to chemical stabilization
2. Ordinary Portland Cement Type I and some pozzolanic material such as silica fume were used as stabilizers in this study.
3. Engineering properties of the treated materials such as permeability (7 and 28 days) and unconfined compressive strength (3, 7, 14 and 28 days) were performed in order to elucidate the degree of stabilization.
4. X-ray diffraction analysis (XRD) and Scanning Electron Microscopic Investigations (SEM) are performed in order to evaluate the reaction products and changes in microstructures of the treated dredged materials.

LITERATURE REVIEW

Seabed Dredged Material

Dredged materials are bottom sediments that have been dredged or excavated from improved navigation channels for ship to enter and leave ports efficiently, quickly, and safely.

Figure 1 Enlarging and deepening of navigation channels

According to U. S. Army (1987), there are several types of mechanical dredging techniques. Dipper dredges and clam shell dredges are the two most common. Mechanical dredges are rugged and capable of removing hard-packed materials or debris. They can be worked in tight areas and are efficient when large barges are used for long-haul disposal. Mechanical dredges have difficulty retaining loose, fine materials in buckets, and do not dredge continuously like pipeline dredges.

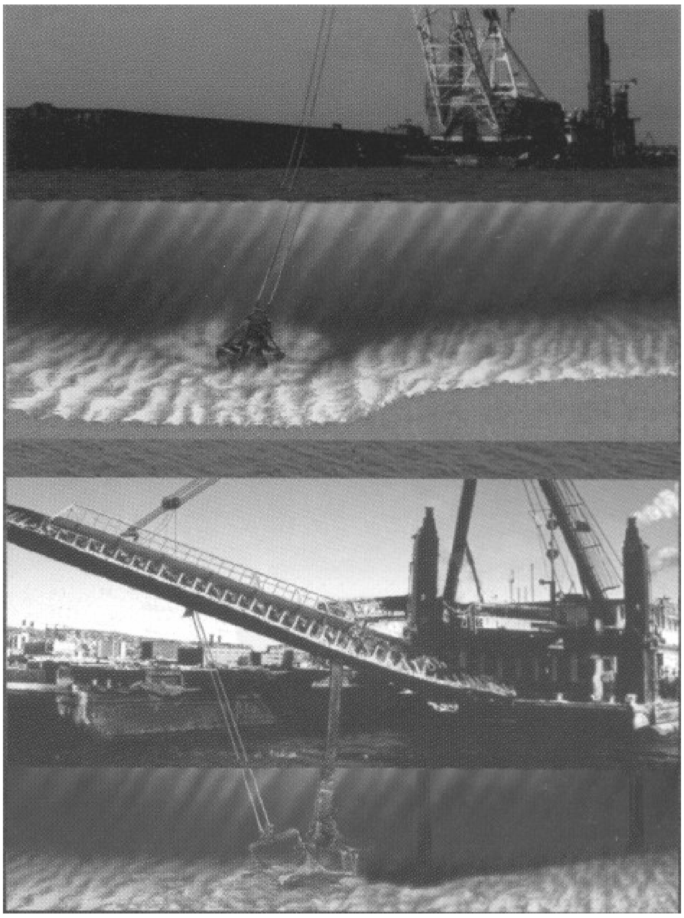


Figure 2 Mechanical dredges, dipper dredges and clam shell dredges

For hydraulic Dredges, there are two primary types of hydraulic dredging techniques: cutterhead pipeline dredge and self-propelled hopper dredge. Advantages of cutterhead pipeline dredges include their ability to excavate most materials, to pump directly to a disposal site, to dredge almost continuously, and to dredge some types of rock without blasting. However, cutterhead pipeline dredges have limited capability in rough weather; have difficulty with coarse sand in swift currents; and, for the most part, are not self-propelled.

Oweis and Khera (1990), dredged materials comprise natural sediments such as rocks, gravel, sands, silts and clays. These materials may be contaminated by various types of waste or runoff from land. The dredging generates a large amount of waste. About 20% of dredged materials are placed in landfills. These are filled hydraulically, placing slurry in dike containment areas. Water content of these slurries ranges from 200 to 300%. They consist primarily of organic silts and clays and may be contaminated with heavy metals and other pollutants.

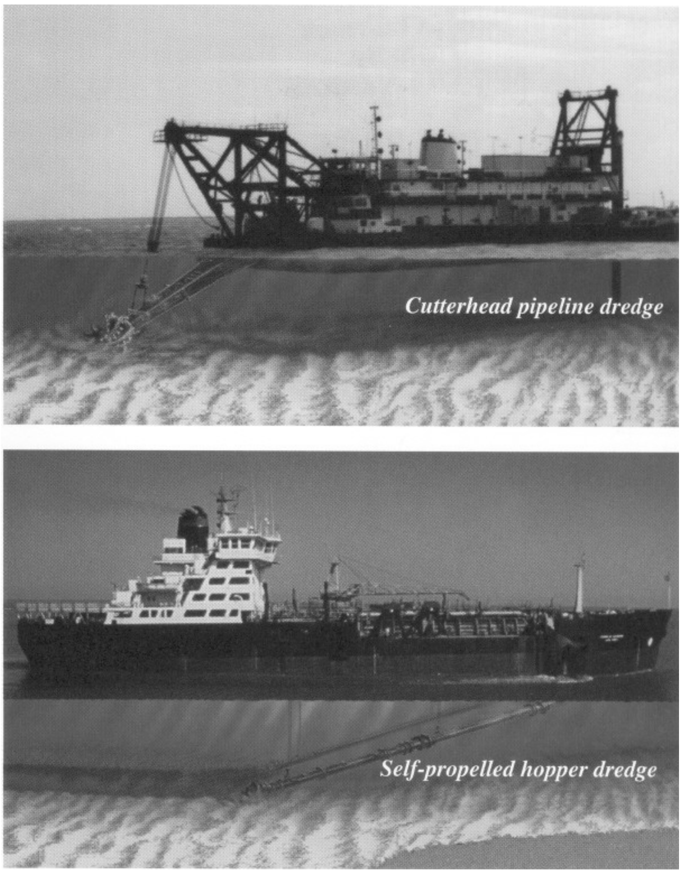


Figure 3 Hydraulic dredges, cutter head pipeline dredge and self-propelled hopper dredge

The fine particles of the dredged material are clays and silts of high compressibility. Because of their high compressibility and low strength they are the least desirable materials from a geotechnical engineering viewpoint. Because of its higher clay content, soil deposited from the lowest water-clay ratio will have the smallest bearing capacity. Overall about 85% of the dredge materials consist of particles smaller than sand and may contain a large proportion of organic silts and clays. Index properties of these materials are shown in table 1.

Table 1 Index properties of dredge materials

Description	Sand (%)	Silt (%)	Clay (%)	Organic (%)	w_n (%)	Ip	Gs
Toledo, Ohio	14-19	46-50	31-40	4-8	55-95	12-57	
Mobile, Alabama	7	18	75	5	100	35	2.72
Average, USA	16	50	33		80-120	15-55	2.65
West Germany	0-5	35-60	10-40				
Seawater	5-95	5-70	0-40		45-212	25-65	

Source: Oweis and Khera (1990)

Table 2 The chemical compositions of dredged material

Type	**Base**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO / MgO**	**Na_2O / K_2O**
Clay / Sand	Dredged material [1)]	58-42 %	8-13 %	4-6 %	3-23 %	3-4.5 %
Clay / Sand	Dredged material [2)]	65.55 %	14.86 %	6.01 %	3.29 %	2.73 %

[1)] Dredged material from Port of New York (USA.) , Columbia University in the City of New York

[2)] Dredged material from Ariake Sea (Japan) , H.Inoue, S. Kidera , N. Miura

Source: Oweis and Khera (1990)

Oweis and Khera (1990) referred the data to the Atterberg limit tests by Bromwell (1978). It expressed that all the points were plot close to the A line, except for a brackish water environment for which the liquid limit was somewhat higher. Plastic properties decrease when a soil was either air-dried, oven dried or freeze dried.

Chemical characteristics of dredged materials are reflected by their chemical compositions depending strongly on its mineralogy. The chemical compositions of dredged material are given as shown in Table 2.

Chemical Stabilization

Portland Cement is one of the most suitable materials used for stabilization. Cement stabilization differs from other chemical stabilization such as advantage uses, cementitious compounds, and hydration products. The Portland Cement stabilization can improve soil properties such as reducing LL and PI of the soil, increasing soil strength, reducing volume change (shrinkage and swelling), and improving permeability.

As Haussmann (1990) referred to Diamond and Kinter (1965), the shear strength of the stabilized soil gradually increases with time mainly due to pozzolanic reaction. Calcium hydroxide in the soil water reacts with the silicates and auminates (pozzolans) in the clay to form cementing materials or binder, consisting of calcium silicates and/or aluminate hydrates. The dissolved dissociated Ca^{++} ions react with the dissolved SiO_2 and Al_2O_3 from the clay partical's surface and from hydrated gels.

Haussmann (1990) suggested that cement is more effective than lime for uses as a stabilizer of cohesionless soil and that pozzolanic material such as fly ash could be used as filler for coarse grained material. With addition of some pozzolanic materials, it can result in the chemical stabilized reaction mechanisms of the cement-stabilized soil, as shown in Figure 4.

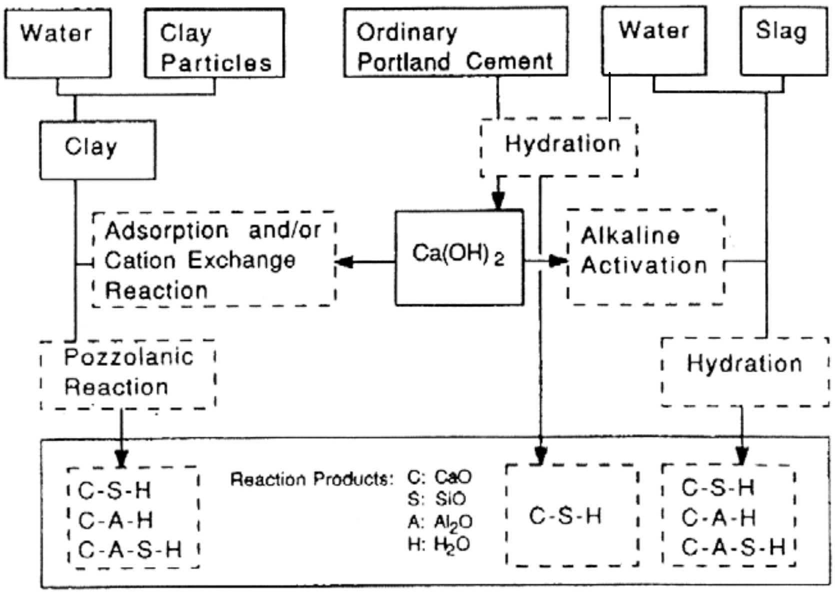


Figure 4 Chemical reactions between untreated soil and hardening material

Source: Haussmann (1990)

Haussmann (1990) mentioned the idea of soil cement structures from Mitchell and Jack (1966) as shown in Figure 5. It shows 3 steps of changes on soil cement structures.

1. In the compacted condition, the hydration reaction could not form but cement particles interfere between soil particles.

2. After short curing period, the cement hydration could generate. The results were cement gel interfering between voids of soil particle and released lime reacts with active soil silica and active soil alumina. The cation exchange reaction was formed during the reaction of released lime.

3. After long curing period, the cement hydration was complete. The cement gel was spread all of soil lump. It would make the soil strength increase with time.

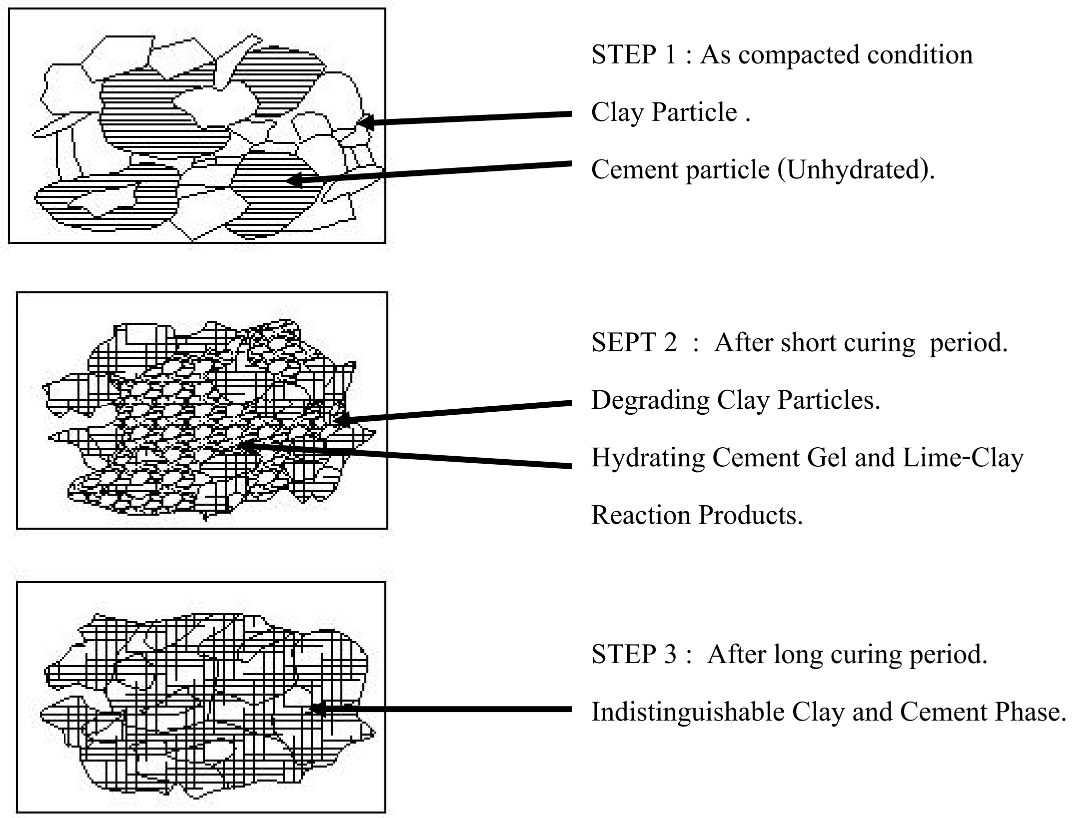


Figure 5 Soil cement structure as suggested by Mitchell and Jack (1966)

Pozzolanic Materials and Silica Fume

Researchers are always in search of waste materials that can be reutilized as a cement replacement material to improve its quality and reduce the cost. Concretes as well as soils stabilized with blended cements can have properties that are desirable for particular purposes. A number of other waste materials such as silica fume are also being used extensively as a cement replacement material.

Silica fume is a by-product of producing silicon metal or ferrosilicon alloys. One of the most beneficial uses for silica fume is in concrete. Because of its chemical and physical properties, containing approximately 95% SiO_2 and a very high surface area, it is a very reactive pozzolan. Concrete containing silica fume can have very high strength and can be very durable. The physical properties and the chemical compositions of silica fume are illustrated in Table 3.

Table 3 The physical properties and the chemical compositions of silica fume

Physical properties	
Particle size (typical)	< 1 µm
Bulk density (as-produced)	130 to 430 kg/m^3
(slurry)	1320 to 1440 kg/m^3
(densified)	480 to 720 kg/m^3
Specific gravity	2.2
Surface area (BET)	13,000 to 30,000 m^2/kg
Chemical compositions	**% by wt.**
SiO_2	95.10
Al_2O_3	0.09
Fe_2O_3	0.10
CaO	0.24
MgO	0.43
Na_2O	0.23
K_2O	0.93

Landfill Liners

A sanitary landfill is a containment system for waste disposal. The site of the landfill must be designed based on geological, hydrological, and environmental suitability. A landfill must not be an open dump due to nuisance conditions such as smoke, odor, insect and bird problems. Good planning and engineering supervision are required to design and construct a landfill that serves good functions especially prevention of leachate into the ground water. The major sections consist basically of a top cover, side and bottom liners. Each of these main components in turn comprises a system of barrier and drainage layers (Qian *et al.*, 2002).

Recently, concepts of Environmental geotechnology can provide sound design principles and construction procedures which ensure short- and long-term stability and performance of landfill. The strength, landfill stability, permeability and durability of the lining system are of important factors for well engineered landfill to be achieved. Precise quality control of construction materials is considered important and has to be performed carefully (Qian *et al.*, 2002).

The U.S. Environmental Protection Agency (EPA) and the various states have detailed regulations governing landfill siting, design, construction, operation, groundwater and gas monitoring, landscaping plan, closure monitoring, and maintenance for 30 years. Figure 6 illustrates a schematic diagram of a Municipal Solid Waste (MSW) landfill containment system.

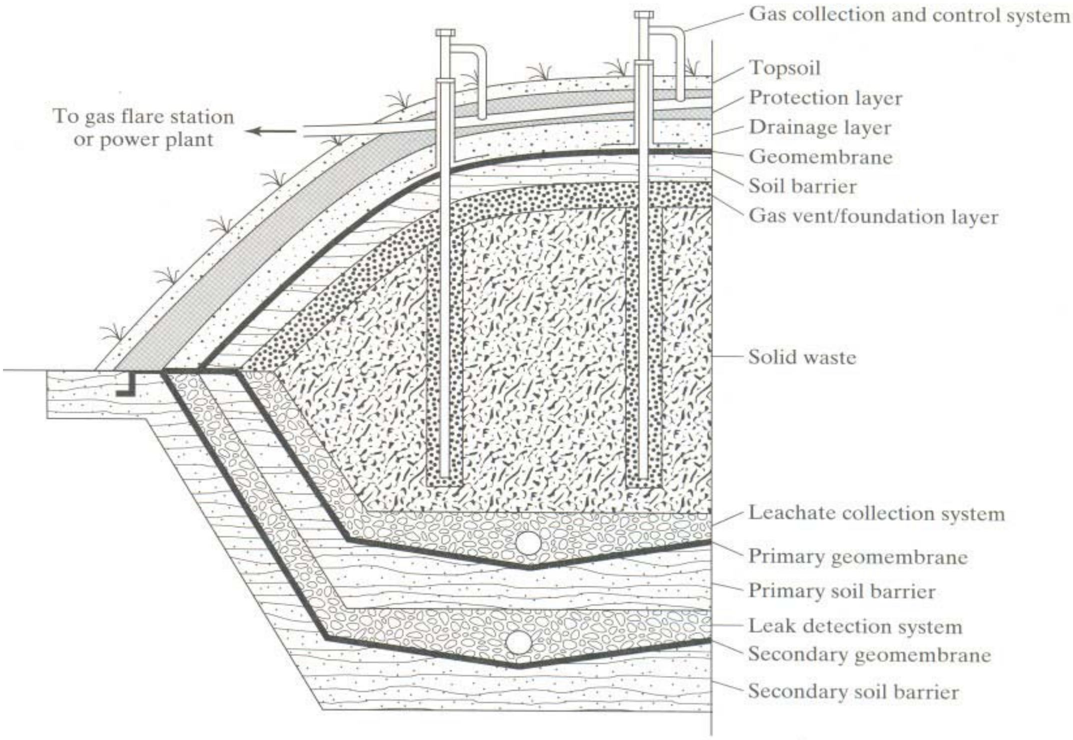


Figure 6 Schematic Diagram of a Municipal Solid Waste Landfill Containment System

Source: Qian *et al.* (2002)

Specifications of Landfill Liners

As it was refered by Qian *et al.* (2002), Daniel (1993) suggested the minimum requirements to achieve a coefficient of permeability (k < 1 x10^{-7} cm/s) for general soil liners as follows;

- Plasticity index 7 - 10 %
- Percentage of fines 20 - 30 % (particles passing No. 200 sieve)
- Percentage of gravel 30 % (particles retained on No. 4 sieve)
- Maximum particle size 25 - 50 mm.

Daniel and Wu (1993) suggested that required shear strength for clay liner to support the maximum bearing stress in a landfill project should be greater than 2.0 kg/cm^2 when measured by the unconfined compression test (UCS) or unconsolidated undrained triaxial (UU) test. The required shear strength given by Daniel and Wu (1993) was calculated based on an average unit weight of solid waste (10 kN/m^3).

Daniel and Wu (1993) found that for compacted clayey soil an acceptable limiting value of volumetric strain to prevent desiccation for this soil should be less than or equal to 4%. Their experimental result is shown in Figure 7.

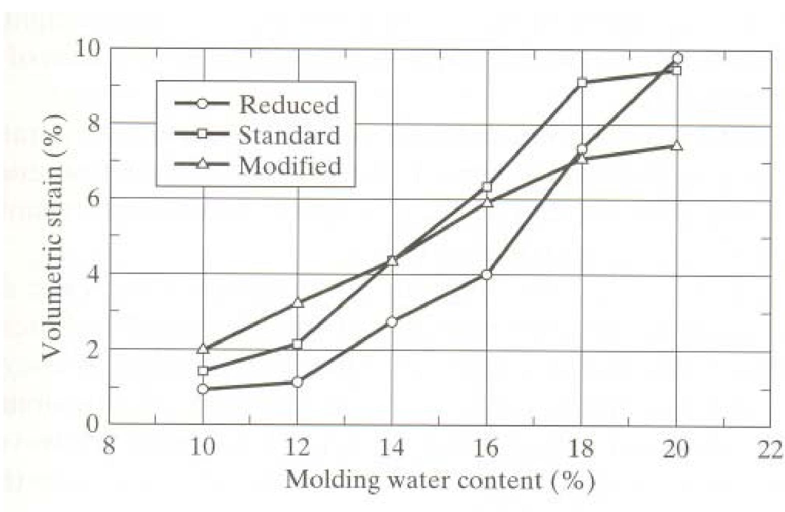


Figure 7 Volumetric Strain Caused by Drying versus Molding Water Content

Source: Qian *et al.* (2002)

Omidi, Prasad, Thomas and Brown (1994) reported that the amendments of either 4% lime or 40 to 50% sand resulted in reduced shrinkage and increased hydraulic conductivity. The addition of 3% cement reduced shrinkage by up to 50% and simultaneously reduced hydraulic conductivity by 2 orders of magnitude. Thus, amendment of clay soils having a high shrink-swell potential with Type I Portland Cement has the greatest poetential for field application as an amendment to help maintain the integrity and improve the long term performance of compacted clay liners.

This study proposed techniques of stabilization and attempts to investigate the degree of improvement for the cement-stabilized dredged materials in order to obtain the properties which conform to requirements for landfill liner. Specifications of landfill liners used in this study can be summarized in Table 4.

Table 4 Guidelines for selection of material used as landfill liner for this study and as summarized by Jirathanathaworn (2003).

<table>
<tr><td rowspan="2">Properties of soil liners</td><td colspan="2">Guideline for material used as landfill liner</td></tr>
<tr><td>Targets for this study</td><td>Jirathanathaworn (2003)</td></tr>
<tr><td>Plasticity index (PI)</td><td>10 - 30 %</td><td>10 - 30 %</td></tr>
<tr><td>Compaction method</td><td>Non compaction</td><td>Standard Proctor compaction</td></tr>
<tr><td>Water content</td><td>Predetermined by dewatering</td><td>0 - 2 % wet of optimum water content</td></tr>
<tr><td>Coefficient of permeability</td><td>$< 1 \times 10^{-7}$ cm/s</td><td>$< 1 \times 10^{-7}$ cm/s</td></tr>
<tr><td>Unconfined Compressive strength (UCS tests)</td><td>> 2.0 kg/cm^2</td><td>> 2.0 kg/cm^2</td></tr>
<tr><td rowspan="2">Volumetric strain</td><td>$< 4\%$
(for the most preferable)</td><td rowspan="2">$< 4\%$</td></tr>
<tr><td>$< 10\%$
(target for this study)</td></tr>
</table>

MATERIALS AND METHOD

Apparatus

The experimental apparatus and devices used in this study are listed below.

1. Atterberg's limit device
2. Permeability test device
3. Compressive strength test machine
4. Compaction standard mold (ϕ4" x 4.6") and standard hammer (5.5lbs.)
5. Cylindrical mold (ϕ 2" x 4") and hammer (1.8 lbs.)
6. Scanning Electron Microscope (JEOL JSM-5600LV) for microstructures investigation
7. X-ray Diffractometer (Philips X'Pert) for chemical analysis

Materials

1. Dredged material

The representative dredged material of this research was collected during dredging operation in Samutprakan province (Figure 8). Due to the extremely high water content of the dredged material, the suitable dewatering technique was to be applied.

2. Stabilizers

- Ordinary Portland Cement Type 1, and
- Silica fume (a byproduct of silica metal furnace producing), with
- Fine sand as replacement materials for modifying soil gradation

Figure 8 Dredging operation in Samutprakan province

Testing Procedures

Flow chart of testing procedures of this study can be illustrated in Figure 9.

1. Onsite Dewatering

Seabed sludge was collected and put in a container. Density of the sludge was measured using mud balance. As shown in Fig. 10, onsite dewatering was performed to drain out surplus water and then the container was sealed, preventing loss on moisture content.

2. Laboratory Dewatering

Since the onsite dewatered dredged materials still contained very high water content, the range of suitable water contents should be obtained prior to chemical stabilization. This study therefore proposed a laboratory dewatering technique as shown in Fig.11. The predetermined water contents were set to be 1.1 – 1.4 times Liquid Limits in order to assure good workability and homogeneous mix as well as strength development. During the onsite and laboratory dewatering processes, water contents and bulk densities are measured timely; the bulk densities are measured by mud density test.

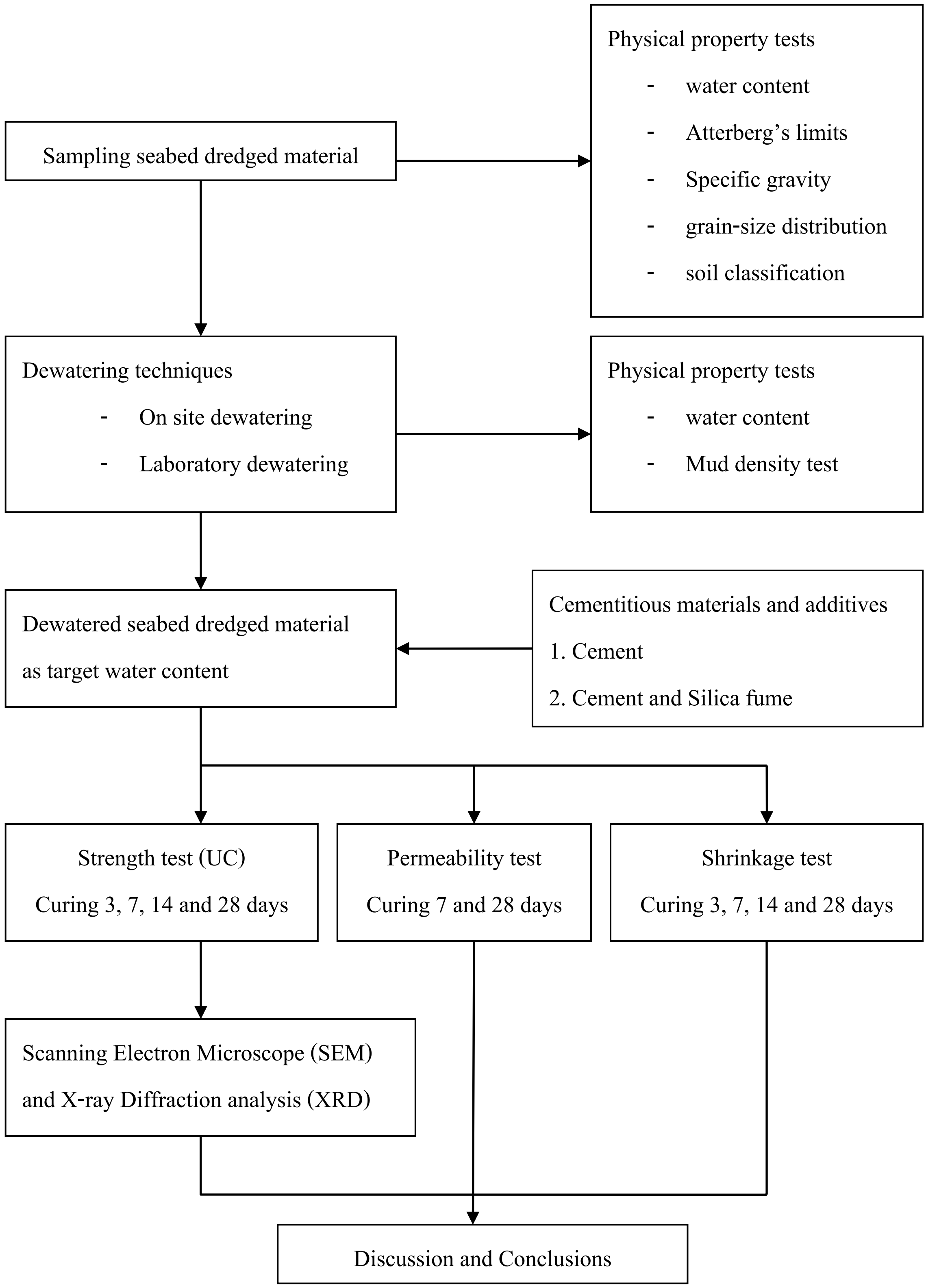


Figure 9 Flow chart of Research Procedures

Figure 10   On site dewatering apparatus

Figure 11 Laboratory dewatering apparatus

3. Trial Mixes and Specimen Preparation

The dredged materials with predetermined water contents were subjected to perform trial mixes. The main stabilizer used in this study was Portland Cement Type I. In addition, Silica Fume was a pozzolanic material used to partially replace the cement content. In certain mixtures, fine sand was also mixed in order to modify the overall gradation of the dredged materials. Mixtures and numbers of test specimen are summarized in Table 5. Based on the standard of JSF T821-1990 – practice of making and curing non-compacted stabilized soil specimens, specimens were prepared by placing the mixtures in a cylindrical mold (ϕ 2” x 4”) and then sealed in plastic bags and cured by storing in the temperature-control room.

4. Unconfined Compressive Strength tests

The unconfined compression tests were performed in accordance with ASTM D2166-85 (Figure 12). The tests were performed after curing periods of 3, 7, 14 and 28 days. After strength tests, water contents were tested in accordance with ASTM D 2216-92.

5. Permeability Tests

Specimens were compacted in a standard cylindrical mold (ϕ4” x 4.6”). The permeability tests were performed after curing time of 7 and 28 days. The tests were performed by constant head method (ASTM D2434-68) under constant water pressure of 1 kg/cm^2 as shown in Figure 13.

6. Linear shrinkage tests

Linear shrinkage tests of the specimens being cured for 3, 7, 14 and 28 days were performed in accordance with BS 1377 testing standard. Linear shrinkage (Ls) was converted to volumetric shrinkage (Sv) using the following equation.

$$Sv = 1 - (1 - Ls)^3$$

Figure 12 Unconfined compression test apparatus

Figure 13 Permeability test apparatus

Figure 14 Volumetric shrinkage test apparatus

7. Scanning Electron Microscopic (SEM) investigations

Scanning Electron Microscope (SEM) were used to examine the microstructures of both untreated soil and the stabilized dredged materials for curing times of 7, 14, 28 days. The Scanning Electron Microscope (SEM) investigations were performed on a JEOLJSM-5600LV. After, strength testing samples were desiccated and mechanically broken with an approximate size of 5 mm x 5 mm to expose a surface for viewing. The specimens were then placed on an aluminum stub and coated by gold (Au) to make samples electric-conductible before installing in a vacuum chamber for microscopic investigations of microstructures (Figure 15).

8. X-ray Diffraction (XRD) analysis

The X-ray diffraction patterns were obtained on a Philips X'Pert diffractometer (Figure 16), using Cu as a target inside X-ray tube and Ni as a filter. X-ray diffractometer was used to examine the compounds of the specimens obtained after strength tests at 3, 7, 14, 28 days.

Figure 15 Scanning Electron Microscope (JEOL JSM-5600LV)

Figure 16 X-ray Diffractometer (Philips X’Pert) for chemical analysis

Table 5 The numbers of test specimens according to test variables

Unconfined compressive strength test	
Soil type :	Dewatered seabed dredged materials
Stabilizer :	Ordinary Portland Cement Type I
Curing time :	3, 7, 14, and 28 days
Quantity of sample / specific curing time :	3 samples
% of silica fume replacement :	5, 10, and 15 %
% of additional sand :	5%
Quantity of cement :	100, 125, 150, 200, and 250 kg/m^3
Total number of specimens :	120 samples
Permeability Test	
Soil type :	Dewatered seabed dredged materials
Stabilizer :	Ordinary Portland Cement Type I
Curing time :	7, and 28 days
Quantity of sample / specific curing time :	3 samples
% of silica fume replacement :	5, 10, and 15 %
% of additional sand :	5%
Quantity of cement :	100, 125, 150, 200, and 250 kg/m^3
Total number of specimens :	60 samples
Linear Shrinkage Test	
Soil type :	Dewatered seabed dredged materials
Stabilizer :	Ordinary Portland Cement Type I
Curing time :	3, 7, 14, and 28 days
Quantity of sample / specific curing time :	3 samples
% of silica fume replacement :	5, 10, and 15 %
% of additional sand :	5%
Quantity of cement :	100, 125, 150, 200, and 250 kg/m^3
Total number of specimens :	120 samples

Table 5 The numbers of test specimens according to test variables (Cont'd)

For scanning electron micropic	
Specimens from unconfined compressive strength test	
- curing time 3 days	6 samples
- curing time 7 days	7 samples
- curing time 14 days	7 samples
- curing time 28 days	7 samples
Total number of specimens :	27 samples

Places and Duration

1. Places

Experiments are performed mainly in the laboratory as listed below

- Geotechnical Engineering Laboratory, Department of Civil Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand.
- Materials Engineering Laboratory, Department of Materials Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand

2. Duration

Duration of research was done from October, 2005 to October, 2006.

RESULTS AND DISCUSSIONS

1. Physical Properties of Untreated Seabed Dredged Materials

Naturally, untreated seabed dredged materials were in slurry state with dark color and strongly organic and salty smell. They contain very high water content (w_n approximately 200 - 300%). Their particle compositions were 2–5 % sand, 25-30% silt and 60-65% clay as shown the grain size distribution curves in Figure 17. According to the Unified Soil Classification System (USCS), they were classified as CH (clay with high plasticity and small amount of fine sand). In addition, based on the American Association of State Highway and Transportation Officials (AASHTO), they were classified as A-7-5 (clay with high liquid limit and high shrinkage-swelling). Physical Properties of untreated dredged materials are summarized in Table 6.

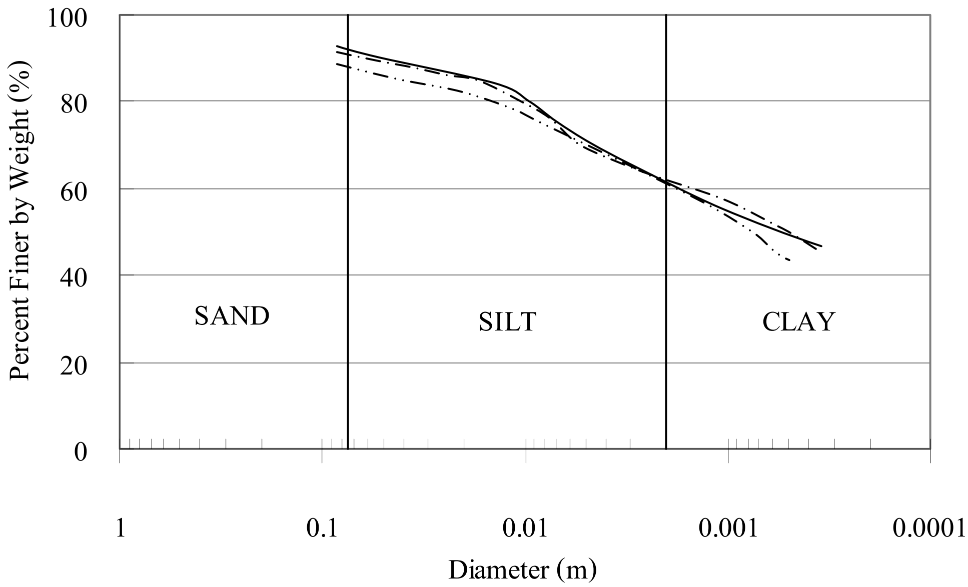


Figure 17 Grain size distribution of untreated seabed dredged materials

Table 6   Physical properties of untreated dredged materials

Physical Properties of Seabed Dredge Material	
Soil Classification (USCS)	CH
Soil Classification (AASHTO)	A-7-5
Sand (smaller than 0.475 mm. and larger than 0.075 mm.), %	2 - 5
Silt (smaller than 0.075 mm. and larger than 0.002 mm.), %	25 - 30
Clay (smaller than 0.002 mm.), %	60 - 65
Natural Water Content (w_n) , %	200 - 300
Bulk Density (γ_t), t/m^3	1.27
Specific Gravity (Gs)	2.62-2.72
Liquid Limit (LL), %	99.64 – 101.69
Plastic Limit (PL), %	35.81 – 37.95
Shrinkage Limit (SL), %	18.67
Plasticity Index, PI	63.79

2. Engineering Properties of Untreated Seabed Dredged Materials

Figure 18 and Figure 19 show the results of consolidation test of untreated seabed dredged materials, using relatively low applied stresses in the range of 0.010 to 0.155 kg/cm^2.

The consolidation parameters can be summarized as follows:

- Void ratio (e_0) = 5.13
- Compression index (Cc)= 1.6 - 1.8
- Swell index (Cs)= 0.3
- Coefficient of consolidation (Cv)=0.405 x 10^{-4} to 1.771 x 10^{-4} cm^2/sec

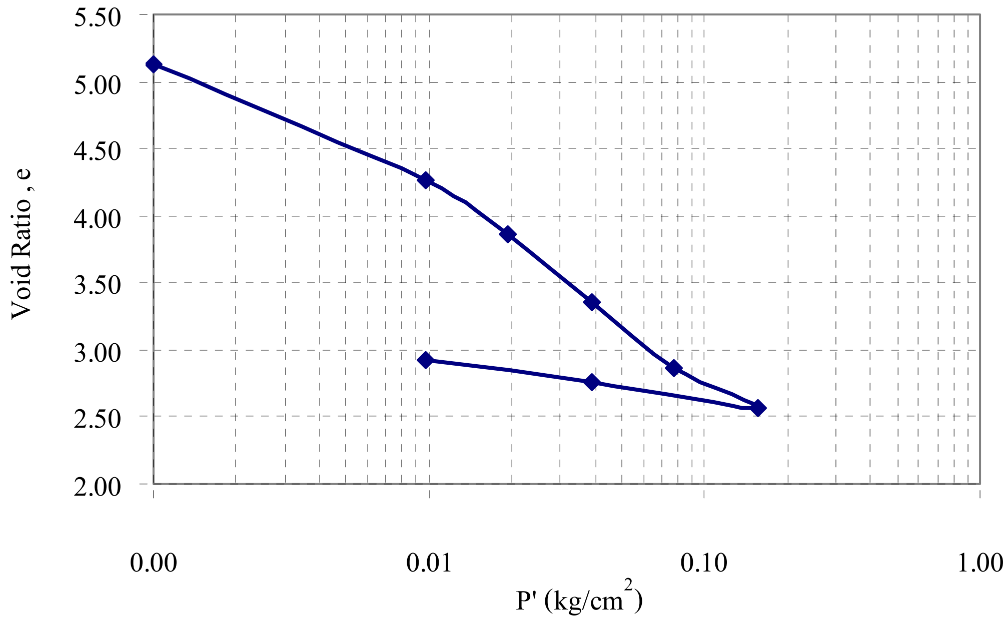


Figure 18 Void ratio and effective axial pressure relationship from consolidation test

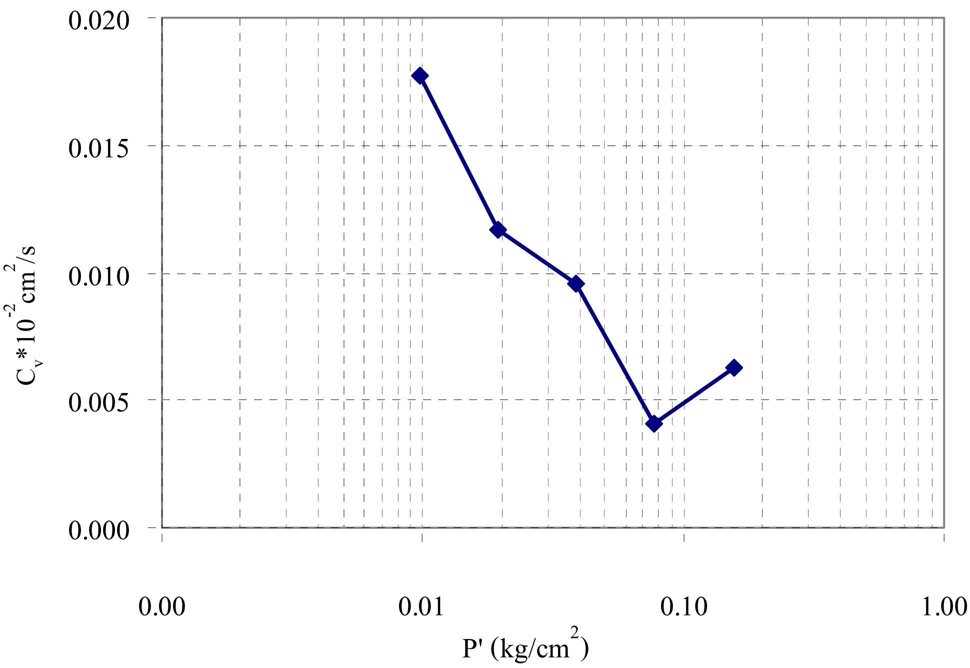


Figure 19 Coefficient of consolidation and effective axial pressure relationship from consolidation test

The results based on the property tests of seabed dredged materials in natural condition show that their physical and engineering properties were not suitable for construction materials. Untreated seabed dredged materials after onsite dewatering were more viscous but still in liquid state which induced very low shear strength. In addition, it was obvious that the untreated seabed dredge materials had high compressibility. Therefore, the combined concepts of mechanical modification and chemical stabilization were proposed in this study to improve their major properties prior to utilization.

3. Targets of Improvement

Regarding guideline and suggestions for selection of material used as landfill liners; the unconfined compressive strength (UCS) should be greater than 2 kg/cm^2, the coefficient of permeability (k) should be less than 10^{-7} cm/sec (Jirathanathaworn, 2003), and in case that the liners are susceptible to environmental change such as wetting and drying, the acceptable value of volumetric shrinkage to prevent desiccation cracking for clay liner is less than or equal to 4%. However, other applications such as subbase for pavement are also recommended based on the improved properties of the stabilized materials.

4. Concepts of Improvement

In this study, the following technical concepts were proposed, as shown in Table 7, in order to solve the problems of extremely soft soil, and in order to obtain sufficient improvement and new construction materials.

Table 7 Technical concepts of Improvement of the seabed dredge materials

Step	Process	Purpose
1	On Site Dewatering	To reduce the surplus water in the seabed dredged materials
2	Laboratory Dewatering	To adjust and obtain the suitable water content before mixing
3	Mixing with cement / Silica fume	To improve physical and engineering properties as required specifications
4	Sand modification	To modify the seabed dredged materials in term of volumetric shrinkage potential

5. Improvement by On Site Dewatering Process

On site dewatering apparatus was designed in order to simply reduce the surplus water in the seabed dredged materials just after material collection. This apparatus applied load by placing weight approximately 56 kg (0.029 kg/cm^2) on top of container and sustained loading for 24 hrs. By this process, the slurry became more viscous. Water content significantly reduced and could be lowered to 190% - 150%.

6. Improvement by Laboratory Dewatering Process

Laboratory dewatering apparatus was introduced to further lower water content. The target water contents during laboratory dewatering were within the range of 1.4 to 1.1 times Liquid Limits (approximately 140% and 110%, respectively), in order to assume that at these target water content, good mixing efficiency (consumed relatively low energy), homogeneous mixtures and required properties could be achieved.

This apparatus applied steady pneumatic load equal 400 kg (0.168 kg/cm^2) via hydraulic jack installed under the reacting frames. The dredged material was placed in a large cylindrical tank (55 cm. in diameter and 65 cm. height). During the process of dewatering, the water content could be reduced from approximately 190% to 137% for 48 hours loading period and to 108% for 96 hours loading period.

7. Properties of Improved Seabed Dredged Materials by Dewatering Process

7.1 Bulk densities of dewatered seabed dredged materials

The bulk densities of dewatered seabed dredged materials as measured by mud density test and as calculated using phase relationships are as shown in Figure 20. The dewatered seabed dredged material's water contents were significantly reduced from approximately 190% to 108% while the bulk densities were increased in the range of 1.27 to 1.412 t/m^3. The correlation of water content and subsequent bulk densities can be illustrated in Figure 20.

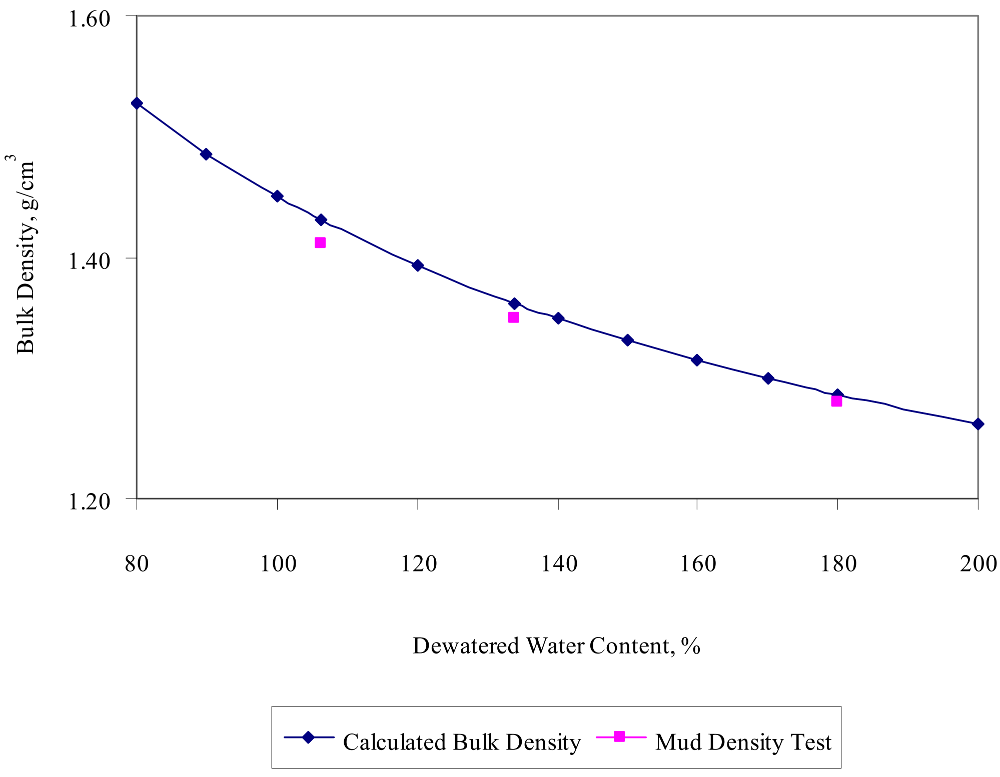


Figure 20 Bulk densities and dewatered water content

7.2 The volumetric shrinkage of dewatered seabed dredged materials

The volumetric shrinkages, as measured on dewatered seabed dredged samples, seemed to be very high and may cause severe desiccation cracking when samples were dried.

Table 8 Volumetric shrinkage of dewatered dredge materials

Water content (%)	Volumetric Shrikage (Sv) (%)	Remarks
209.33	123.89 [1)]	Calculated volumetric shrinkage. Natural water content causes extreme desiccation crack.
137.87	56.76	Dewatered water content for subsequent trial and investigate the improvement effects of cement stabilization.
108.99	51.09	Dewatered water content for subsequent trial and investigate the improvement effects of cement stabilization.
100.67	68.01	Calculated from liquid limit
52.33	4 [1)]	Required water content to optimum volumetric shrinkage. High degree dewatering.

[1)] Based on average Liquid Limit = 100.67 % , $\gamma_d = 0.676$ t/m^3

$S_v = (V_{LL} - V_f) / V_{LL}$, $V_{LL} = V_i - [(w_i - w_L)W_s/\gamma_w]$

As shown in Table 8, the most suitable water contents which could prevent desiccation cracking of dewatered seabed dredge materials were 50.5 % - 52.3 %. It was expected that water contents within this range would exist when the dewatered seabed dredge material almost complete their primary consolidation. This process may certainly take long period of loading. Although, these suitable water content (50.5 % - 52.3 %) could be reached, other difficulties occurred since it consumed high energy for mixing and thus made it difficult to produce homogeneous mixture (i.e., mixing dewatered seabed dredged material and cement).

Therefore, it was believed that the combined concepts of improvement; dewatering, and physical modification and chemical stabilization could compensate all requirements.

7.3 Shear strength of dewatered seabed dredged materials

The shear strengths of the dewatered seabed dredged materials were performed by using vane shear proctor, the average undrained shear strength was approximately 0.27 kg/cm^2.

8. Improvement by Cement Stabilization

Cement stabilization has been practically used for a long time and considered as one of the most successful stabilizer due to increasing of shear strength, reducing of compressibility and permeability, and increasing volume stability against shrinkage. Cement stabilization was applied in this study. The fundamental trial mixes are shown in Table 9.

Table 9 Mixtures and symbols of cement stabilization

Symbol	Water Content (%)	Stabilizer ingredients			w / c ratio	Sand content,%
		Content,kg/m^3	% cement	% Silica Fume		
SC137/250	137.87	250	100	0	3.08	0
SC137/200	137.87	200	100	0	3.85	0
SC137/150	137.87	150	100	0	5.14	0
SC108/150	108.99	150	100	0	4.91	0
SC108/125	108.99	125	100	0	5.89	0
SC108/100	108.99	100	100	0	7.36	0

9. Unconfined Compressive Strength of Improved Seabed Dredged Materials by Cement Stabilization

The results from unconfined compressive strength test of dewatered seabed dredged material mixed with cement; SC108/100, SC108/125, SC108/150, SC137/150, SC137/200, and SC137/250; revealed that the strength increased with curing time. At early curing times (3 to 14 days), strengths increased rapidly. In addition, the strengths increased slightly at long curing time (14 to 28 days), as shown in Figure 21 and Figure 22.

As shown in Figure 21, SC108/100 has the average strength, 1.00 kg/cm^2 at 7 days curing time, 1.2 kg/cm^2 at 14 days curing time, and 1.47 kg/cm^2 at 28 days curing time. The results revealed that strengths gained in a uniform rate for all curing time. Strengths of SC108/100 were lower than all mixtures and lower than the required strength (2 kg/cm^2) for all curing time.

For SC108/125, the strengths also gained in a slowly increasing rate for all curing time. The average strength at 7 days curing time is 2.21 kg/cm^2, at 14 days curing time is 2.67 kg/cm^2, and at 28 days curing time is 3.42 kg/cm^2. It could be observed that the average strength at 7 days curing time was higher than the required strength (2 kg/cm^2).

The strengths of SC108/150 increased rapidly and higher than SC108/100 and SC108/125 at early curing time. However, the strengths of this mixture increased slightly at long curing time. The average strength of this mixture increased to 2.70, 3.97, and 5.01 kg/cm^2, at 7, 14, 28 day respectively.

As shown in Figure 22, the average strength of SC137/150 at 3 days curing time was 2.91 kg/cm^2. The average strength at 7 days curing time increased to 4.92 kg/cm^2, at 14 days curing time was 5.59 kg/cm^2. Then the average strength at 28 days curing time steadily increased to 6.40 kg/cm^2. The average strength at 3 days curing time was also higher than the required strength (2 kg/cm^2).

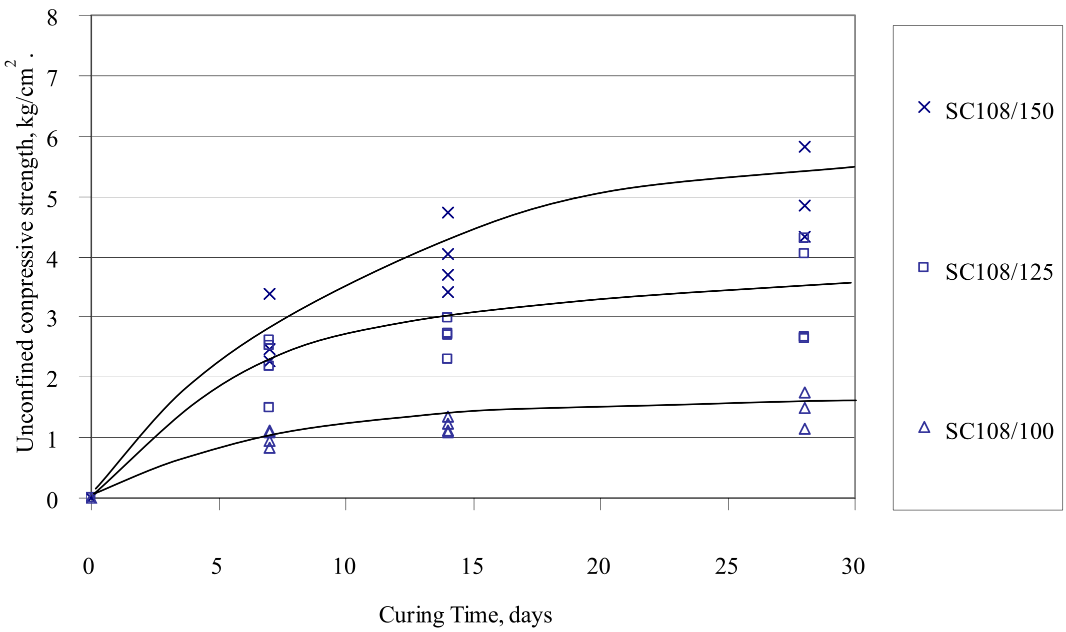


Figure 21 Unconfined compressive strength of cement mixed dredged materials with curing time (initial water content before mixing was 108.99 %)

For SC137/200, the average strength at 3 days curing time was 4.25 kg/cm^2, at 7 days curing time was 6.11 kg/cm^2, at 14 days curing time is 7.01 kg/cm^2, and then slightly increased to 11.25 kg/cm^2 at 28 days curing time. It could be observed that the required strength (2 kg/cm^2) could be satisfied by the average strength of SC137/200 at 3 days curing time.

SC137/250 obtained the highest strength when compared with all mixtures for all curing times due to the highest cement mixed proportion. The average strength at 3 days curing time was 8.01 kg/cm^2, at 7 days curing time was 10.61 kg/cm^2, and then the average strength steadily increased from 13.78 kg/cm^2 (at 14 days curing time) to 14.02 kg/cm^2 (at 28 days curing time). The average strength at 3 days curing time was higher than the required strength (2 kg/cm^2).

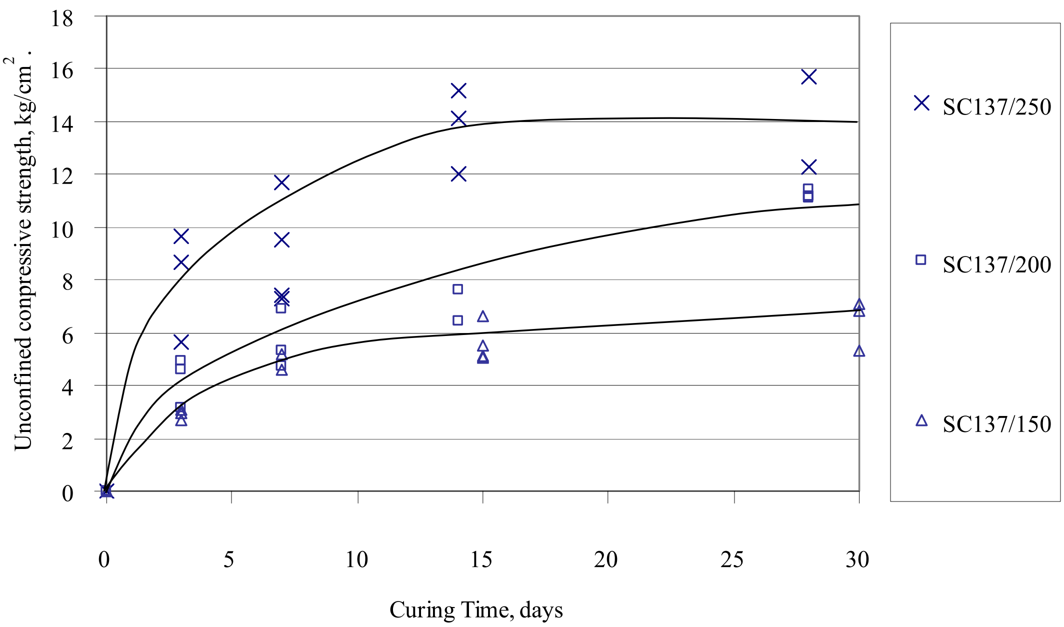


Figure 22 Unconfined compressive strength of cement mixed dredged materials with curing time (initial water content before mixing was 137.87%)

It could be concluded that the strength of higher cement content mixtures were significantly higher for all curing time and it can be ranked from SC108/100, SC108/125, SC108/150, SC137/150, SC137/200 and SC137/250. Markedly increasing rates of strength at early curing time were due to increase in cement content. While, the strength seemed to be more uniform at longer curing time, it was clear that the strength development of seabed dredge depended on not only cement content but also the initial water content before mixing.

For initial water content before mixing at 108.99% with a low to medium ratio of cement content (100-150 kg/m^3), the strength of these mixtures (SC108/100, SC108/125, and SC108/150) increased linearly with increase in cement content as shown in Figure 23. For initial water content before mixing at 108.99% with a medium to high ratio of cement content (150-250 kg/m^3), as shown in Figure 24, the strength of these mixtures (SC137/15, SC137/200 and SC137/250) significantly increased when cement content was greater than 200 kg/m^3.

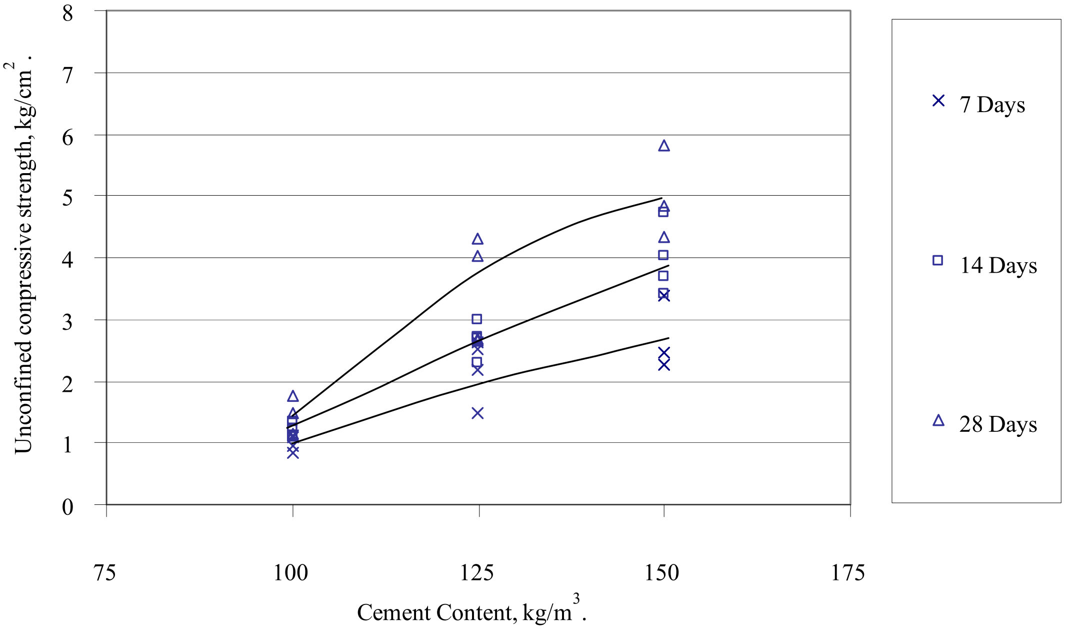


Figure 23 Unconfined compressive strength of cement mixed dredged materials with cement content (initial water content before mixing was 108.99%)

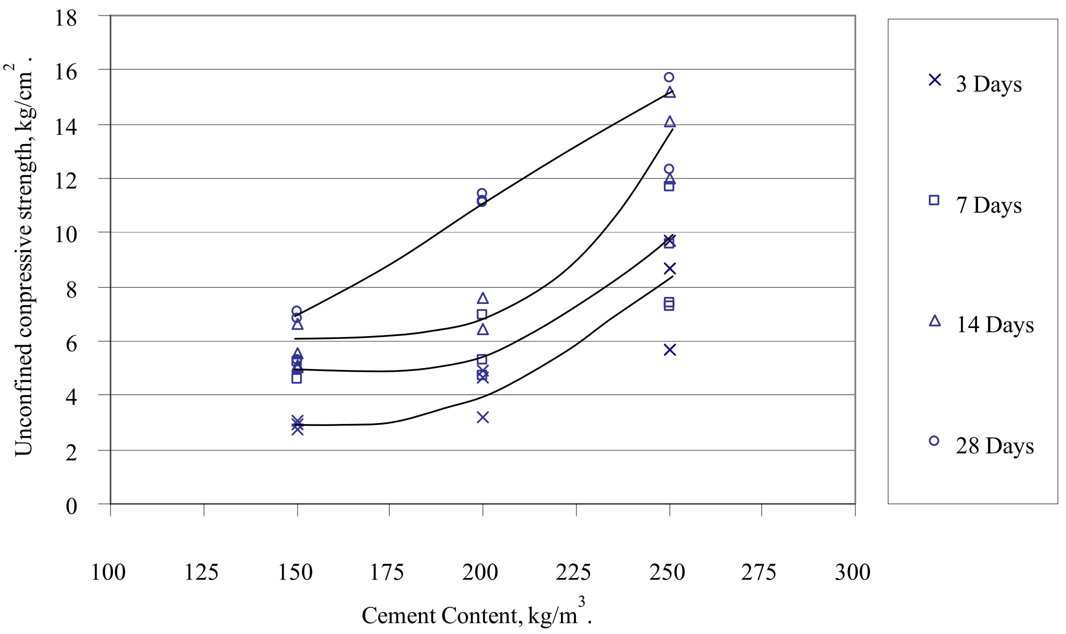


Figure 24 Unconfined compressive strength of cement mixed dredged materials with cement content (initial water content before mixing was 137.87 %)

Therefore, analyses based on the water to cement ratio (w/c) were performed to estimate the strength development in this study. As illustrated in Figure 25, the strength for 7, 14 and 28 days could be evaluated as expressed by the following equations:

q_u (7 days) $= 0.40 (w/c)^2 - 5.94(w/c) + 23.22$ … eq.1

q_u (14 days) $= 0.70(w/c)^2 - 9.97(w/c) + 37.12$ … eq.2

q_u (28 days) $= 0.59(w/c)^2 - 9.19(w/c) + 37.22$ … eq.3

In order to meet the requirement of strength (2 kg/cm^2) for use at landfill liner, the recommended w/c ratio should be with in a range of 5.5-6.5.

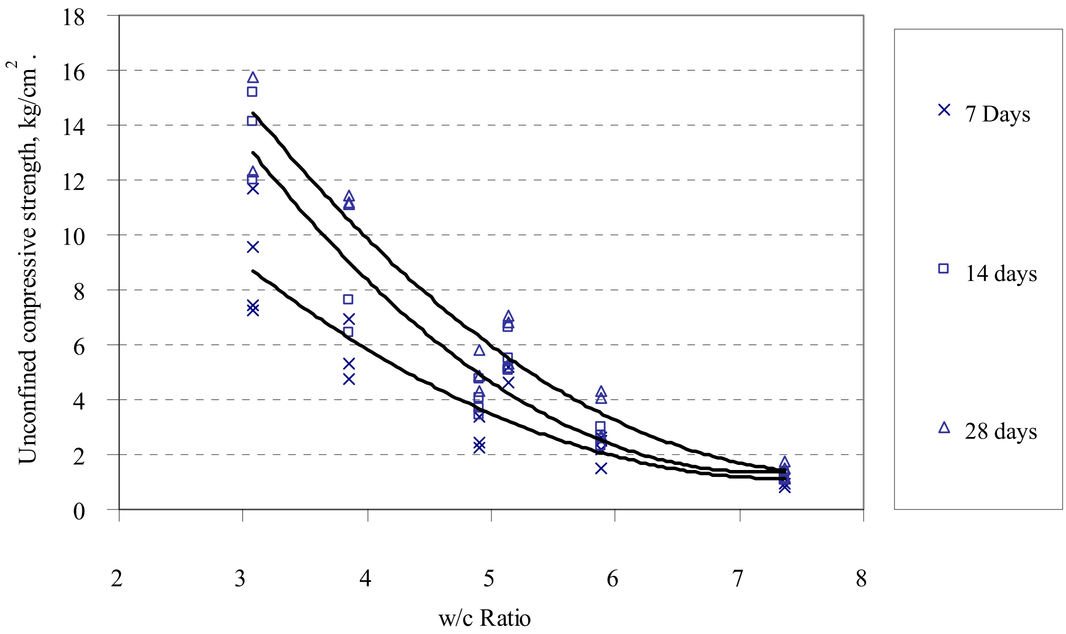


Figure 25 Unconfined compressive strength of cement mixed dredged materials with w/c ratio.

10. Coefficient of Permeability of Improved Seabed Dredged Materials by Cement Stabilization

Based on the results of permeability test, Figure 26 and Figure 27 revealed that the coefficients of permeability of cement-stabilized dewatered seabed dredged materials markedly decreased for all cement contents and lower than an average coefficient of permeability at 5.54×10^{-7} cm/sec dewatered seabed dredged material could be lowered about 10 times after 7 days curing time. It was evident that the coefficients of permeability at early curing time decreased as cement content increased.

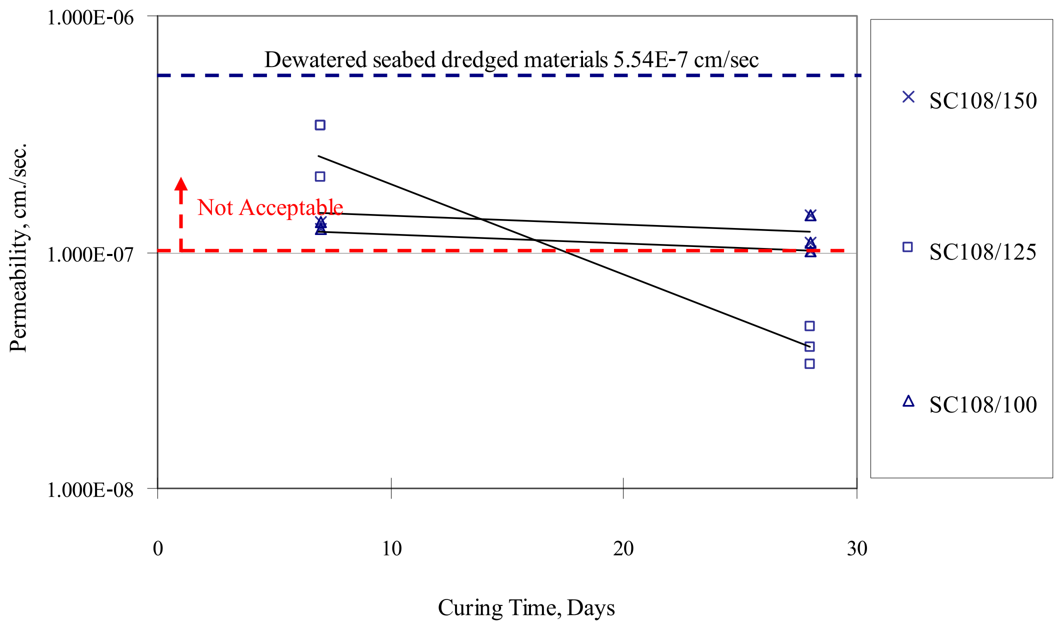


Figure 26 Permeability of cement mixed dredged materials with curing time (initial water content before mixing was 108.99 %)

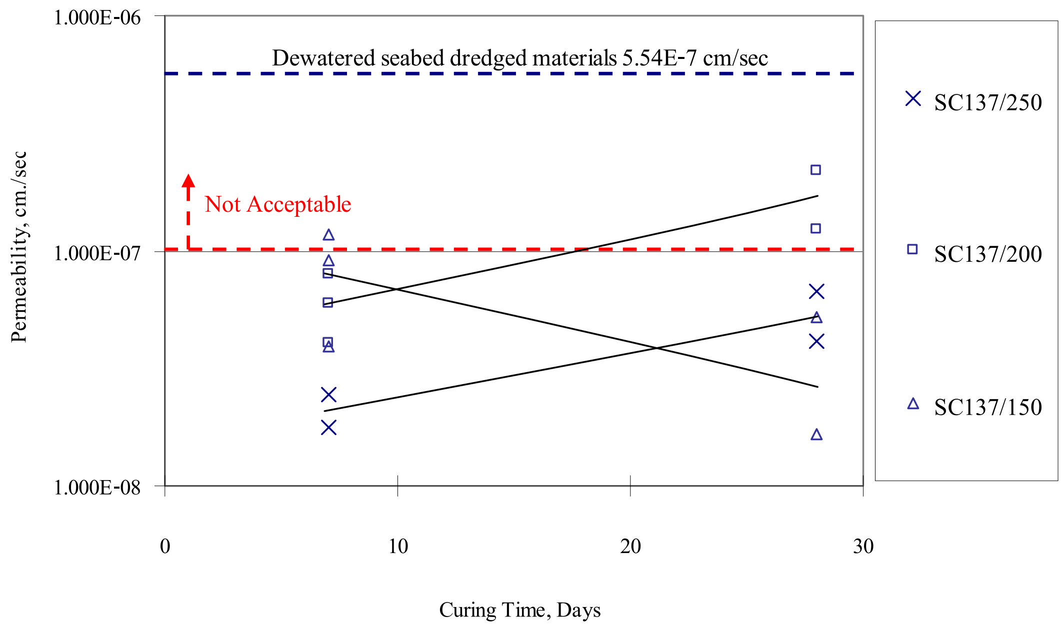


Figure 27 Permeability of cement mixed dredged materials with curing time (initial water content before mixing was 137.87 %)

Figure 28 and Figure 29 showed the relation of the coefficients of permeability and curing time with cement content. It could be observed that the coefficients of permeability of initial water content before mixing at 108.99% (SC108/100, SC108/125, and SC108/150) were slightly increased at long curing time for all cement content, as shown in Figure 28. The coefficients of permeability of initial water content before mixing at 137.87% slightly decreased for cement content at 150 kg/m^3(SC137/150), and slightly increased for cement content at 200, and 250 kg/m^3 (SC137/200 and SC137/250), as shown in Figure 29.

As that result, analysis based on water to cement ratio (w/c) were introduced to evaluate coefficient of permeability in this study. As illustrated in Figure 30, the recommended w/c ratio should be within a range of 5.5-6.5 in order to meet the requirement for use as sanitary landfill liner, the range was conformed to the recommended w/c ratio for strength.

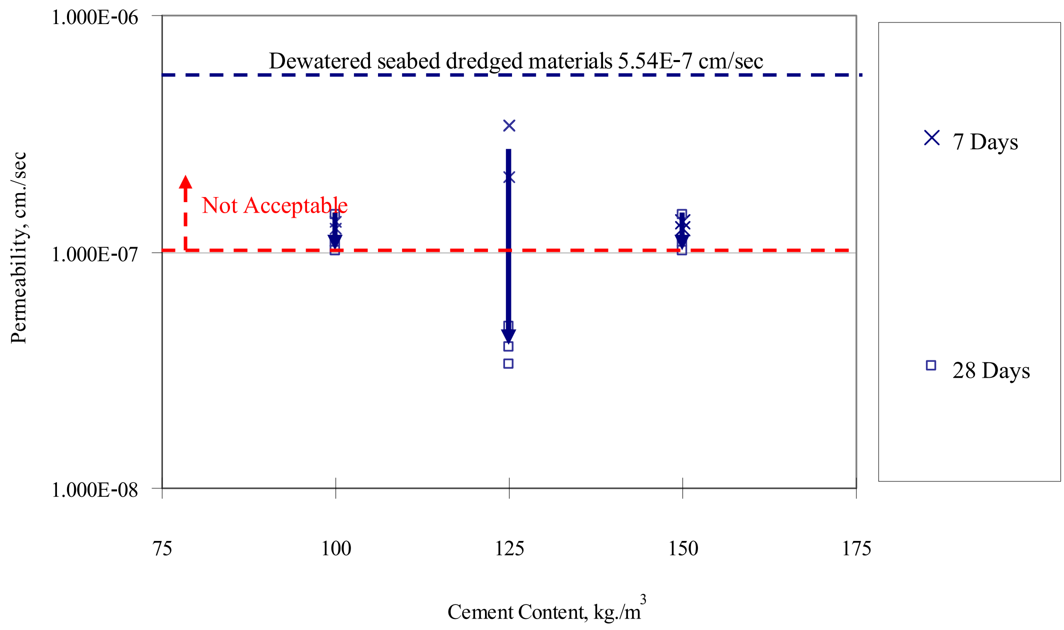


Figure 28 Permeability of cement mixed dredged materials with cement content (initial water content before mixing was 108.99%)

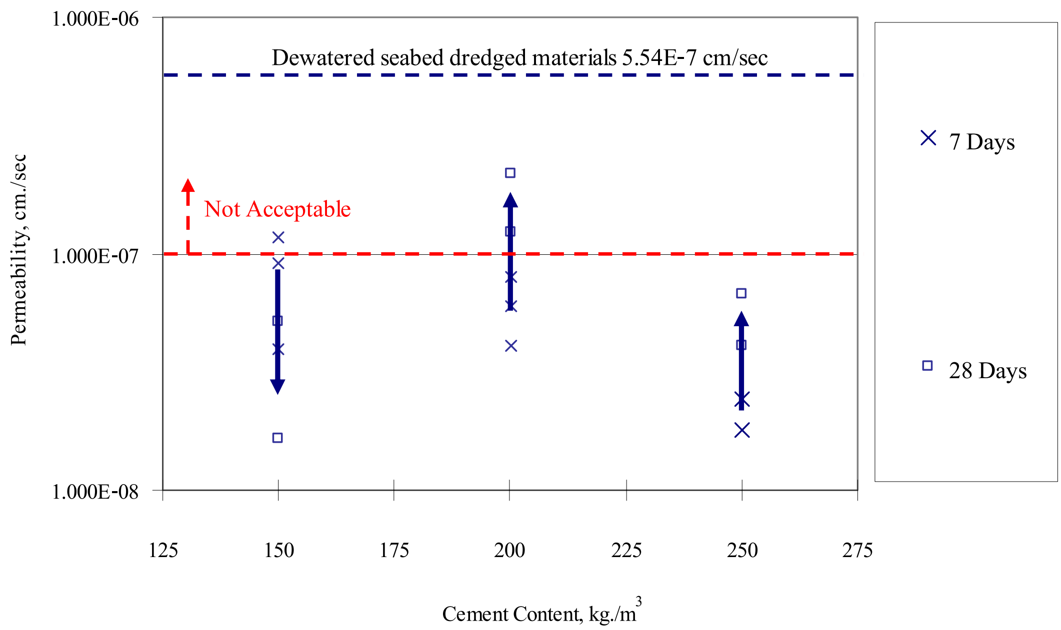


Figure 29 Permeability of cement mixed dredged materials with cement content (initial water content before mixing was 137.87%)

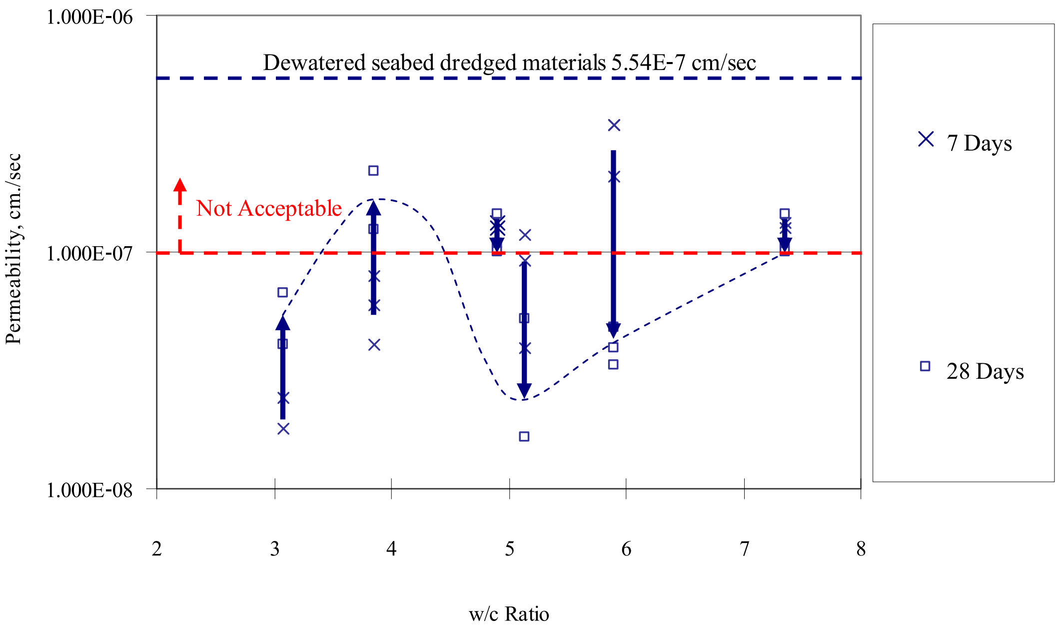


Figure 30 Permeability of cement mixed dredged materials with w/c ratio.

10. The Volumetric Shrinkage of Improved Seabed Dredged Materials by Cement Stabilization

Figure 31 and Figure 32 shows the volumetric shrinkages of mixtures with initial water content at 108.99% with curing time (SC108/100, SC 108/125, and SC108/150) and at 137.87 % (SC137/150, SC137/200, and SC137/250), respectively. It could be observed that the volumetric shrinkages were significantly decreased for early curing time (3 days to 7 days), and then steadily decreased for long curing time (7 days to 28 days). And, it revealed that the volumetric shrinkages of these mixtures were decreased when cement content was increased. While, the decrease rate of volumetric shrinkage at early curing time was substantially due to increasing of cement content. The volumetric shrinkage tended to be uniform rate at long curing time. It was found that there were no mixtures which could satisfy the required volumetric shrinkage (4%).

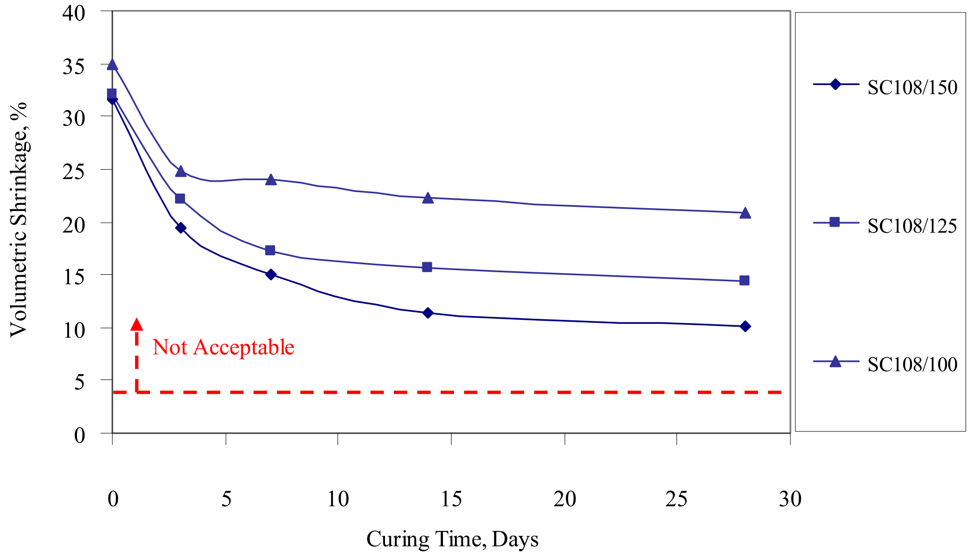


Figure 31 Volumetric shrinkage of cement mixed dredged materials with curing time (initial water content before mixing was 108.99 %)

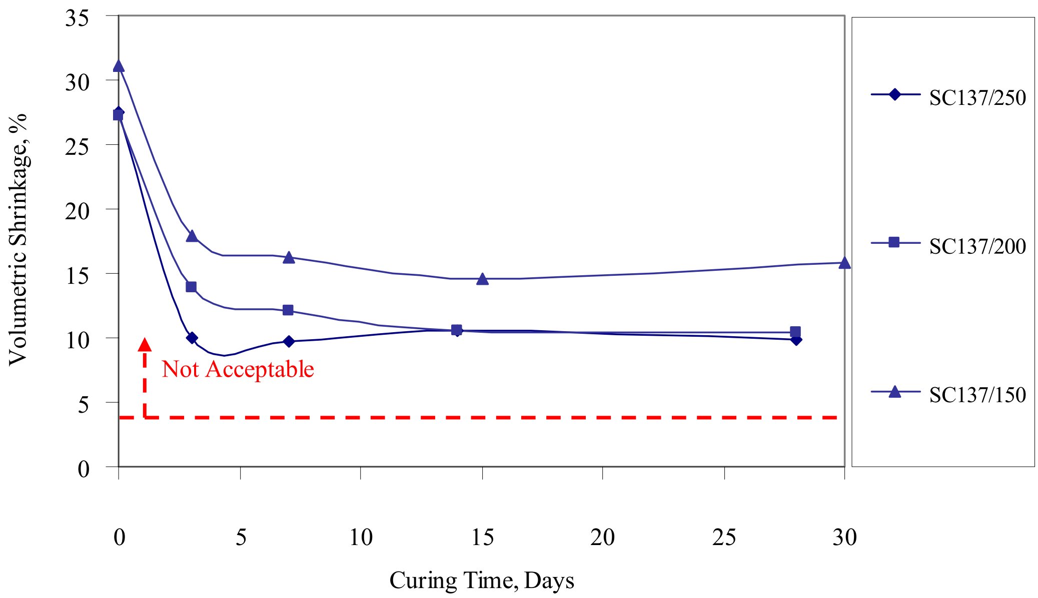


Figure 32 Volumetric shrinkage of cement mixed dredged materials with curing time (initial water content before mixing was 137.87 %)

11. Changes of Water Content of Improved Seabed Dredged Materials

Changes of water content with curing time are illustrated in Figure 33 and Figure 34. Reduction of water content showed that the reaction took place rapidly after mixing, and then proceeded slowly thereafter. It was observed that reduction of water content characteristics were similar to the volumetric shrinkage characteristics.

As the results of cement stabilization, it could be concluded that the unconfined compressive strengths gained the requirement (higher than 2 kg/cm^2) by the water-cement ratio within a range of 5.5–6.5. The coefficients of permeability also satisfied the requirement (k less than 10^{-7} cm/sec) by the water-cement ratio within a range of 5.5–6.5. And, it required the addition of certain amounts of amended materials to satisfy the required volumetric shrinkage (less than 4%). For alternative approaches, other supplement techniques such as sandwich clay covering could be applied in order to control shrinkage cracking in the field.

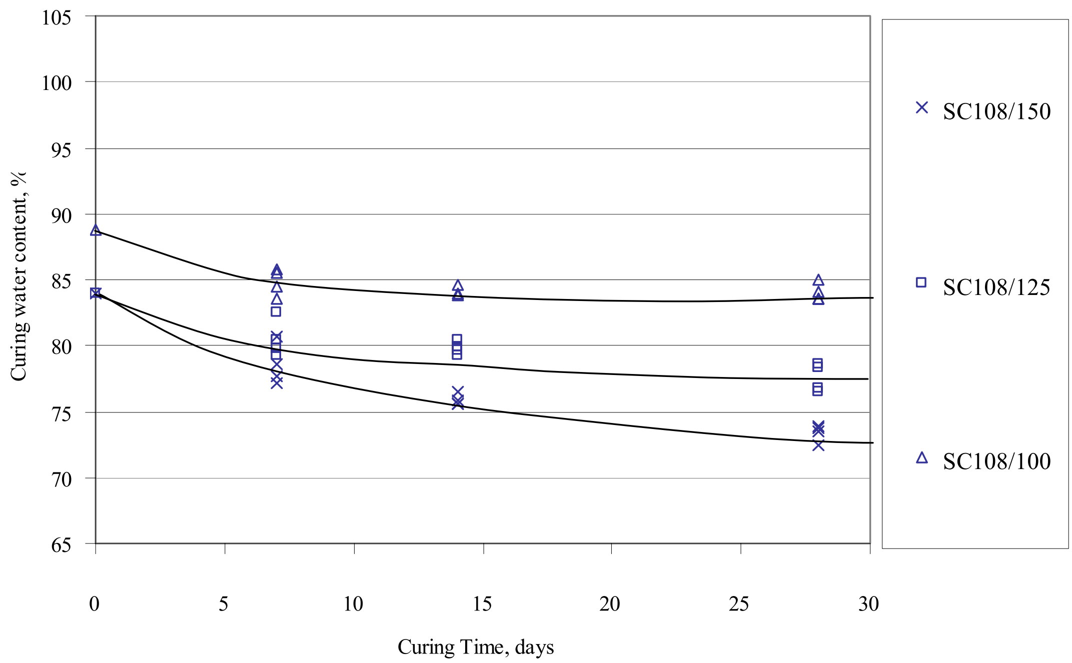


Figure 33 Curing water content of cement mixed dredged materials with curing time (initial water content before mixing was 108.99 %)

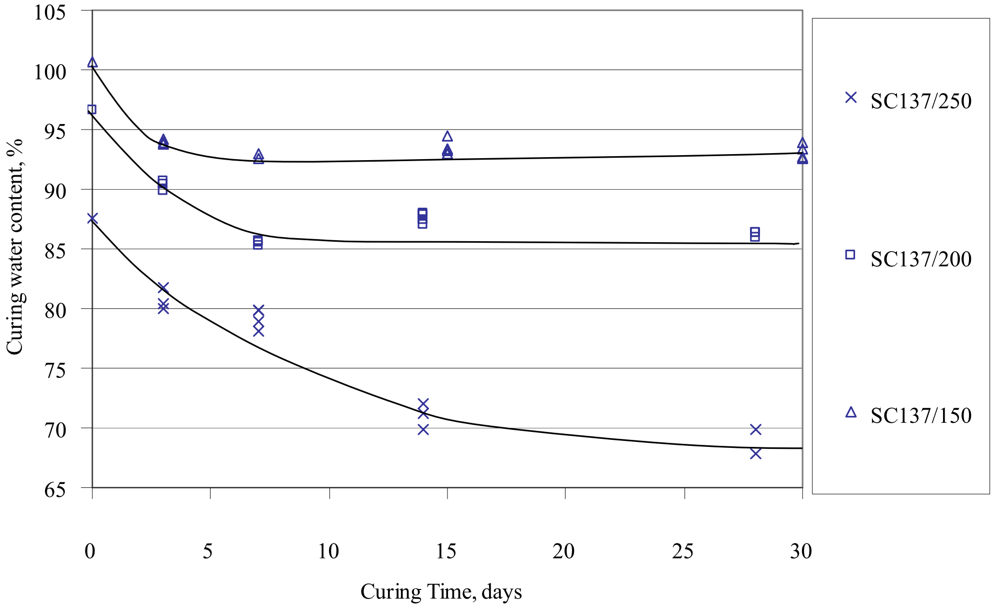


Figure 34 Curing water content of cement mixed dredged materials with curing time (initial water content before mixing was 137.87%)

12. Improvement by Cement and Pozzolanic Admixture Stabilization

Cement with pozzolanic admixture was introduced as stabilizer to improve physical and engineering properties. The trial mixes are shown in Table 10.

Table 10 Mixtures and symbols of cement with silica fume stabilization

Symbol	Water Content (%)	Stabilizer ingredients			w / c ratio	Sand content,%
		Content,kg/m^3	% cement	% Silica Fume		
SC137SF/0	137.87	200	100	0	3.85	0
SC137SF/5	137.87	200	95	5	3.85	0
SC137SF/10	137.87	200	90	10	3.85	0
SC137SF/15	137.87	200	85	15	3.85	0

13. Unconfined Compressive Strength of Improved Seabed Dredged Materials by Cement and Silica Fume Stabilization

The unconfined compressive strength development characteristics of dewatered dredged material mixed with cement and silica fume were efficiently improved from the early curing time as shown in Figure 35.

As observed in Figure 36, when compared with mixture SC137SF/0 (mixed only with cement at 200 kg/m^3), the unconfined compressive strength of SC137SF/10 (cement partially replaced with silica fume 10% by weight) seemed to be more effective than SC137SF/5 and SC137SF/15 mixtures (silica fume replacement were 5% and 15%, respectively), especially for early curing time (3 days to 14 days).

Although, the unconfined compressive strengths of these mixtures (SC137SF/5, SC137SF/10, SC137SF/15) were slightly higher than mixture the control mixture (SC137SF/0), they gave higher strengths than the required strength (2 kg/cm^2) for all curing time.

In other words, additions of silica fume as cement replacement material could improve early strength.

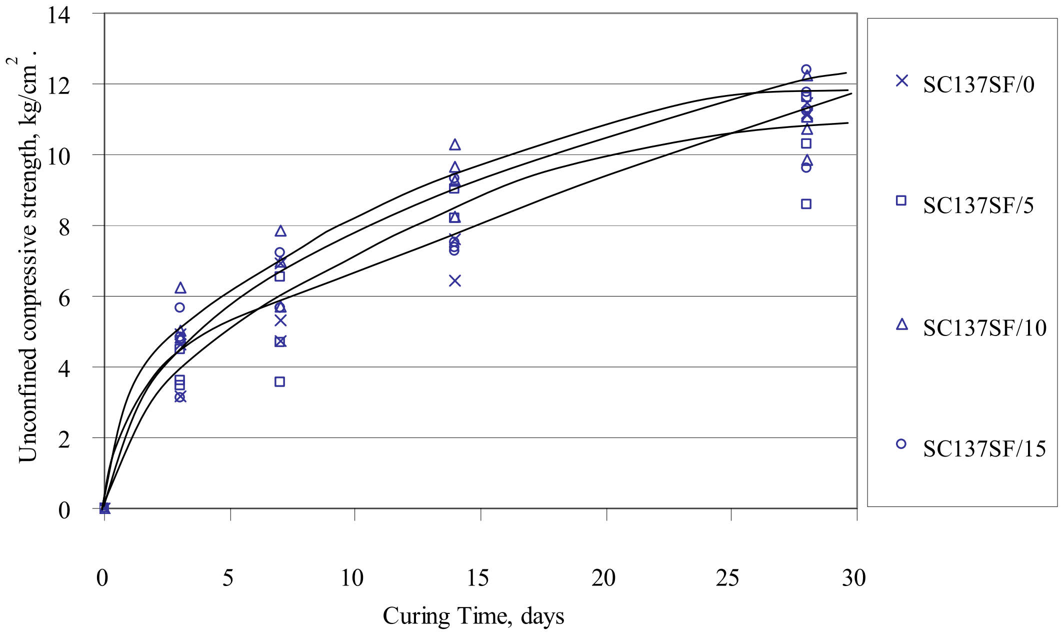


Figure 35 Unconfined compressive strength of cement and silica fume mixed dredged materials with curing time (initial water content before mixing was 137.87 %)

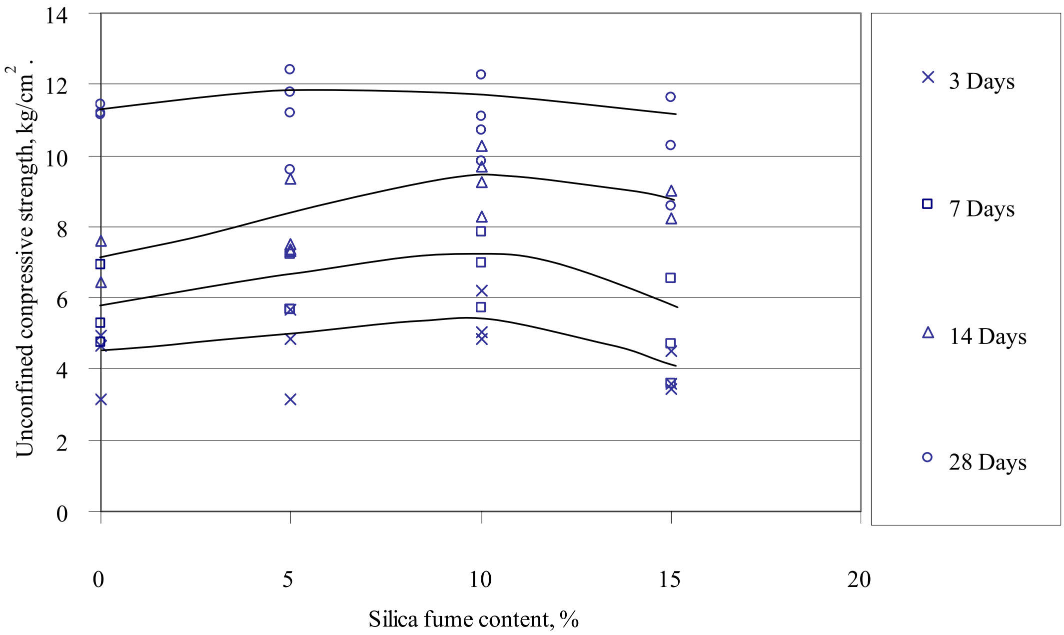


Figure 36 Unconfined compressive strength of cement and silica fume mixed dredged materials with silica fume content (initial water content before mixing was 137.87 %)

14. Coefficient of Permeability of Improved Seabed Dredged Materials by Cement and Silica Fume Stabilization

The results of permeability tests of dewatered dredged material mixed with cement and silica fume, as shown in Figure 37, showed that the coefficient of permeability of these mixtures; SC137SF/5, SC137SF/10, and SC137SF/15; were markedly decreased and lower than that of dewatered dredged material approximately 10 times at early curing time. From that result, the coefficient of permeability of these mixtures was slightly decreased for long curing time.

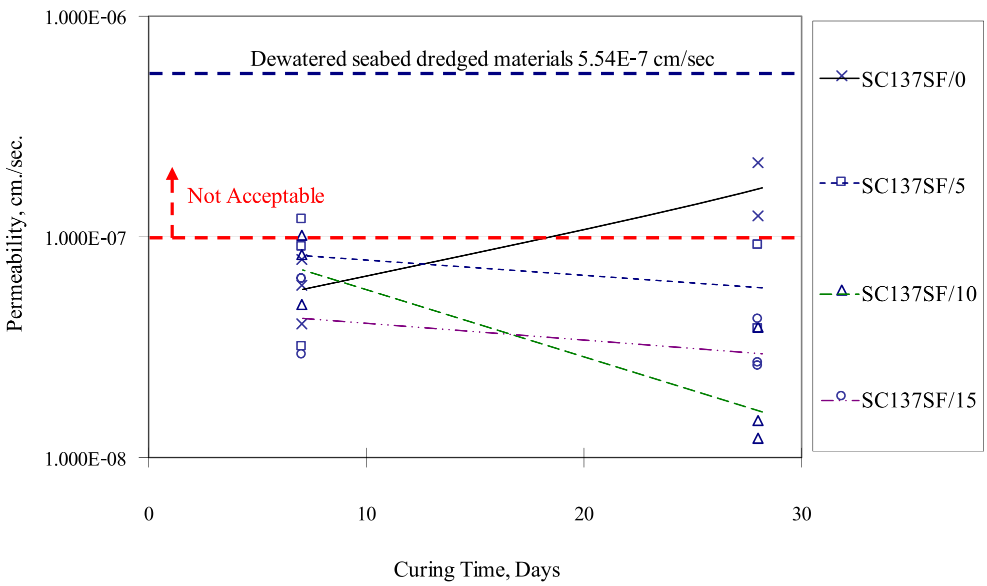


Figure 37 Permeability of cement and silica fume mixed dredged materials with curing time (initial water content before mixing was 137.87%)

As is obvious in Figure 38, the coefficients of permeability of cement and silica fume stabilization mixtures seemed to be decreased when silica fume content was increased for early curing time. In addition, for long curing time, the coefficients of permeability of these mixtures slightly decreased and were lower than the coefficients of permeability of cement stabilization mixtures, SC137SF/0. And, the coefficients of permeability of these mixtures were also lower than the requirement (the coefficients of permeability should be less than 10^{-7} cm/sec.). It could be concluded that silica fume had beneficial effects on the permeability development at long curing time. And, SC137SF/10 (cement is replaced 10% by weight with silica fume) was the most effective silica fume proportion, which conformed to the recommended silica fume content for the strengths.

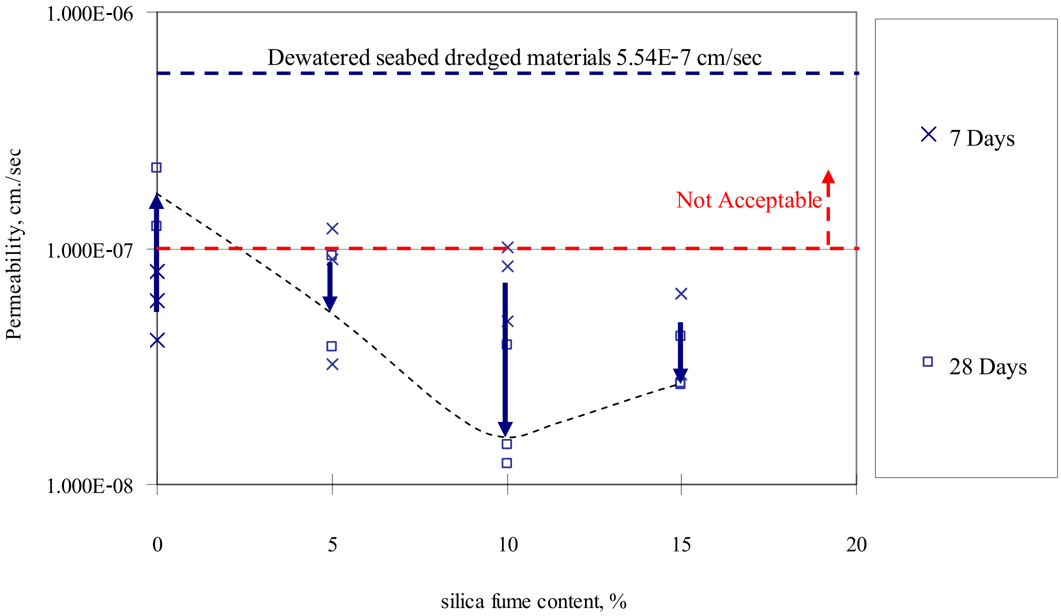


Figure 38 Permeability of cement and silica fume mixed dredged materials with silica fume content (initial water content before mixing was 137.87%)

15. Volumetric Shrinkage of Improved Seabed Dredged Materials by Cement and Silica Fume Stabilization

The volumetric shrinkage characteristics of cement and silica fume stabilization were similar to characteristics of cement stabilization, as shown in Figure 39 and Figure 40. The results showed that the volumetric shrinkages of cement and silica fume stabilization mixtures (SC137/5, SC137/10, and SC137/15) were lower than those of cement stabilization mixtures (SC137/0) at the early curing time (3 days to 14 days). Thereafter, the differences of volumetric shrinkages were small for long curing time (14 days to 28 days).

Figure 40 revealed that silica fume contents used in this study were not sufficient to stabilize the volumetric shrinkage of dewatered dredged material since all mixtures could not achieved the required volumetric shrinkage (4%).

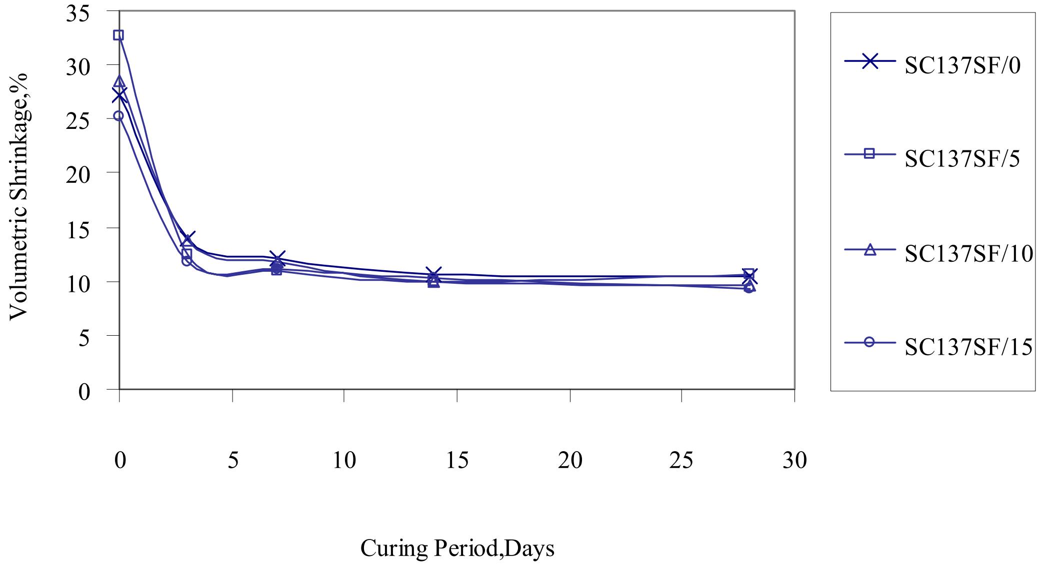


Figure 39 Volumetric shrinkage of cement and silica fume mixed dredged materials with curing time (initial water content before mixing was 137.87%)

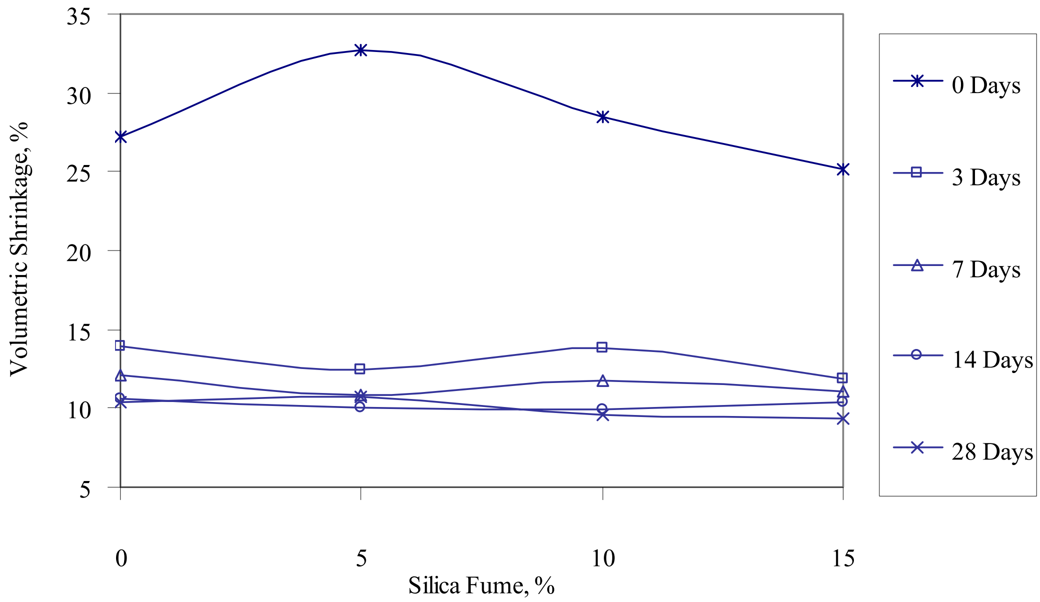


Figure 40 Volumetric shrinkage of cement and silica fume mixed dredged materials with silica fume content (initial water content before mixing is 137.87%)

16. Changes of Water Content of Improved Seabed Dredged Materials by Cement and Silica Fume Stabilization

The changes of water content characteristics of cement and silica fume stabilization were also similar to cement stabilization, as shown in Figure 41. The water content of mixtures SC137/5 and SC137/15 were lower than SC137/0 at curing time 3 to 7 days, and then lowered close to those of SC137/0 at curing time 7 to 28 days. It could also be observed that the mixture SC137/10 had the most effect in term of water content reduction for all curing time.

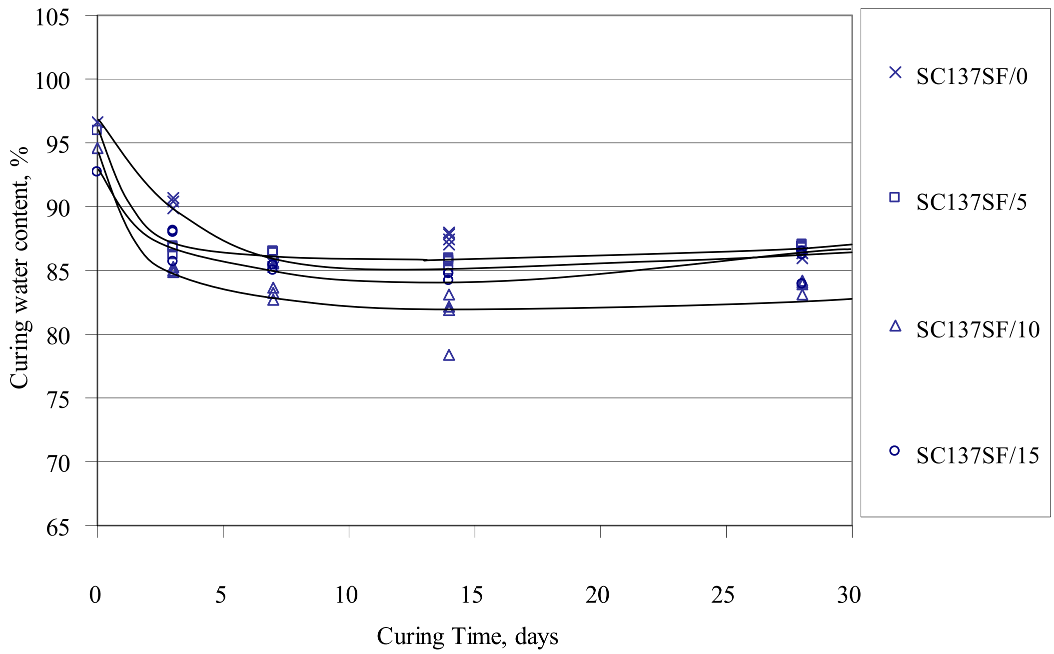


Figure 41 Curing water content of cement and silica fume mixed dredged materials with curing time (initial water content before mixing was 137.87%)

Based on the results, it revealed that the improvement on the unconfined compressive strength by substitution of 10 % silica fume for cement was obvious especially for the early strength development. The improvement in permeability could be obtained by using silica fume. Improvement on volumetric shrinkage could also be observed, however, needed to be further improved to obtain the target. Thus, in the next session, sand modification was provided in order to minimize the volumetric shrinkage.

17. Improvement by Sand Modification

Sand modification was introduced to modify the seabed dredged materials in term of volumetric shrinkage potential. It was assumed that sand particles are very rigid as they provide a stable matrix which is resistant to shrinkage. Although, the addition of sand also increases the coefficient of permeability, it may be acceptable to use as sanitary landfill liner, if a careful balance is given to get the optimum for rigidity and permeability. However, in this study, sand modification was primary performed as a guideline and an alternative amendment in reducing volumetric shrinkage. The test condition and symbol of sand modification mixtures are shown in Table 11.

Table 11 Mixtures and symbols of sand modification

Symbol	Water Content (%)	Stabilizer ingredients			w / c ratio	Sand content,%
		Content,kg/m^3	% cement	% Silica Fume		
SC108S/0	108.99	125	100	0	5.89	0
SC108S/5	108.99	125	100	0	5.89	5

18. Unconfined Compressive Strength of Improved Seabed Dredged Materials by Sand Modification

As illustrated in Figure 42, the strengths of dewatered seabed dredged material at initial water content 108.99% mixed with cement and sand mixture (SC108S/5) increased significantly for early curing time. In addition, the strength of SC108S/5 gained a uniform rate for long curing time. It was found that, the strengths of SC108S/5 increased slightly higher than SC108S/0 (the cement-stabilized mixture) for all curing time.

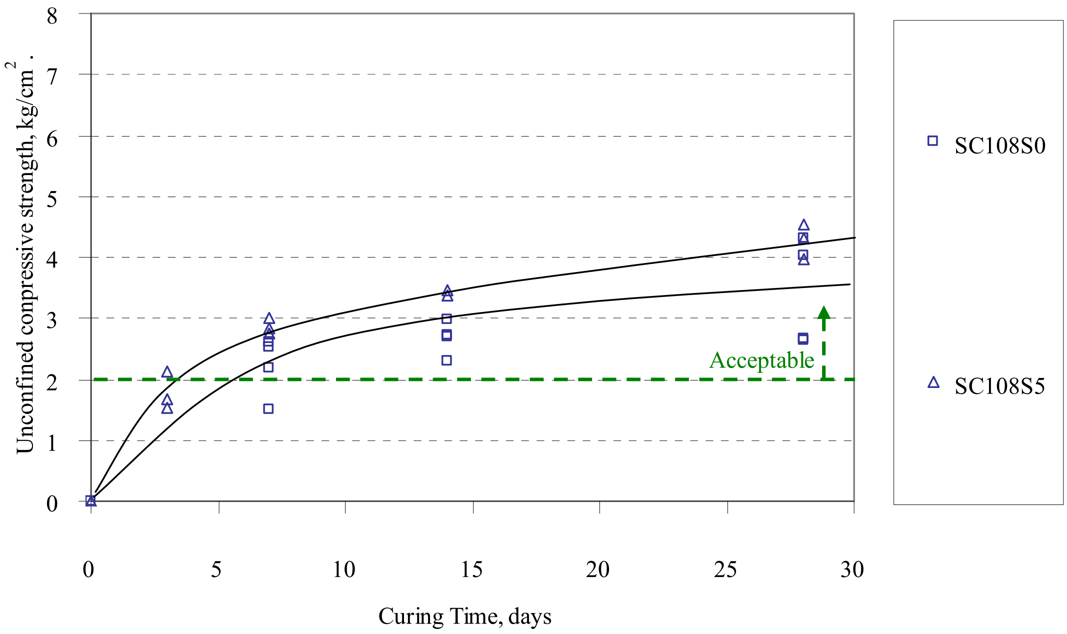


Figure 42 Unconfined compressive strength of cement and sand mixed dredged materials with curing time (initial water content before mixing is 108.99%)

19. The Coefficient of Permeability of Improved Seabed Dredged Materials by Sand Modification

Figure 43 shows the results of the coefficients of permeability and curing time. It could be observed that the coefficients of permeability of SC108S/10 were markedly decreased lower than an average coefficient of permeability of dewatered seabed dredged material after 7 days, then, they were slightly increased at long curing time. However, the coefficients of permeability of SC108S/10 were significantly increased higher than SC1108/0 at long curing time. In other words, the addition of sand also increased the coefficient of permeability. Therefore, it required further study to compensate structural rigidity and permeability.

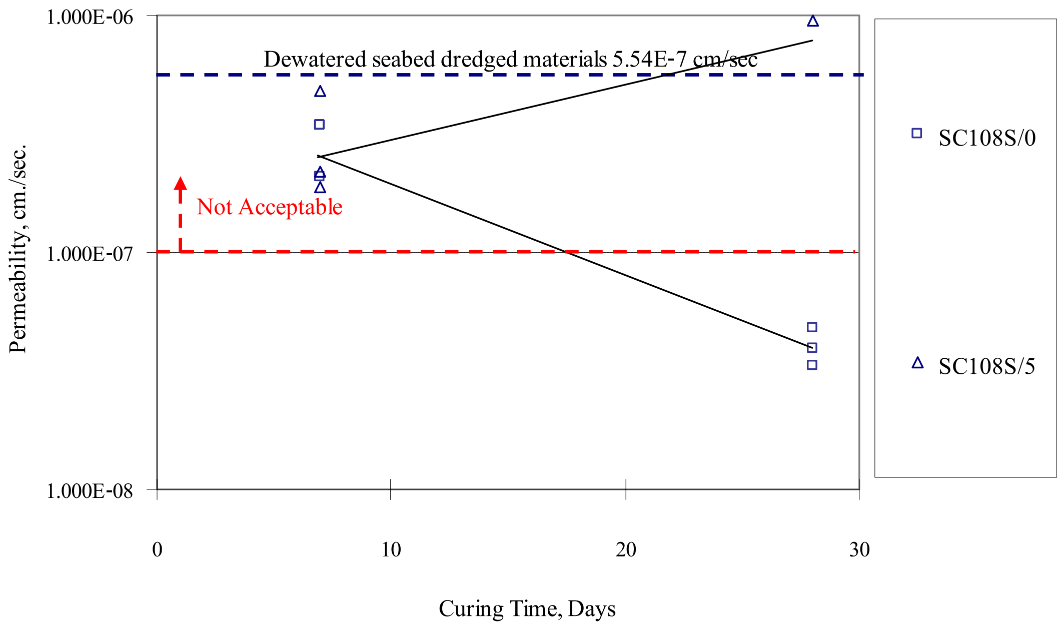


Figure 43 Permeability of cement and sand mixed dredged materials (initial water content before mixing was 137.87%)

20. The Volumetric Shrinkage of Improved Seabed Dredged Materials by Sand Modification

The results as shown in Figure 44 illustrated the volumetric shrinkage characteristics of the dewatered seabed dredged material at initial water content 108.99% mixed with cement and sand mixture (SC108S/5) compared with cement-stabilized mixture (SC108S/0). It could be observed that the characteristics of SC108S/5 were similar to those of SC108S/0, and, the volumetric shrinkage of SC108S/5 was reduced lower than SC108S/0 for all curing times. It could be concluded that addition of sand had beneficial effect to reduce the volumetric shrinkage for all curing times.

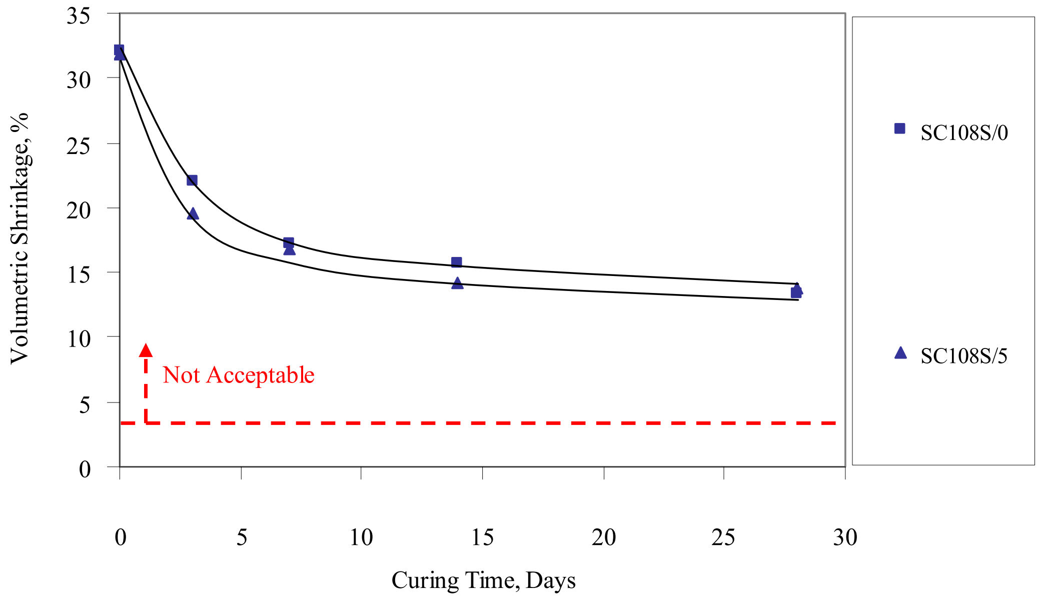


Figure 44 Volumetric shrinkage of cement and sand mixed dredged materials with sand content (initial water content before mixing is 108.99%)

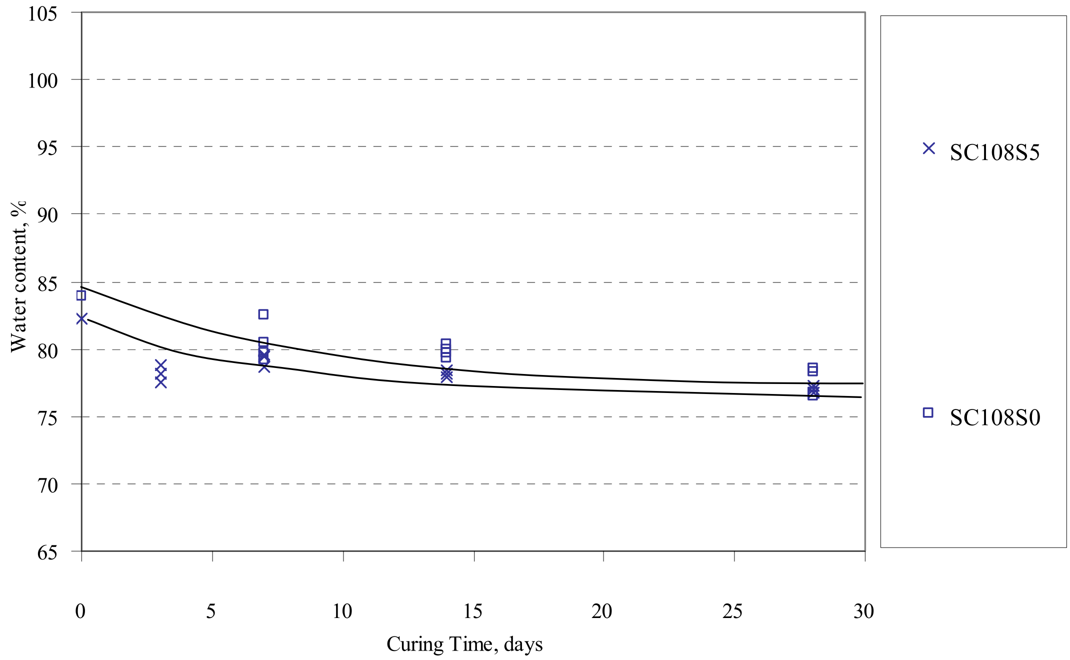


Figure 45 Curing water content of cement and sand mixed dredged materials with curing time (initial water content before mixing is 108.99%)

21. The Changes of Water Content of Improved Seabed Dredged Materials by Sand Modification

Changes of water content with curing time are illustrated in Figure 45. The results revealed that reduction of water content occurred rapidly after mixing, and then proceeded slowly thereafter. It was also observed that water content reduction characteristics were similar to the volumetric shrinkage characteristics.

22. Investigation for Microstructures and Chemical Compositions

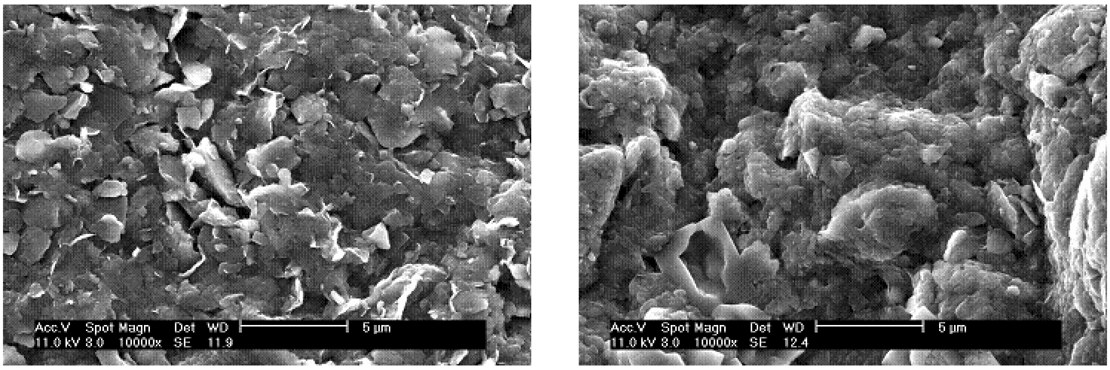
Technical investigations were performed by scanning electron microscopic (SEM) observations and X-ray diffraction (XRD) analysis. XRD analysis and SEM investigation were used to elucidate chemical compounds in soil matrix and the main reaction products in the stabilized seabed dredged materials.

23. Microscopic investigation by SEM of dewatered seabed dredged materials

The SEM observation, Figure 46, showed significant changes in soil fabrics. It revealed that the seabed dredged materials in natural condition had platy and sheet-like pattern in particle shapes. Their structures had relatively high void ratio. After dewatering process, the seabed dredged material's particles become flocculated, resulting in markedly reduced void ratio.

24. Scanning Electron Microscopic (SEM) investigations

Yoobanpot (2004) reported that the cement hydration formed immediately after cement mixed was with watere. The major reaction products produced were Calcium Silicate Hydrated gel (CSH) and needle-like crystals of Ettrigite respectively. The growths of reaction products resulted in hardening in a stabilized soil.



(a.) Untreated seabed dredged materials (w_n ~ 209 %)

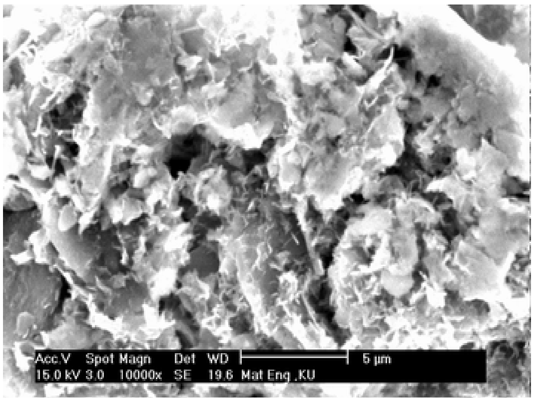
(b.) Dewatered seabed dredged materials (w_n ~ 108 %)

Figure 46 SEM micrographs of seabed dredged materials before and after dewatering

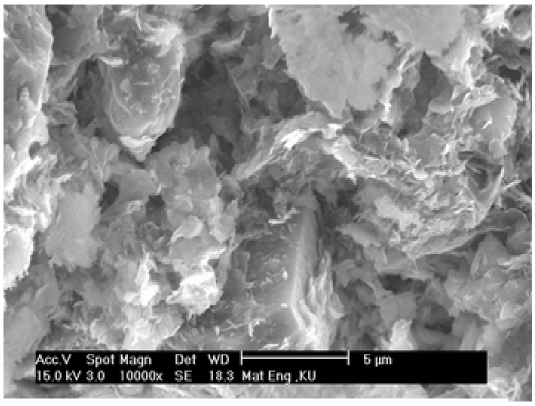
The SEM micrographs of the dewatered seabed dredged materials stabilized with cement were investigated by SEM after the unconfined compressive strength test. The results could be reported as follows.

24.1 SEM micrographs of SC108/100

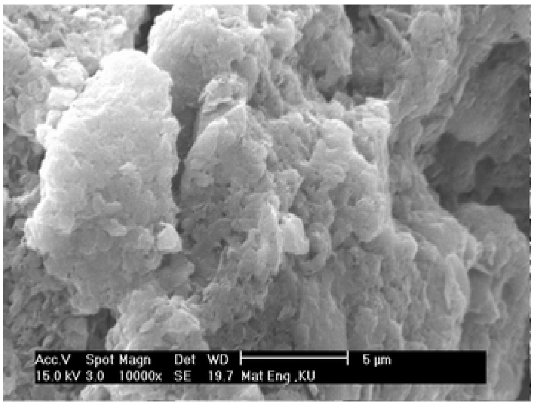
Figure 47 illustrated the SEM micrographs of SC108/100. It revealed that the structure of SC108/100 was relatively denser than untreated dewatered seabed dredged materials. The CSH gel and needle-like crystals formed in early curing time, Figure 47 (a). At long curing time as shown in Figure 47 (c), the structure became hardened and denser. These results agreed with the results of the unconfined compressive strength and permeability test results.



(a) 7 days curing time



(b) 14 days curing time

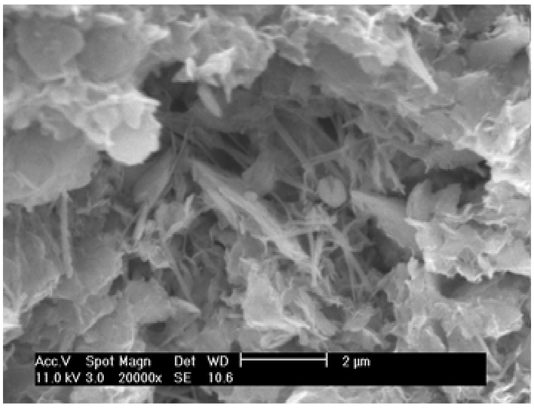


(c) 28days curing time

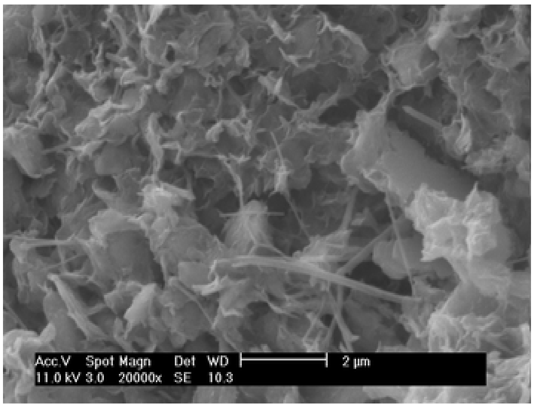
Figure 47 SEM micrographs of cement-stabilized mixture, SC108/125

24.2 SEM micrographs of SC137/150

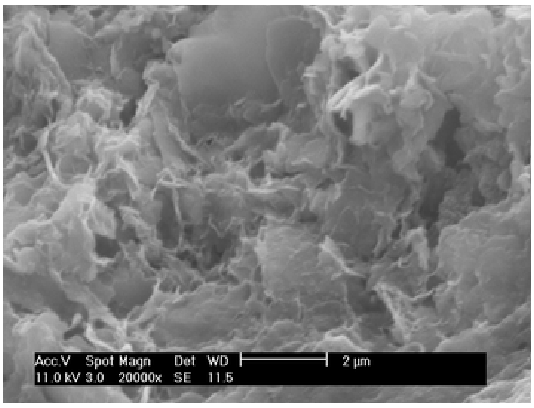
The reaction products of SC137/150, CSH and needle-like crystals of Ettringite, significantly formed at the beginning as illustrated in Figure 48. The amounts of reaction products seemed to slightly increase for longer curing time. However, its structure was denser when curing time increased. When compared with SEM micrographs of SC108/125, it was clear that the CSH and Ettringite in SC137/150 structure were markedly formed higher amount than SC108/125 that had lower cement content or higher w/c ratio.



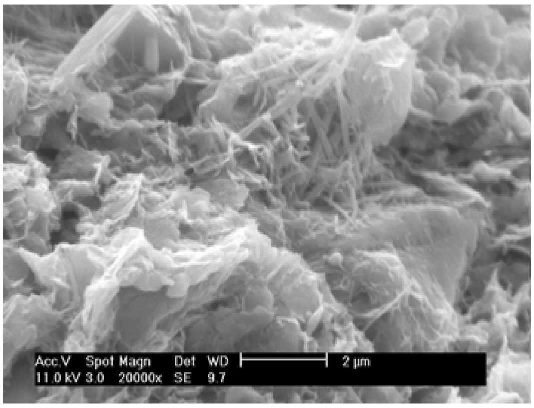
(a) 3 days curing time



(b) 7 days curing time



(c) 15 days curing time

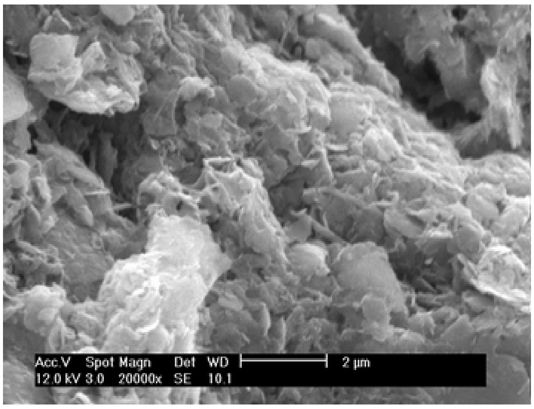


(d) 30 days curing time

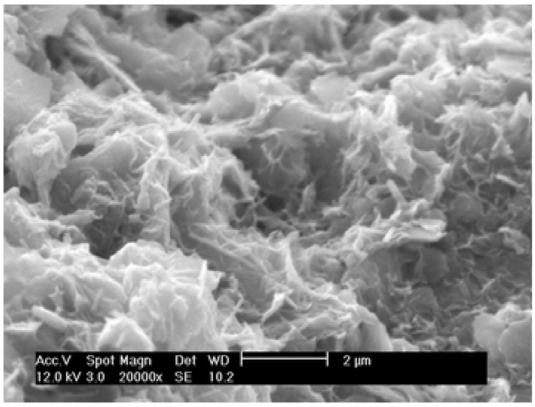
Figure 48 SEM micrographs of cement-stabilized mixture, SC137/150

24.3 SEM micrographs of SC137/250

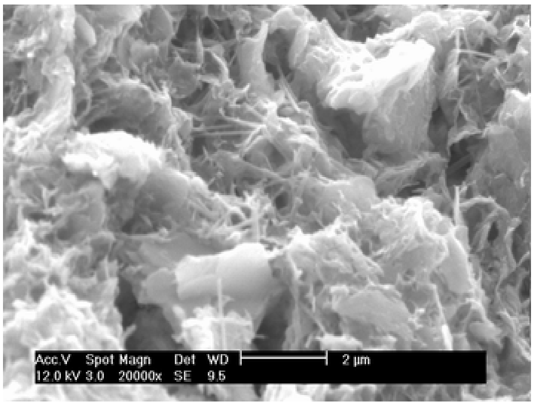
Figure 49 illustrated SEM micrographs of SC137/250. It was observed that CSH rapidly formed at early curing time, Figure 49 (a) and (b). For long curing time, Figure 49 (c) and (d), Ettringite could be clearly observed. Due to the highest cement content mixture, SEM micrographs of SC137/250, Figure 49, shown the CSH and needle-like crystals of Ettringite were produced higher than those mixtures. It could be concluded that formation of these reaction products changed in microstructure hardener. The reaction products significantly increased at early curing time, and they slightly increased for longer curing time. In addition, formations of these reaction products were substantially influenced by cement content, which was agreeable to strength results.



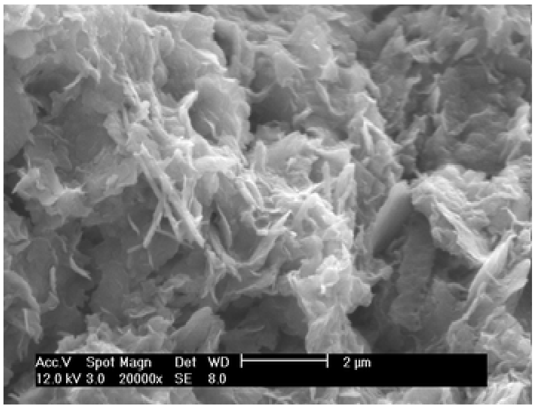
(a) 3 days curing time



(b) 7 days curing time



(c) 14 days curing time



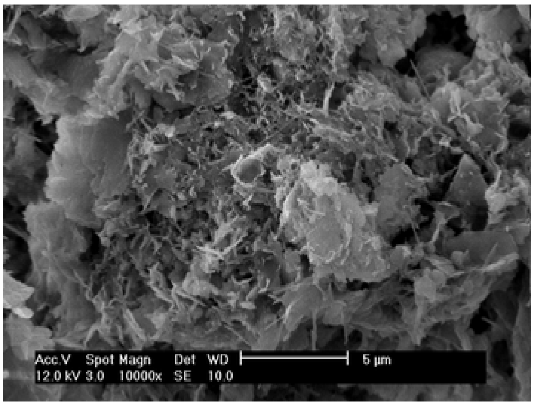
(d) 28 days curing time

Figure 49 SEM micrographs of cement-stabilized mixture, SC137/250

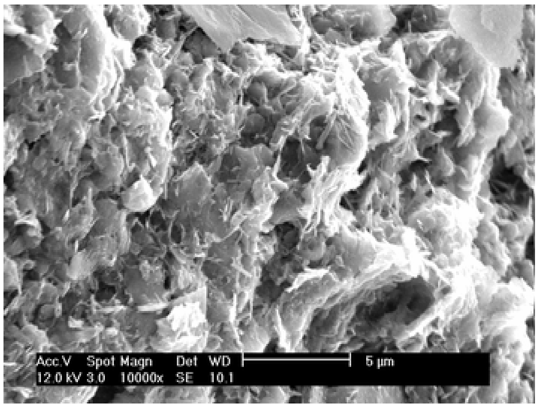
24.4 SEM micrographs of SC137SF/10

The dewatered seabed dredged materials stabilized with cement and silica fume mixtures, SC137SF/10 were also investigated by SEM as shown in Figure 50. It was found that changes in microstructure of this mixture were attributed to rich formation of the reaction products. The CSH and Ettringite were clearly observed and significantly produced at the early curing time, Figure 50 (a) and (b). Binding between reaction products and soil particles made microstructures become denser and harden at long curing time, Figure 50 (c) and (d).

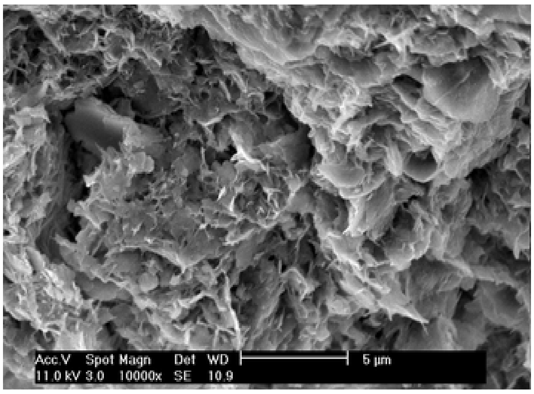
It was clear that appropriate silica fume content increased the rate of formation of reaction products. These results thus conformed to the strength and permeability test results.



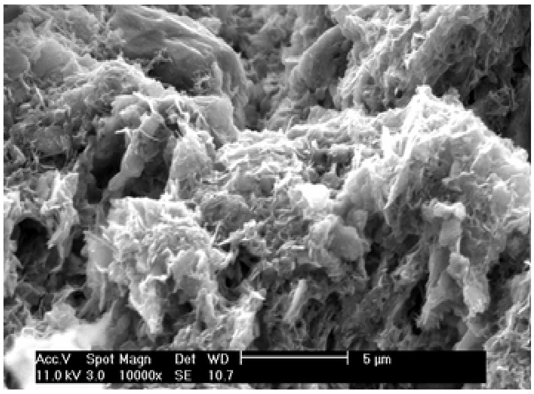
(a) 3 days curing time



(b) 7 days curing time



(c) 14 days curing time



(d) 28 days curing time

Figure 50 SEM micrographs of cement and silica fume-stabilized mixture, SC137SF/10

25. XRD analysis of the Improved Seabed Dredged Materials

Boonyong (2004) reported that the major reaction products of hydration such as CSH) and Ettringite related directly to strength development. Indentifications of the chemical compounds were performed by XRD analysis in order to elucidate on the production of reaction products in relation to strengths of the stabilized dewatered seabed dredged materials. In this study, calcium silicate hydrate (CSH) and Ettringite are observed at d-spacing 3.02 Å and 3.88 Å, respectively.The results are illustrated as followed.

25.1 XRD patterns of SC108/125

The XRD patterns of SC108/125 are illustrated in Figure 51, Figure 52 and Figure 53 for curing time at 7, 14, and 28 days, repectively. The results indicated the peaks that demonstrate the chemical compounds of reaction products. Growth in XRD intensity of CSH and Ettrigite agreed with those as observed qaulitatively in SEM micrographs.

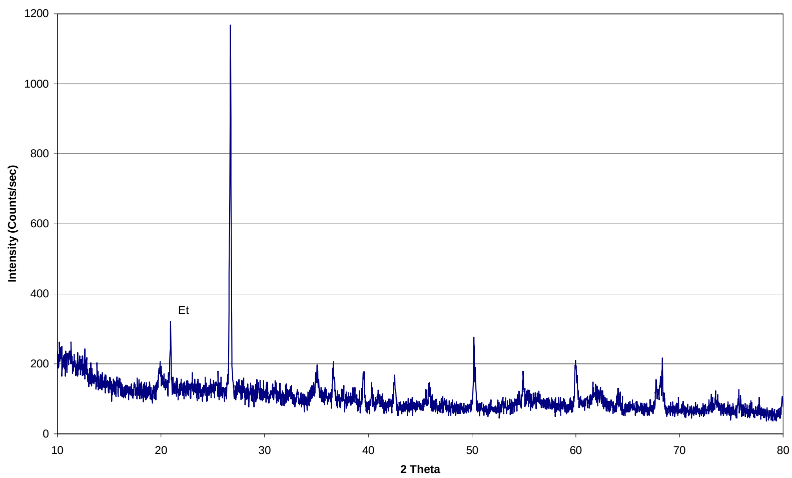


Figure 51 XRD pattern of cement-stabilized mixture, SC108/125 (7 days)

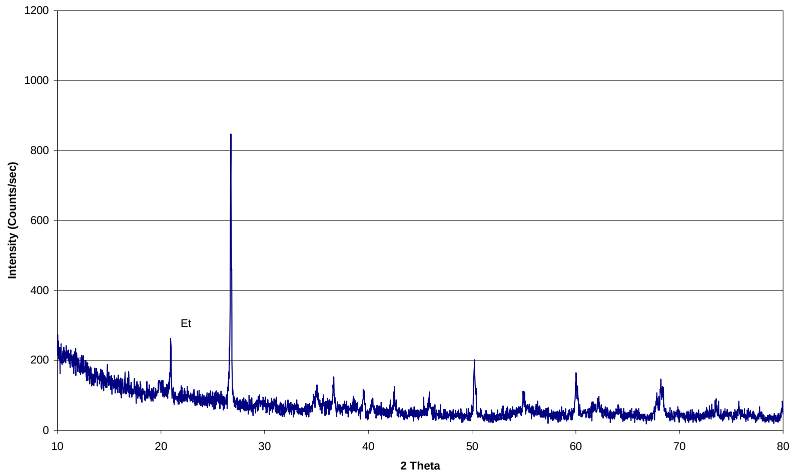


Figure 52 XRD pattern of cement-stabilized mixture, SC108/125 (14 days)

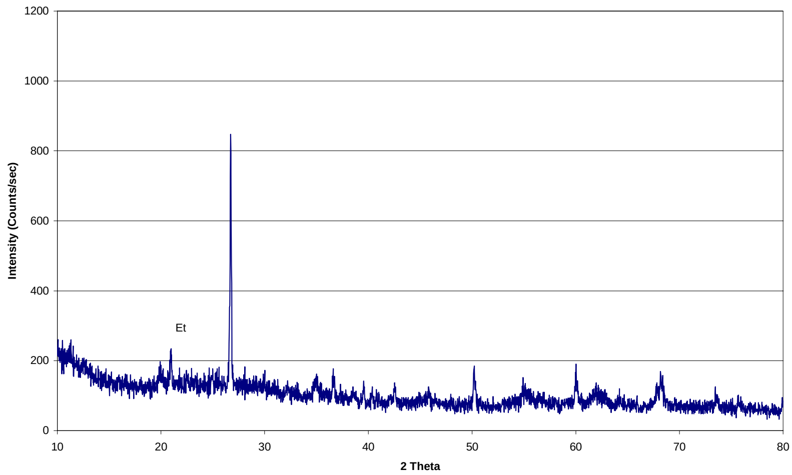


Figure 53 XRD pattern of cement-stabilized mixture, SC108/125 (28days)

25.2 XRD patterns of SC137/150

Figure 54, Figure 55, Figure 56, and Figure 57 illustrate the XRD patterns of SC137/150 for curing time at 3, 7, 14, and 28 days, respectively. The results showed that CSH and Ettringite intensities markedly increased during the first two weeks then slightly increased and became almost constant at long term. As observed from XRD patterns and SEM micrographs, it was found that growths of CSH and Ettringite were similar to strength characteristic curves.

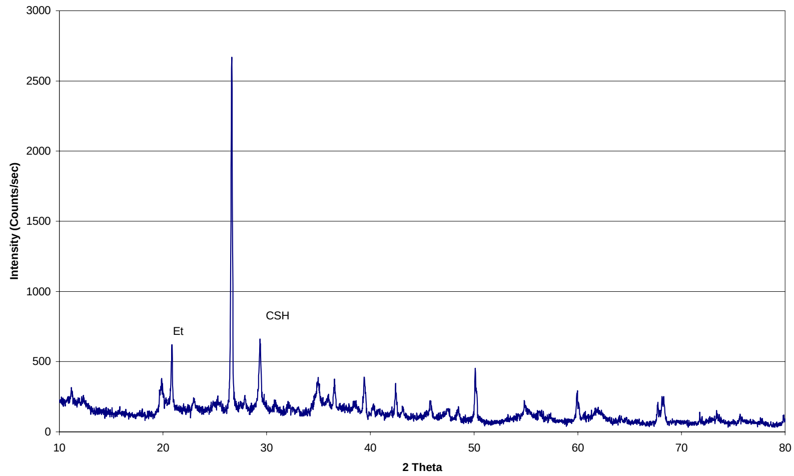


Figure 54 XRD pattern of cement-stabilized mixture, SC137/150 (3 days)

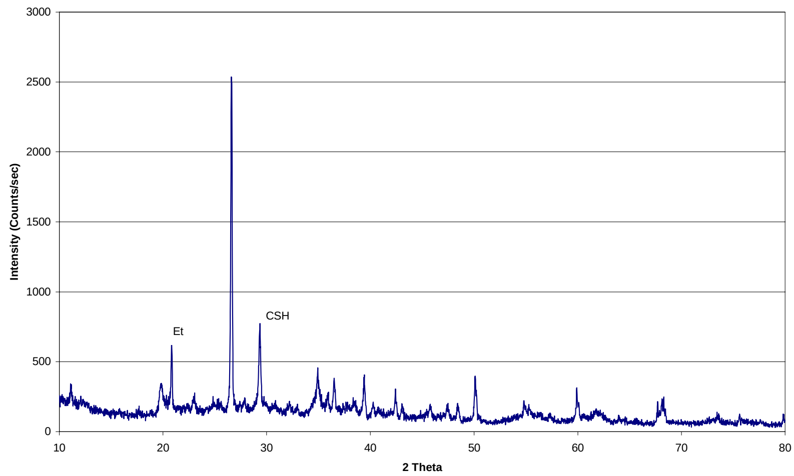


Figure 55 XRD pattern of cement-stabilized mixture, SC137/150 (7 days)

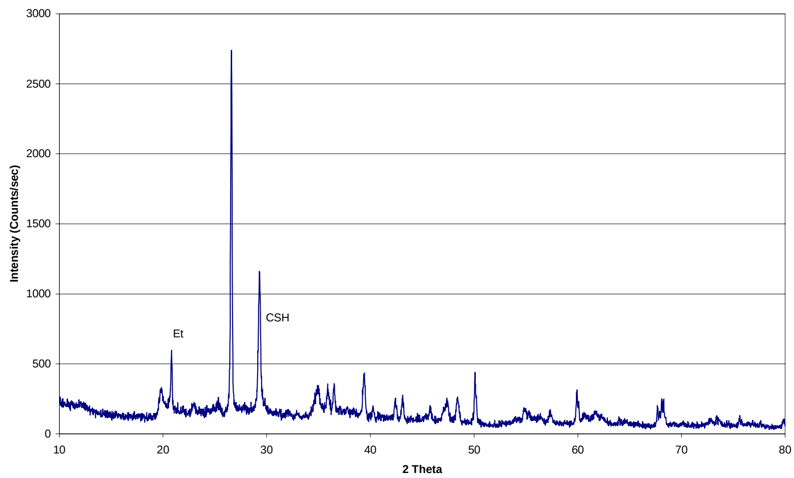


Figure 56 XRD pattern of cement-stabilized mixture, SC137/150 (15 days)

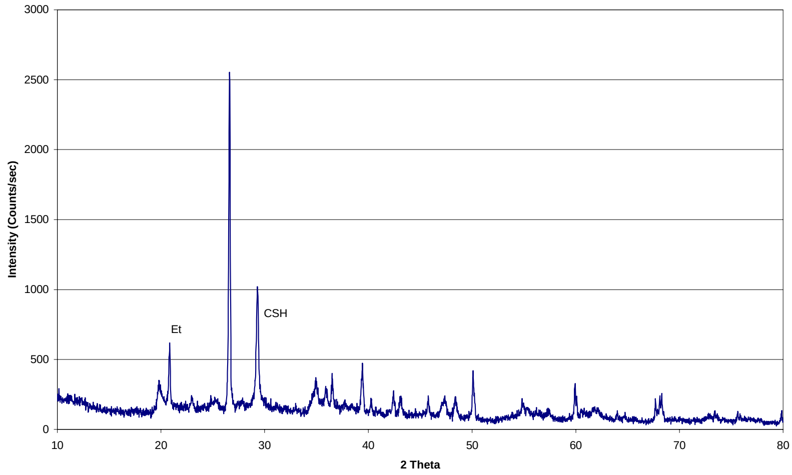


Figure 57 XRD pattern of cement-stabilized mixture, SC137/150 (30days)

25.3 XRD patterns of Mixture SC137/250

The XRD patterns of SC137/250 at curing 3, 7, 14, and 28 days are illustrated in Figure 58, Figure 59, Figure 60, and Figure 61, respectively. The XRD patterns of SC137/205 showed that the CSH and Etringite intensities which were produced higher than those mixtures, due to the highest cement content mixture. It could be concluded that formations of these reaction products were substantially influenced by cement content, which was agreeable to SEM micrographs and strength results.

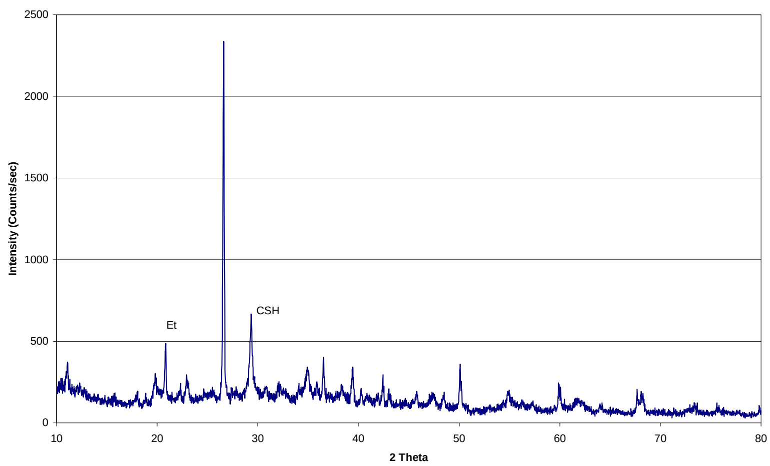


Figure 58 XRD pattern of cement-stabilized mixture, SC137/250 (3 days)

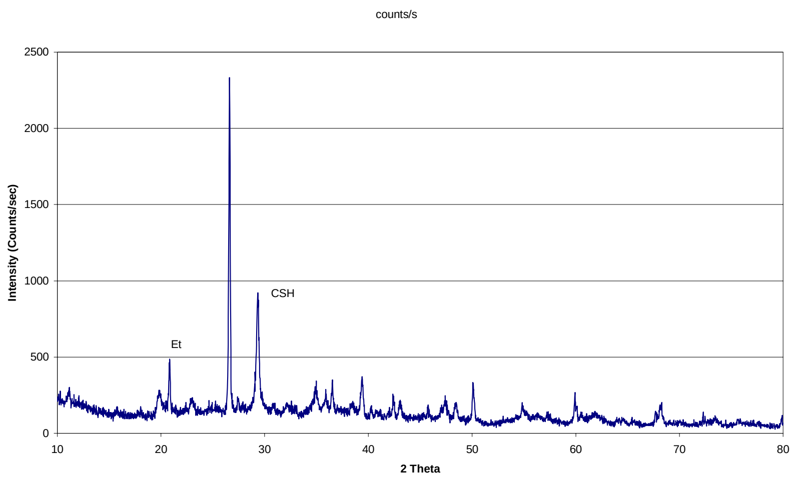


Figure 59 XRD pattern of cement-stabilized mixture, SC137/250 (7 days)

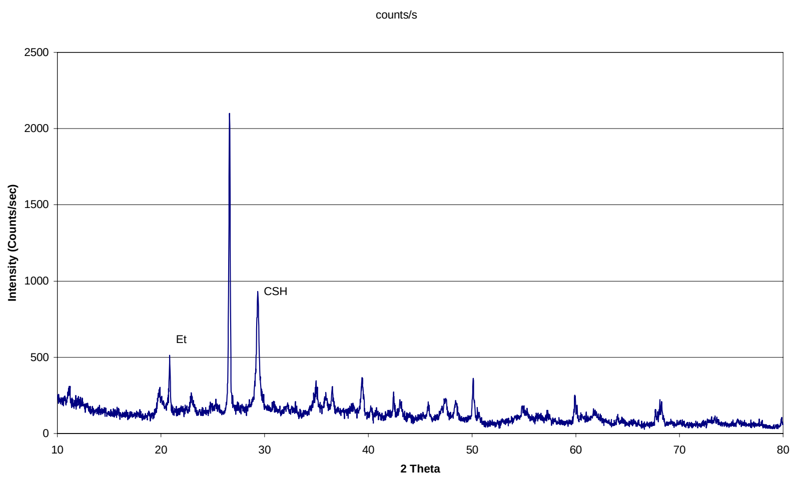


Figure 60 XRD pattern of cement-stabilized mixture, SC137/250 (14 days)

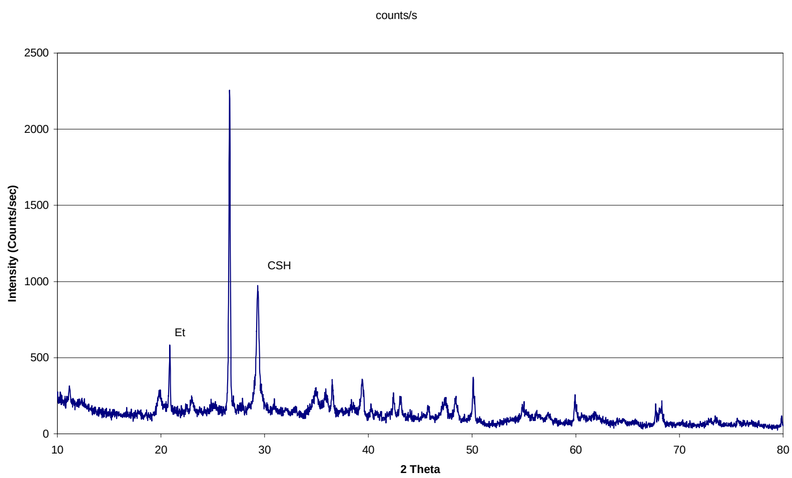


Figure 61 XRD pattern of cement-stabilized mixture, SC137/250 (28days)

25.4 XRD patterns of Mixture SC137SF/10

Reaction products of SC137SF/10 as investigated by XRD analysis are shown in Figure 62, Figure 63, Figure 64, and Figure65. It was clear that a suitable silica fume content increased the rate of reaction product formation. As a result, it thus conformed to SEM micrographs.

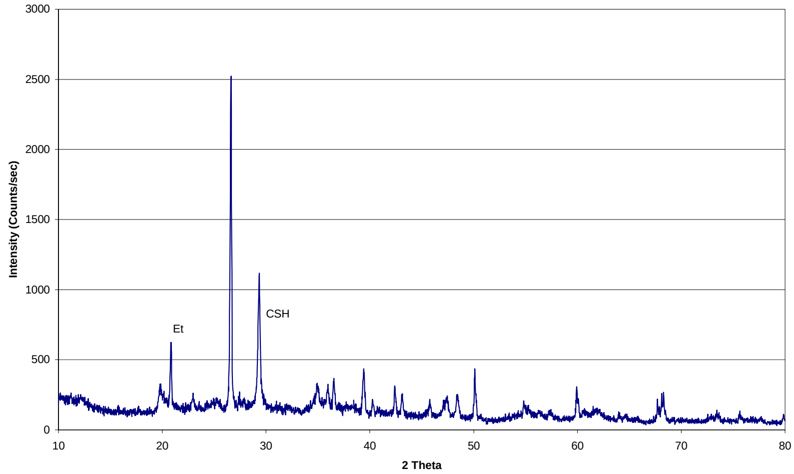


Figure 62 XRD pattern of cement-stabilized mixture, SC137SF/10 (3 days)

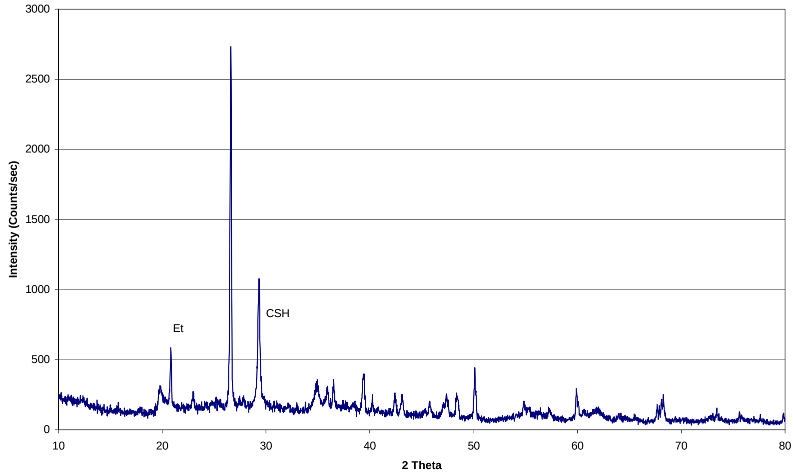


Figure 63 XRD pattern of cement-stabilized mixture, SC137SF/10 (7 days)

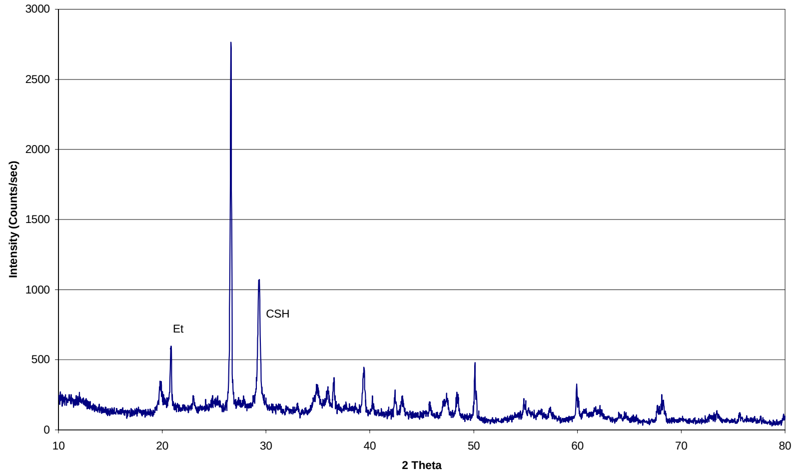


Figure 64 XRD pattern of cement-stabilized mixture, SC137SF/10 (14 days)

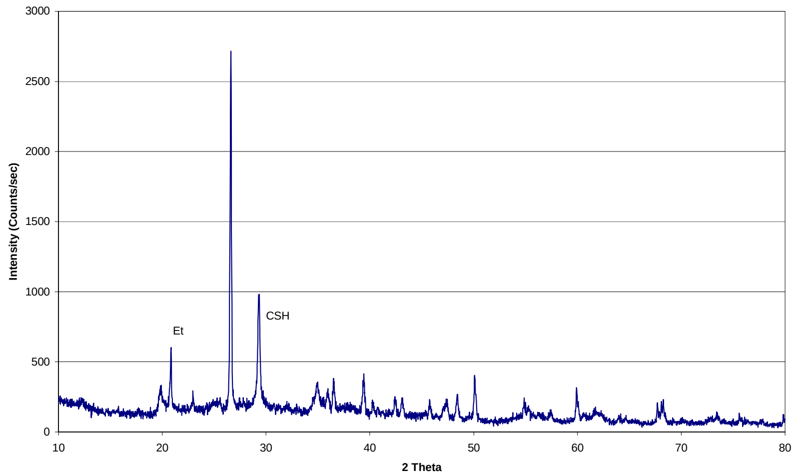


Figure 65 XRD pattern of cement-stabilized mixture, SC137SF/10 (28 days)

CONCLUSIONS

The main results on this study can be summarized as follows:

1. Based on the geo-environmental engineering viewpoint, when a combined concept of mechanical modification and chemical stabilization were appropriately applied, the physical and engineering properties of seabed dredged materials could be significantly improved; increasing in strengths, reducing in permeability and increasing in durability.

2. The onsite dewatering combined with the laboratory dewatering techniques was proposed as mechanical modification method to simply modify physical properties of seabed dredged materials having extremely high water content ($w_n \approx 200$ %), prior to chemical stabilization. Consequently, water content could be lowered to obtain a suitable range for chemical stabilization. In this study, initial water content of 110-140% (approximately 1.1 - 1.4 times liquid limit) provided appropriate water for hydration as well as suitable workability for preparation of homogeneous soil cement mixtures.

3. For chemical stabilization, cement could be used effectively to improve properties of the seabed dredged materials having the predetermined initial mixing water content. Strength development was influenced by both initial water content and cement content. Sufficient degree of stabilization on the dewatered seabed dredged materials could be achieved using the optimum mix proportion based on the water to cement ratio (w/c) ratio. In addition, the following equations were proposed for estimations of the unconfined compressive strength (q_u) for 7, 14 and 28 days, respectively.

$$q_u \text{ (7 days)} = 0.40 (w/c)^2 - 5.94(w/c) + 23.22$$

$$q_u \text{ (14 days)} = 0.70(w/c)^2 - 9.97(w/c) + 37.12$$

$$q_u \text{ (28 days)} = 0.59(w/c)^2 - 9.19(w/c) + 37.22$$

4. The results of permeability test showed that the coefficient of permeability (k) of cement-stabilized dewatered seabed dredged materials markedly decreased for all cement content at the early curing time. An average coefficient of permeability of the dewatered seabed dredged materials decreased about 10 times after 7 days (k $< 10^{-7}$ cm/sec).

5. The cement could be effectively used to minimize the shrinkage potential in dewatered seabed dredged materials. For low-medium (100 – 150 kg/m^3) and medium-high (150 – 250 kg/m^3) cement contents, the volumetric shrinkages were reduced to approximately 15%-20% and 10%-15%, respectively. The resultant volumetric shrinkages were decreased close to the target value for this study.

6. The stabilized seabed dredged materials had potential for use as construction materials such as liner for landfill. Based on w/c ratio analysis, in order to fulfill strength requirement (2.0 kg/cm^2) and permeability requirement (k $< 10^{-7}$ cm/sec), the recommended w/c ratio suitable for stabilization of the dewatered seabed dredged materials should be within the range of 5.5- 6.5.

7. Using cement and silica fume to stabilize dewatered seabed dredged materials, the strengths characteristic curves were similar to those of cement stabilization. As observed in the test results, the strengths of cement-silica fume stabilization were increased during the first two weeks approximately 1.0 - 2.0 kg/cm^2. However, hardening effect seemed to be less pronounced at long term. It was found that approximately 10% cement replacement by silica fume markedly affected the strength development, especially for the early curing time. The volumetric shrinkages could be lowered to approximately 9-12%. In addition, coefficients of permeability had trends to decrease slightly lower than those of cement stabilization.

8. The results form XRD analysis showed that calcium silicate hydrate (CSH) and Ettringite were main reaction products contributing to strength development of the stabilized dredged materials. Based on the Scanning Electron microscope (SEM) observations, microstructures of the seabed dredged materials changed through the processes of stabilization. In natural condition, they were flocculated after the process of dewatering, resulting in markedly

reduced void ratio. For stabilized dewatered seabed dredged materials, due to the formation of reaction products, the microstructures markedly changed and seemed to agree with results obtained form strength test and XRD analysis.

RECOMMENDATION

Recommendations for further study are summarized as follows:

1. The stabilized dewatered seabed dredged materials had potential to be used as landfill liners. However, the resultant volumetric shrinkages could meet the target value of this study which was slightly higher than the most preferable requirement. Therefore, supplementary improvement techniques or construction methods are needed for future study.

2. The improvement effects based on the proposed techniques have to be clarified on other dredged materials having different soil compositions. In order to obtain more effective stabilizations, the reaction products and rate of production in relation to the strength development mechanisms also need further elucidation.

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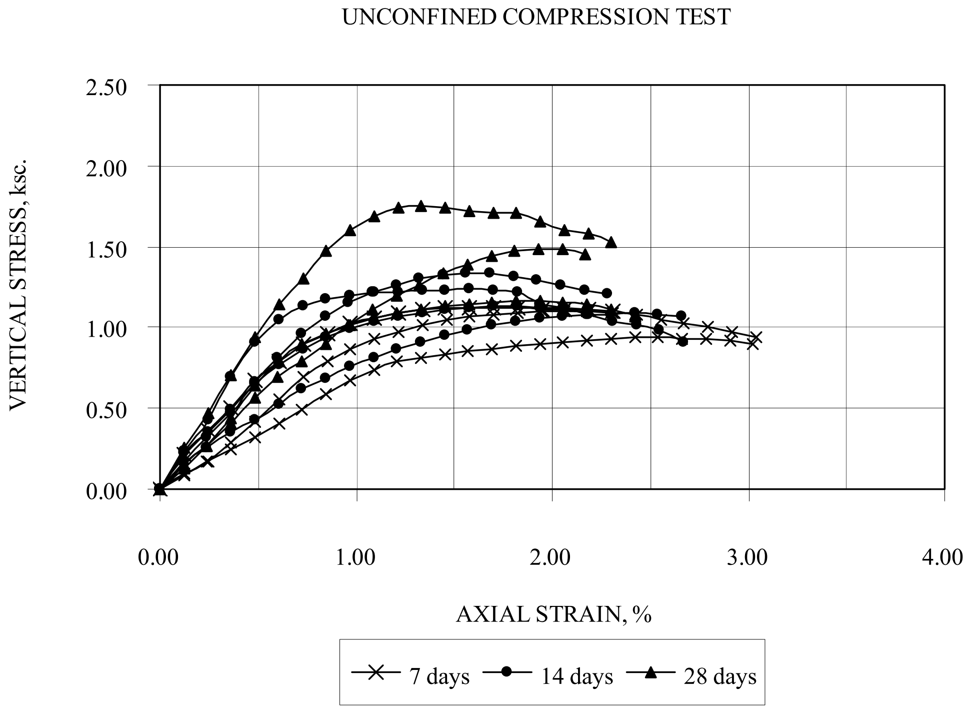
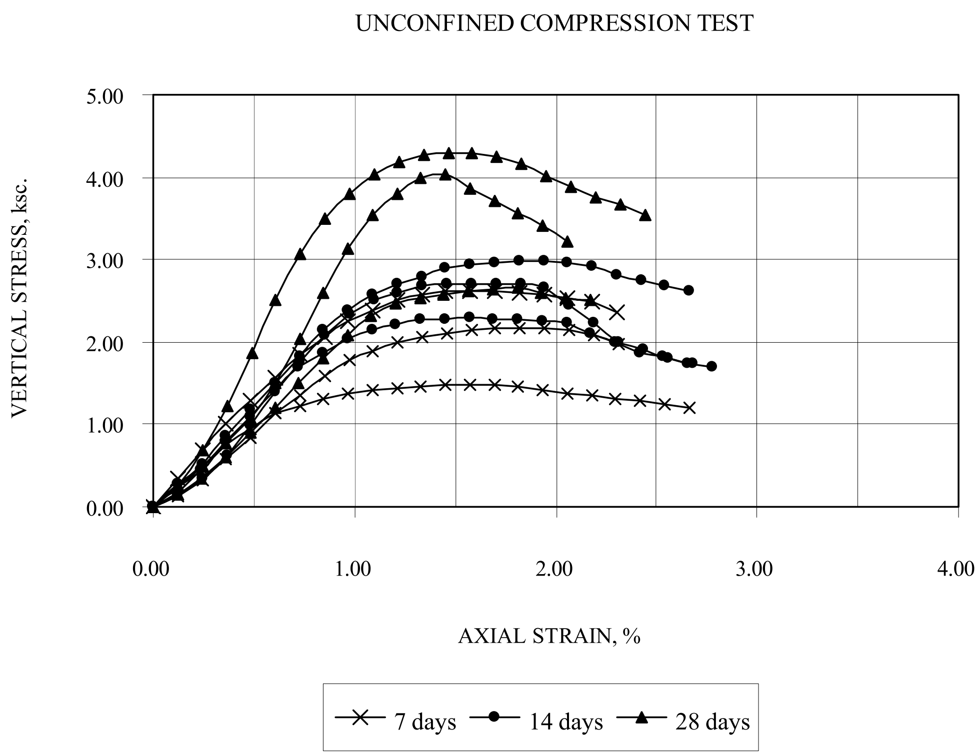
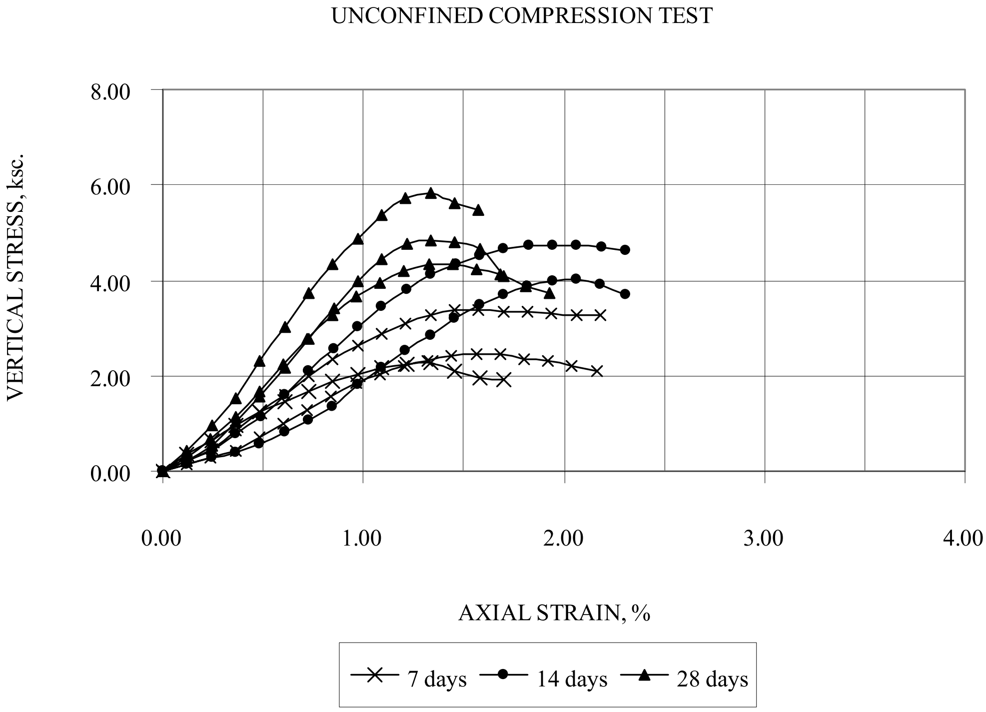
APPENDIX



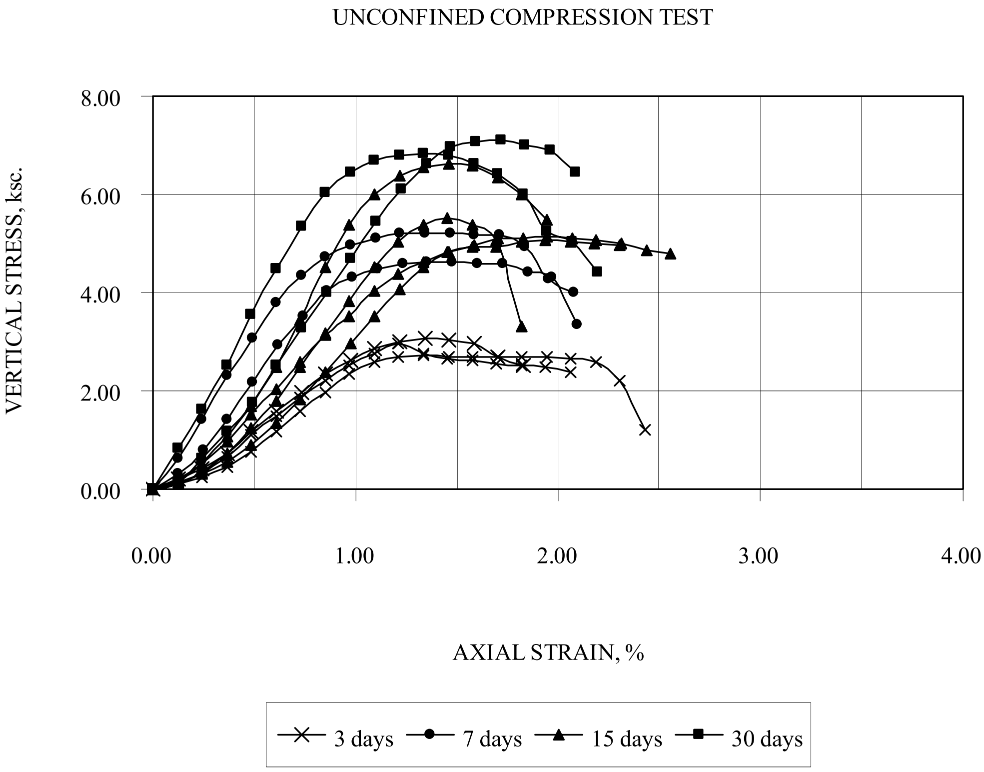
Appendix Figure 1 Stress-strain characteristics of SC108/100



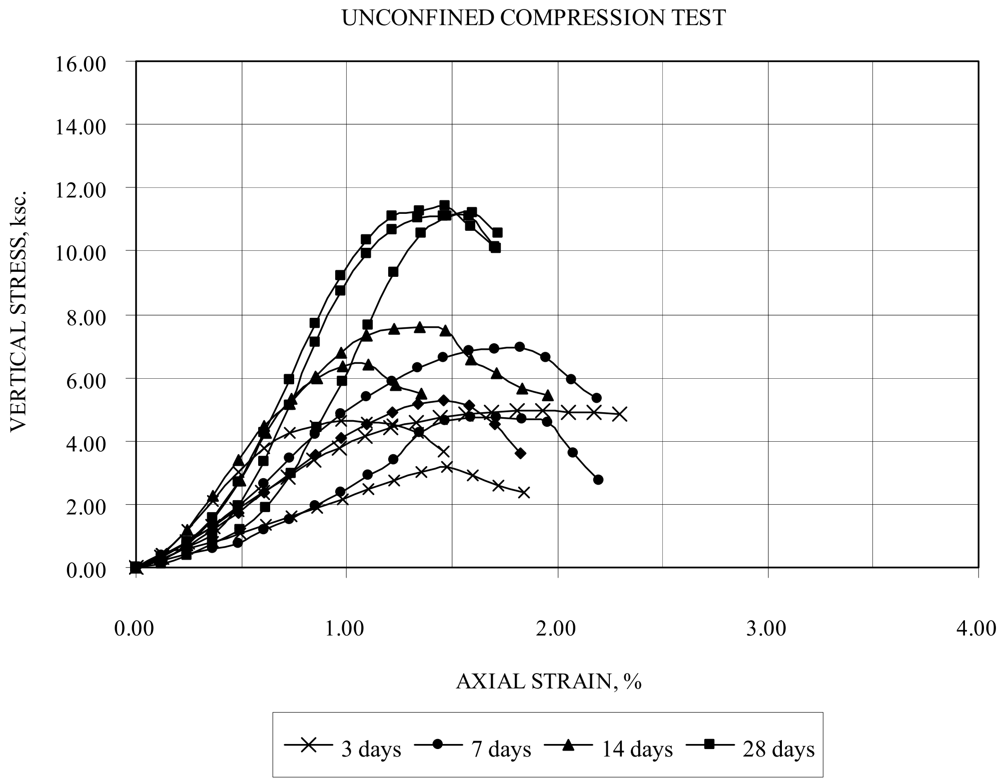
Appendix Figure 2 Stress-strain characteristics of SC108/125



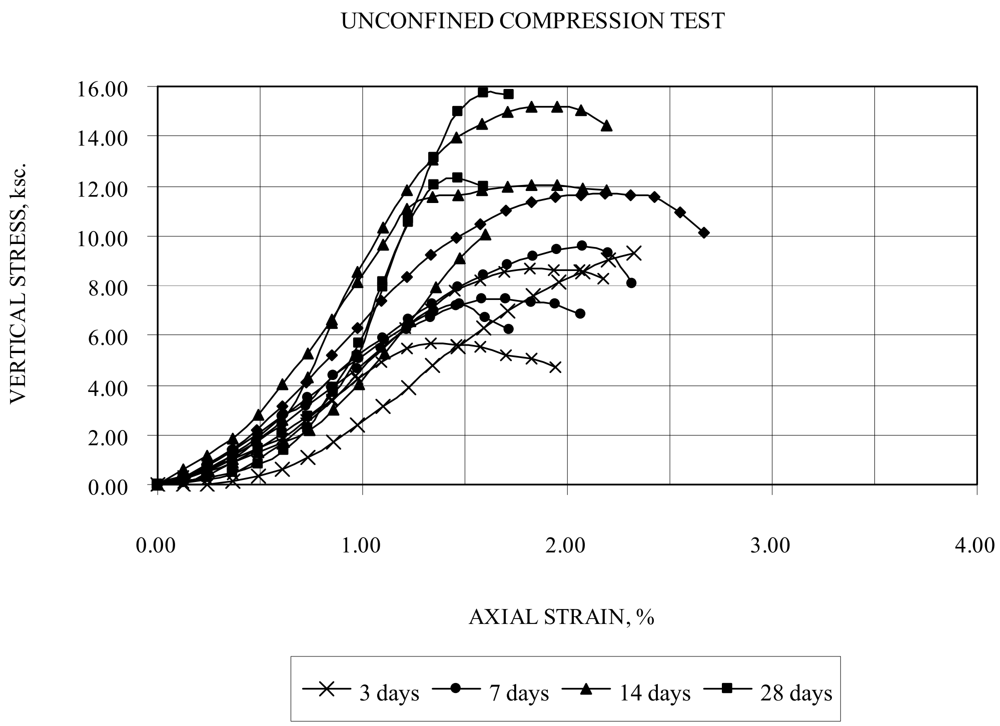
Appendix Figure 3 Stress-strain characteristics of SC108/150



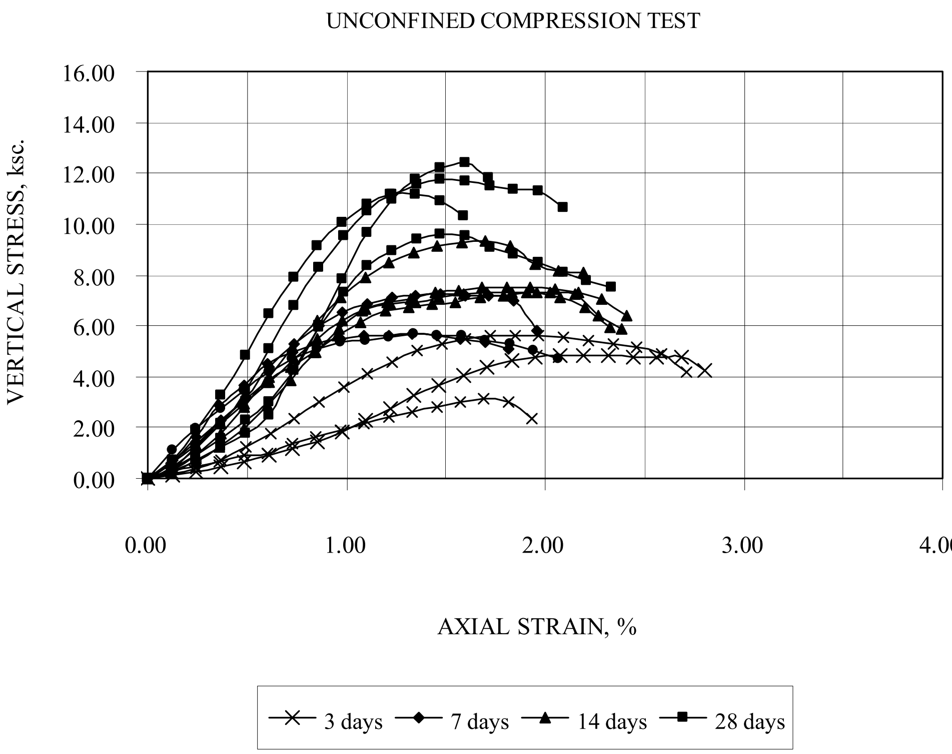
Appendix Figure 4 Stress-strain characteristics of SC137/150



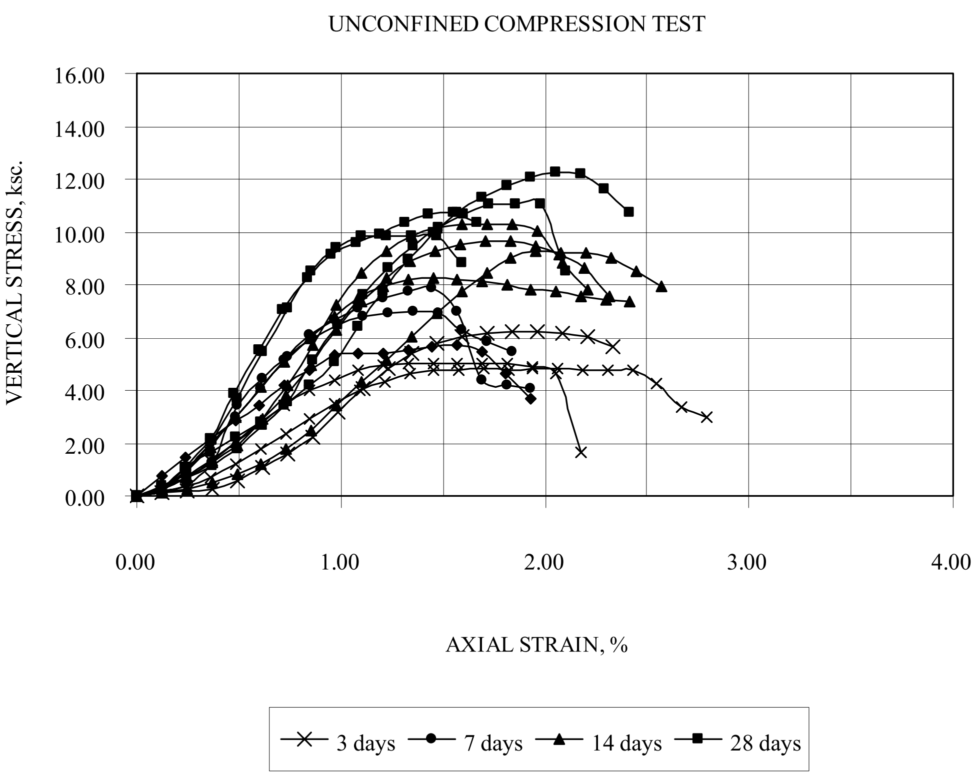
Appendix Figure 5 Stress-strain characteristics of SC137/200



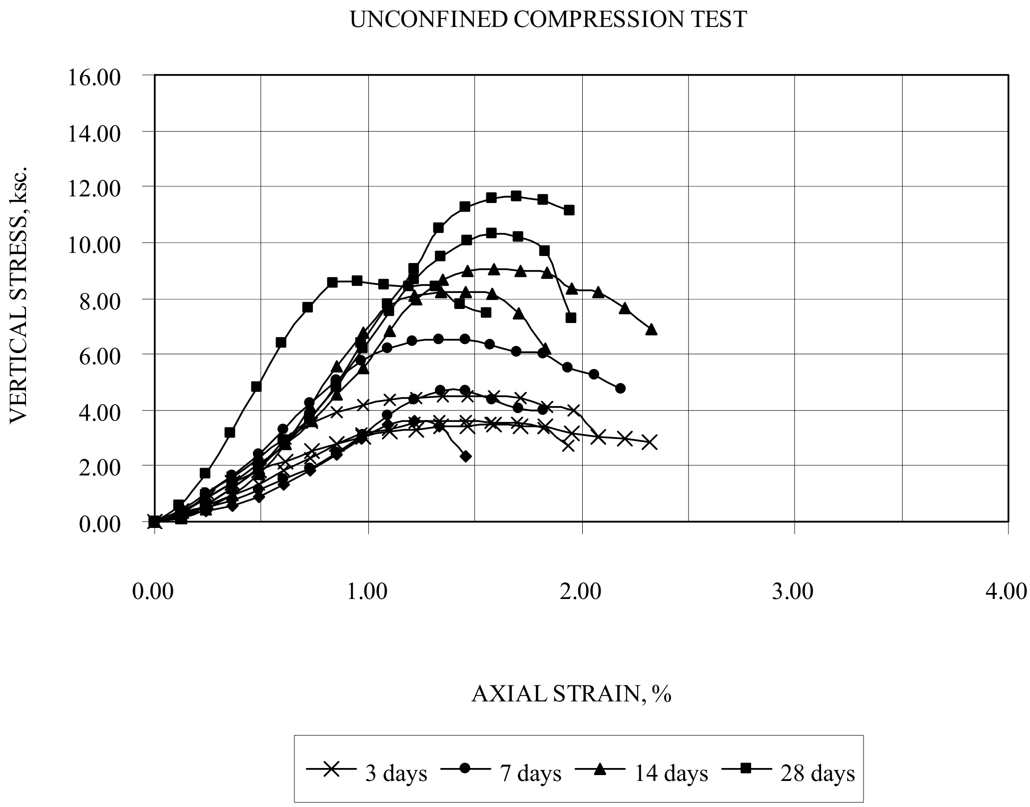
Appendix Figure 6 Stress-strain characteristics of SC137/250



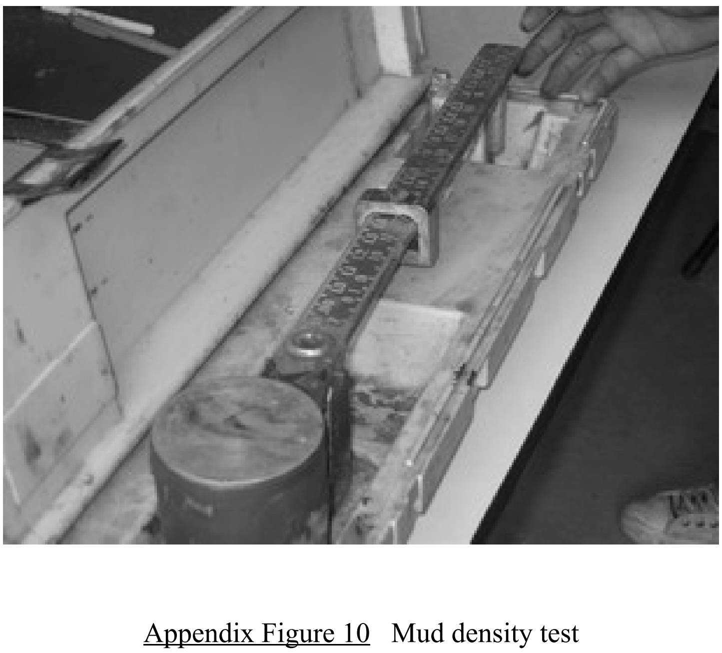
Appendix Figure 7   Stress-strain characteristics of SC137SF/5



Appendix Figure 8   Stress-strain characteristics of SC137SF/10



Appendix Figure 9 Stress-strain characteristics of SC137SF/15



Appendix Figure 10 Mud density test