STABILIZATION OF DREDGED SLUDGE AS CONSTRUCTION MATERIALS

INTRODUCTION

General

Dredging is a necessary process to maintain harbors, navigational channels and to deepen them to accommodate larger shipping vessels. Poor management of dredged material may affect the environment. So, the objective of this thesis is to reutilize dredged sludge for construction materials which thus can preserve and protect the environment.

Dredging means to excavate and gather seabed sediments in order to deepen waterway with a dredging machine. After the sediment has been excavated, it is transported from the dredging site to the placement site or disposal area. Dredging is often carried out using trailing cutter dredge, which has three cycles: loading, sailing and unloading or using more modern machinery. The transport operation, most often, is accomplished by the dredge plant or by using additional equipment such as barges, scows, pipeline, and booster pumps. The actual depth to which a channel may be dredged is referenced to an appropriate low water elevation. It may be greater than the authorized depth to accommodate needed vessel clearances. Dredging "over depth" also allows for the accuracy of excavation.

The tendency of the shipping industry is to design and construct larger vessels for increased efficiency. This in turn, requires harbor channels to be periodically deepened, which increases the dredging requirement.

There are three general alternatives that may be considered for placement or disposal of dredged material open water disposal, confined (diked / dredged fill containment areas located in an upland environment) disposal and beneficial use applications. Beneficial reuses involve the placement or use of dredged material for some productive purpose. Generally, beneficial reuse involves either open water or confined placement in some form. Some beneficial reuses involve unconfined disposal, e.g. wetland creation or beach nourishment. Other disposal methods such as mine reclamation and aquaculture are occasionally used or considered but there are usually limitations imposed (Palmero & Wilson, 1997). Dredged material has also been used for landfill capping and lining. Brick manufacture using dredged sediments is another innovation being explored (Hamer & Karius, 2001). Selection of a disposal alternative is made based on considering the technical, economic, and environmental issues.

Statement of problem

Dredged sediments are obtained from the process of dredging coastal areas and harbors in order to maintain navigable waterways. Most of dredging is done for the approach of harbor in Thailand. The main steps of dredging are digging, transportation and dumping it in the sea. The huge amount of waste dredging sludge can affect aquatic animals.

The main sources of sea pollution are from five factors which are natural field, oil spill, red tide, offshore mining and dredging as shown in Figure 1. At present, the waste dredging sludge operation has two ways; the first one is to throw the dredged sludge in the sea. This way gives a quantity of grain sedimentation and suspension which affects plants and animals in the sea. And the other is to throw away the dredged sludge on the coastal area or other places. The pollution of this way is on oceanography and natural environment.

The management of dredging sludge is very important because approximately 8 million cubic meters of dredged sludge is produced annually in Thailand. This study brings dredged sediment as construction material by mixing Portland Cement and fine sand.

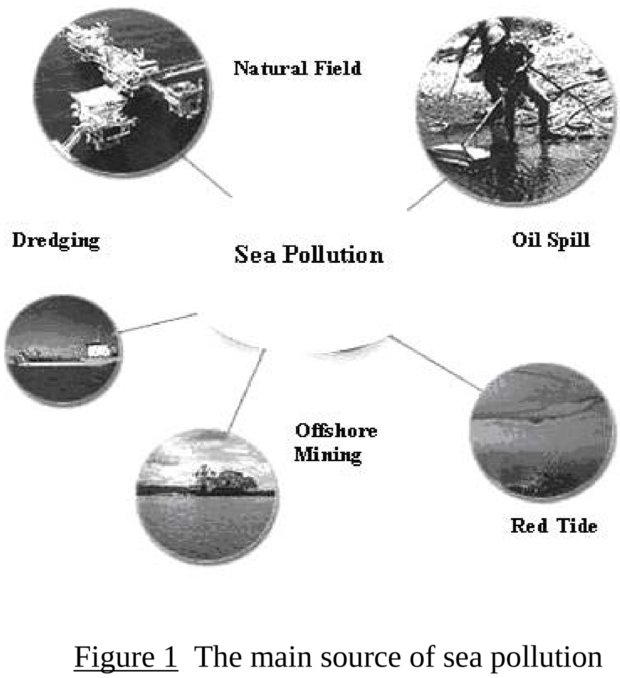


Figure 1 The main source of sea pollution

Objectives

The objectives of this study are as follows.

1. To evaluate the most suitable soil stabilization techniques to improve the properties of a dredged sludge for use as construction materials.

2. To evaluate correlations between major reaction products and strength development.

Scope of study

The study consists of laboratory test on cement and fine sand treated dredged sludge as follows.

1. In order to evaluate the most suitable techniques, combination concepts of mechanical and chemical stabilization are applied to improve dredged seabed sludge.

2. In this study, dewatering with partially replaced Portland Cement with some fine sand is selected as improvement techniques via mechanical stabilization technique. Substantially, cement is used as a soil stabilizer for an improvement of a pre-treated sludge for further improvement, i.e., chemical stabilization.

3. Unconfined compression tests are performed mainly to determine the strength characteristics gain with time, using cement with various contents and curing periods of 3, 7, 14 and 28 days. For the successful mixtures, CBR tests for both unsoaked and soaked samples are performed at curing period of 7, 14 and 28 days.

4. In order to evaluate correlations between major reaction products and strength development, X-ray diffraction analysis is performed on untreated samples and treated sample cured at 3,7,14 and 28 days. In addition, Scanning Electron Microscope (SEM) is performed on untreated sample and treated sample with successful mix proportions.

LITERATURE REVIEW

Dredging Processes

The dredging process requires a dredging unit (dredger) and a transportation or placement unit. Usually dredge material is distributed by barge or pipeline. There are basically four different types of dredgers available:

Cutter Suction Dredgers

Cutter suction dredgers free the material to be excavated by cutterheads and pump it through pipelines, called ladder, to the distribution unit as shown in Figure.2.

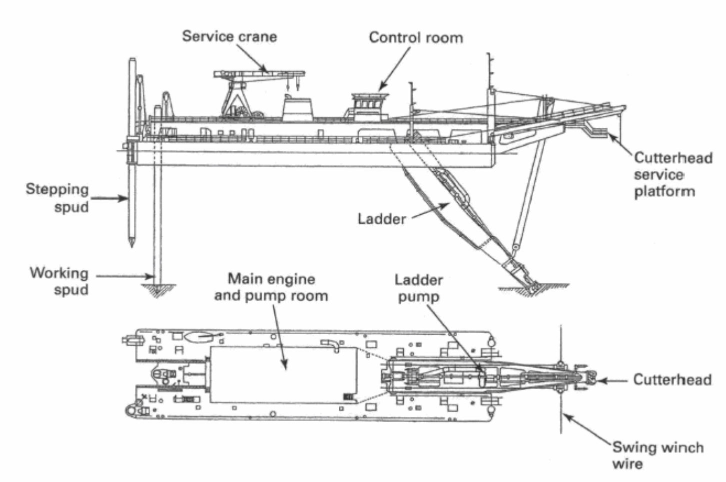


Figure 2 Cutter Suction Dredger

Suction dredging can be stationary or continuous. The cutterhead is mounted on top of the pipeline and consists of a ring and a basket as shown in Figure 3. Teeth on the basket loosen the material, which is then pumped through the opening by a vacuum pump. Strength and length of teeth and arms can be adapted to specific site conditions.

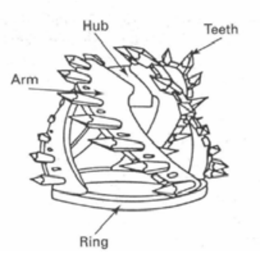


Figure 3 Cutterhead

Backhoe or Grab Dredgers

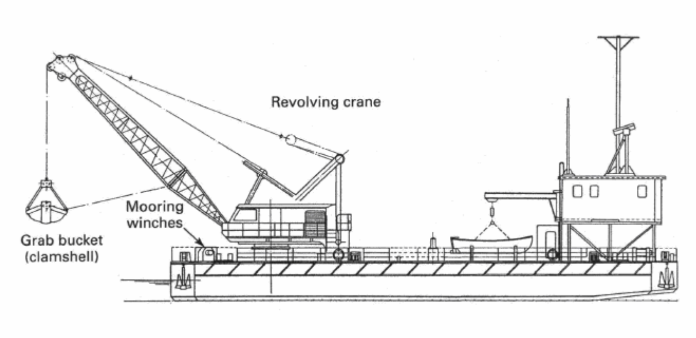


Figure 4 Grab Dredger

Figure 5 Chain Bucket Dredger

Grab dredgers as shown in Figure 4 and backhoe dredgers as shown in Figure 5 are excavators mounted on top of pontoons or barges. Backhoe dredgers are most frequently used since the excavator unit consists of regular construction equipment fixed on a floating unit. Acquisition and maintenance costs are relatively low. Of the available dredging systems, the backhoe or grab dredgers are most efficient when used for small sites. The main disadvantage of backhoe and grab dredging is a discontinuous material flow.

Bucket Dredgers

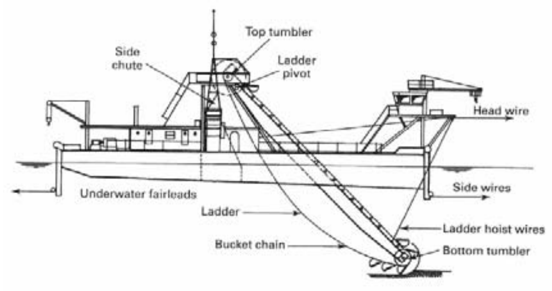


Figure 6 Chain Bucket Dredger

A bucket dredger is the chain bucket dredger as show in Figure 6. Buckets fixed to a chain scratch on the surface and transport the loosened material to the distribution unit as shown in Figure 7.The process is continuous; but due to high maintenance costs, chain bucket dredgers are no longer competitive with other dredgers.

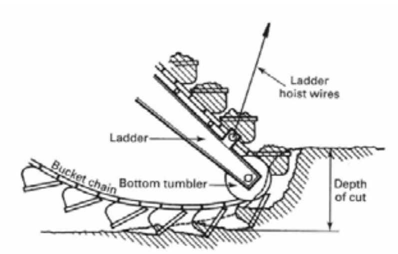


Figure 7 Cutting with bucket chain

Trailer Dredgers

Trailer dredgers tow nets above the submarine surface and thus fill them with material. These are not widely used due to high environmental impact (similarities with the trailer fishing process are obvious) and difficulties in setting the right parameters for successful dredging.

Also available are scrapers, which combine dredging, transport and/or distribution in one unit. Relatively low load capacities and long interruptions for transportation limit the use of scraper dredgers to small sites with short travel distances or one-day operations. For environmental protection the amount of particles spread out by dredging is often limited. Thus closed pipeline dredgers such as suction dredgers are preferred when the danger of material loss during the dredging process is high. This can occur in the presence of strong current or tidal movements. Usually the dredging process is only possible when the sea is relatively calm.

Characteristics of dredged material.

Physical properties of dredged material.

When hydraulically placed into a disposal area, dredged slurry can have a dry solids content ranging from near 0 to approximately 20 percent by weight. Generally, this value is about 13 percent. As the slurry flows across the disposal area, the solid particles settle from suspension coarse particles near the inlet (dredge pipe), fine particles farther into the area and finest materials in the immediate vicinity of the outlet weir. As a disposal operation progresses, coarse-grained dredged material may accumulate in a mound and displace the soft fine-grained dredged material. During and after the disposal operation, surface water is drained from the disposal area. A surface crust begins to form on fine-grained dredged material as it desiccates. Over time, surface and base drainage cause some lowering of the ground-water table, the surface crust continues to increase in thickness, secondary compression effects develop and consolidation occurs as the effective material weight above the ground-water level is increased from a submerged weight to a saturated weight. The dredged material below the surface crust remains very soft and weak. The water content of fine-grained dredged material in disposal areas is generally less than 1.5 times the LL of the material and it is possible that in freshwater areas the water content is about equal to the LL. The LL of dredged material is generally less than 200 with most values being between 50 and 100.

The initial properties of sediments dredged from the bottom of a harbor are shown in Table 1. The sediments mainly consist of a silt fraction and have an average bulk density of 76.2 pcf. The initial water content exceeds 200%. These properties are usual for silty sediments in rivers and seas.

Table 1 Physical properties of dredged harbor bottom sediment/organic deposits
Source: US Army Corps of Engineer (1987)

Property	Test Method	Result
Bulk Wet Unit Weight	AASHTO T-19	74.2 – 78.1 pcf
Water Content	Modified AASHTO T255	260 – 270 %
Specific Gravity Solids	AASHTO T-100	2.26
pH	ASTM D4972	8 - 9
Organic Content	AASHTO T-267	< 1%
Classification	AASHTO M 145	Low Plasticity Inorganic to Organic Silt

Chemical properties of dredged material.

Generally, dredged material characteristics reflect composition of dredged material and depend strongly on its mineralogy. Main components are various clay minerals, silt, or sand. The chemical compositions of dredged and similar material composition are given in Table 2.

Table 2 The chemical compositions of dredged and similar material compositions

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 %
	Dredged material (2)	65.55 %	14.86 %	6.01 %	5.64 %	4.65 %
Clay	Bentonite	45-66 %	16.4-22 %	2.5-16.5 %	0.8-2 %	2-4 %
Clay	Kaolin	52%	41 %	4.3%	0.3%	0.9%
Sand	Quartz (fines)	90-95 %				

(1) Dredged material from Port of New York (USA.), Columbia University
(2) Dredged material from Ariake Sea (Japan), H.Inoue, S. Kidera , N. Miura

Physical properties and particle size distribution are determined by the laboratory test. Particle size distributions can range from relatively coarse to very fine with median sizes well below 1 micron. Table 3 shows mineralogy and particle size ranges of dredged material and similar mineralogical compositions.

Table 3 Mineralogy and partical size range of dredged and similar material
Source: Dredged material from Port of New York (USA.), Columbia University

Type of Filler Base	Mineralogical nature	Particle Size Range
Dredged Material	Clay minerals : Illite, Chlorite Silt Minerals : Mica & Feldspars Sand : finely grained Quartz	0.8 – 40 μm
Bentonite	Montmorillonite and other clay minerals	0.6 – 1.2 μm
Kaolin clay / China clay	Kaolinite Alumino - silicates	0.5 μm
Sand filler	Quartz	0.075 – 2 mm

Fundamental Concepts of Cement Stabilization

Portland Cement is one of the older materials used for stabilization. The objectives for cement stabilization of soils are two fold. The first objective is to improve the engineering characteristics of the soil, including reduction of the PI of the soil, strength increase, reducing volume change characteristics (shrinkage / swell), and reducing permeability .This is attained primarily though hydration of the cement added to the soil. In addition to the cementing reaction, the surface chemistry of any clay particles is improved by the cation exchange phenomenon. The second objective is to increase the strength of the soil cement mixture over the long term. This objective is attained though continued hydration of the cement with time.

Types of Portland Cement

American Society for Testing and Material (ASTM) has divided Portland Cement categorized as type I, II, III, IV and V for different uses.

1. Portland Cement Type I or Ordinary Portland cement
2. Portland Cement Type II or Modified Portland cement. The cement properties are moderately sulfate resistant and moderately heat generating.
3. Portland Cement Type III or High Early Strength Portland cement. The cement hardening can occur in a few minutes.
4. Portland Cement Type IV or Low heat Portland cement.
5. Portland Cement Type V or Sulfate Resistant Portland cement. Normally , it is used for construction work in the sea or the areas that have high quantity of sulfate.

Mechanisms of Stabilization

Portland Cement is manufactured by inter-grinding clinker, a pyro-processed hydraulic material, made from raw materials in a cement kiln with calcium sulfate (usually gypsum rock at approximately 5% by weight).A Portland Cement particle is a heterogeneous substance, containing minute tricalcium silicate (C_3S) , dicalcium silicate (C_2S) ,tricalcium aluminate (C_3A) and a solid solution decribed as tetracalcium alumino-ferrite (C_4AF) (LEA,1956).

According to the standard notation used in cement chemistry, C = CaO, S = SiO_2, A = Al_2O_3, and F = Fe_2O_3. The clinker is ground to a sufficiently fine powder to increase the rate of hydration. In the context of soil stabilization through the cation exchange and flocculation-agglomeration, which requires a supply of calcium, the two calcium silicate phases, C_3S and C_2S, are the most important. The reactions which take place in soil cement stabilization can be represented in the equation as shown in equation 1 and 2.

$C_3S + H_2O \rightarrow C_3S_2H_x$(Hydrated gel) + $Ca(OH)_2$ ………..(1)

(Primary cementitious products)

$Ca(OH)_2 \rightarrow Ca^{2+} + 2(OH)^-$ ………..(2)

The formation of calcium hydroxide as a by-product of the hydration reaction of the calcium silicate phases in Portland Cement is a through-solution process. As Ca^{2+} ions are released into the pore fluid, they are available for stabilizing the surrounding clay soil. Upon initial absorption of Ca^{2+} ions by clay, the absorption rate slows down as it becomes increasingly diffusion dependent. When such conditions prevail, depending on the rate of supply of Ca^{2+} by the hydrating cement particles, Ca^{2+} ion concentration may rise locally to a level high enough to cause precipitation of $Ca(OH)_2$. Cement particles in cement modified soil are so highly dispersed that the opportunity of $Ca(OH)_2$ crystals to grow is very low.

$Ca^{2+} + 2(OH)^- + SiO_2$(Soil silica) $\rightarrow$ CSH ………..(3)

(Secondary cementitious products)

$Ca^{2+} + 2(OH)^- + Al_2O_3$(Soil alumina) $\rightarrow$ CAH ………..(4)

(Secondary cementitious products)

When pH < 12.6 , then the following reaction occurs

$C_3S_2H_x \rightarrow C_3S_2H_x$ (Hydrated gel) + $Ca(OH)_2$ ………..(5)

The hydration of cement leads to a rise of PH value of the pore water, The strong bases dissolve the soil silica and alumina (which are inherently acidic) from both the clay materials and amorphous materials on the clay particle surface, in a manner similar to the reaction between a weak acid and a strong base. The hydrous silica and alumina will then gradually react with the calcium ions liberated from the hydrolysis of cement to form insoluble compounds (secondary cementitious product), which hardens when cured to stabilize the soil. This secondary reaction is known as the pozzolanic reaction. However, the PH drops during pozzolanic reaction and a drop in the PH tend to promote the hydrolysis of $C_3S_2H_x$ to form CSH.The cement hydration and pozzolanic reaction can last for months, or even years, after the mixing.

In summary, the formation of calcium-silicate-hydrate (CSH), upon hydration of Portland Cement, is attributed to the development of its strength. Therefore, the formation of CSH may further strengthen a soil that is stabilized with the $Ca(OH)_2$ produced as the by-product of cement hydration. This process is known as a pozzolanic reaction. Calcium may also react with alumina and produce CAH that is cementitious in nature.These reactions can be expressed as shown in equations 3, 4 and 5.

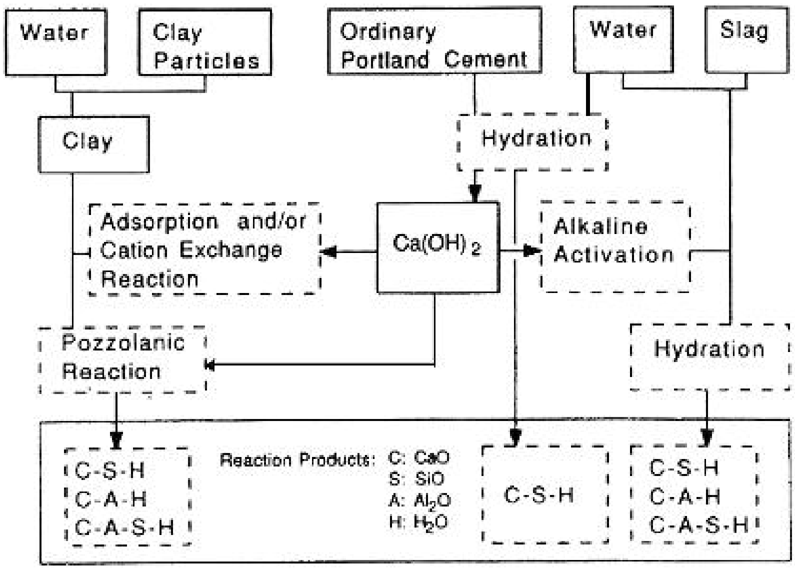


Figure 8 Chemical reaction between soil and hardening agent.
Source: After Saitoh et al. (1985)

Based upon the results of the analytical and mechanical characterizations, the following hypothesis for clay-Portland Cement and pozzolalanic materials interactions was reported by Saitoh *et.al* (1985), as shown in Figure 8. Herzog and Mitchell (1963) also suggested that the overall effect of the cement-clay interaction would be the formation of primary and secondary cementitious matter. The primary products harden into a high strength aggregate and differ from normally hydrated cement in that their calcium content is lower. The secondary processes enhance the strength and stability of soil cement by producing additional cementitious matter which increases interparticle bond strength. In this way Michell and Jack (1966) and Czernin (1862) reported that the formation changing cement – clay interaction has 3 steps as shown in Figure 9.

Step1. In the compacted condition, the cement hydration could not react but cement particle interferes between soil particles.

Step2. After short curing period, the cement hydration could generate. The result was the Cement Gel interferes between the void of soil particle and released lime reacts with active soil silica and active soil alumina. These reactions separate soil silica and soil alumina spread in all of soil.

Step3. After long curing period, the cement hydration was complete. The cement gel was in-situ in all of soil. It would make the soil strength increase with time.

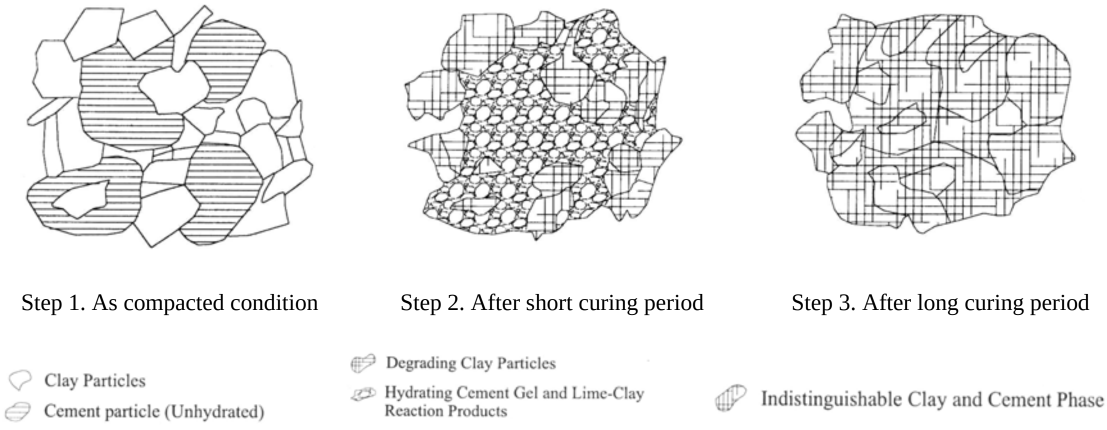


Figure 9 The formation changing cement – clay
Source: Site by Yoobanpot. (2004)

Effect of Cement on the Properties of Soil

There are six effects of cement on the properties of soil.

1. Strength.

The strength of cement-stabilized cohesionless soil increases with higher densities. For cohesionless soils with and without cement, water content and method of compaction are also important. Other factors, such as the time elapsed between mixing and compaction, length of curing, temperature, humidity, and specimen size should also be considered when comparing laboratory test results. The unconfined compressive strength (qu) generally increases linearly with the percent cement content, as illustrated in Figure 10.

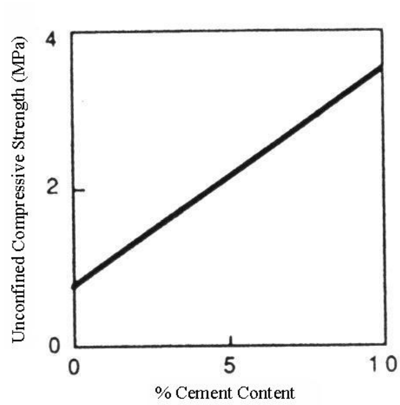


Figure 10 Gain in strength versus percent of admixture
Source: Mitchell. (1976)

2. Density and Plasticity.

Kezdi (1979) reported that cement treatment may slightly increase the Proctor maximum dry density of sands and highly plastic clays, but that of silts may be decreased; small changes in the optimum moisture content also occur. Cement reduces the plasticity index of a cohesive soil. However, an increase in the plastic limit or a reduction of the liquid limit depends on the type of soil (Housmann, 1980).

Handy *et al*. (1955) studied relationship between plasticity and cement quantity. The result showed the suitable cement quantity increase with plastic limit and liquid limit but not more than 17 percent of cement weight.

Portland Cement Association, PCA (1995) presents typical relationships for plasticity with cement content as shown in Figure 11.

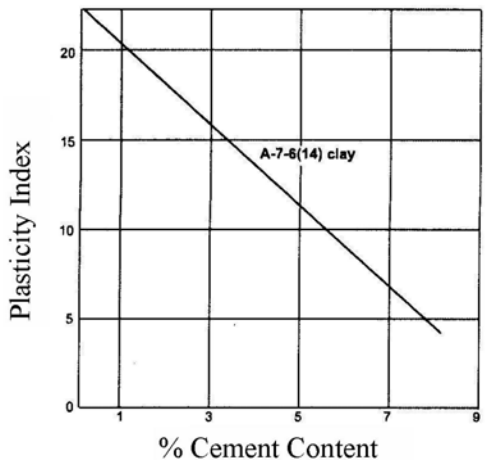


Figure 11 Plasticity vs. cement content for A-7-6 (14) clay
Source: After PCA. (1995)

3. Permeability

Addition of cement to the clay increases permeability of soils due to flocculation of soil particles. Permeability of cement treated clay is reduced with increasing cement content and curing period. This is most probably due to the impervious hardened cement hydrates, which hinder the movement of the pore water in the enclosed matrix.

4. Compressibility

Suzuki (1982) reported that the compressibility of the soft clay undergoes to a reduced value after treatment. The preconsolidation pressures of the treated soil are increase with increasing cement content. The compression indices at consolidation stress conditions less when the preconsolidation pressure are extremely small, while the compression indices at consolidation stress conditions greater when the preconsolidation pressure are the same.

5. Swelling and shrinkage.

Even small addition of cement to an expansive subgrade soil significantly reduces shrinkage and swell, generally below 1%. Cement also provides stability against, freeze-thaw cycles and repealed wetting and drying.

6. Cracking.

Cracking of cement-treated pavement layers takes place initially because of hydration of the cement and drying of the soil. Later, traffic may induce fatigue cracking. Both types of cracking are considered in the design of pavement incorporating stabilized layers.

Factors affecting hardening characteristics of Soil - Cement

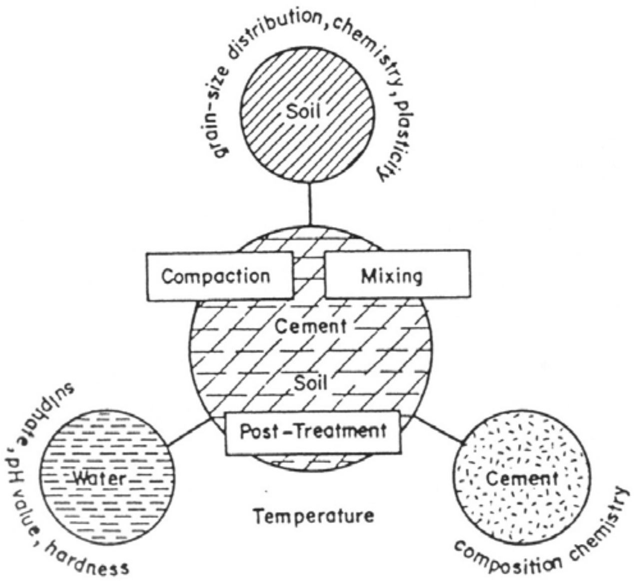


Figure 12 Factors affecting the properties of Soil-Cement
Source: Kezdi. (1979)

Hardening characteristics of cement treated soils are developed by number of factors. There are four factors affecting the hardening characteristics of soil cement, as illustrated in Fig 12.

1. Type of Cement

The differences in improvement of cement treated clays by using different types of Portland Cement have been investigated by many researchers. The stabilization by Type III Portland Cement renders better improvement of soil than the Type I cement does Davision and Bruns (1960). However, the Type I Portland Cement is the most popular cement used in soil stabilization. This is because it is the most readily available and cheapest compared with other types of cement (Ruenkrairergsa and Aiam-Chang, 1981).

Research by Felt (1955) revealed that strengths of sandy loam, silty loam and silty clay mixed with varies of cement 6 to 30 percentage of volume, range from 2 days to 1 year, gained with curing time. The bigger soil particles had more strength and the soil that consisted of more clay contents had low strength.

2. Cement Content

In general, it has been found that the greater the cement content, the greater was the strength of the cement treated clay (Broms, 1984).

Ingle and Metcalf (1972) and Ruenkrairergsa (1982) suggested that soil cement strength gain with quantity of cement in linear regression equation. In addition, rate of strength development depended on soil type, as shown in Figure 13. The suitable cement content would be experimented using trail mix method.

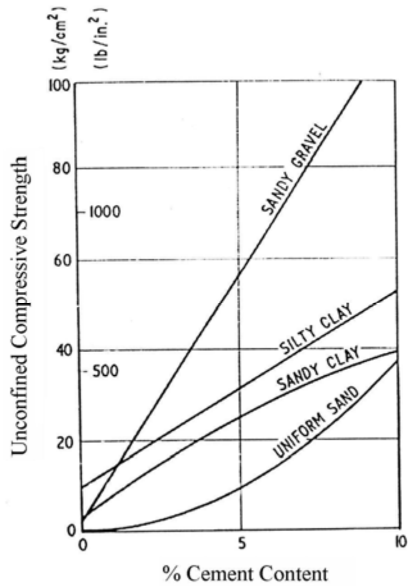


Figure 13 Strength development of soil type at 7 days
Source: Ingles and Metcalf (1972)

Portland Cement Association, PCA (1995) presents typical relationships for unconfined compressive strength with cement content for coarse-grained and fine-grained soils as shown in Figure 14.

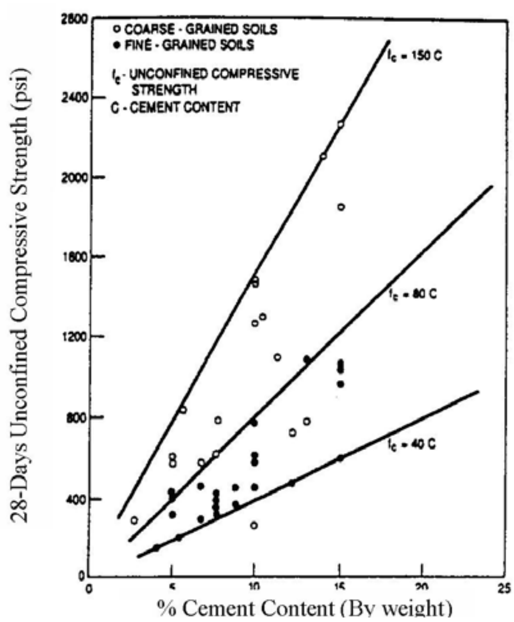


Figure 14 Unconfined compressive strength vs. cement content for A-7-6 (14) clay
Source: After PCA. (1995)

3. Curing Time

In a manner similar to that of concrete, strength of cement treated clay increases with time. Rate of increase in strength was generally rapid in the early stages of the curing period.

Ingles and Metcaft (1972) suggested soil cement strength gain with curing time as shown in Figure 15.

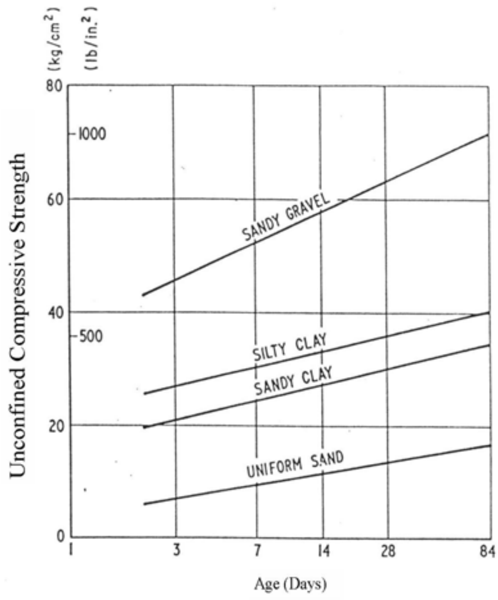


Figure 15 Effect of age on strength of various soils stabilized with 5% cement
Source: Ingles and Metcaft (1972)

4. Soil Type

Effectiveness of cement decreases with increasing water content and organic content. The improvement decreases generally with increasing plasticity index of the clay (Broms, 1986). The strength increase of cement treated clay on organic soils was often very low. However, cement was more effective than lime in the stabilization of organic soils (Miura *et al*.1986).

Davidson (1961) found that the difference of each soil type chemical reaction depened on type of cation in the soil particles. The organic clay has many effects in chemical reaction process.

Ingles and Metcaft (1972) suggested that with more organic soil cement and sulfate content in the soil, the cement hydration process is delayed and the strength of soil cement would decrease too.

Soil Minerals and Fabric

Clay Minerals

Clay minerals are crystalline substances evolved primarily from chemical weathering of certain rock-forming minerals. All clay minerals are very small, colloidal-sized crystals (diameter less than 1 μm), and they can only be seen with an electron microscope. The individual crystals look like tiny plates or flakes. From X-ray diffraction studies scientists have determined that these flakes consist of many crystal sheets which have repeating atomic structures. Major clay minerals are:

a) Kaolinite

Kaolinite consists basically of repeated layers of one tetrahedral (silica) sheet and one octahedral (alumina or gibbsite) sheet. Because of the stacking of one layer of each of the two basic sheets, kaolinite is called a 1: 1 clay mineral as shown in Figure 16(a).

b) Montmorillonite (Smectite)

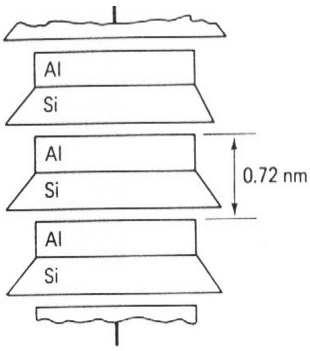
Montmorillonite is composed of two silica sheets and one alumina (gibbsite) sheet as shown in Figure 16(b). The octahedral sheet is between the two silica sheets with the tips of the tetrahedrons combining with the hydroxyls of the octahedral sheet to form a single layer.

c) Illite

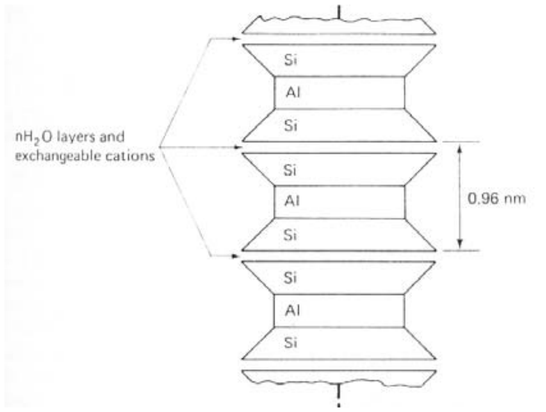
Illite is constituent of clay soils. It also has a 2:1 structure similar to montmorillonite, but the interlayers are boned together with a potassium atom as showed in Figure 16(c).

d) Chlorite

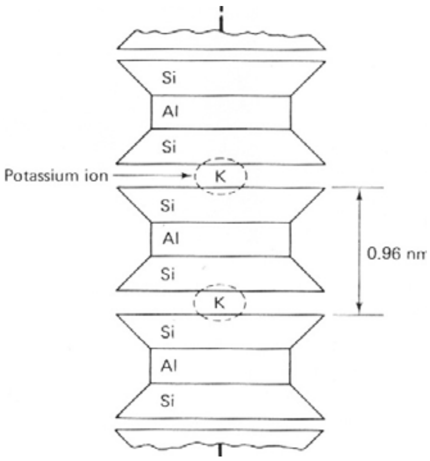
Chlorite is made of repeated layers of a silica sheet, an alumina sheet, another silica,and then either a gibbsite (Al) or brucite (Mg) sheet .It is called a 2:1:1 as shown in Figure 16(d).



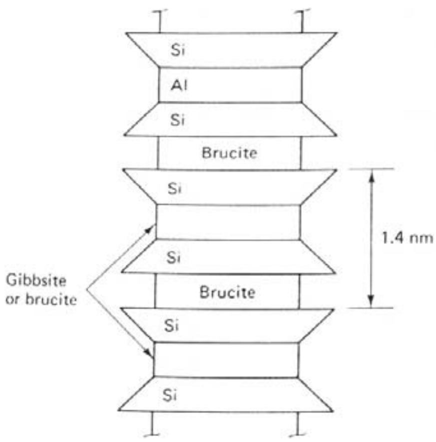
a). Kaolinite
Source: After Lambe (1953)



b). Montmorillonite
Source: after Lambe (1953)



c). Illite
Source: After Lambe (1953)



d). Chlorite
Source: After Mitchell (1976)

Figure 16 Schematic diagrams of clay mineral.

Soil structure and fabric

1. Natural structure clay

In geotechnical engineering, structures mean both geometric arrangement of particles or mineral grains as well as the interparticle forces among them. Soil fabrics refer to the geometric arrangement of the clay particles. Studies using the scanning electron microscope (SEM) can identify individual clay particles as aggregated or flocculated structures. Soil fabric units group together in form of clusters which are large enough to be investigated by a microscope. Clusters group together to form peds and even groups of peds, which can be seen by visual inspection..Other macrostructural features such as joints and fissures constitute macrofabric system. A schematic sketch of this system (Young and Sheeran (1973) and Pusch (1970, 1973)) is shown in Figure 17.

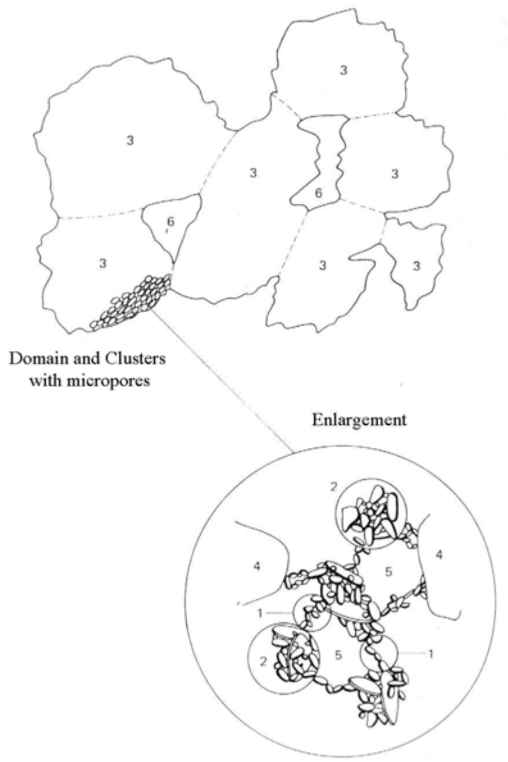
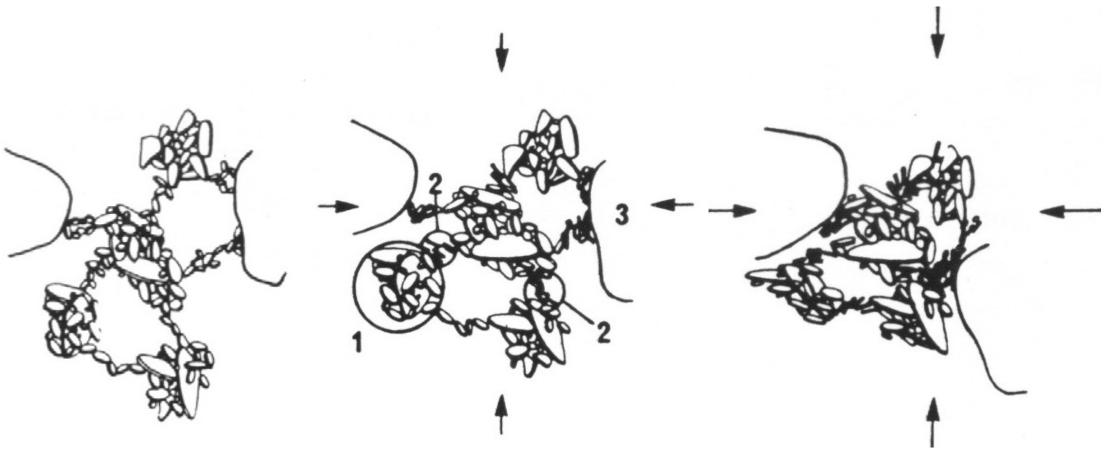


Figure 17 Schematic diagram of the soil microfabric and macrofabric system proposed by Yong and Sheeran (1973) and Pusch (1973): 1.domain or links, 2.cluster or aggregate, 3. ped , 4. silt grain , 5. micropore and 6. macropore.

Pusch (1973) reported that in regular state the aggregates are particles closely packed together as shown in figure 18a. The aggregates are much stronger than the links. When shear stress is greater than the pre consolidation stress, the links break down, causing particles parallelly formed as aggregates and moved into more stable positions as shown in figures 18b and 18c.



a) Clay Structure

b) Applied Pressure

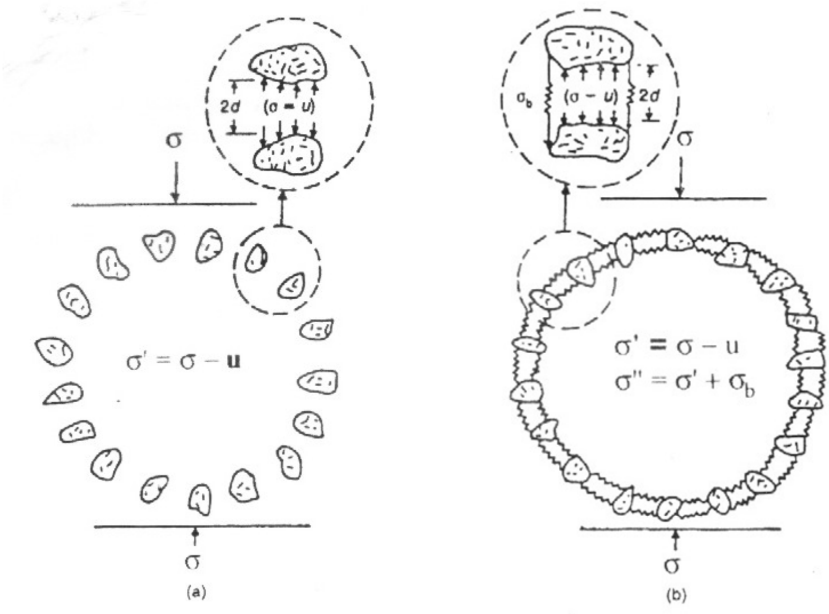
c) Applied Pressure

Figure 18 Fabric formation in an aggregated clay when pressure is applied. (Pusch,1973) : 1. domain or links , 2.cluster or aggregate , 3. ped

2. Cemented Structure Clays

Leroueil et al. (1979) defined the cemented soil as “structured soil” which was destructured due to stresses applied much greater than its yield stress.

Nagaraj *et al.*(1990),Yamadera 1999,Nagaraj and Miura 2001 found that the stress transfer in clay water system took place though an interacting fluid phase .The soil state realized is due to the equilibrium between long range forces and the externally applied stress. There is nothing in principle to bar the coexistence of long range forces and cementation bonds. They have revealed that clay microfabric consists of aggregated clay particles and the consequent enclosed capillary pore as shown as Figure 19(a) and in Figure 19(b) to show cement is added to a system with a preformed fabic and to weld the fabric in order to strengthen the fabric at the intercluster spacing.



(a). Uncemented Soil (b). Cemented Soil

Figure 19 Possible clay fabric and its cementation
Source: Nagaraj *et al*. (1994, 1998)

Fabric Determinations

A variety of methods, both direct and indirect, has been used to study the fabric and features in soils, as listed in Table 4. Of the methods listed in the table, optical and electron microscopy, X-Ray diffraction and pore size distribution offer the advantages of providing direct, unambiguous data on specific fabric features, provided the samples studied are representative and the sample preparation method has not destroyed the original fabric. In this thesis fabric and features were studied by X-Ray diffraction and scanning electron microscope.

1. X-Ray Diffraction Analysis

X-Ray diffraction is the most widely used method for identification of fine-grained soil minerals and study of their crystal structures. X- Ray is one of the several types of waves in the electromagnetic spectrum and has wave lengths in the range of 0.01 to 100 $\mathring{A}$ .When high speed electrons strike on surfaces of target material one of two phenomena may occur:

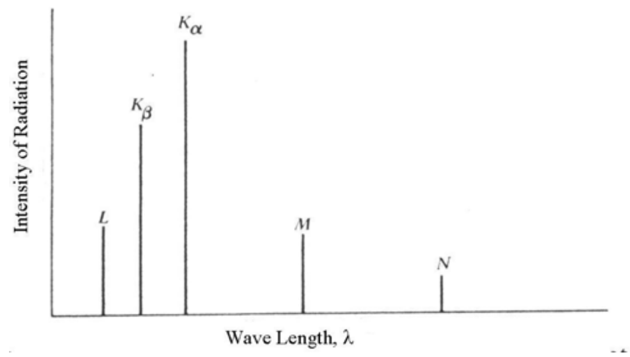
First, the high speed electron may strike and displace an electron from an inner shell of one of the atoms of the target material. An electron from one of the outer shells then falls into the vacancy to lower the energy state of the atom. An X-Ray of wave length and intensity characteristic of the target atom and of the particular electronic positions are emitted. Because electronic transfers may take place in several shells and each has a characteristic frequency, the result is a relationship between radiation intensity and wave length such as shown in Figure 20(a).

Second, if the high speed electron does not strike an electron in the target material but slows down in tile intense electric fields near atomic nuclei, then the decrease in energy is converted to heat and to X-ray protons. X-rays produced in this way are independent of the nature of the bombarded atoms and appear as a band of continuously varying wave length as shown in Figure 20(b). The resultant output of X-Ray from these two effects acting together is shown in Figure 20(c).

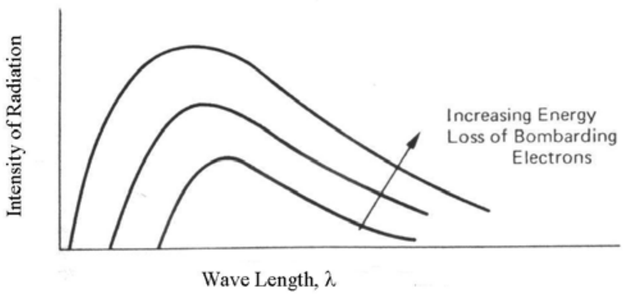
Table 4 Techniques for study of soil fabric

Method	Basis	Scale of Observations and Features Discernable
Optical Microscope (Polarizing)	Direct observation of fracture surfaces or thin sections	Individual particles of silt size and larger, clay particle groups, preferred orientation of clay, homogeneity on a millimeter scale or larger, large pores, shear zones Useful upper limit of magnification about x 300
Electron Microscope	Direct observation of particle of fracture surfaces through soil sample (scanning electron microscope - SEM) observation of surface replicas (transmission electron microscope - TEM)	Resolution to about 100 A°,large depth of field with SEM ; direct observation particles ; particle groups and pore space ; details of microfabric
X – Ray Diffraction	Groups of parallel clay plates produce stronger diffraction than randomly oriented plates	Orientation in zones several square millimeters in area and several micrometers thick; best in single mineral clays.
Pore Size Distribution	(1) Forced intrusion of nonwetting fluid (usually mercury) (2) Capillary condensation	(1) Pores in range from ~0.01 to ~10 μm (2) 0.1 μm maximum
Acoustical Velocity	Particle alignment influences velocity	Anisotropy; measures microfabric averaged over a volume equal to sample size [a]
Dielectric Dispersion and Electrical Conductivity	Variation of dielectric constant and conductivity with frequency	Assessment of anisotropy ; flocculation and deflocculation ; measure microfabric averaged over a volume equal to sample size [a]
Thermal Conductivity	Particle orientations influence thermal conductivity	Anisotropy ; measures microfabric average over a volume equal to sample size [a]
Magnetic Susceptibility	Variation in magnetic susceptibility with change of sample orientation relative to magnetic field	Anisotropy ; measure microfabric average over a volume equal to sample size[a]
Mechanical Properties Strength Modulus Permeability Compressibility Shrinkage and Swell	Properties reflect influences of fabric	Microfabric averaged over a volume equal to sample size[a] ; anisotropy ; macrofabric features in some cases.

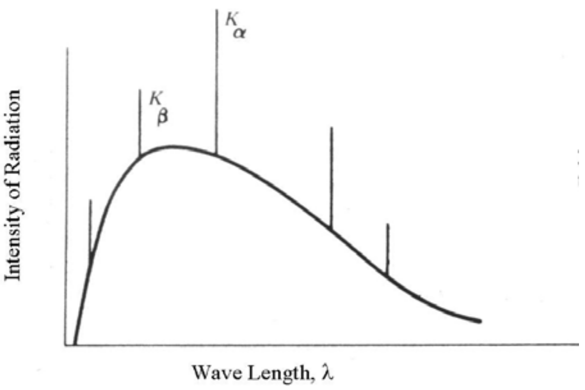
[a] For a homogeneous sample. Discontinuities, stratification, and so on, on a macroscale can override effects of microfabric
Source: Mitchell. (1976)



a) Electron displacement. Letter designate shells in which electron transfer takes place.



b) Deceleration of electrons in an electric field.



c) Composite relationship for X-Ray intensity as a function of wave length.

Figure 20 Phenomena of X-Ray generation
Source : Mitchell (1976)

The different clay minerals are characterized by first order basal reflection at 7, 10, or 14 Å. Positive identification of specific mineral groups ordinarily requires certain pretreatments. There are three minerals of X-Ray diffraction pattern as followed (Figure 21):

a) Kaolinite minerals.

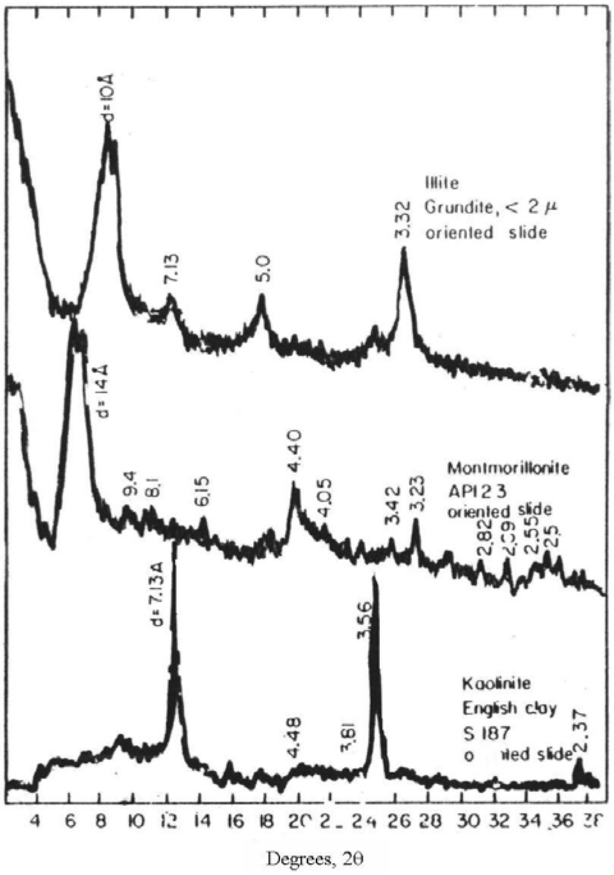
Kaolinite has a basal spacing of about 7.2 Å, which is insensitive to drying or moderate heating. Kaolinite minerals are destroyed by heating to 500°C. The other clay minerals are not. Hydrated halloysite has a basal spacing of 10 Å, which collapses irreversibly to 7 Å on drying at 110°C. The electron microscope is often needed to distinguish dehydrated halloysite (metahalloysite), with its tubular morphology, from kaolinite.

b) Illite (Hydrous mica) minerals.

The illites are characterized by a d- spacing of about 10 Å, which remains fixed both in the presence of polar liquids and after drying.

c) Montmorillonite (Smectite) minerals.

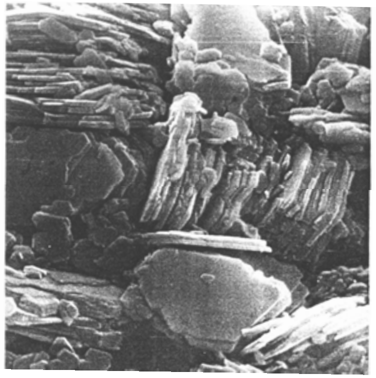
The expansive character of this group of minerals provides the basis for their positive identification. When air dried, these minerals may have basal spacing of 12 to 15 Å. After treatment with ethylene glycol or glycerol, the smectites expand to a d- spacing value of 17 to 18 Å. When oven dried, peak drops to about 10 Å as a result of the removal of interlayer water.



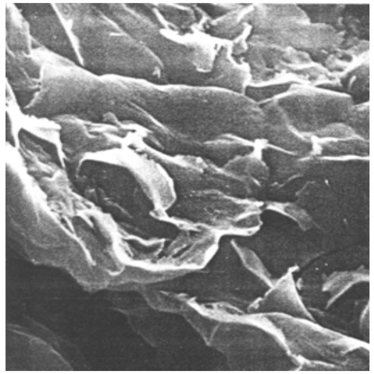
<u>Figure 21</u> Typical X-ray diffraction pattern of kaolinite, montmorillonite and illite minerals (oriented particles using CuK ∝ radiation)
Source: Mitchell. (1976)

Electron Microscope and SEM of clay minerals

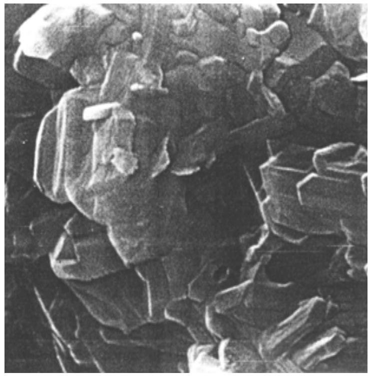
The electron microscope is method that can reveal particles and particle arrangements directly. An electron microscope is a microscope in which the image is formed by a detector synchronized with a focused electron beam scanning the object. Magnetic lenses, which refract an electron beam, from the basis of the transmission electron beam are focused on the surface of specimen and thus reflect structure of material. Some of the electrons are scattered from the specimen, and different parts of the specimen appear light or dark in proportion to the amount of scattering. After passing though a series of lenses, the image is displayed on a monitor for viewing. The examples of each clay mineral are shown in Figure 22.



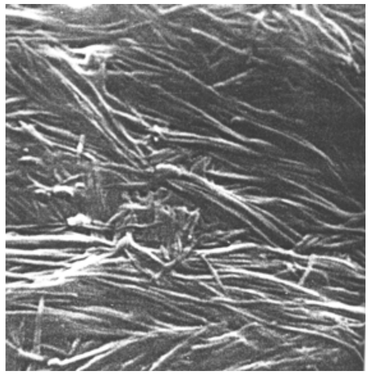
a). SEM of Kaolinite
from St.Austell, Cornwall, English.



b). SEM of Montmorillonite
from Clay Spur ,Wyoming ,USA.



c). SEM of Illite
from Morris , Illinois,USA.



d). SEM of Chlorite
from Attapulgis , Georgia, USA.

<u>Figure 22</u> Electron Photomicrograph
Source: Tovey. (1971)

Specification and Criteria for Cement Stabilization

General Criteria

Soil-cement mixture design criteria are used to apply to the general soil cement mixture during a design procedure. This section presents range of unconfined compressive strengths of soil cement as summarized in Table 5 and typical cement requirement for various soil groups as summarized in Table 6.

Table 5 Ranges of unconfined compressive strengths of soil-cement.
Source: After ACI 230.1R - 90

Soil Type	7-Day Soaked Compressive Strength ,psi	28 – Day Soaked Compressive Strength ,psi
Sandy and gravelly soils	300-600	400-1000
Silty soils	250-500	300-900
Clayey soils	200-400	250-600

Table 6 Typical cement requirements for various soil groups
Source: After ACI 230.1R - 90

AASHTO soil Classification	ASTM soil Classification	Typical range of cement, %by weight	Typical cement content for moisture density test, cement, %by weight	Typical cement content for durability tests, %by weight
A-1-a	GW,GP,GM SW,SP,SM	3-5	5	3-5-7
A-1-b	GW,GP,SM,SP	5-8	6	4-6-8
A-2	GM,GC,SM,SC	5-9	7	5-7-9
A-3	SP	7-11	9	7-9-11
A-4	CL,ML	7-12	10	8-10-12
A-5	ML,MH,CH	8-13	10	8-10-12
A-6	CL,CH	9-15	12	12-12-14
A-7	MH,CH	10-16	13	11-13-15

Pavement Design Criteria

Portland Cement Association (PCA) suggested the characteristic of cement stabilization as are presented in Table 7 and 8.

Table 7 PCA Criteria for Soil-Cement
Source: Standard for Construction, PCA

Purposes	Strength-UCS		CBR	Swell	Loss in wet / Dry test
	Kgf/cm^2	Lbf/in^2	(%)	(%)	
Road sub- base, backfill for trench	3.5-10.5	50-150	20-80	2	7
Road sub- base, base for light traffic	7-14	100-200	50-150	2	10
Base for heavy traffic,Building blocks	14-56	200-800	200-600	2	14
Embankment protection,Floodways	> 56	> 800	> 600	2	14

Table 8 Cement content for various soil types for pavement construction
Source: Standard for Construction, PCA

Soil Type	Suggested cement content (%)
Fine crushed rock	0.5-2
Well graded sandy clay gravels	2-4
Well graded sand	2-4
Poorly graded sand	4-6
Sandy clay	4-6
Silty clay	6-8
Fat clay	8-12
Very fat clay	12-15
Organic soils	10-15

2. United State Army Corps of Engineer (USAGE)

USAGE suggested the minimum unconfined compressive strength for cement stabilization of pavement material as shown in Table 9.

Table 9 USAGE Minimum Unconfined Compressive Strength Criteria
Source: Standard for Construction**,** USAGE

Stabilized Soil layer	**Minimum UCS at 7 days,psi**
Base course	750
Subbase course , Select material	250

3. The Japanese Road Association

The criteria of Japanese Road Association is essentially based on the consideration unconfined compressive strength and the modified CBR value associated with the types of the stabilization techniques and the degree of significance , as illustrated in Table 10 .

Table 10. The Japanese Road Association Criteria
Source: Standard for Highway Construction , The Japanese Road Association

Technique	**Types**	**Modified CBR**	**q_u strength**
Cement Stabilization	Lower base	> 10 %	10 kgf / cm^2 , 7 days
	Upper base	> 20 %	30 kgf / cm^2 , 7 days
Lime Stabilization	Lower base	> 10 %	7 kgf / cm^2 , 10 days
	Upper base	> 20 %	10 kgf / cm^2 , 10 days

4. Department of Highways, Thailand

Department of Highways, Thailand (DOH) suggested that materials for pavement construction should be based on Minimum Unconfined Compressive Strength at 7 days (soaked 2 hours before test) as shown in table 11.

Table 11 Department of Highways Thailand (DOH) Criteria
Source: Source: Standard for Highway Construction, DOH

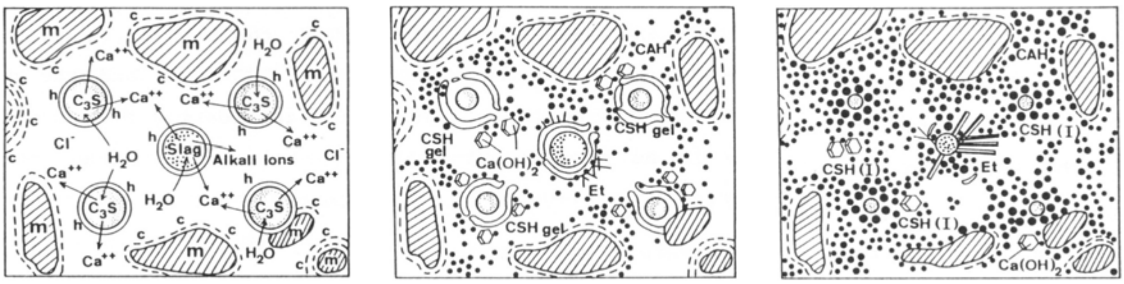
Standard No.	Stabilized Soil layer	Minimum UCS at 7 days,psi	Minimum UCS at 7 days,ksc
DH-S 206/2532	Subbase	100 psi	7 ksc
DH-S 204/2533	Base	250 psi	17.5 ksc

Review of recent researches

Review of dredged sludged and similar materials

1. Kamon and Nontananandh (1990) studied on the topic “Contribution of Stainless-Steel Slag as Cement Replacement Materials to The Development of Strength for Seabed Sludge”.

The research clarified the potential use of a stainless-steel slag as a blended cement material, and the contribution of blended slag cement to development of strength for seabed dredged sludge.The stainless-steel slag can be potentially used as a cement replacement material when the slag content is 20 percent or less. Kamon and Nontananandh (1990) found that the strength developing mechanism of the stabilized hedoro was sub-statically influenced by the initial reaction rate of the tricalcium silicate (C_3S). The explanation of the strength development mechanism of soil stabilizer mixture is illustrated simply by consideration of the changes of phases during the course of reaction as shown in Figure 23.

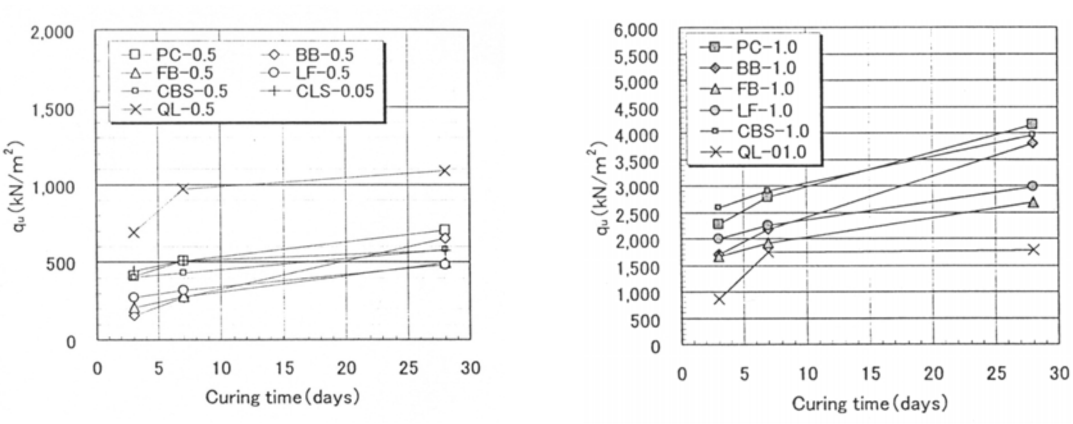


Gelatineous Phase Harding Phase Hardened Phase

Figure 23 Ideal schematic diagrams illustrating the reaction mechanisms of C_3S in the presence of s-slag in relation to the development phases of strength
Source: Kamon and Nontananandh (1990)

2. H. Inoue, S. Kidera and N. Miura (2004) studied on the topic "Mechanical and Chemical Analyses of Improvement Effect on Stabilized Ariake Clay by Cement and Quick Lime".

This research clarified the effects of admixtures on the improvement of marine clay, using Ariake clay. The improvement of ariake clay using Portland Cement stabilization was changed by high-level strength about 2500-4000 kN/m^2 as compared with the improvement of soft ground like other organic soil shown in Figure 24. This result was also proved by X-ray diffraction and SEM as shown in Figure 25 and 26.



Strength q_u (0.5 kN / m^3) Strength q_u (1.0 kN / m^3)

Figure 24 Unconfined compressive strength of Ariake Clay
Source: H. Inoue, S. Kidera and N. Miura (2004)

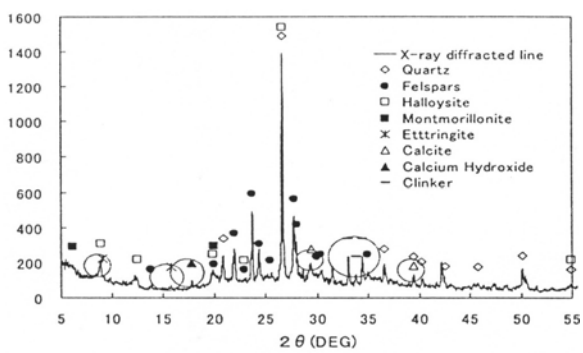


Figure 25 X-Ray diffracted line

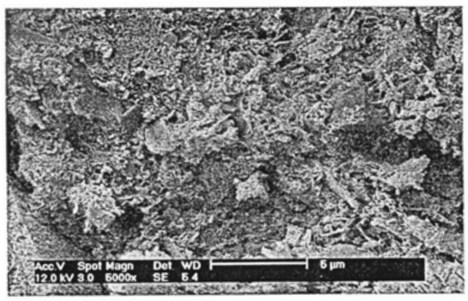


Figure 26 Micrograph by SEM

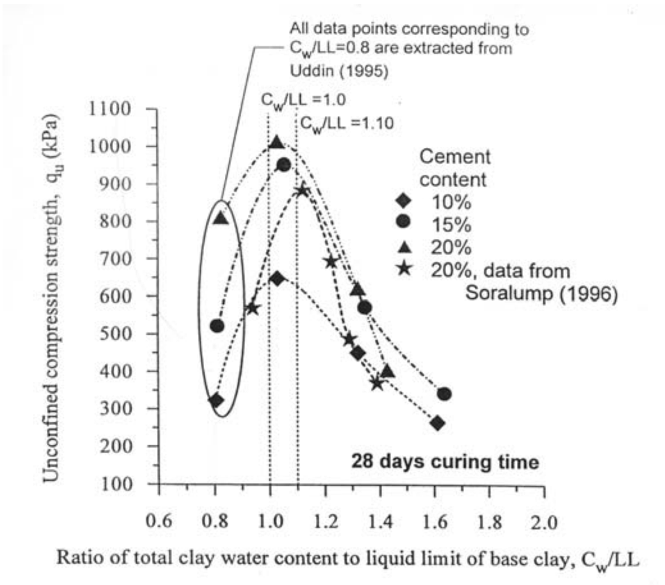
Source: H. Inoue, S. Kidera and N. Miura (2004)

3. Anika Crawford (2004) studied on the topic “Beneficial Reuse of Baltimore Dredged Sediments as Vertical Cutoff Wall Backfill Material”.

This research performed an appropriate mix of dredged sediments and bentonite suitable for a vertical cut-off wall backfill material. The preliminary tests on the bentonite were carried out for screening purposes and to find an appropriate water content that satisfied the desired viscosity range.

The mud weight density of the dredged sediments was 10.77 kN/m³ (68.49 pcf) and this value falls within the range of bentonite slurries 10.06 - 12.58 kN/m^3 (64-80 pcf).The mixing of dredged sediments with increase in bentonite content, resulted in a decrease in hydraulic conductivity and increasing the flyash content resulted in increase in the hydraulic conductivity.

4. Bergado and Lorenzo (2005) studied relationships between ratio after mixing water content and liquid limit with yield the highest unconfined compressive in order to consider effectiveness and economy for deep mixing pile. Figure 27 demonstrates that ratio water content after mixing and liquid limit fell within the range from the liquid limit (LL) up to about 1.10 LL of clay.



C_w = Total clay water content (Water content after mixing clay water and cement)
LL = Liquid Limit

Figure 27 Strength curves of cement admixing clays showing the range of ratio after mixing water content and liquid limit for effectiveness to produce an efficient and economical deep mixing pile.
Source: Bergado and Lorenzo (2005)

Review of dredge sludge production system.

1. Pollice,A./Chin, P.A./Breslin,V.T , (1998) studied on the topic “Evaluation of Available Technologies for Dredging and Disposal of Contaminated Harbour Sediments”.

This research suggested production system for dredge sludge treatment in solid phase as shown in Figure 28.

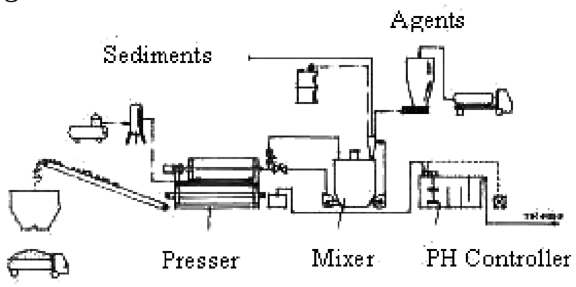


Figure 28 Production system for solidification of dredge material.
Source: Pollice,A./Chin, P.A./Breslin,V.T , (1998)

2. H.Miki and S.Chida (2005) studied on the topic “New Technologies for Soft Ground Improvement in Japan – Low Improvement Ratio Cement Column Method and Lightweight Banking Method”.

Foam mixed soil has been used extensively in Japan for road widening and back-filling project. Production system for foam mixed light weight soil is shown in Figure 29.

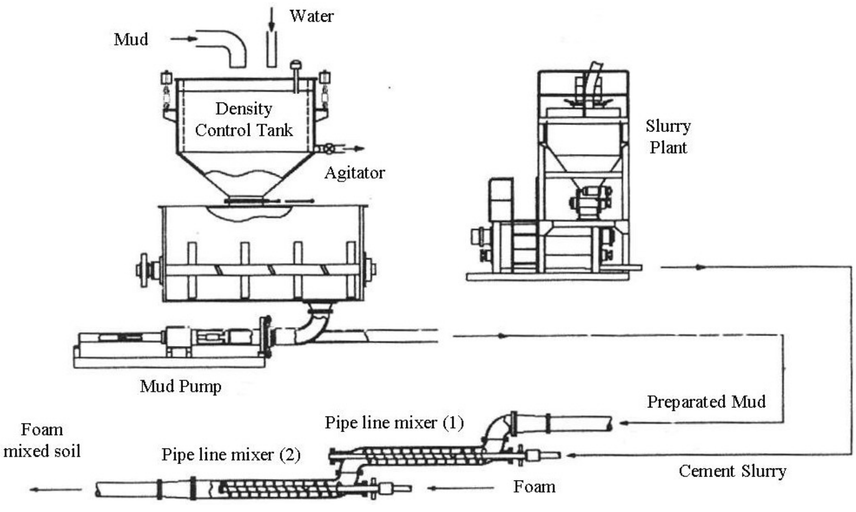


Figure 29 Production system for foam mixed light weight soil
Source: H.Miki and S.Chida (2005)

3. Wisconsin Department of Natural Resources (2000) studied on the topic "Sediment Dewatering and Water Treatment System".

The dredged sediment slurry was delivered to the treatment system as shown in Figure 30 where a 3/8-in shaker screen was used to remove gravel-sized stones and debris from the slurry. The remaining slurry dropped into a 12,000-gal volume-bottom tank. The settled slurry was augured and pumped through two hydro cyclones to remove +200 sieve materials (remained). The remaining slurry was then delivered to four 20,000-gal mixing tanks where polymer was added and mixed with the slurry to provide conditioned slurry to increase the percent solids by weight in the finished filter cake.

The conditioned slurry was then pumped into two 200-cubic feet filter presses and loaded to a pressure of 200 psi. Upon completion of pressing, the filter cake were delivered to 250-cu yd stockpiles and tested for PCBs, mercury, free water and percent solids.

Filtrate (carriage water) generated from the presses was pumped through bag filters, to sand filters, and finally liquid phase carbon absorbers before being discharged back to the river.

The overall processes can be illustrated as show in Fig 30.

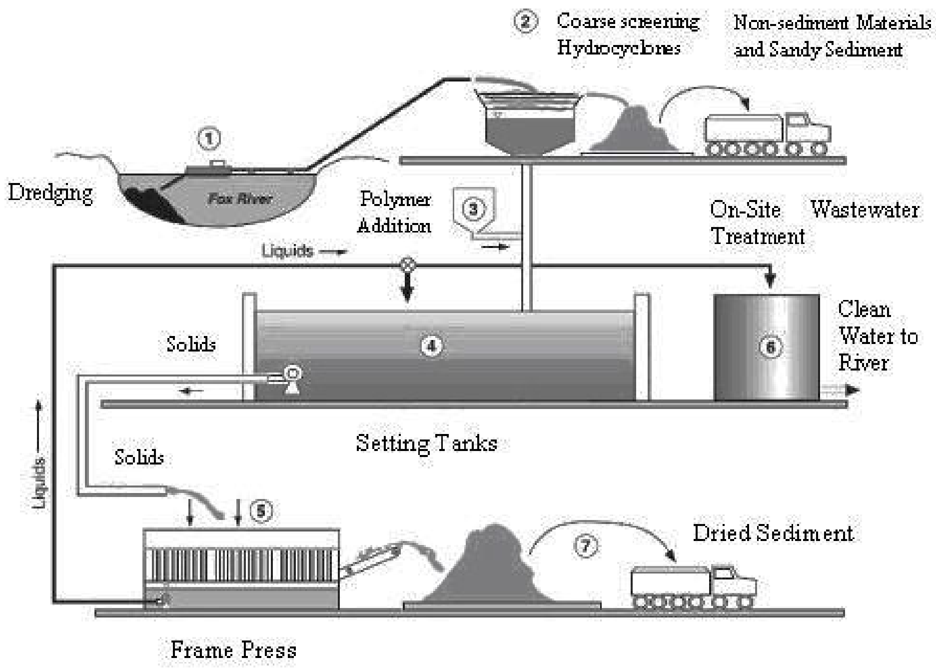


Figure 30 Sediment removal, Dewatering and water treatment process.
Source: Wisconsin Department of Natural Resources (2000)

Review of dewatering method.

1. Hirotoshi Mori and Hidetoshi Kohashi (2005) studied on the topic "The Eco-tube method of reusing high water content soil".

An Eco-tube is a kind of geosynthetic container made of a permeable geo-textile tube. When dredged soil is injected into an Eco-tube, the filtration effect of the geo-textile ejects water from the tube while the soil remained inside. Production system for Eco-tube method is shown in Figure 31 and schematic of Eco-tube method of reusing high water content soil is shown in Figure 32.

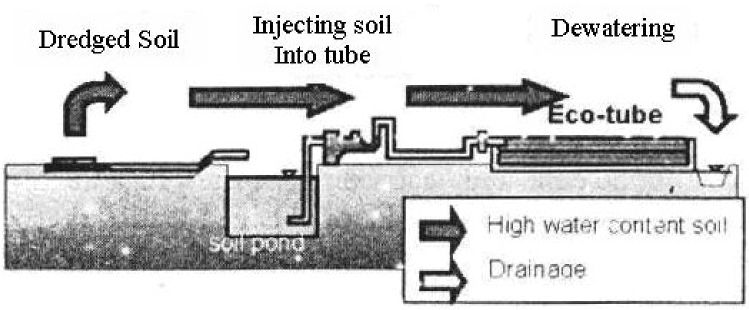


Figure 31 Production system for Eco-tube method
Source: Hirotoshi Mori and Hidetoshi Kohashi (2005)

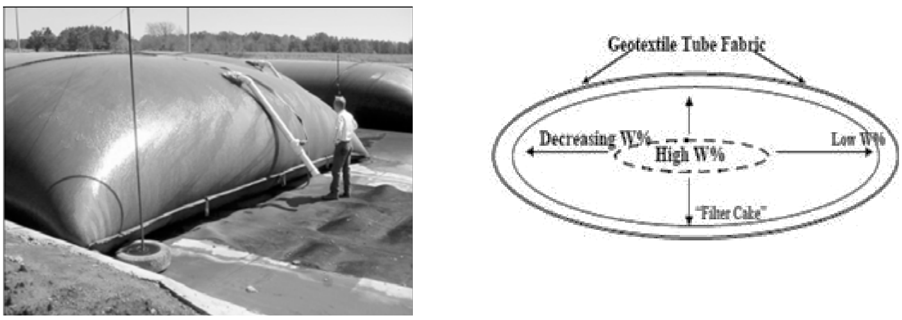


Figure 32 Schematic of Eco-tube method of reusing high water content soil.
Source: Hirotoshi Mori and Hidetoshi Kohashi (2005)

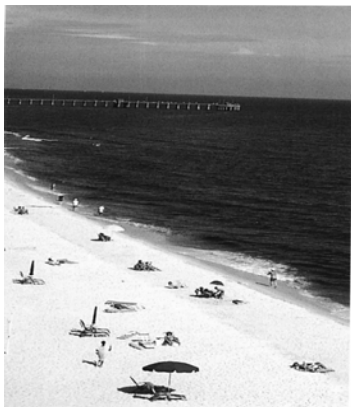
Projects and Beneficial Uses of Dredge Material

Beneficial Use of Dredge Material

It has been established that there are several beneficial engineering uses for dredged material, US Army Corps of Engineer (1987).

1. Beach nourishment

Beach nourishment is the placement of the material on or near the beach, usually to renourish an eroding beach. In some cases, suitable material is placed just offshore on an eroding beach, and natural drift processes may carry the material onto the beach over a long period of time. Beach nourishment is typically done with pipeline and hopper dredges. The material usually comes from inlet, bar, and approach navigation channels as shown in Figure 33.



Before After

Figure 33 Beach nourishment before and after placement of the material

2. Upland placement

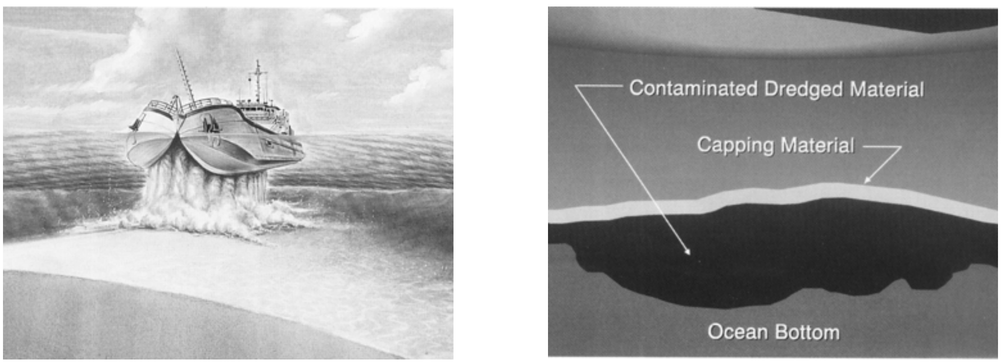
Upland placement isolates the material from the environment by placing it in diked areas where the material is contained as shown in Figure 34. Upland placement usually occurs by pipeline dredge, but in special circumstances dredged material is pumped or mechanically rehandled directly from barges or hopper dredges.

Before After

Figure 34 Upland placement before and after placement of the material

3. Open-water placement

Open-water placement refers to dredged material placement in near-coastal and inland waters and might also include capping, which a special is engineering method to contain contaminated sediments as shown in Figure 35. The contaminated dredged material is placed on a level bottom or in deep pits or bottom depressions and capped in a precisely engineered manner to ensure that the cap stays in place and the contaminated material remains isolated from the environment.



Before After

Figure 35 Open-water placement before and after placement of the material

MATERIALS AND METHODOLOGY

Apparatus and materials were prepared according to the objectives of study as follow.

Apparatus

1. Natural water content test device
2. Liquid Limit test device
3. Plastic Limit test device
4. Grain Size Distribution test device
5. Specific Gravity test device
6. Mixing machine for mix soil with additive
7. Cylinder molds inside diameter 50 mm height 100 mm.
8. Unconfined Compression test machine.
9. California Bearing Ratio test device
10. X-Ray Diffractometer (Philips X'Pert) for chemical analysis
11. Scanning Electron Microscope (JEOL JSM-5600LV) for soil structural analysis.

Materials

Location of Dredged Samples

Dredged sludge sample used in this study was sampled from the second navigation channel for access to Bangkok Port Project, Samut Prakarn Province as shown in Figure 36-38.

Figure 36 Geographic map of second navigation channel for access to Bangkok Port Project
Source: Google Earth

Figure 37 Geographic map of dredged sample
Source: Google Earth

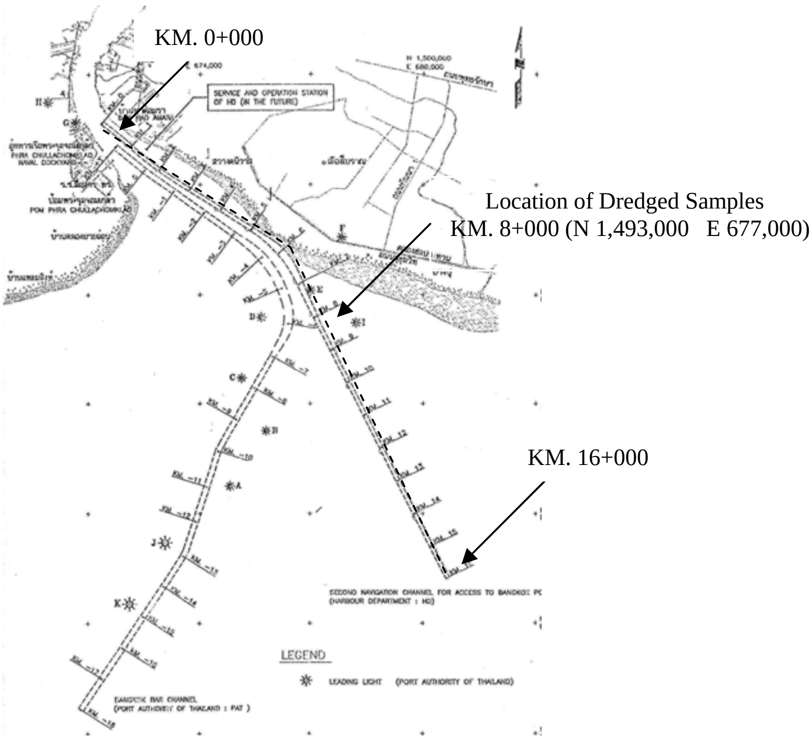


Figure 38 Location of dredged sample
Source: Port Authority of Thailand (1999)

Position of dredged sample

The sample was taken from a depth of -8.5 MSL by Cutter Dredgers process as shown in Figure 39.

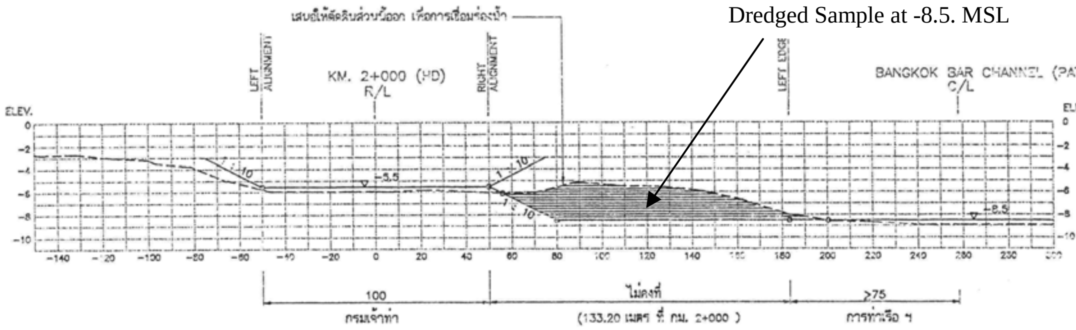
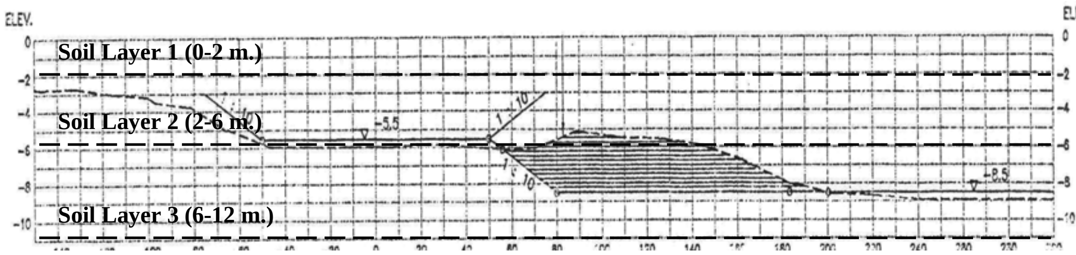


Figure 39 Position of dredged sample
Source: Port Authority of Thailand (1999)

Soil Profile and Soil Properties of sea base

The second navigation channel for access to Bangkok Port Project was designed 16 km in length and 100 meters in width. The soil profile and soil properties of sea base are shown in Figure 40.



Soil Properties		
Soil Layer	Density (T / m^3)	Shear Strength (T / m^2)
Layer 1 (0-2 m.)	1.20	0.20
Layer 2 (2-6 m.)	1.40	0.45
Layer 3 (6-12 m.)	1.50	1.20

Figure 40. Soil Profile and Soil Properties
Source: Port Authority of Thailand (1999)

<u>Admixtures</u>

The admixtures used in this study can be divided into 2 groups as follows.

Cement

The Ordinary Portland Cement type I (Elephant Brand) was main admixture used in this study. Since Portland Cement Type I is more available and cheaper in the market compared with other type, it is preferred in soil stabilization. The properties of Portland Cement type I are shown in Table 12.

Table 12 Properties of Portland Cement type I (Elephant Brand)
Source: Thakon, Sanupong (2004)

Chemical Composition	**By weight (%)**
Silicon Dioxide , SiO_2	19.97 %
Aluminum Oxide , Al_2O_3	6.02 %
Ferric Oxide , Fe_2O_3	3.36 %
Calcium Oxide , CaO	66.01 %
Magnesium Oxide , MgO	0.90 %
Sulfur Trioxide , SO_3	2.72 %
Loss on Ignition	1.51 %
Specific Gravity	2.96

Fine Sand

Fine Sand used in this study was prepared based on the Standard test method for Particle size analysis of soils in accordance with ASTM Designation D 2487 as shown in Table 13.

Table 13 Unified Soil Classification System of sand (ASTM Designation D 2487)

Sand	**Sieve No.**	**Diameter Size (mm.)**
Coarse Sand	Passing # 4 Retain # 10	4.75 - 2
Medium Sand	Passing # 10 Retain # 40	2 – 0.425
Fine Sand	Passing # 40 Retain # 200	0.425 – 0.075

Testing Procedures

Flow chart of testing procedures of this study can be illustrated in Figure 41.

1. Collected soil samples

Soil samples were taken from the second navigation channel for access to Bangkok Port Project, Samut Prakarn Province, Thailand. The soil samples (dredged sludge) were obtained from a depth of -8.5 MSL by cutter dredger process. After that, the soil samples were put in plastic container and taken back to the Geotechnical Engineering Laboratory, Department of Civil Engineering, Kasetsart University and stored in the humid room for further test.

2. Preliminary test on physical properties were performed soon after soil sampling.

Physical properties testing consisted of determination of Atterberg's limit, water content, specific gravity and grain size distribution.

3. Pre -treated sludge by dewatering.

Pre-treated sludge consisted of 3 parts;

a) Dewatering machine

The mechanical properties of the soil can be improved if its moisture content is lowered and void ratios are minimized by the methods of pore water squeezing (dewatering). This can be achieved by the application of certain pressure (preloading) to squeeze away water from the pore space, leading to the reduction of void volume. Dewatering machine consists of steel frame, chamber, hydraulic jack capacity 100 kilogram, air pump, air pressure control and filter. Filter material has 2 layers; the first layer was geotextile which can isolate water from dredged sludge. The second layer was medium sand, which can help drainage system and distribute force equally to all contact surfaces. The double drainage system is provided to shorten time to dewatering. Model of equipment is illustrated in Figure 42 and dewatering machine used in this study is shown in Figure 43.

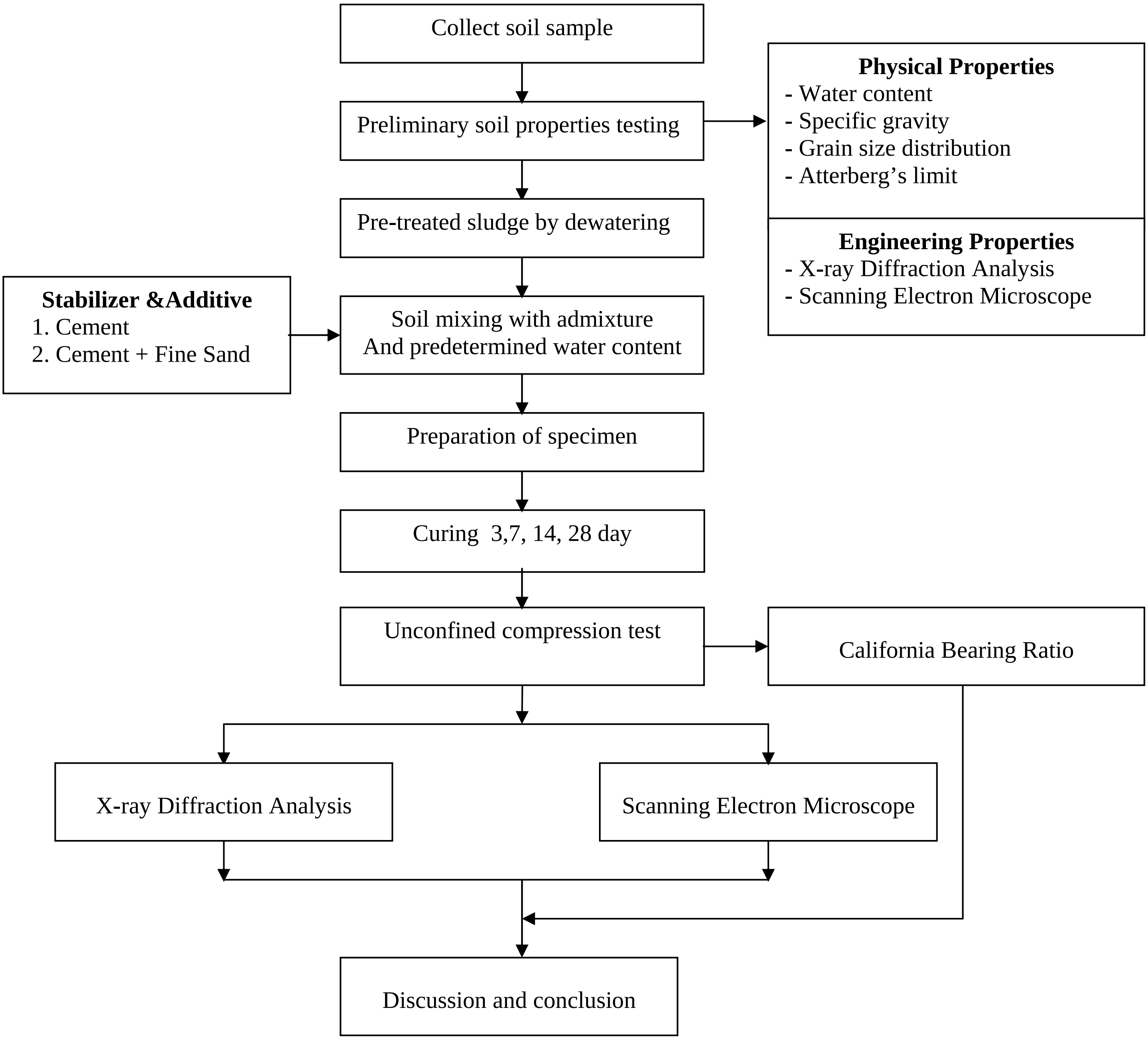


Figure 41 Framework of research

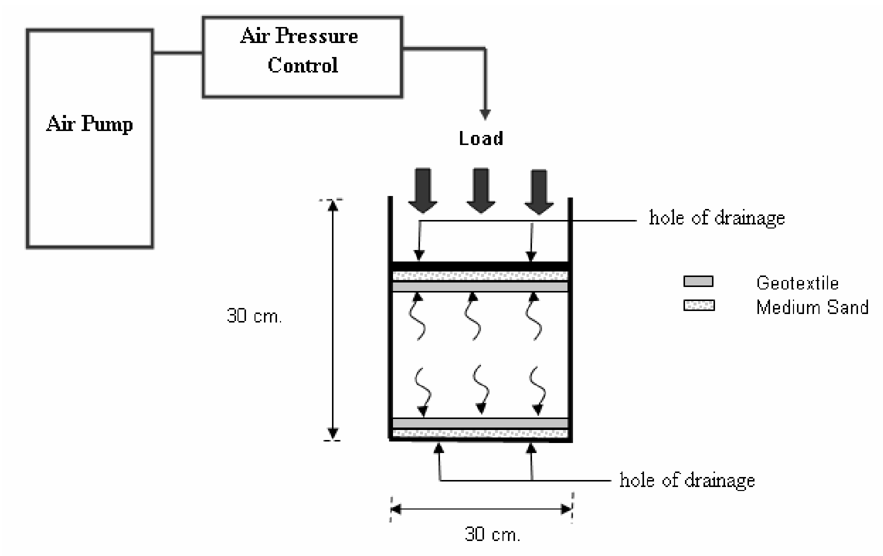
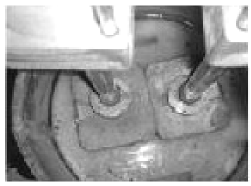


Figure 42 Model of Dewatering Machine

Dewatering Machine

Pressure Control



Preloading Condition

Drain water

Figure 43 Dewatering Machine and Drainage System in this study

b) Mud density test (Mud Balance)

The mud balance consisted of volume cup and beam. It is operated by the fixed volume cup at the one end of the beam. It was balanced by a fixed counterweight at the opposite end, with a sliding weight rider free to move along the graduated scale. A level bubble mounted on the beam indicates when the system is in balance as shown in Figure 44. This study used mud balances at saturated condition and neglected little air bubbles occurred in mud sample.

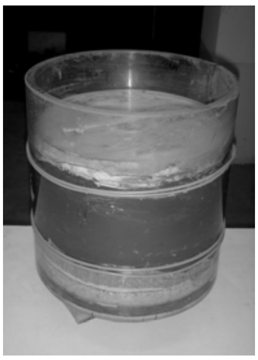
Filling process

Sliding weight process

Figure 44 Mud density test for dredged sludge

c) Laboratory density test

Laboratory density test was used in case of unsaturated soil as shown in Figure 45. This study used a square box sample size of 5 cm x 5 cm by 2 cm. in height in order to weigh for calculation density.



Chamber

Box Sample
(5cm.x5cm.x2cm)

Weight

Figure 45 Laboratory density test

d) Process of dewatering

Dredged sludge was placed in the dewatering apparatus, The water was squeezed out continuously until the pre-determined range of water content of 140-180% was obtained cement content 150-250 kg/m^3 were selected for trial mixes.

In addition, fine sand with a content of 0-40% by dry weight was also replaced into dredged sludge in order to improve their grain size distribution.

4. Soil mixing with admixture

Soil mixing was prepared by mixing dredged sludge with admixture mentioned above by soil mixer for 5 minutes to assure a uniform mixture, this process could be inspected by visual observation.

5. Engineering properties tests

a) Unconfined Compression test.

In accordance with ASTM D 2166-97, unconfined compression tests were performed on unsoaked and soaked samples to determine strength characteristics gain with curing time at 3,7,14 and 28 days. Soaked condition was done as recommended by the Department of Highways. Figure 46 shows unconfined compression test. Preparations of samples are illustrated in Figure 47.

Unconfined Compression Test Machine

Proving Ring (1000 kg)

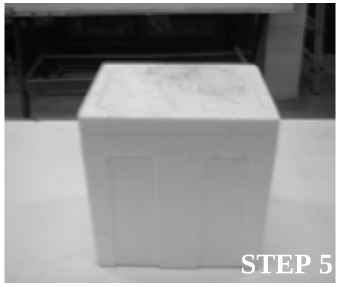
Figure 46 Unconfined Compression Test.

Mix dredged material with
Cement in soil mixer for 5 minutes.

Place soil cement in a mold

Wrapped with plastic sheets

Seal in plastic bag.

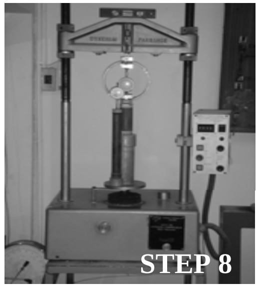


Cure in container.

Place container in
humidity control room.

Unsoaked sample

Soaked sample



Unconfined
Compression Test

Figure 47 Preparation of sample for Unconfined Compression Tests

b) The California Bearing Ratio (CBR)

CBR tests were performed in accordance with ASTM D1883, to measure shearing resistance of unsoaked and soaked sample with curing time of 7,14 and 28 days. Figure 48 shows CBR test. Preparation of samples is illustrated in Figure 49.

California Bearing Ratio Test Machine

Proving Ring (6000 lbs)

Figure 48 California Bearing Ratio Test

Mix dredged material with Cement in
soil mixer and mix for 5 minutes.

Place soil cement in
a CBR mold.

Seal with plastic sheets

Seal with aluminum sheets
and paraffin wax.

Place in plastic bag.

Place container in
humidity control room.

Unsoaked sample

Soaked sample

California Bearing
Ratio Test

Figure 49 Preparation of sample for California Bearing Ratio Test

c) X-Ray Diffraction Analysis (XRD)

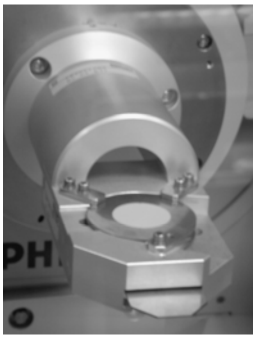
X- Ray Diffraction analysis was used to identify clay mineral and reaction products in order to evaluate correlations with strength development.

The X- Ray Diffraction patterns were obtained by using the Philips X'Pert Diffractometer as shown in Figure 50. Preparation of samples is shown in Figure 51.

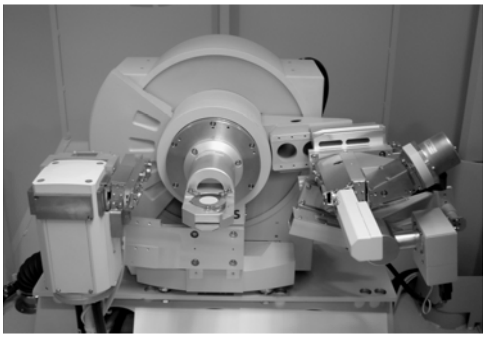
The samples for XRD analysis were divided into 2 groups;

1. The sample was prepared after Unconfined Compression Test on unsoaked and soaked samples at curing times of 3,7,14 and 28 days.

2. The sample was prepared after CBR Test on unsoaked and soaked samples at curing time of 7, 14 and 28 days.



Powder specimen



X – Ray Diffractometer

Figure 50 X-Ray Diffractometer.

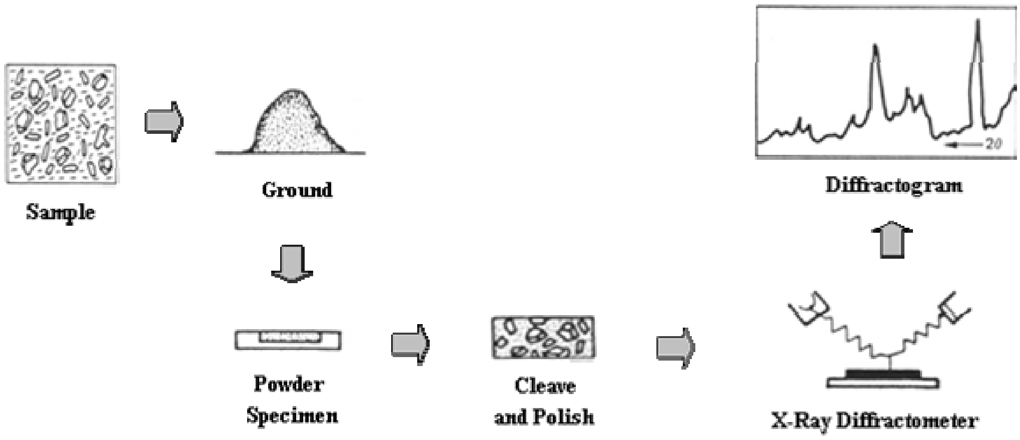


Figure 51 Methods of examining mineralogy, fabric, and structure of soils using XRD
Source: R.N. Yong ,McGill University Soil Mechanics Laboratory

d) Scanning Electron Microscope (SEM)

The micrographs showed the general views of textures, the growth of reaction products and exhibit sequential changes in microstructures for chemically treated materials.

The samples for SEM observation and compositional analysis were performed on a Scanning Electron Microscope model JEOL JSM-5600LV as shown in Figure 52. Preparation of samples is shown in Figure 53.

The samples for SEM analysis were divided into 2 groups;

1. The samples were prepared after Unconfined Compression Test on all unsoaked and suitable mixture for soaked samples at curing time of 3,7,14 and 28 days.

2. The suitable mixture samples were prepared after CBR Test on all unsoaked and suitable mixture for soaked sample at curing times of 7,14 and 28 days.

Vacuum Etched and Coating Cast

Scanning Electron Microscopy

Figure 52 Scanning Electron Microscope

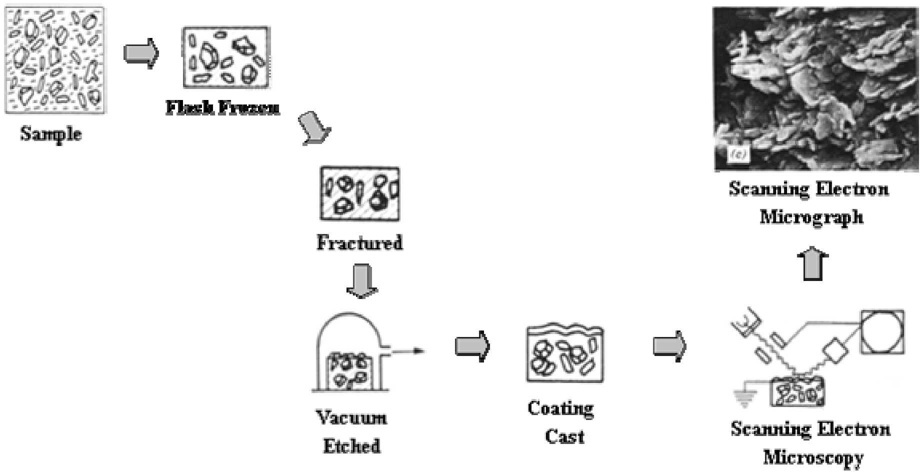


Figure 53 Methods of examining mineralogy, fabric, and structure of soils using SEM
Source: R.N. Yong ,McGill University Soil Mechanics Laboratory

<u>Numbers of Test Specimens</u>

The numbers of test specimens were summarized according to test variables.

Unconfined compression test

Condition 1 Determine suitable range of moisture content and cement content

Soil type	Dredged Sludge
Admixture	Portland Cement type I
Range of water content	140,160 and 180 %
Curing time	7 days
Quantity of sample/mixture	3 samples
Quantity of cement	150,175,200,225 and 250 kg/m^3
Type of test condition	unsoaked
<u>Total numbers of samples</u>	45 samples

Condition 2 Determine suitable volume of fine sand

Soil type	Dredged Sludge
Admixture	Portland Cement type I
Water content	160 %
Curing time	3,7, 14 and 28 days
Quantity of sample/mixture	3 samples
% Fine Sand replacement	0,20 and 40%
Quantity of cement	200 kg/m^3
Type of test condition	unsoaked and soaked
<u>Total numbers of samples</u>	72 samples

The California Bearing Ratio (CBR)

Soil type	Dredged Sludge
Admixture	Portland Cement type I
Water content	160 %
Curing time	7, 14 and 28 days
Quantity of sample/mixture	3 samples
% Fine Sand replacement	20%
Quantity of cement	200 kg/m^3
Type of test condition	unsoaked and soaked
<u>Total numbers of samples</u>	18 samples

X-ray Diffraction Analysis

1. Untreated samples

Untreated dredged sludge	1	samples
Untreated dredged sludge + 20% sand	1	samples
Untreated dredged sludge + 40% sand	1	samples
<u>Total numbers of samples</u>	3	samples

2. Treated samples

a) Unconfined compression test

Mix 1 : Dredged sludge + 200 % cement content
(unsoaked and soaked condition)

At 3 days	2	samples
At 7 days	2	samples
At 14 days	2	samples
At 28 days	2	samples

Mix 2 : Dredged sludge + 200 % cement content + 20% Sand
(unsoaked and soaked condition)

At 3 days	2	samples
At 7 days	2	samples
At 14 days	2	samples
At 28 days	2	samples

Mix 3 : Dredged sludge + 200 % cement content + 40% Sand
(unsoaked and soaked condition)

At 3 days	2	samples
At 7 days	2	samples
At 14 days	2	samples
At 28 days	2	samples
<u>Total numbers of samples</u>	24	samples

b) The California Bearing Ratio (CBR) for successful mix proportions

Mix 2 : Dredged sludge + 200 % cement content + 20% Sand
(unsoaked and soaked condition)

At 7 days	2	samples
At 14 days	2	samples
At 28 days	2	samples
<u>Total numbers of samples</u>	6	samples

Scanning Electron Microscope (SEM)

1. Untreated samples

Untreated dredged sludge	1	samples
Untreated dredged sludge + 20% Sand	1	samples
Untreated dredged sludge + 40% Sand	1	samples
<u>Total numbers of samples</u>	3	samples

2. Treated samples

a) Unconfined compression test

Mix 1 : Dredged sludge + 200 % cement content
(unsoaked condition)

At 3 days	1	samples
At 7 days	1	samples
At 14 days	1	samples
At 28 days	1	samples

Mix 2 : Dredged sludge + 200 % cement content + 20% Sand
(unsoaked and soaked condition)

At 3 days	2	samples
At 7 days	2	samples
At 14 days	2	samples
At 28 days	2	samples

Mix 3 : Dredged sludge + 200 % cement content + 40% Sand
(unsoaked condition)

At 3	days	1	samples
At 7	days	1	samples
At 14	days	1	samples
At 28	days	1	samples
<u>Total numbers of samples</u>		16	samples

b) The California Bearing Ratio (CBR) for successful mix proportions

Mix 2 : Dredged sludge + 200 % cement content + 20% Sand
(unsoaked and soaked condition)

At 7	days	2	samples
At 14	days	2	samples
At 28	days	2	samples
<u>Total numbers of samples</u>		6	samples

Standards of Tests

Standards of Tests performed in this research are as shown below.

ASTM D 4318-93	Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of soils.
ASTM D 2487-93	Standard Classification of Soils for Engineering Proposes (Unified Soil Classification System)
ASTM D 2216-92	Standard Test Method for Laboratory Determination of Water (Moisture) Content of soil and rock by mass.
ASTM D 854-92	Standard Test Methods for Specific Gravity of Soil Solids by water Pycnometer
ASTM D 2166-91	Standard Test Method for Unconfined Compressive Strength of Cohesive Soil.
ASTM D422-63	Standard test method for Particle Size Analysis of Soils.
ASTM D1883	Standard test method for California Bearing Ratio (CBR)
JGS 0821-2000	Practice for Making and Curing Stabilized Soil Specimen without Compaction

Place and duration

Places

The main laboratories where the experiments were performed are as follows.

1. Unconfined Compression Tests and The California Bearing Ratio (CBR) were tested at Geotechnical Engineering Laboratory, Department of Civil Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand.

2. X-ray Diffraction Analysis and Scanning Electron Microscope (SEM) were tested at Materials Engineering Laboratory, Department of Materials Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand.

Duration

Duration of research was from June 2005 to February 2007

RESULTS AND DISCUSSION

The properties of dredged sludge used in this study were obtained from laboratory test. The study concentrated on unconfined compression tests, The California Bearing Ratio (CBR), X-ray Diffraction Analysis (XRD) and Scanning Electron Microscope (SEM) in order to observe correlation between strength and fabric structures of dredged sludge.

General Properties of dredged sludge

Physical Properties

Based on visual inspection, untreated dredged sludge had dark- grey color and high water content. Physical properties of dredged sludge are shown in Table 14. Materials were classified as CH in according to the Unified Soil Classification System and A-7-6 in according to AASHTO System as shown in Figure 54.

Table 14 Physical properties of dredged sludge

Physical properties	Characteristics values
Soil Classification System (USCS)	CH
Soil Classification System (AASHTO)	A-7-6
Liquid Limit (%)	106
Plastic Limit (%)	31.35
Plastic index (%)	74.65
Shrinkage Limit (%)	19.6
Natural water content (%)	190-300
Specific gravity	2.56
Silt + Clay / Sand Ratio	80/20

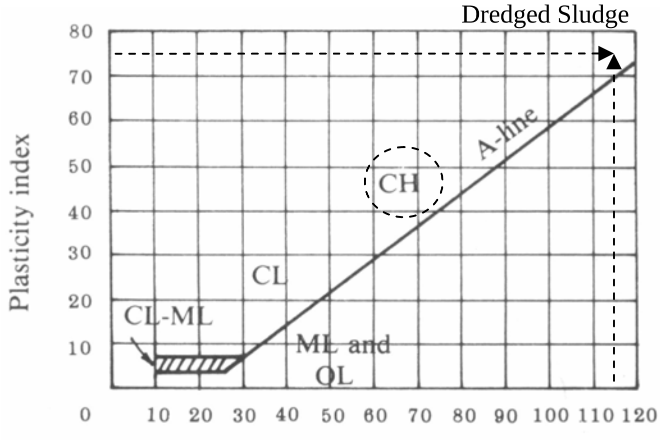


Figure 54 Unified Soil Classification System (ASTM Designation D 2487)

Clay Minerals

a) The X-ray Diffraction Analysis of untreated dredged

The X-ray Diffraction Analysis of untreated dredged sludge identifies that there are various chemical compositions detected from untreated dredged sludge. Clay minerals mainly consist of Montmorillonite, Illite and Kaolinite as shown in Table 15 and Figure 56.

Table15 Compositions of clay minerals of untreated dredged sludge

No.	Clay Minerals	Intensity (Counts/s)
1	Montmorillonite	433
2	Illite	372
3	Kaolinite	317

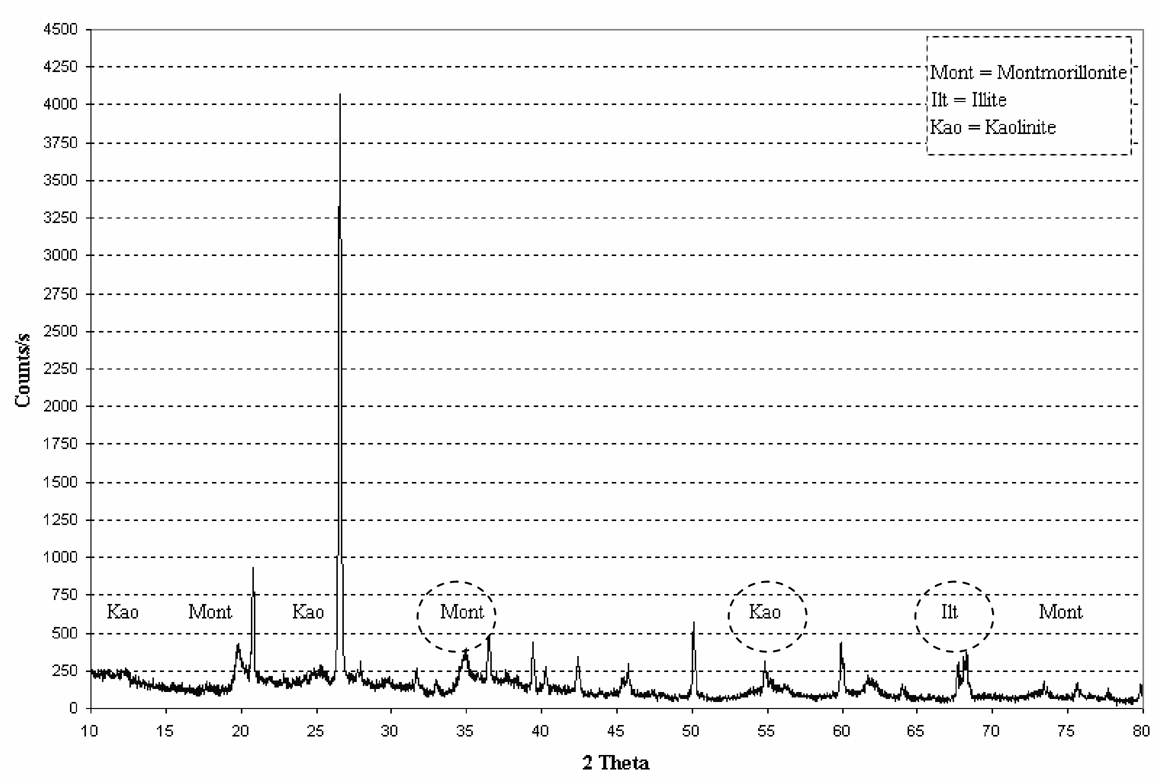


Figure55 X-ray Diffraction patterns of untreated dredged sludge

b) Scanning Electron Microscope of untreated dredged sludge

SEM micrographs of untreated soil are illustrated in Figure 56.

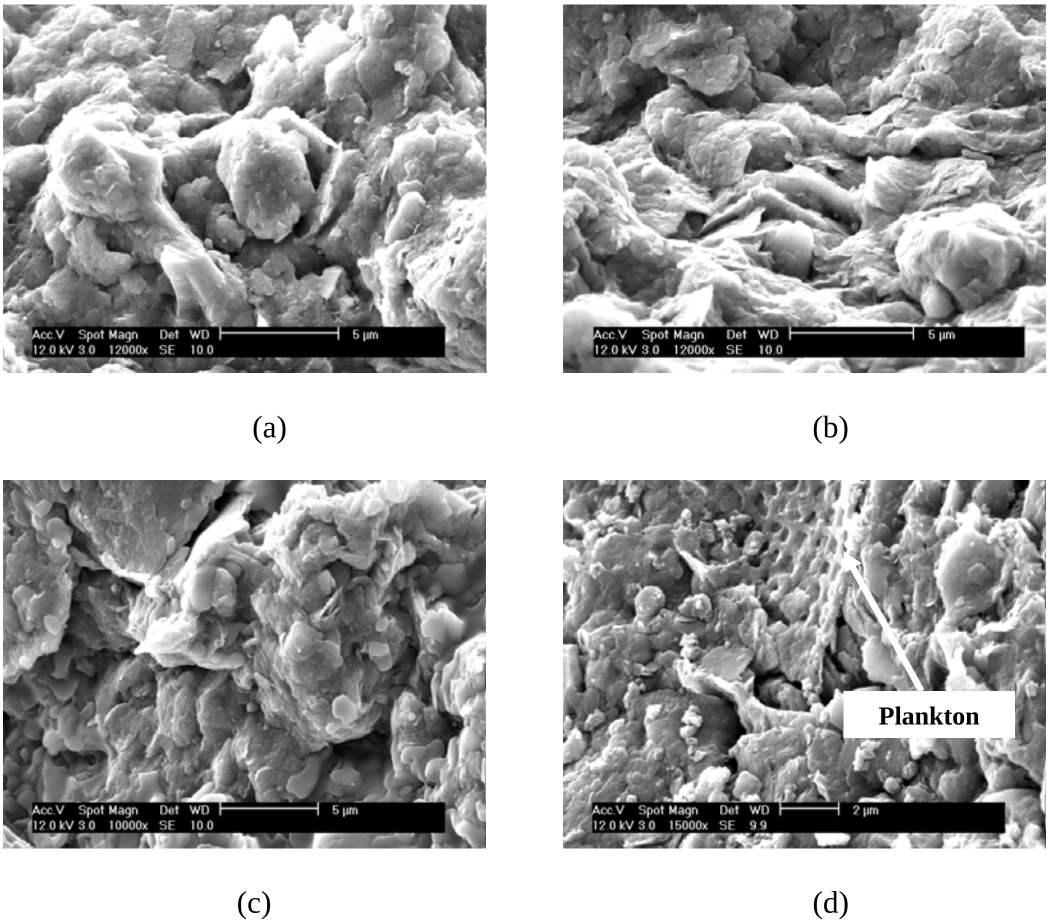


Figure 56 SEM micrographs of untreated dredged sludge

The dredged sludge texture consists of many sheet-like particles. The shapes of sheets were flaky and plate-like grains. The shape of sheets depends on types of clay minerals that are found in the soil. The X-ray Diffraction Analysis identifies that most clay minerals consist of Montmorillonite, Illite and Kaolinite. The shapes of Montmorillonite were plate or sheets, Illite and Kaolinite are flaky grain. The pattern of shape depends on amount and types of clay minerals that are found in the soil. Figure 57 (d) shows diatom interferes between soil sheets.

Stabilization of Dredged Sludge and Testing

Dewatering Machine and Density test

Natural dredged sludge in the sea has high water content at about 200-300%. Stabilization of dredged sludge was difficult because use of high cement content may cause high shrinkage in soil. Therefore, it was necessary to reduce surplus water from natural dredged sludge and find suitable ranges of moisture content prior to determination of suitable mixes between cement and dredged sludge.

The process of mechanical dewatering with applied pressure is shown in Table 16. The mud density test was used when an applied load was zero and the water content was 190%. Also, the laboratory density test was used with an applied load from 0.057 - 0.283 ksc and the water content could be lowered to140% - 89%.The result of dewatering is shown in Figure 57 and 58.

Table 16 Mechanical dewatering and result

No.	Loading Period (Hr.)	Applied Load (kg)	Pressure (ksc)	Water Content (%)	Density (T / m^3)
1	0	0	0.000	190	1.267 (1)
2	0 - 24	40	0.057	140	1.410 (2)
3	24 - 48	80	0.113	123	1.457 (2)
4	48 – 72	120	0.170	107	1.508 (2)
5	72 – 96	160	0.226	98	1.546 (2)
6	96 – 120	200	0.283	89	1.576 (2)

(1) From mud density test   (2) From laboratory density test

As shown in Figure 57, the natural dredged sludge has high water content at about 200-300 %. However, water content could be lowered to appoximately 190% at starting point of dewatering due to self-sedimentation.

When applied loads was 0.057 ksc, the water content rapidly decreased from 190% - 140%, where void ratios gradually decrease when the applied load was increased from 0.057-0.226 ksc. Finally, the water content slight changed at a pressure of 0.283 ksc.

From the result of relationship between water content and time, the cross section of tangents line of water content was closely to liquid limit.

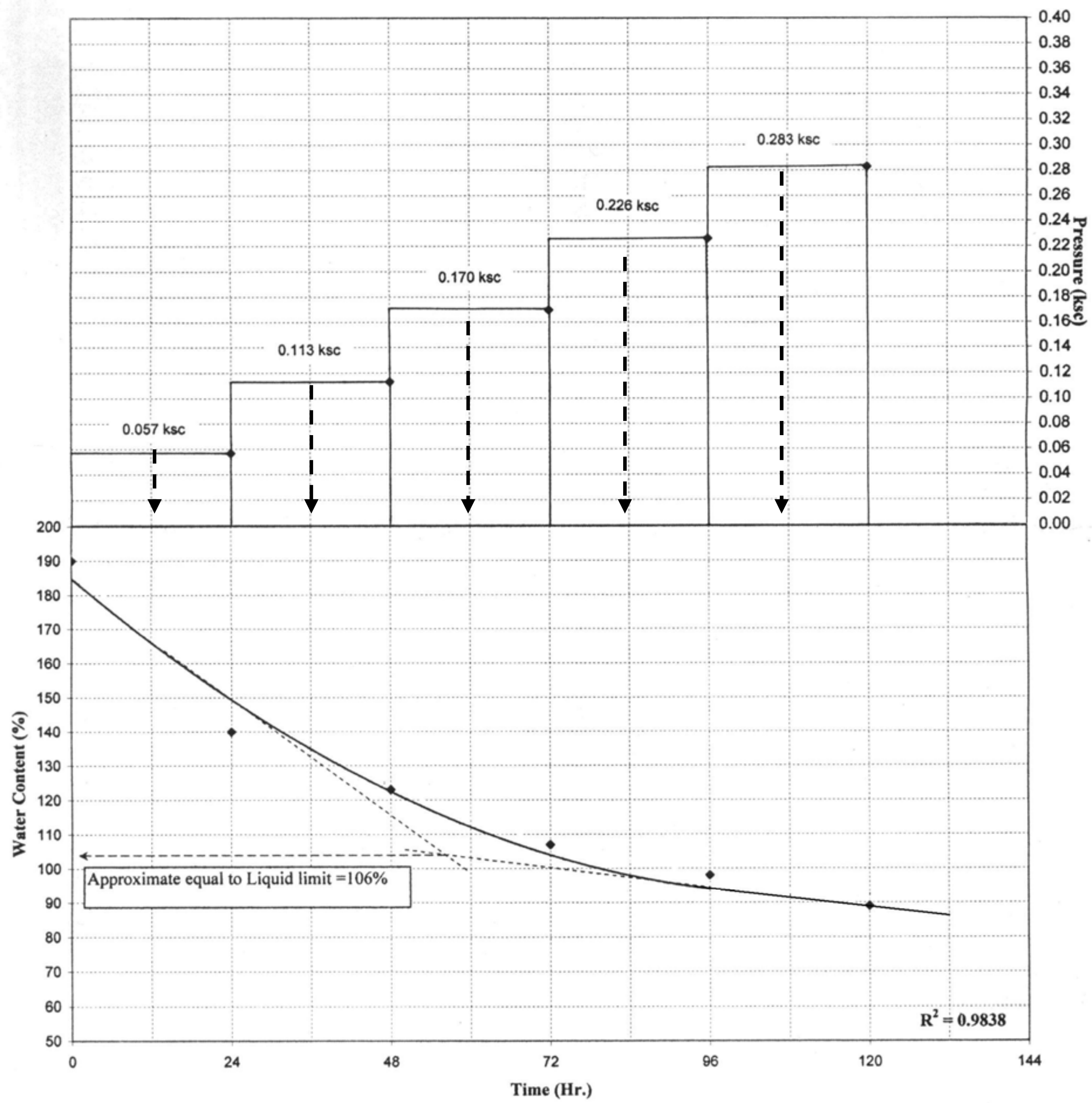


Figure 57 Relationship between pressure, water content and time

As shown in Figure 58, the water content decreased while bulk density increased. The correlation is used to measure volume of the dredged sludge in order to calculate mixing cement content for each proportion.

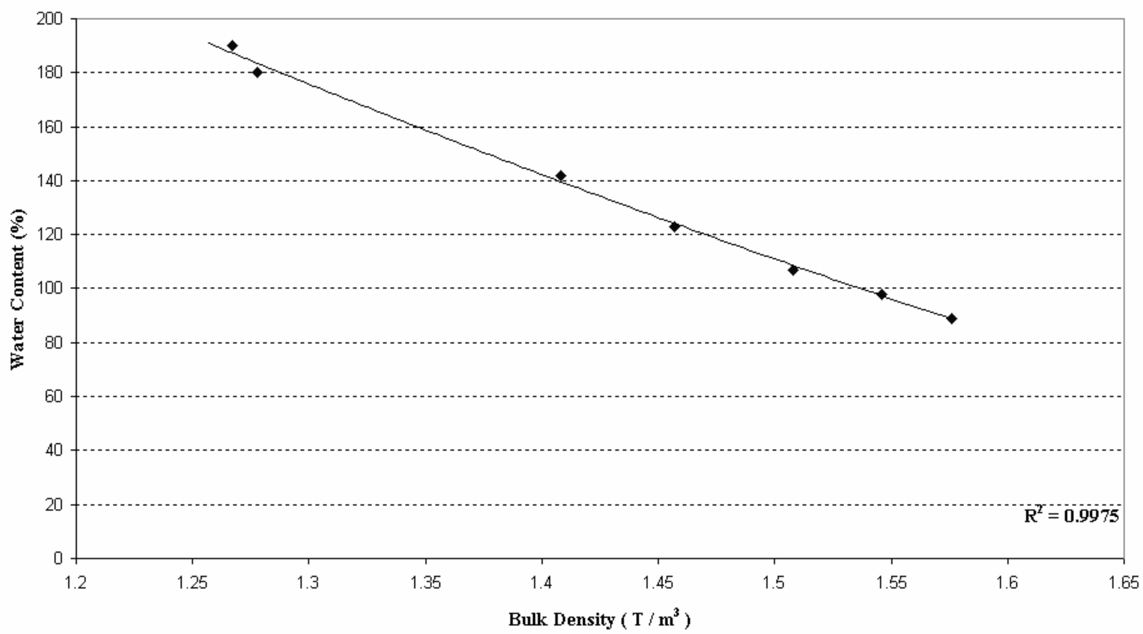


Figure 58 Relationship between water content (%) and Bulk Density (T/m^3)

Determination of suitable cement admixtures

Chemical admixtures change strength characteristics fundamentally due to the hardening effects. Pore space is filled by reaction products which harden after mixing, bonding soil particles together.

Water is essential for mixing cement into clay. When cement is mixed with clay, water is required for good and efficient mixing. Besides, water is acting as a medium that enables the cementing ions to be dispersed within the voids of soil mass. On the other hand, the presence of too much water in the oversaturated clay eventually requires large amount of cement to bind together soil particles that had been loosely dispersed by the presence of excessive water.

Relationship between unconfined compressive strength, water content after mixing and cement content

As shown in Table 17, relationships between unconfined compressive strength, water content after mixing and cement content are important parameters to determine ranges of water content suitable for cement reaction. It is believed that suitable ranges of water content can provide homogeneous mixtures and can reduce mixing cement content ($C_w \cong 1$ to 1.1 Liquid limit, Bergado and Lorenzo, 2005) as shown in Table 18.

Preliminary tests also revealed that the unconfined compressive strength rapidly decreased with the water content mixture at 200% and slightly decreased with the water content mixture at 120%. On the other hand, when dredged sludge was mixed with various water contents and cement contents with a range of 150 kg/m^3 to 250 kg/m^3, it was found that unconfined compressive strength were almost the same for water content from 140% to 180%, as shown in Figure 59.

Based on test results of the dredged sludge mixed with various cement contents and water content after mixing as shown in Figure 60, it was found that the ratio of water content after mixing and percentage of weight of cement to dry weight of soil (C_w/A_w) within the range of 2.75 – 3.02 provides homogeneous mixtures with good workability. So the selected value was 2.85 at 160% water content and 200 kg/m^3 cement content. Subsequently, unconfined compressive strength (UCS) of the cement-stabilized dredged sludge as a function of C_w/A_w at a curing time of 7 days can be estimated using the following equation.

$$UCS_{7\ days} = 1.88(C_w/A_w)^2 - 16.40(C_w/A_w) + 39.39$$

Table 17 Average unsoaked unconfined compressive strength at various cement contents and initial water content

Cement content (kg/m^3)	Average unsoaked unconfined compressive strength (ksc) at 7 days		
	w*=140%	w*=160%	w*=180%
150	3.25	4.02	3.46
175	5.08	5.73	5.61
200	6.95	8.10	7.66
225	9.67	10.63	11.35
250	12.81	13.32	13.87

Remark :

w* = Water content before mixing (initial water content)

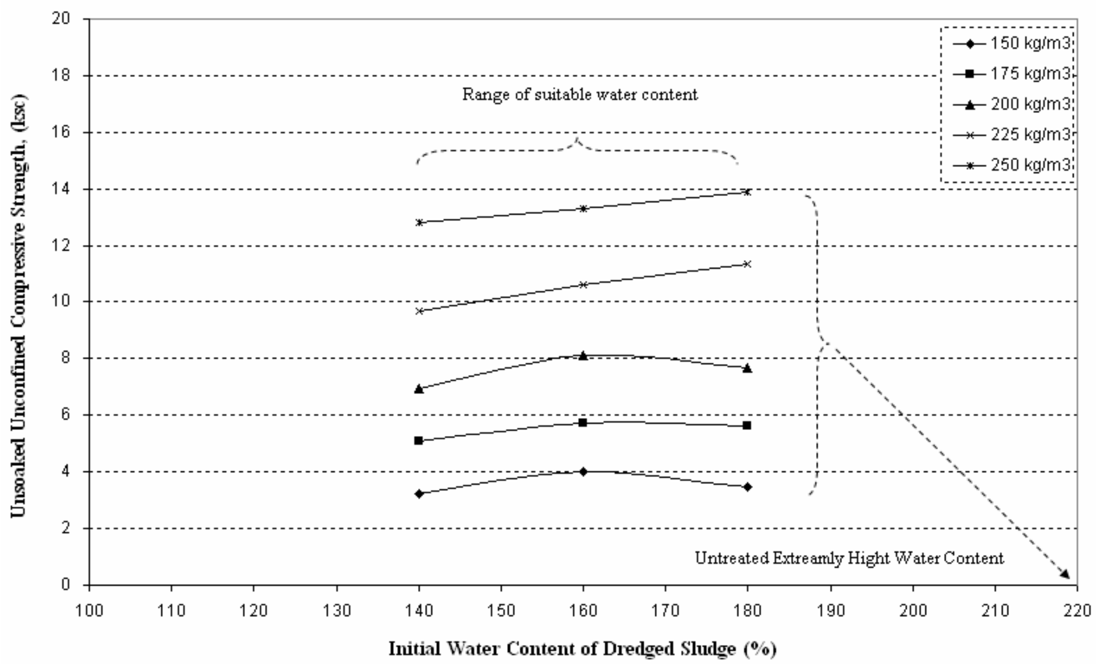


Figure 59 Relationship between unsoaked unconfined compressive strength at various cement contents and initial water content

Table 18 Calculation of water content after mixing and percentage ratio of weight of cement to dry weight soil

Cement content	Cement content (% Dry weight soil) : A_w			Water content after mixing: C_w			C_w/A_w		
				w*=140%	w*=160%	w*=180%			
150 kg/m^3	25.71	28.85	32.61	104.29	121.15	137.39	4.06	4.20	4.21
175 kg/m^3	30.00	33.65	38.04	100.00	116.35	131.96	3.33	3.46	3.47
200 kg/m^3	34.29	38.46	43.48	95.71	111.54	126.52	2.79	2.90	2.91
225 kg/m^3	38.57	43.27	48.91	91.43	106.73	121.09	2.37	2.47	2.48
250 kg/m^3	42.86	48.08	54.35	87.14	101.92	115.65	2.03	2.12	2.13

Remark :

C_w = 1 to 1.1 Liquid limit, Bergado and Lorenzo (2005)
C_w = 107 % to 117.7 %, Liquid limit of base clay = 107 %

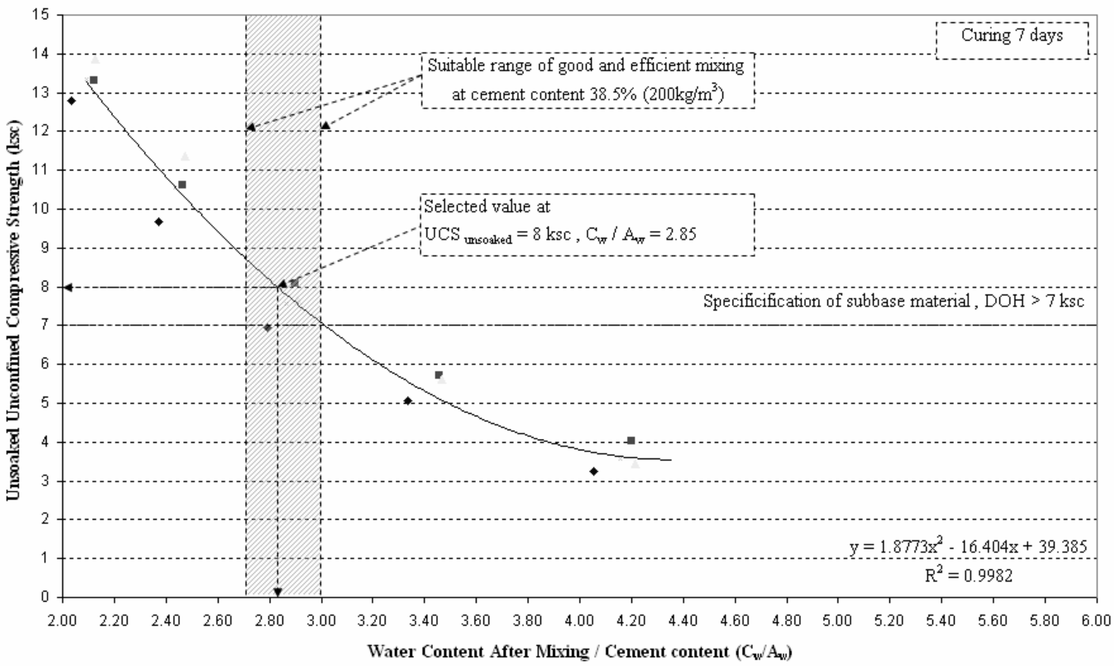


Figure 60 Relationship between unsoaked unconfined compressive strength and ratio of water content after mixing with % cement content

Effects of fine sand on physical properties

The untreated dredged sludge has a lot of clay and little sand which may affect strength development. In this study fine sand was added into dredged sludge in order to improve material gradation and initial dry density and to modify soil structure of clayey dredged sludge to clayey-sand. It is believed that the effects can enhance better bonding and reactions, which thus increase strength of treated soil**.**

Table 19 shows soil fractions of the dredged sludge modified by substituted with sand at 20%-40% by dry weight. Based on the mud density test as shown in Table 20 and Figure 61, it was found that the dry density slightly increased with increase sand content.

Similarly, to analysis by X-Ray diffraction analysis of quartz shown in Table 21 and illustrated in Figure 62 also revealed that intensity of quartz increased as sand content increase. Furthermore, changes in microstructure can be observed by SEM as illustrated in Figure 63.

Table 19 Soil fractions of modified dredged sludge

Description	Soil fractions of Dredged sludge					
	Clay	Sand			Clay/Sand	Ratio Clay/Sand
	Original	Original	Fill	Total		
Mix 1+ 0% Sand	80	20	0	20	80/20	4 : 1
Mix 2 + 20% Sand	80	20	20	40	80/40	4 : 2
Mix 3+ 40% Sand	80	20	40	60	80/60	4 : 3

Table 20 Average wet density test of dredged sludge

Description	Bulk Density (T/m^3)	Δ Bulk Density	Testing
Mix 1+ 0% Sand	1.345	-	Mud density test
Mix 2+ 20% Sand	1.365	Mix2-Mix1 = 0.02	Mud density test
Mix 3+ 40% Sand	1.385	Mix3-Mix1 = 0.04	Mud density test

Table 21 X – Ray diffraction of quartz (SiO_2)

Description	Intensity of Quartz (Counts/s)	Δ Intensity of Quartz
Mix 1+ 0% Sand	4075	-
Mix 2+ 20% Sand	5030	Mix2-Mix1 = 955
Mix 3+ 40% Sand	5957	Mix3-Mix1 = 1882

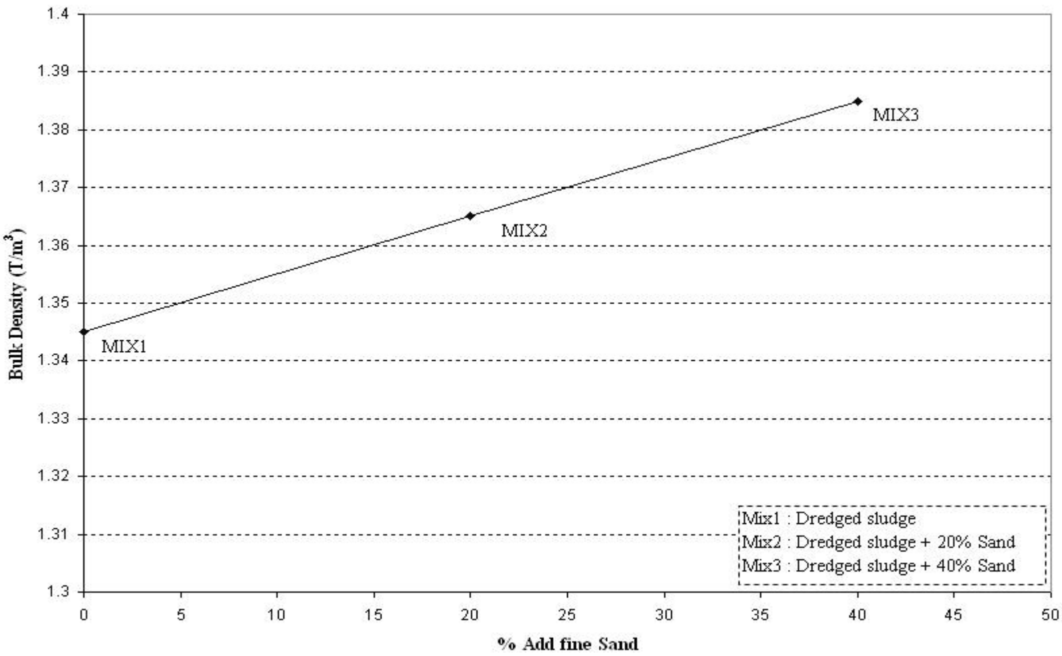


Figure 61 Relationship between bulk density and % add fine sand

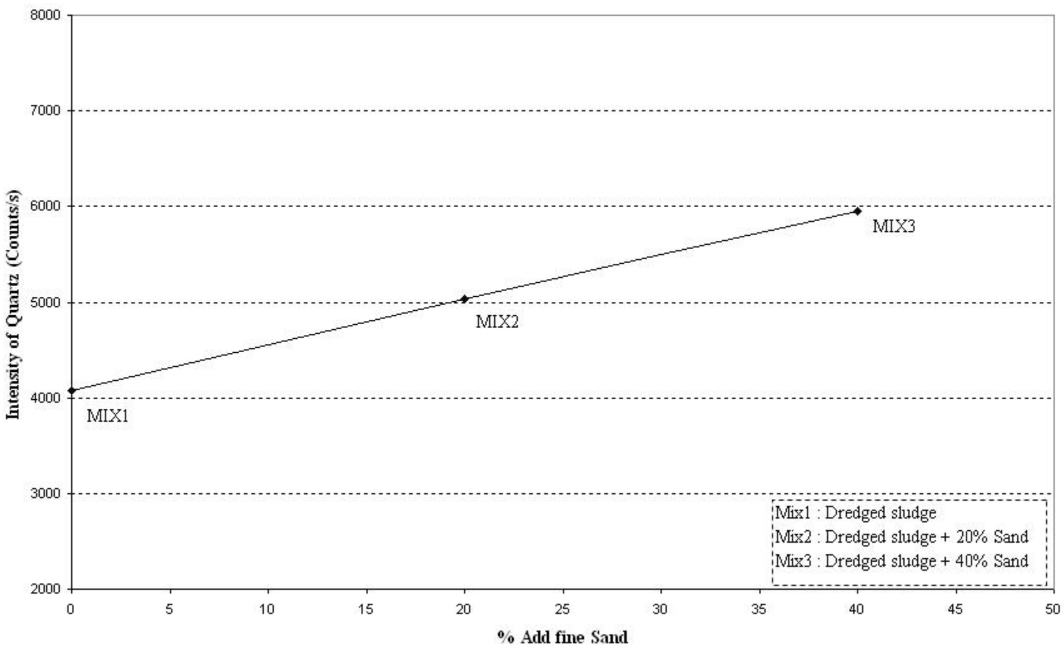
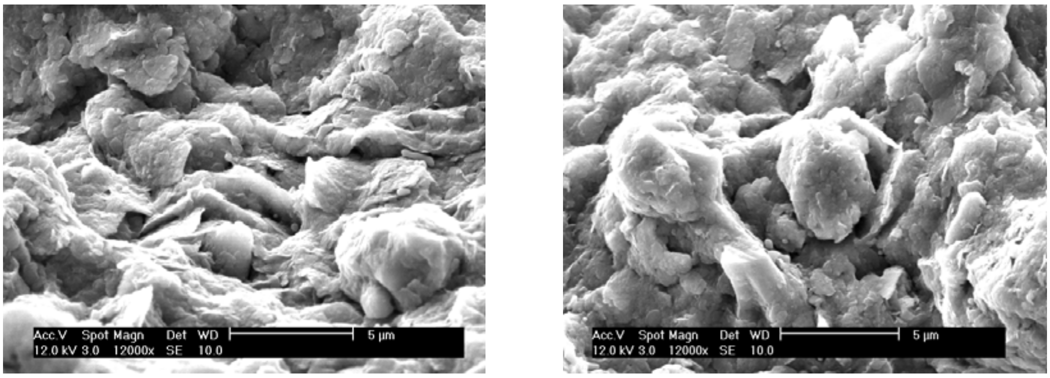
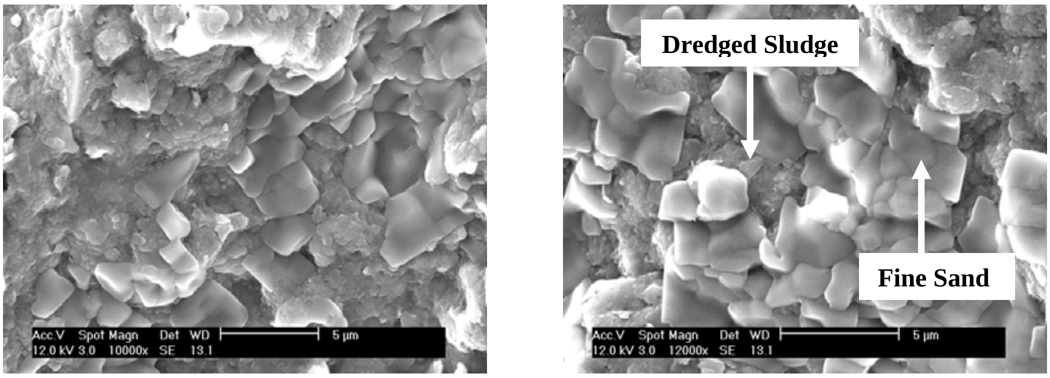


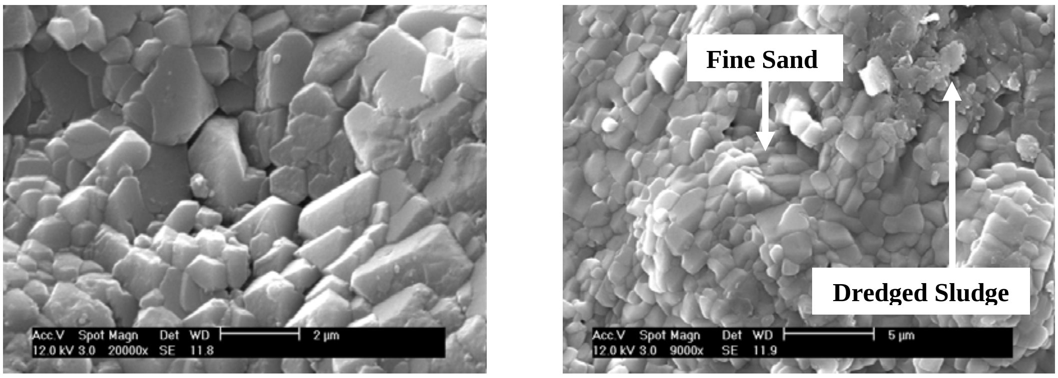
Figure 62 Relationship between Intensity of Quartz and % add fine sand



a) Untreated dredged sludge at 160% water content



b) Untreated dredged sludge + 20% sand at 160% water content



c) Untreated dredged sludge + 40% sand at 160% water content

Figure 63 SEM micrographs of untreated dredged sludge

Unconfined Compressive Strength Test Results of Treated Soils

This step was to stabilize dredged sludge, based on the selected mixture (cement content of 200 kg/m^3 at 160% water mixing) by mixing with sand for unsoaked and soaked conditions in order to obtain mix proportion suitable to be used as subbase materials.

The symbols of soil mixtures are given in Table 22. Experimental results indicated that the unconfined compressive strength changed slightly for the curing time at 3 and 7 days, On the other hand, markedly gains in strengths were observed for curing time at 14 and 28 days. Unconfined compressive strengths of Mix 1 were slightly greater than Mix 2 after 14 days. Mix 3 gained strengths grater than Mix 1 and Mix 2 for all curing time as shown in Table 23 and illustrated in Figure 64. Slight reduction of strength due to soaking could be observed as shown in Table 24 and illustrated in Figure 65. However, unconfined compressive strength of Mix 2 for soaked condition could attain 7.94 ksc. which conformed to specification of subbase materials for road.

Table 22 Test condition and symbols

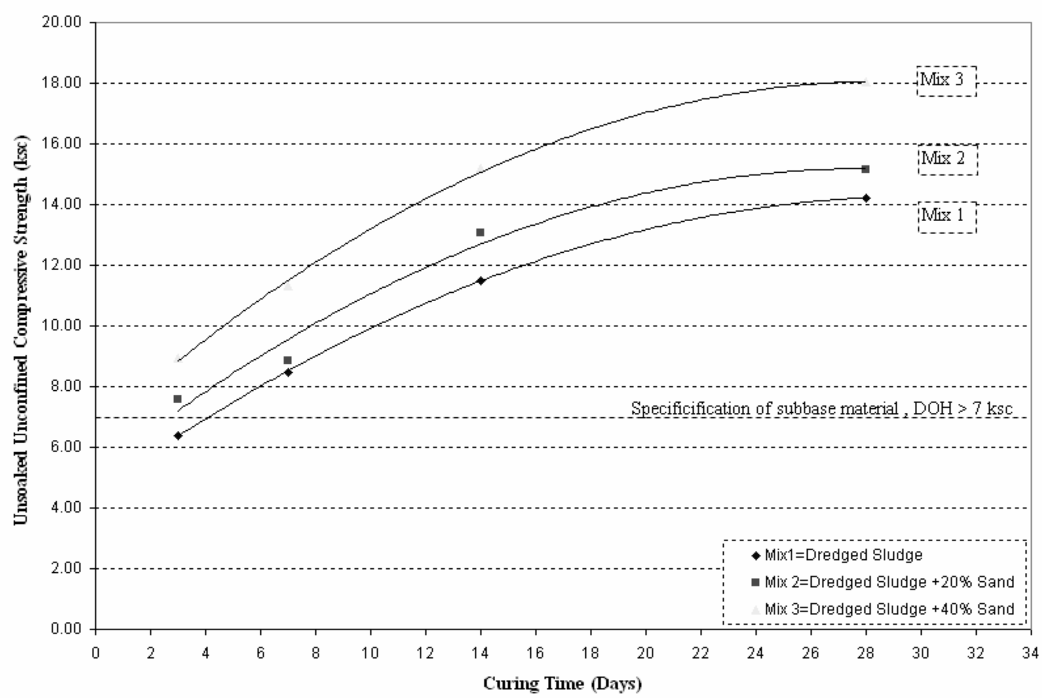
Symbol	Description
Mix 1	Dredged sludge + cement 200 kg/m^3
Mix 2	Dredged sludge + 20% sand + cement 200 kg/m^3
Mix 3	Dredged sludge + 40% sand + cement 200 kg/m^3

Table 23 Unconfined compressive strength of unsoaked strength condition

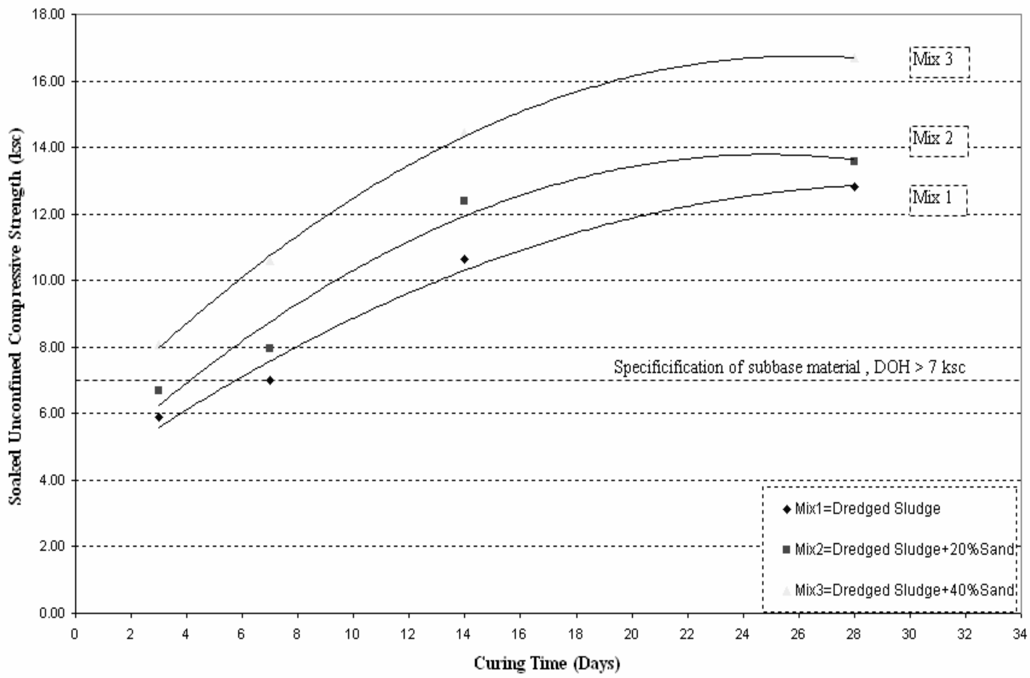
Description	Average UCS : Unsoaked strength (ksc)			
	3 days	7 days	14 days	28 days
Mix1	6.39	8.48	11.51	14.23
Mix2	7.58	8.87	13.08	15.13
Mix3	8.95	11.31	15.18	18.04

Table 24 Average Unconfined Compressive Strength of soaked strength condition.

Description	Average UCS : Soaked strength (ksc)			
	3 days	7 days	14 days	28 days
Mix1	5.91	7.00	10.63	12.81
Mix2	6.69	7.94	12.39	13.57
Mix3	8.06	10.60	14.42	16.68



<u>Figure 64</u> Relationship between unsoaked unconfined compressive strength and curing time



<u>Figure 65</u> Relationship between Soaked unconfined compressive strength and curing time.

The relationships between unsoaked unconfined compressive strength and ratio of water content after mixing with cement content (C_w/A_w), when adding fine sand 20% and 40% are summarized as shown in Table 25 and 26 and illustrated in Figure 66 and 67.

Table 25 The calculation of water content after mixing per cement content and unsoaked unconfined compressive strength

Description	Cement Content Kg / m^3	Cement Content A_w	Water Content Before Mixing	Water Content After Mixing C_w	C_w/A_w	Unconfined Compressive Strength for unsoaked condition (ksc)			
						3 Days	7 Days	14 Days	28 Days
Mix1	200	38.5%	160	110	2.86	6.39	8.48	11.51	14.225
Mix2	200	38.5%	160	96	2.49	7.58	8.87	13.075	15.13
Mix3	200	38.5%	160	82.5	2.14	8.95	11.305	15.175	18.04

Table 26 The calculation of water content after mixing per cement content and soaked unconfined compressive strength

Description	Cement Content Kg / m^3	Cement Content A_w	Water Content Before Mixing	Water Content After Mixing C_w	C_w/A_w	Unconfined Compressive Strength for soaked condition (ksc)			
						3 Days	7 Days	14 Days	28 Days
Mix1	200	38.5%	160	110	2.86	5.91	7.00	10.63	12.81
Mix2	200	38.5%	160	96	2.49	6.69	7.94	12.39	13.57
Mix3	200	38.5%	160	82.5	2.14	8.06	10.60	14.42	16.68

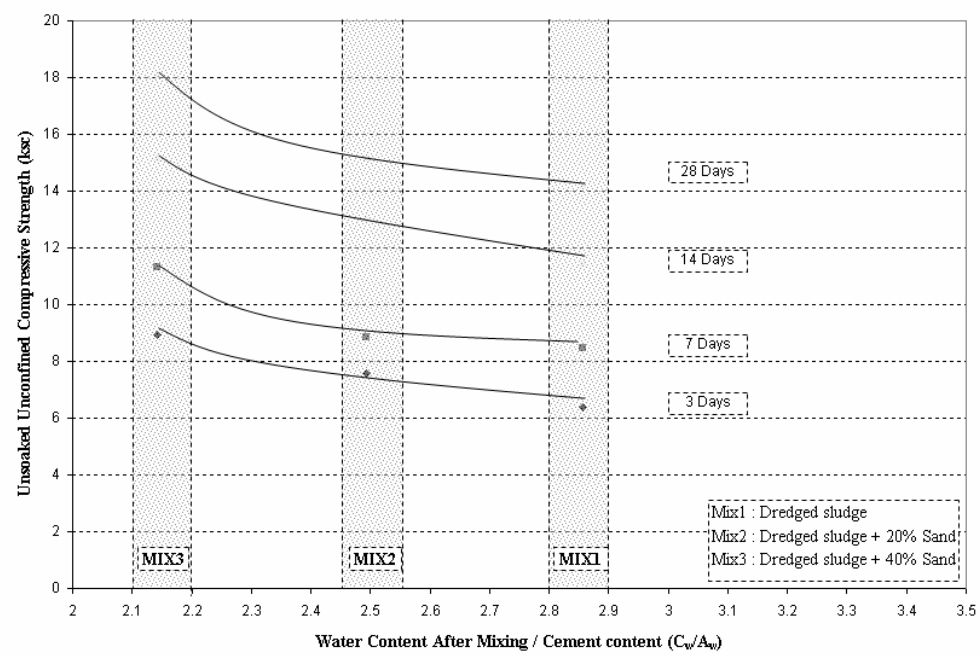


Figure 66 Relationships between unsoaked unconfined compressive strength and ratio of water content after mixing with % cement content when pouring sand 20% and 40%

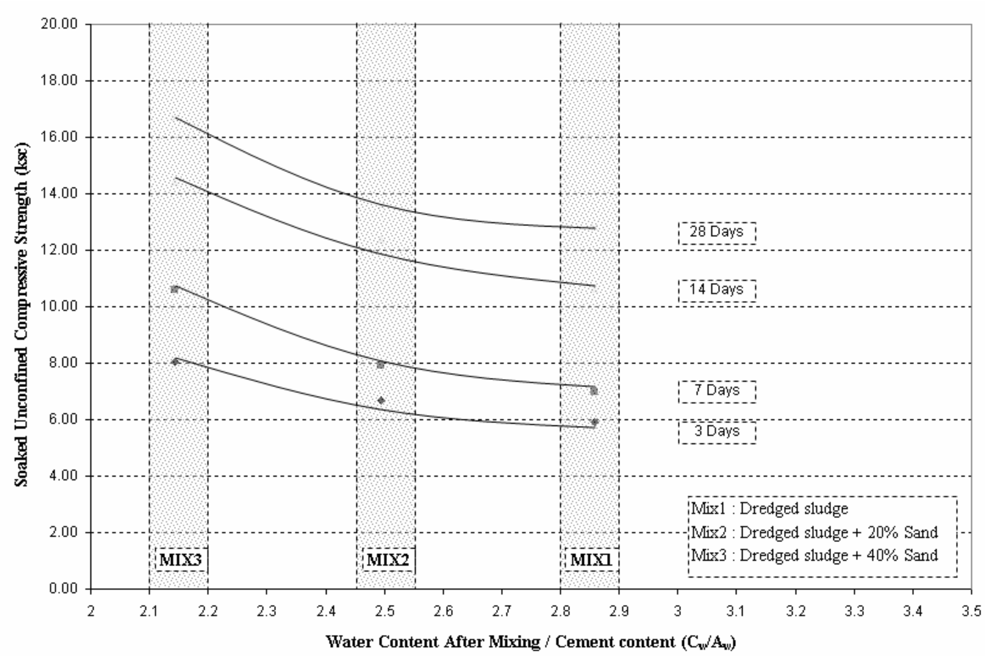


Figure67 Relationships between soaked unconfined compressive strength and ratio of water content after mixing with % cement content when pouring sand 20% and 40%.

Modulus of Elasticity (E_{50})

The deformation characteristics of cement stabilized sludge with sand were significantly improved with curing time. The modulus of elasticity directly correlated to strength. The hardening effects which have been developed establish strong cementing characteristics, resulting increase in modulus of elasticity (E_{50}) of the stabilized soils, as summarized in Table 27 and 28.

Table 27 Unsoaked modulus of elasticity (E_{50}) of soil cement with sand

Mix	Curing Time (Days)	Unsoaked Unconfined Compressive Strength (ksc)	Average E_{50} (ksc)
Mix 1	3	6.39	703.33
Mix 1	7	8.48	852.00
Mix 1	14	11.51	1098.08
Mix 1	28	14.23	1574.44
Mix 2	3	7.58	908.33
Mix 2	7	8.87	848.08
Mix 2	14	13.08	1137.07
Mix 2	28	15.13	1591.67
Mix 3	3	8.95	1161.84
Mix 3	7	11.31	1293.33
Mix 3	14	15.18	2353.13
Mix 3	28	18.04	2139.29

Table 28 Soaked modulus of elasticity (E_{50}) of soil cement with sand

Mix	Curing Time (Days)	Soaked Unconfined Compressive Strength (ksc)	Average E_{50} (ksc)
Mix 1	3	5.91	708.33
Mix 1	7	7.00	592.50
Mix 1	14	10.63	1114.58
Mix 1	28	12.81	1855.71
Mix 2	3	6.69	761.11
Mix 2	7	7.94	795.00
Mix 2	14	12.39	1632.89
Mix 2	28	13.57	1809.21
Mix 3	3	8.06	834.83
Mix 3	7	10.60	1418.42
Mix 3	14	14.42	1788.75
Mix 3	28	16.68	2653.13

Figure 68 and 69 showed that the modulus of elasticity (E_{50}) with curing time for unsoaked and soaked conditions. E_{50} of Mix 1 and Mix 2 increased steadily with curing time. On the other hand, E_{50} of Mix 3 significantly increased at the early curing time and seemed to be constant at long time. In summary, unconfined compressive strengths and modulus of elasticity (E_{50}) illustrated linear relationships, as shown in Figure 70 and 71.

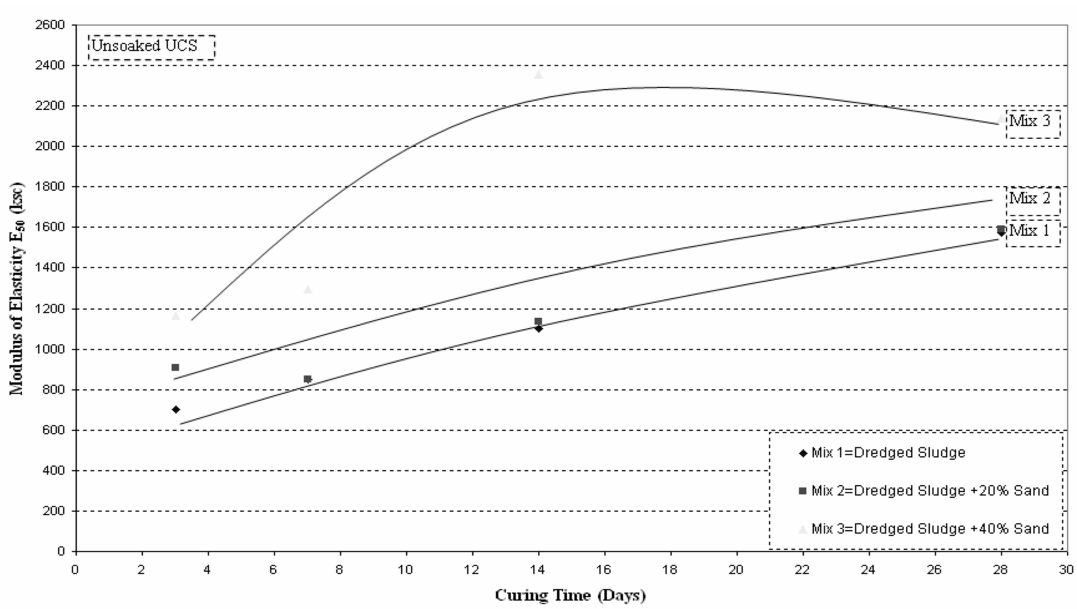


Figure 68 Relationship between unsoaked modulus of elasticity at 50% and curing time of soil cement with sand

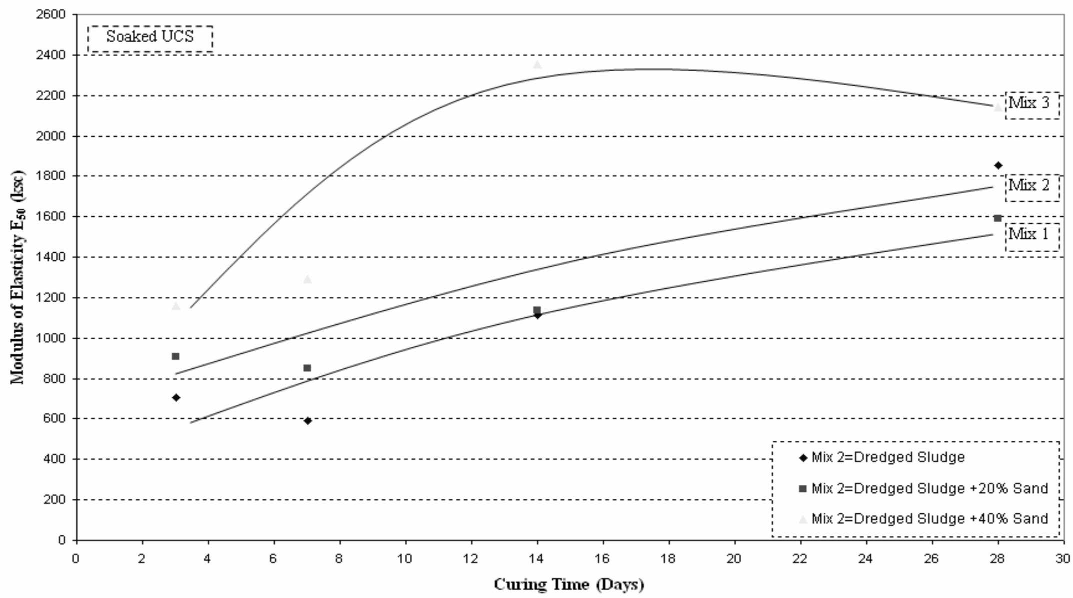


Figure 69 Relationship between soaked modulus of elasticity at 50% and curing time of soil cement with sand

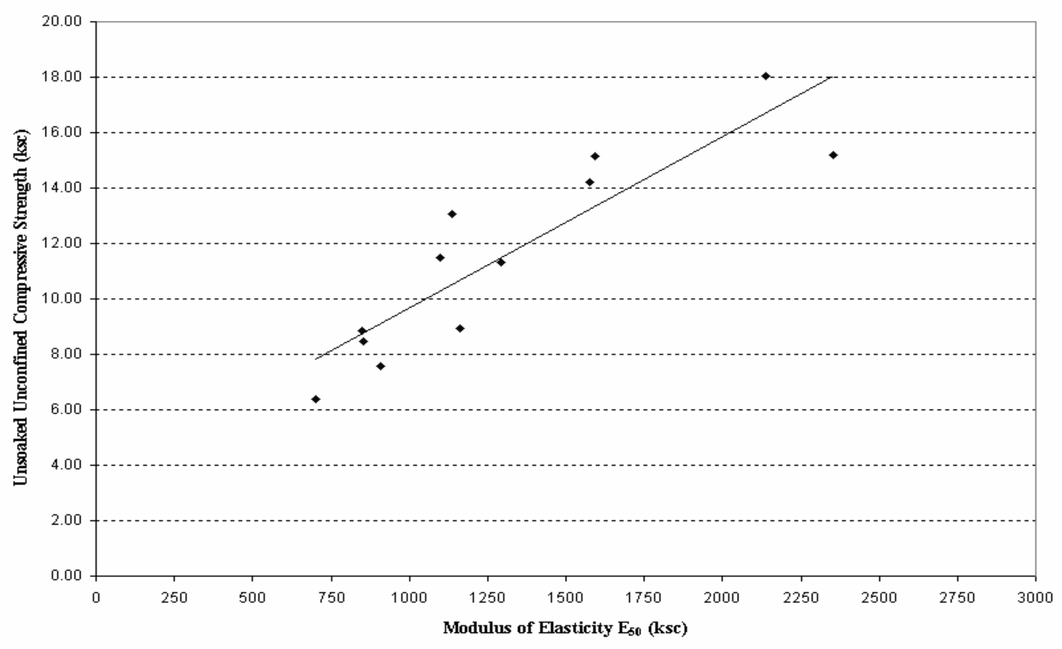


Figure 70 Relationship between unsoaked unconfined compressive strength and modulus of elasticity at 50% of soil cement with sand

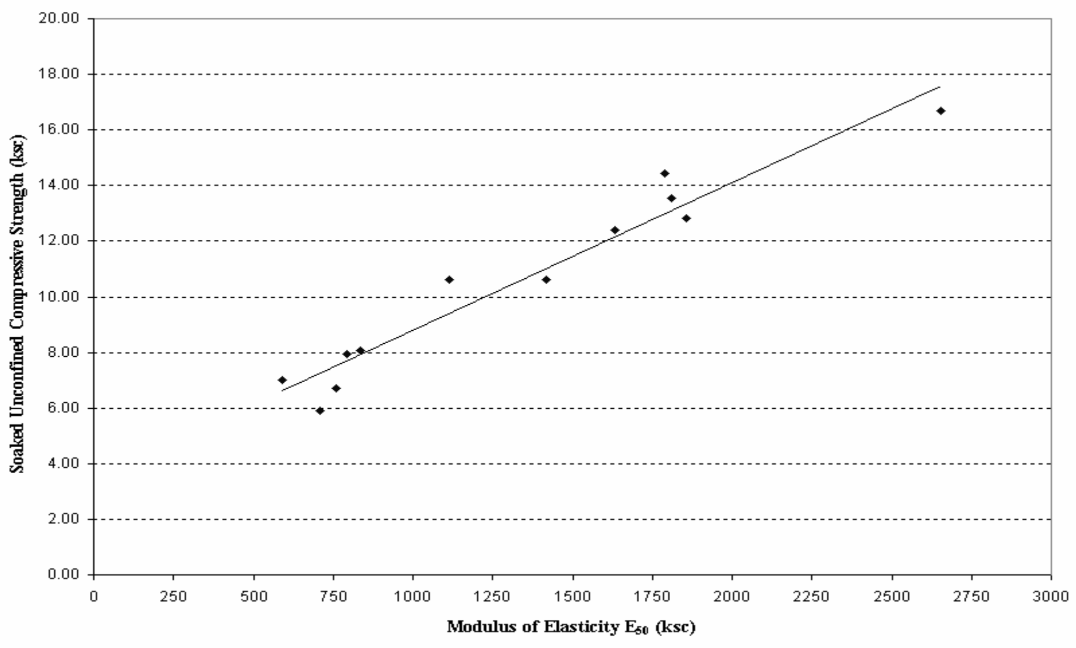


Figure 71 Relationship between soaked unconfined compressive strength and modulus of elasticity at 50% of soil cement with sand

Effects of Soaking on the stabilized soils

Samples were soaked for 2 hours before unconfined compression test, as followed specification of DOH. Experimental results indicated that the unconfined compressive strength of the stabilized soils were decreased approximately 7-10% when the samples were soaked for 2 hours as shown in Table 29 and Figure 72.

Table 29 Average loss in strength due to soaking condition

Mix	Curing Time (days)	Cement Content (kg/m^3)	Cement Content (%)	% Sand	Average Unconfined Compressive Strength (ksc)		Strength loss (%) due to soaking
					Unsoaked	Soaked	
Mix1	3	200	38.5	0	6.39	5.91	7.59
Mix1	7	200	38.5	0	8.48	7.00	7.51
Mix1	14	200	38.5	0	11.51	10.63	7.65
Mix1	28	200	38.5	0	14.225	12.81	9.98
Mix2	3	200	38.5	20	7.58	6.69	11.74
Mix2	7	200	38.5	20	8.87	7.94	10.54
Mix2	14	200	38.5	20	13.08	12.39	5.28
Mix2	28	200	38.5	20	15.13	13.57	10.34
Mix3	3	200	38.5	40	8.95	8.06	9.94
Mix3	7	200	38.5	40	11.31	10.60	6.28
Mix3	14	200	38.5	40	15.18	14.42	4.98
Mix3	28	200	38.5	40	18.04	16.68	7.54

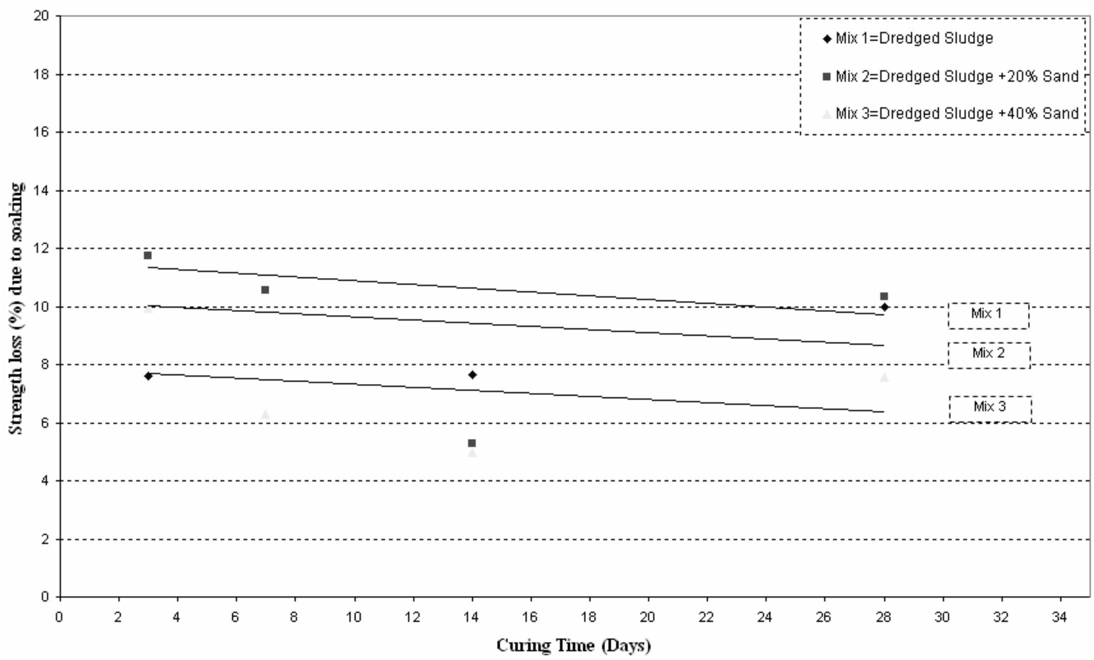
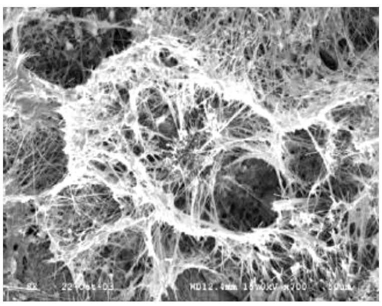


Figure 72 Relationship between strength loss due to soaking and curing time of cement-stabilized soil having sand replacement

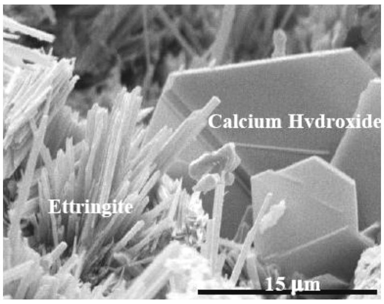
Hydration reaction and products in relation to Unconfined Compressive Strengths

Calcium silicate hydrate (CSH) is the main hydration product which contributes to strength of concrete including soil cement. Figure 73 illustrates major reaction products according to SEM observations.

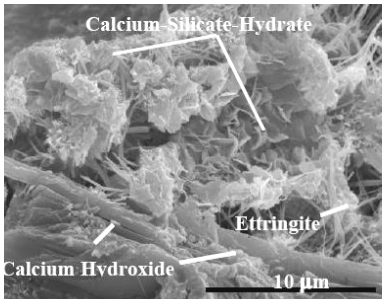


a) Ettringite (Needle – liked)

b) Ettringite (Rod-liked)



c) Ettringite and Calcium Hydroxide



d) CSH and Calcium Hydroxide

Figure 73 Major reaction products
Source: Site by Yoobanpot. (2004)

Development of Calcium Silicate Hydrate (CSH) and Ettringite in relation to unsoaked unconfined compressive strengths

The strength development of stabilized soil has a general trend to increase with the amounts of CSH and Ettringite as detected by XRD analysis. The intensity of CSH and Ettringite are shown in Table 30 and 31.

Table30 CSH intensity of soil mixed with cement content of 200 kg/m^3 and various sand contents.

Type	Curing Time (Days)	Unsoaked Unconfined Compressive Strength (ksc)	Intensity of CSH (Counts/s)
Mix 1	3	8.95	295
Mix 1	7	11.31	468
Mix 1	14	15.18	497
Mix 1	28	18.04	550
Mix 2	3	7.58	283
Mix 2	7	8.87	480
Mix 2	14	13.08	519
Mix 2	28	15.13	560
Mix 3	3	6.39	282
Mix 3	7	8.48	517
Mix 3	14	11.51	545
Mix 3	28	14.23	566

Table31 Ettringite intensity of soil mixed with cement content of 200 kg/m^3 and various sand contents.

Type	Curing Time (Days)	Unsoaked Unconfined Compressive Strength (ksc)	Intensity of Ettringite (Counts/s)
Mix 1	3	8.06	150
Mix 1	7	10.60	203
Mix 1	14	14.42	220
Mix 1	28	16.68	227
Mix 2	3	6.69	158
Mix 2	7	7.94	208
Mix 2	14	12.39	227
Mix 2	28	13.57	232
Mix 3	3	5.91	162
Mix 3	7	7.00	210
Mix 3	14	10.63	235
Mix 3	28	12.81	243

Figures 74 and 75 show that intensity of CSH and Ettingite markedly increased at the early curing time and slightly increased slowly or almost constant after 14 days. It is obvious as shown in Figures 76 and 77 that unconfined compressive strength increased as intensity of reaction products increased.

Significant changes in soil structure due to cement hydration can be observed by X- Ray Diffraction patterns and SEM micrographs. The results from XRD and SEM of Mix 1 (Dredged sludge + cement 200 kg/m^3) after unconfined compression test as illustrated in Figure 78 revealed that in the early stage (3 days) the reactions products such as CSH and Ettringite are slightly formed and rapidly increased at curing time of 7 days, binding with clay fabrics. Substantial growth of reaction products can be observed. after 14 days. For long term CSH fabrics and Ettringite were slightly formed and become hardened with time, linking between stabilized soil particles.

Changes in soil structures of Mix 2 (Dredged sludge + 20% sand + cement 200 kg/m3) can be explained by the relationship between XRD and SEM after unconfined compression test as illustrated in Figure 79. In the early stage (3 days) the reaction products such as CSH and Ettringite were slightly formed and rapidly increased at curing time of 7 days and then slightly increased with time.

Figure 80 illustrates the relationship between XRD and SEM of Mix 3 (Dredged sludge + 40% sand + cement 200 kg/m3) after unconfined compression test. Similar trend as Mix1 and Mix2 could be observed. The reaction products such as CSH and Ettringite were slightly formed at 3 days curing time and rapidly increased at curing time of 7 days and then slightly increased with time.

It can be concluded that these results were conformed to strength characteristic curves. Formation and growth of these major reaction products made the stabilized soil structures denser and stronger, resulting in an increase in strength. Mix 3 had greater strengths than MIX 1 and MIX 2 because the replacement of certain amount of fine sand increased dry density and thus modified soil structures where reaction products could be strongly formed.

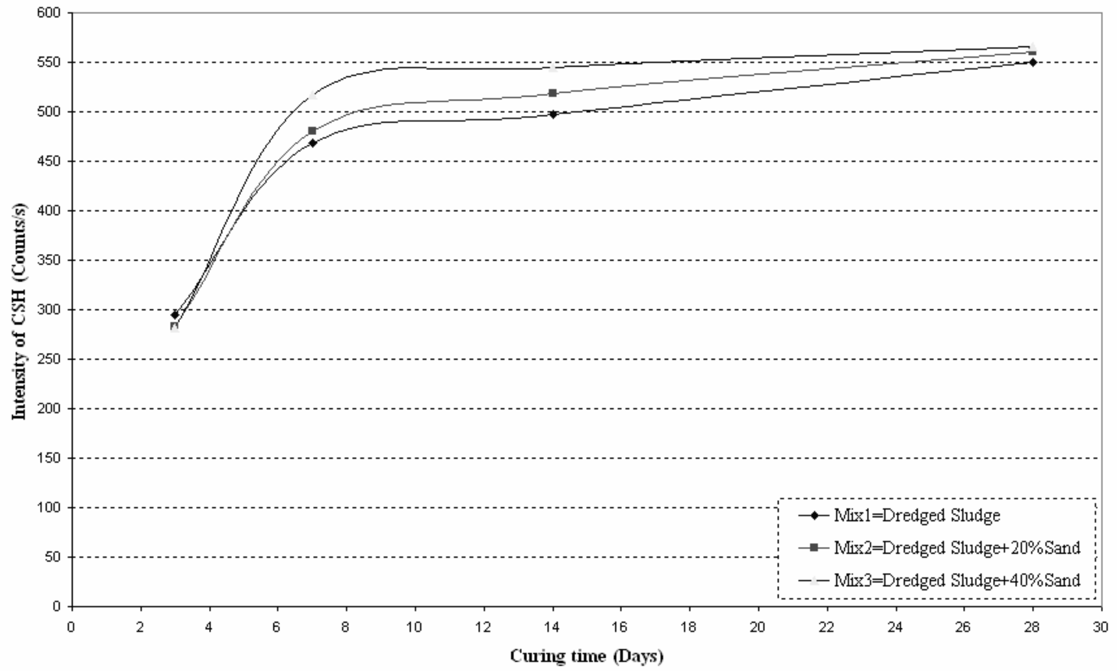


Figure 74 Relationship between calcium silicate hydrate intensity of soil cement with sand and curing time.

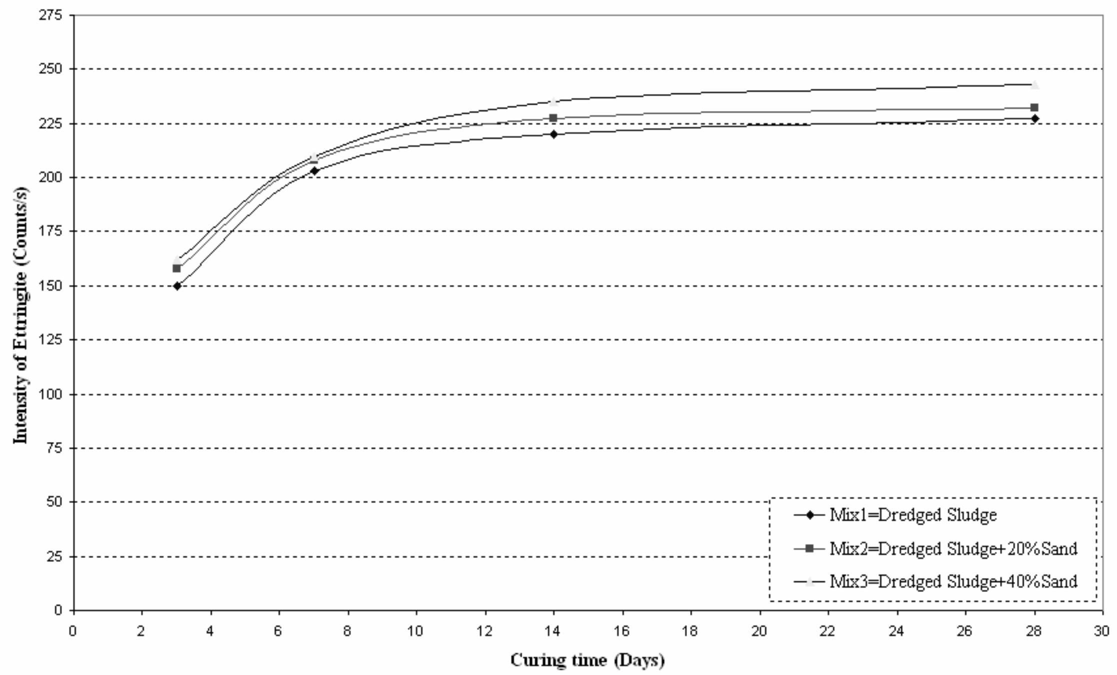


Figure 75 Relationship between Ettringite intensity of soil cement with sand and curing time.

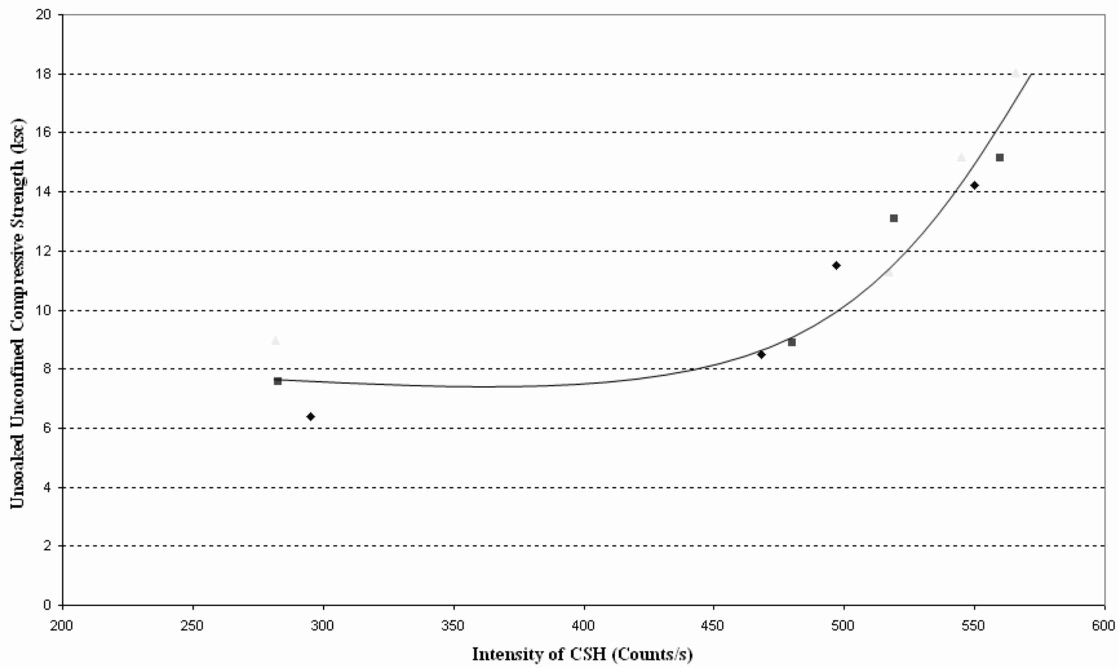


Figure 76 Relationship between calcium silicate hydrate intensity of soil cement with sand and unsoaked unconfined compressive strength.

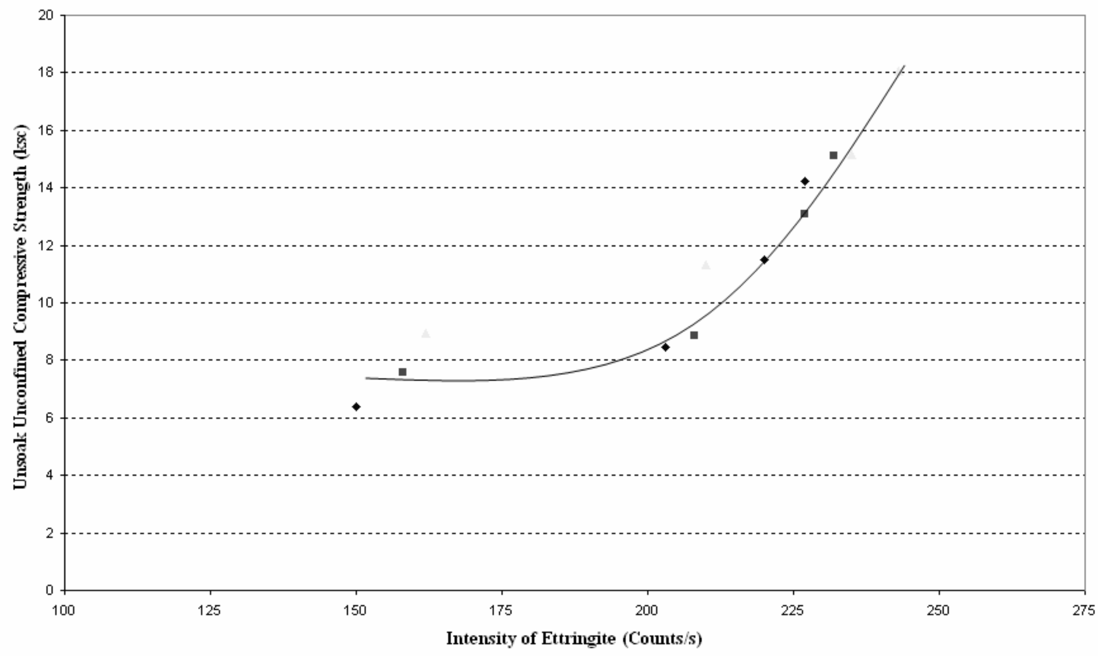


Figure 77 Relationship between Ettringite intensity of soil cement with sand and unsoaked unconfined compressive strength.

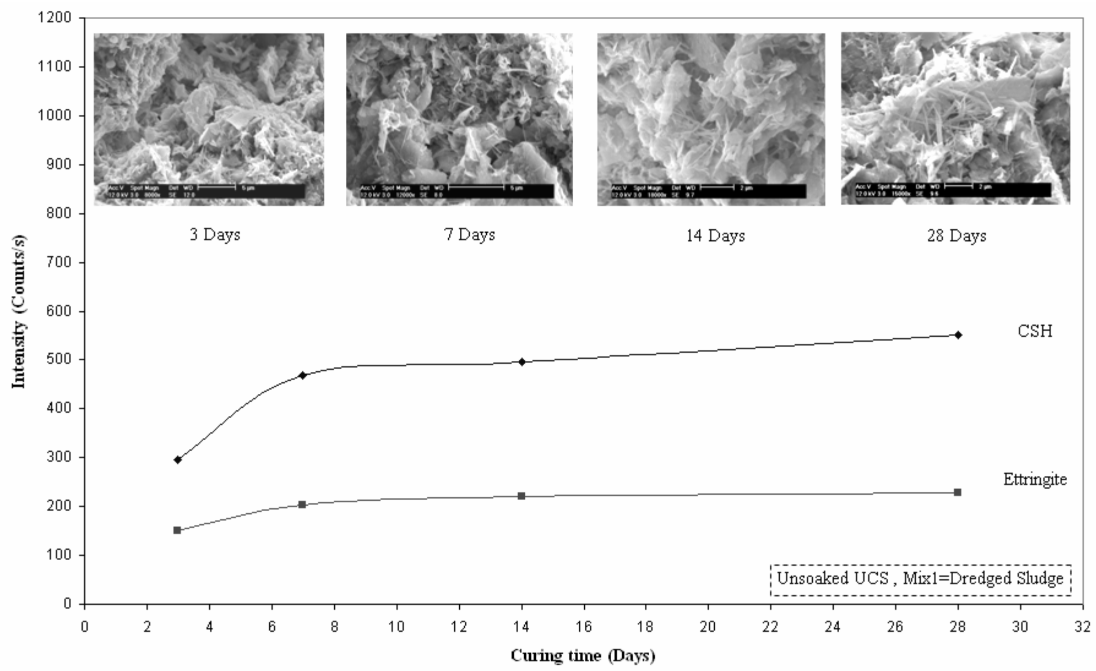


Figure 78 Relationship between XRD and SEM of unsoaked unconfined compressive strength (Mix1)

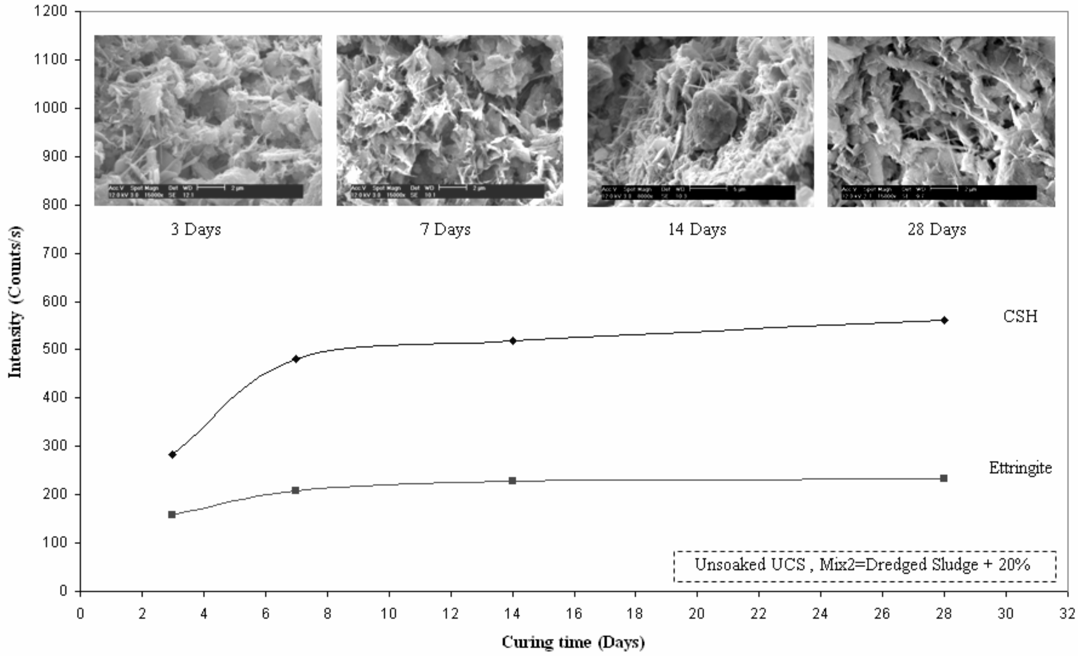


Figure 79 Relationship between XRD and SEM of unsoaked unconfined compressive strength (Mix2)

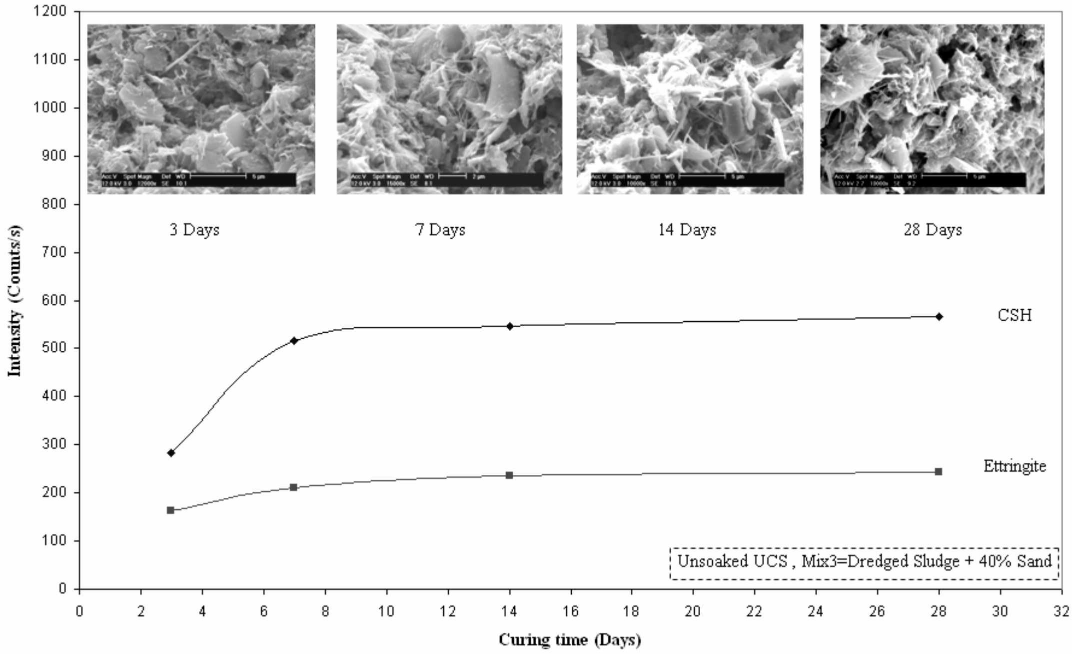


Figure 80 Relationship between XRD and SEM of unsoaked unconfined compressive strength (Mix3)

Development of Calcium Silicate Hydrate and Ettringite intensity in relation to soaked unconfined compressive strengths

XRD analysis and SEM observations were taken on MIX 2 (Dredged sludge + 20% Sand) after soaked unconfined compressive strength tests. The result of reaction products are shown in Table 32 and 33 and illustrated in Figure 81 and 82.

Table 32 CSH intensity of soil with 200 kg/m^3 and 20 % sand content

Mix	Curing Time (Days)	Unconfined Compressive Strength (ksc)		Δ Strength	Intensity of CSH (Counts/s)		Δ Intensity
		Unsoaked	Soaked		Unsoaked	Soaked	
Mix 2	3	7.58	6.69	0.89	283	132	151
Mix 2	7	8.87	7.94	0.93	480	137	343
Mix 2	14	13.08	12.39	0.69	519	488	31
Mix 2	28	15.13	13.57	1.56	560	542	18

Table 33 Ettringite intensity of soil with 200 kg/m^3 and 20 % sand content

Mix	Curing Time (Days)	Unconfined Compressive Strength (ksc)		Δ Strength	Intensity of Ettringite (Counts/s)		Δ Intensity
		Unsoaked	Soaked		Unsoaked	Soaked	
Mix 2	3	7.58	6.69	0.89	158	73	85
Mix 2	7	8.87	7.94	0.93	208	118	90
Mix 2	14	13.08	12.39	0.69	227	202	25
Mix 2	28	15.13	13.57	1.56	232	205	27

The change in soil structure of soaked Mix 2 can be explained by the relationship between XRD and SEM after unconfined compression test as illustrated in Figure 83. In the early stage (3 days) the reaction products such as CSH and Ettringite were slightly formed and rapidly increase after curing time of 7 days and slightly increased with time. Intensities of CSH and Ettringite for unsoaked samples were greater than the soaked samples. The results were agreeable with strength characteristics curves as discussed previously.

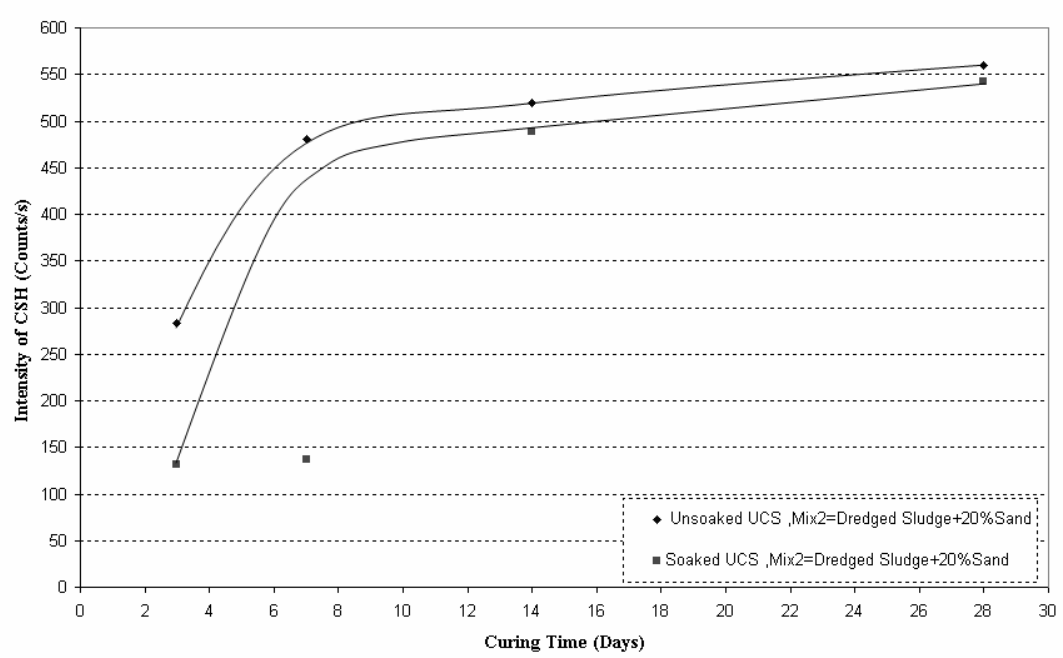


Figure 81 Relationship between calcium silicate hydrate intensity of soil cement with sand and curing time for unsoaked and soaked conditions.

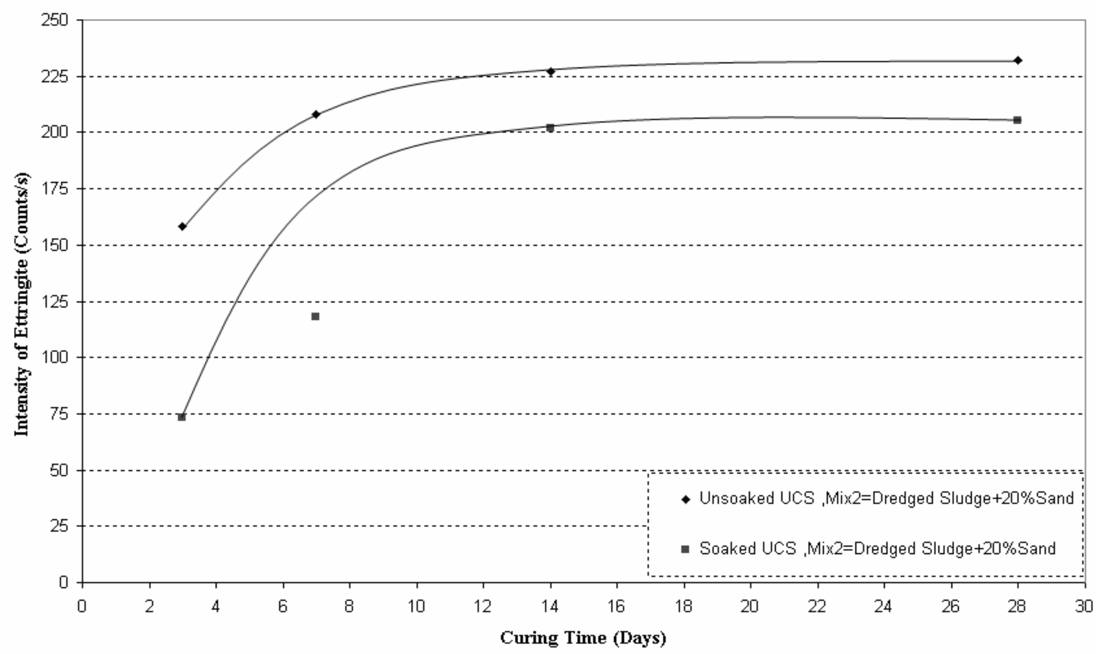


Figure 82 Relationship between Ettringite intensity of soil cement with sand and curing time for unsoaked and soaked conditions.

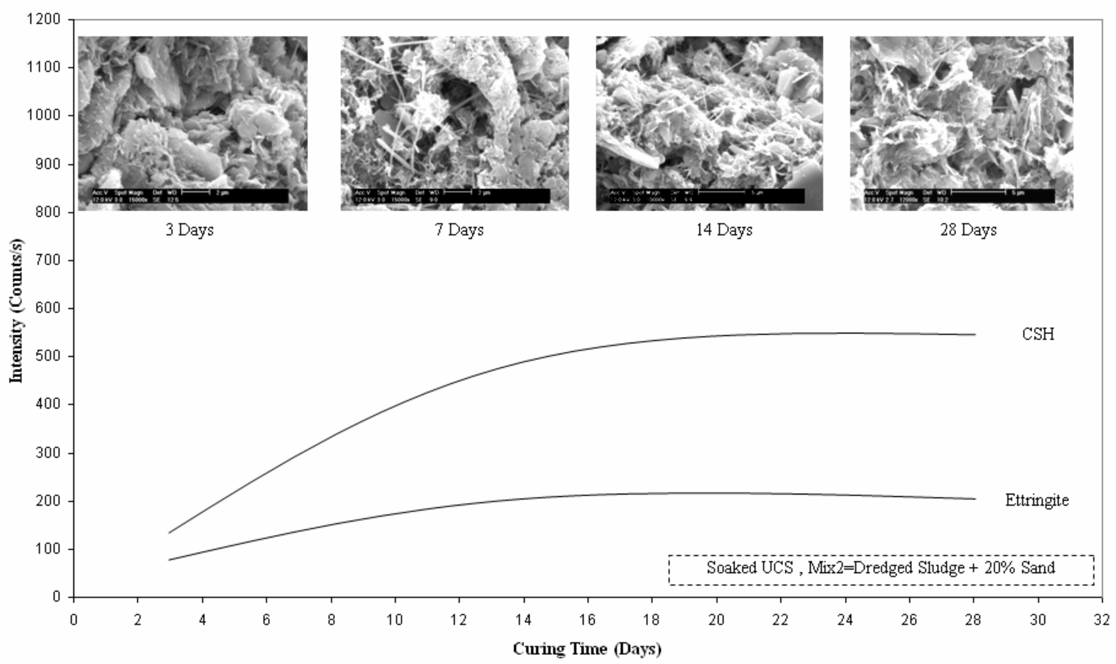


Figure 83 Relationship between XRD and SEM of soaked unconfined compressive strength (Mix2)

California Bearing Ratio Test Results of Treated Soils

California Bearing Ratio Tests in this study were taken on MIX 2 (Dredged sludge + 20% Sand). The results are summarized in Table 34 and illustrated in Fig.84. Experimental results showed that the CBR markedly increased at curing time of 7-14 days and gradually increased afterwards. The 14 days CBR was 30.86% which was greater than requirement for subbase material (CBR > 25%) as recommended by DOH of Thailand.

Based on the experimental results as summarized in Table 35, CBR decreased about 4-8% when the samples were soaked. Rate of loss in CBR seemed to decrease as curing time increased as shown in Figure.85.

Table 34 Average of California Bearing Ratio Test

Description	% CBR		
	7 days	14 days	28 days
Mix2 : Dredged sludge + 20% Sand (Unsoaked)	15.77	32.85	38.20
Mix2 : Dredged sludge + 20% Sand (Soaked)	14.56	30.86	36.46

Table 35 Strength loss due to soaking

Mix	Curing Time (days)	Cement Content (kg/m3)	Cement Content (%)	% Sand	Average CBR (%)		%CBR loss due to soaking
					Unsoaked	Soaked	
Mix 2	7	200	38.5	20	15.77	14.56	7.67
Mix 2	14	200	38.5	20	32.85	30.86	6.06
Mix 2	28	200	38.5	20	38.20	36.46	4.55

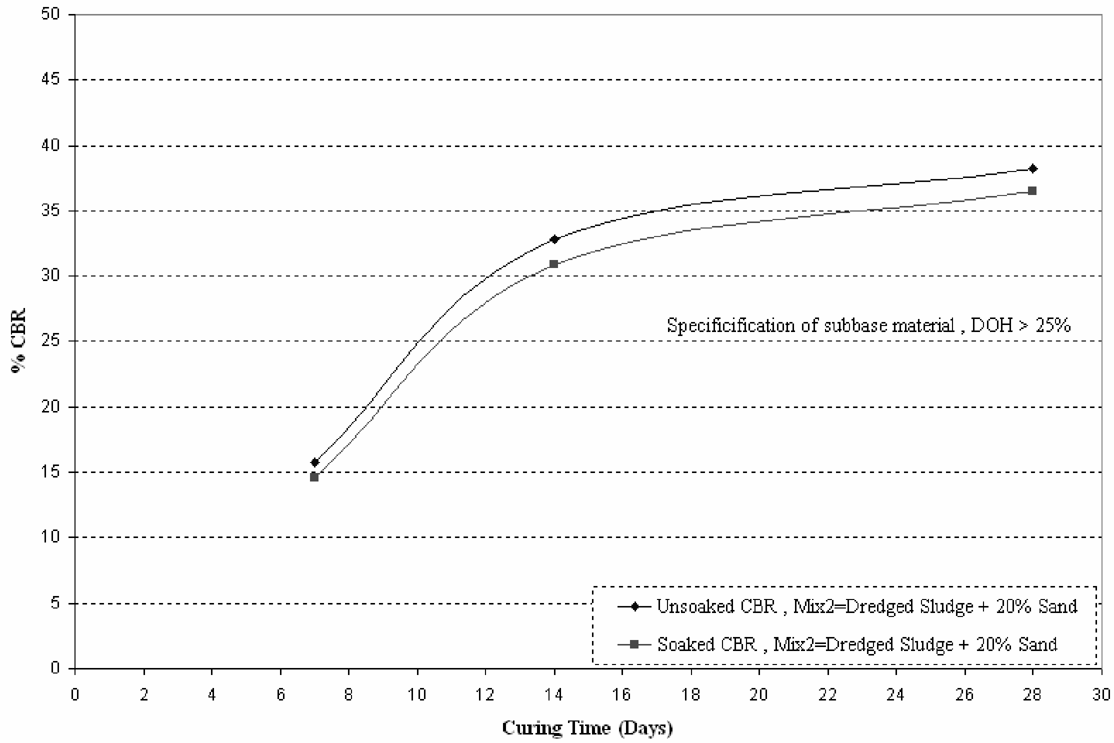


Figure 84 Unsoked CBR and soaked CBR with curing time for MIX 2.

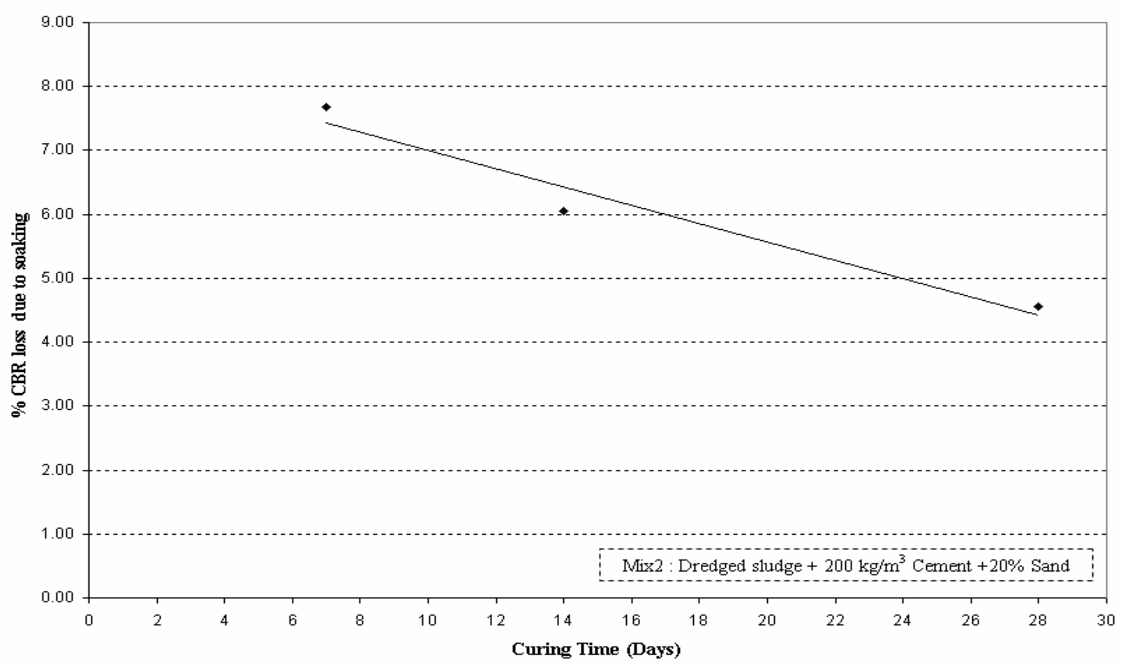


Figure 85 Loss in CBR due to soaking with curing time

Reaction products of Cement-stabilized Sludge after California Bearing Ratio Test

Experimental results analysis by XRD showed that CSH and Ettringite slowly increased in the early age and markedly increased at curing time of 14 days until 28 days as shown in Table 34 and 35, and illustrated in Figure 86 and 89. Moreover, CSH and Ettringite can be observed by SEM as illustrated in Figure 90.

Results from XRD and SEM for unsoaked samples of Mix 2 (Dredged sludge + 20% sand + cement 200 kg/m^3) are illustrated in Figure 90. In the early stage the reaction products such as CSH and Ettringite were rapidly produced at curing time of 7 days, binding with clay fabrics. Substantial growth of reaction products can be observed after 14 days. For long term CSH fabrics and Ettringite were slightly formed and become hardened with time, linking between stabilized soil particles.

Changes in soil structures when Mix 2 (Dredged sludge + 20% sand + cement 200 kg/m3) was soaked can be explained using results from XRD and SEM after CBR test, as illustrated in Figure 91. In the early stage (7 days), the reaction products were richly formed. In the next stage, the products rapidly increased at curing time of 14 days and slightly increased with time. The samples which were soaked for 4 days had slightly lower intensity in major reaction products than those unsoaked samples. This results in a slight reduction in shearing resistance of the stabilized dredged sludge.

Table 34 CSH intensity of soil with 200 kg/m^3 and 20 % sand content

Type	Curing Time (Days)	% CBR		Intensity of CSH (Counts/s)	
		Unsoaked	Soaked	Unsoaked	Soaked
Mix 2	7	15.77	14.56	102	102
Mix 2	14	32.85	30.86	318	252
Mix 2	28	38.2	36.46	445	440

Table 35 Ettringite intensity of soil with 200 kg/m^3 and 20 % sand content

Type	Curing Time (Days)	% CBR		Intensity of Ettringite (Counts/s)	
		Unsoaked	Soaked	Unsoaked	Soaked
Mix 2	7	15.77	14.56	115	118
Mix 2	14	32.85	30.86	143	130
Mix 2	28	38.2	36.46	200	203

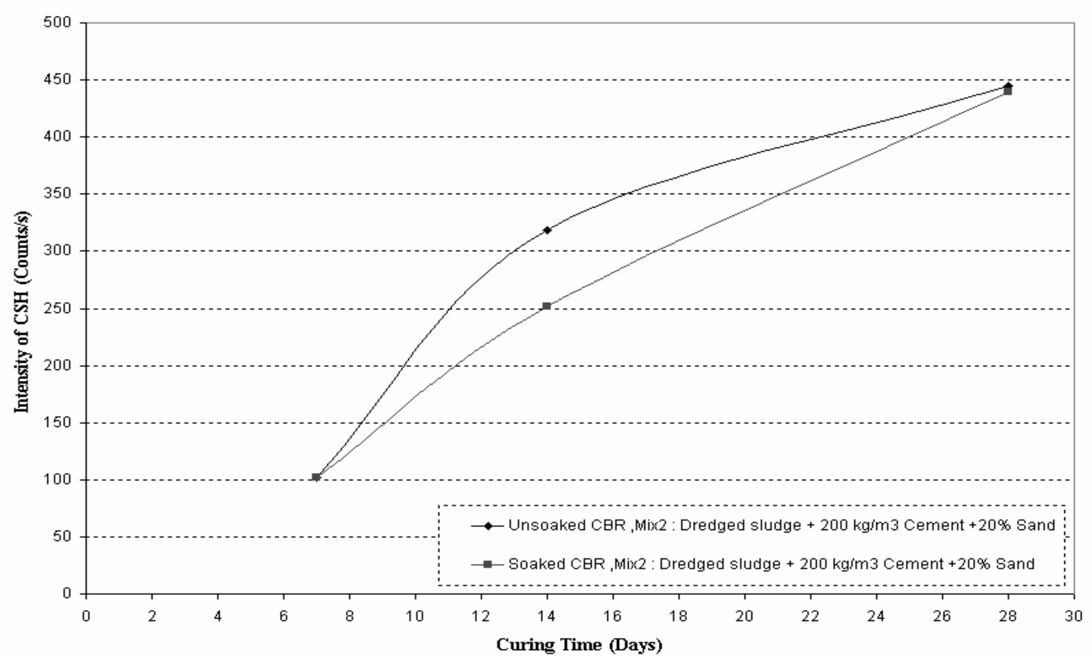


Figure 86 Relationship between calcium silicate hydrate intensity of soil cement with sand and curing time for unsoaked and soaked conditions.

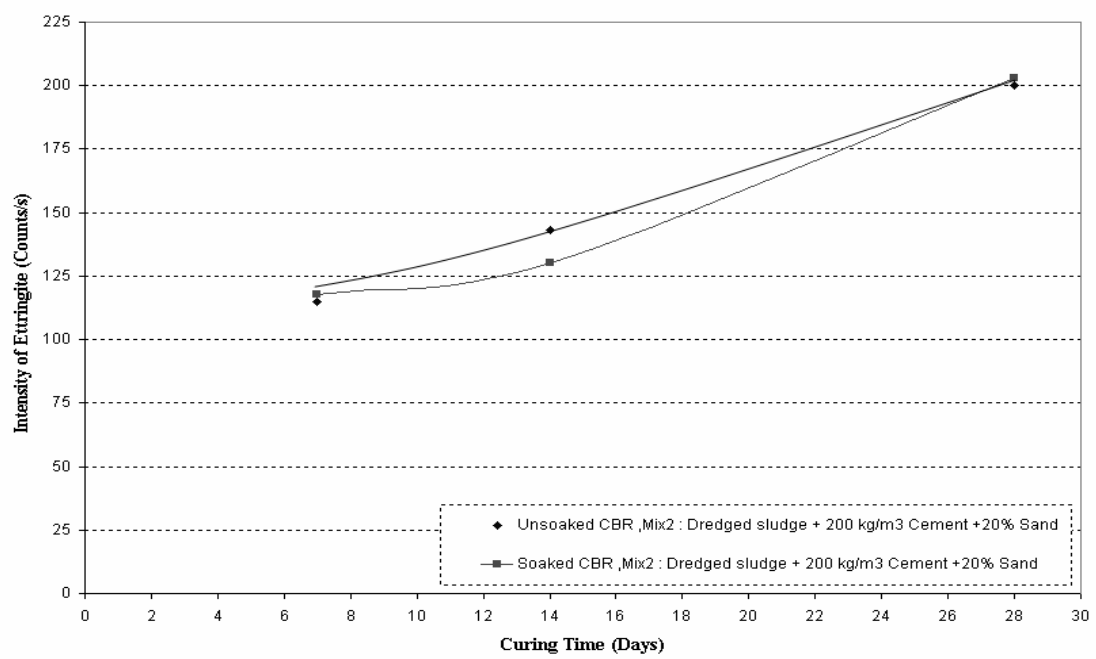


Figure 87 Relationship between Ettringite intensity of soil cement with sand and curing time for unsoaked and soaked conditions.

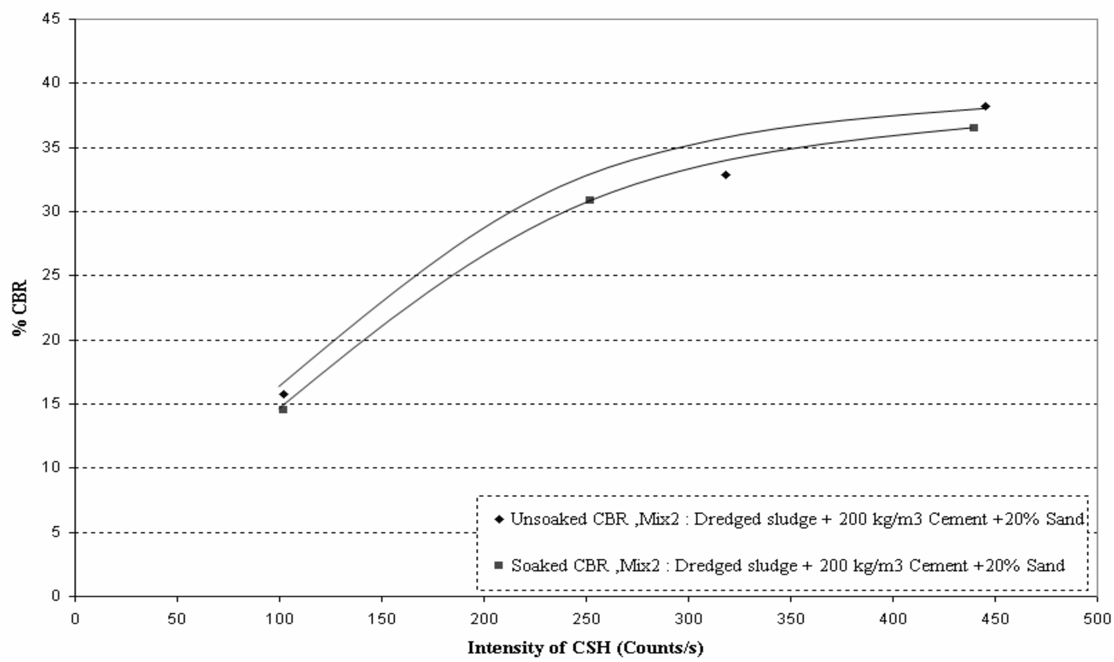


Figure 88 Relationship between CBR and intensity of calcium silicate hydrate.

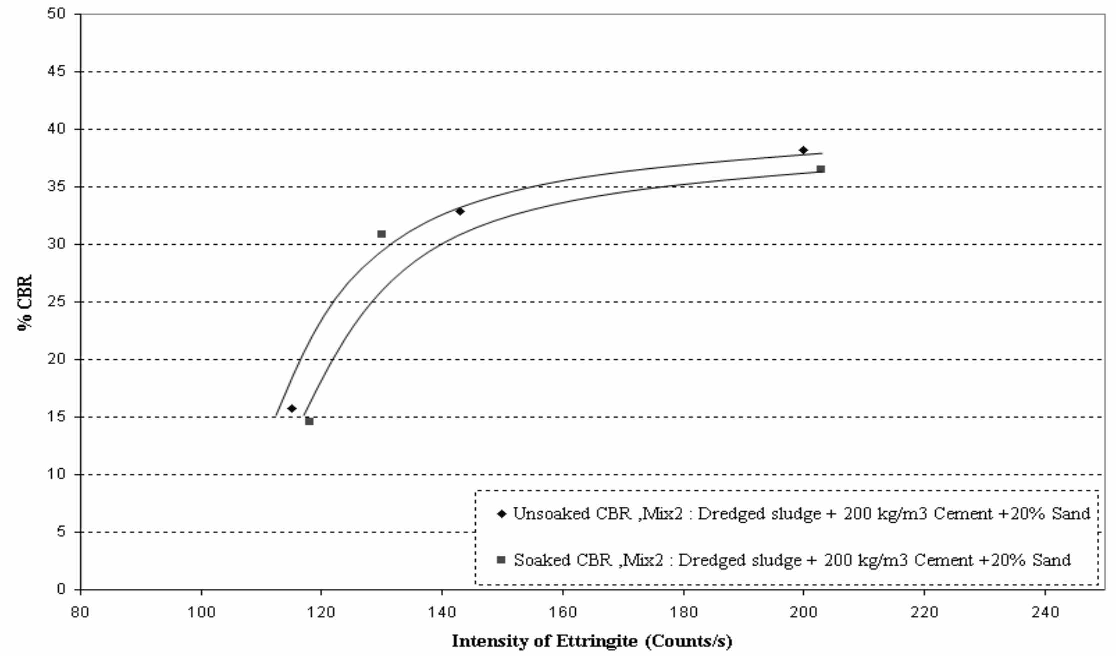


Figure 89 Relationship between CBR and intensity of Ettringite

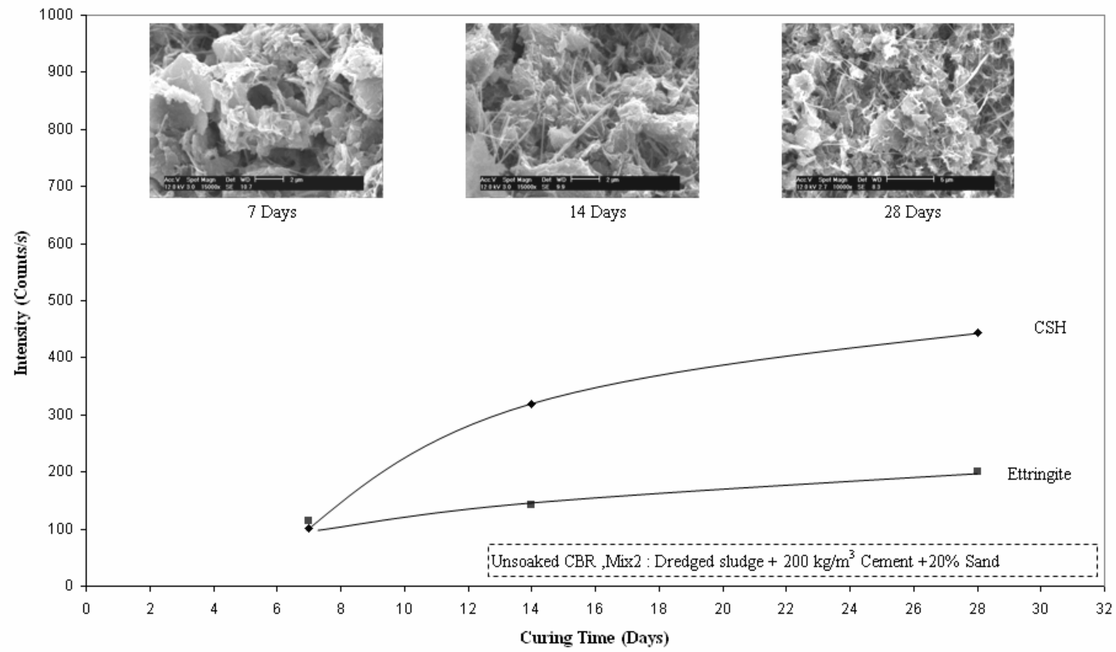


Figure 90 Relationship between XRD and SEM of unsoaked CBR (Mix2)

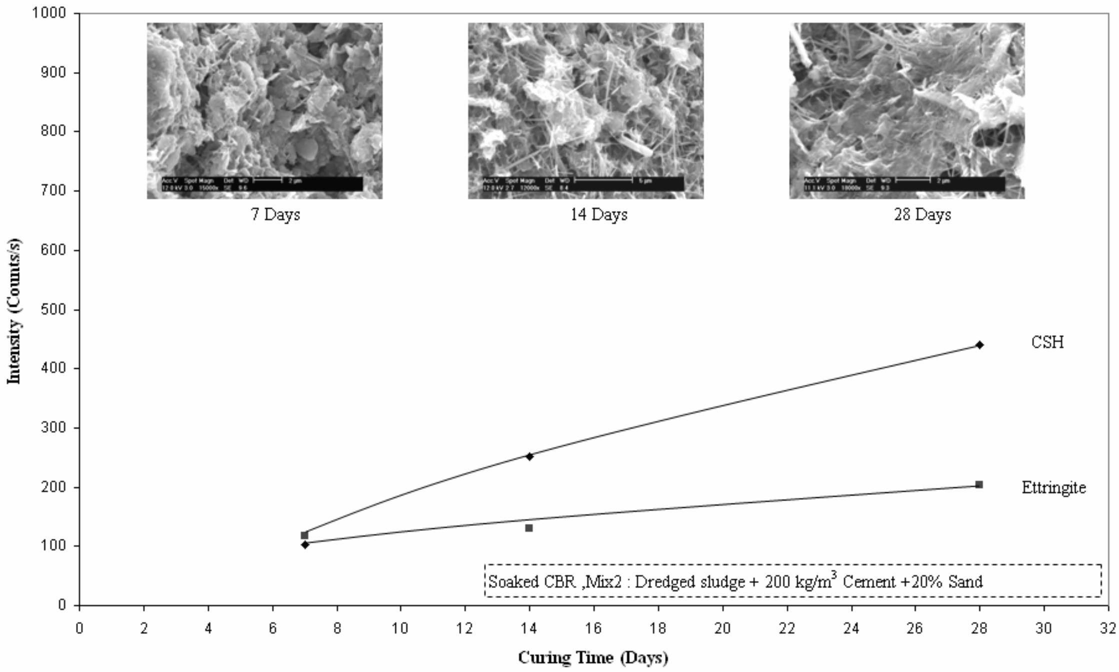


Figure 91 Relationship between XRD and SEM of soaked CBR (Mix2)

CONCLUSIONS

This study has presented research on the stabilization of dredged sludge using cement as stabilizer. Research goal has also been focused on utilization of the improved dredged sludge as pavement materials for road. The main results of this study are summarized below.

1. Technical concept of improvement using combination techniques of physical modification via simple preloading and chemical stabilization via cement mixing method has been proposed. It seems to be applicable especially for materials having extremely high moisture content such as dredged sludge.

2. Using relatively low pressure (0.05 – 0.30 kg/cm^2), surplus water is squeezed out of the dredged sludge. It is found that the most suitable ranges of water content are 140 – 180 % prior to chemical stabilization. The dewatering process can be easily accomplished within 12 – 18 hours. Another successful approach is to partially mix dredged sludge with some amount of fine sand (approximately 20 – 40 % by dry weight). Strength can be improved 10 – 30 % when compared with dredged sludge having no sand replacement.

3. Based on preliminary test on stabilization of the dredged sludge with various cement contents and initial water content, it is found that the ratio of water content after mixing and percentage of weight of cement to dry weight of soil (C_w/A_w) within the range of 2.75 – 3.02 provides homogeneous mixtures with good workability. Unconfined compressive strength (UCS) of the cement-stabilized dredge sludge as a function of C_w/A_w at a curing time of 7 days can be estimated using the following equation.

$$UCS_{7\ days} = 1.88(C_w/A_w)^2 - 16.40(C_w/A_w) + 39.39$$

2. For cement mixing of the pre-treated dredged materials at the pre-determined initial water content of 160 % and 200 kg/m^3 cement, both unsoaked and soaked strengths are markedly improved. Strength increased with curing time. Experimental results showed that gain in strength was more pronounced in the early stage (before 14 days) while, less pronounced at longer curing time.

For dredged sludge mixing with 200 kg/m^3 cement, slight reduction on strength and CBR due to soaking condition, approximately 8 -10 %, could be observed. This illustrates that the stabilized materials have relatively good durability.

For a successful mix proportion, a 7-days soaked strength of 7.94 ksc and a 14-days soaked CBR of 30.86 % are obtained. The improved properties meet technical requirement as recommended by the Department of Highways, Thailand and therefore show potential for use as subbase materials for road.

5. As investigated by XRD analysis, strength development characteristics are identical to characteristic curves plotting between hydration products and curing time. It is found that strength is directly proportional to amounts of the major hydration products such CSH and Ettringite.

6. Based on the Scanning Electron Microscope (SEM) observations, changes on microstructures of the stabilized soils seemed to be agreeable with results obtained from strength and CBR tests. Reaction products such as calcium silicate hydrate (CSH) and Ettringite are richly produced. Formation of such reaction products results in hardening effect of soil structures. Ettringite plays important role in stabilizing soil having high moisture content since growth of their crystals reduce pore spaces between soil particles, contributing to higher strength.

7. Improved strength due to addition of certain amount of fine sand can be attributed to the following reasons. Fine sand particles significantly improve grain size distribution curve of the dredged sludge and thus increase initial dry density. In addition, the optimum amount of sand fraction provides suitable ratio of C_w/A_w, which results in relatively higher strength. It is believed that soil structures are also improved as clearly shown by SEM micrographs.

RECOMMENDATION

Recommendation for further research can be summarized as follows.

1. This research has illustrated applicability of dredged sludge obtained from maintained harbors and navigational channels based on the geotechnical engineering viewpoint. However, other applications and their properties in relation to other environmental concerns have to be clarified for its intensive uses in the future.

2. This research was a study on chemical and mechanical stabilization of soil in laboratory. However, since dredged sludge from different sites may have variations in its properties variations between laboratory test and field construction should be considered.

3. Similar experiments should be performed for other moderately appropriate sand admixtures such as coarse sand, medium sand, etc. to elucidate their use as construction material for pavement materials.

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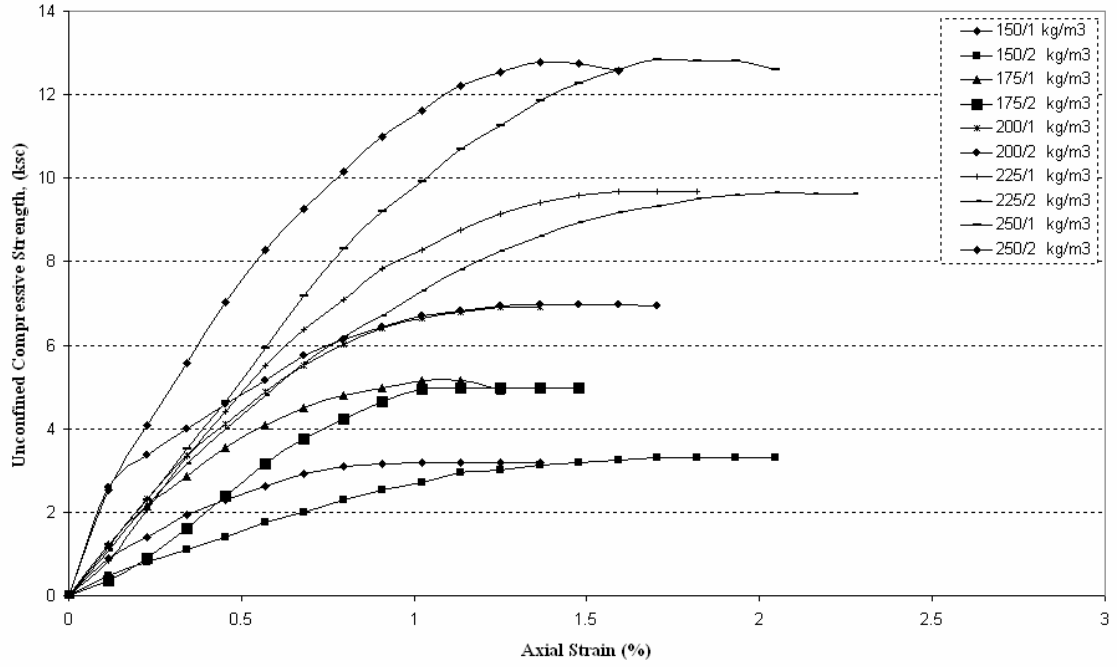
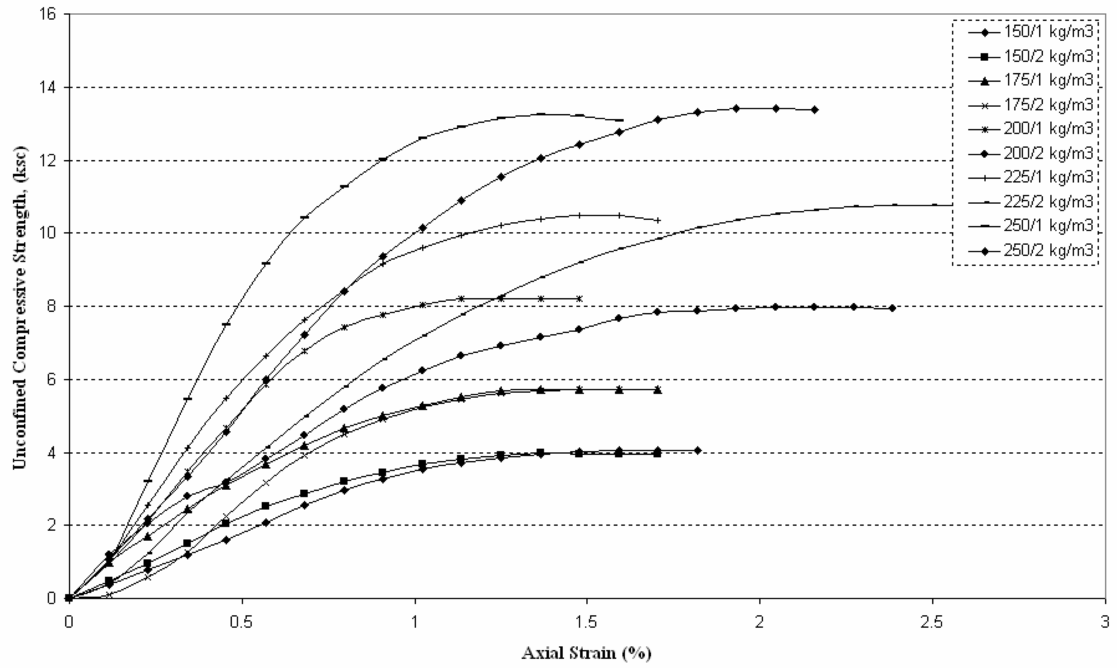
APPENDIX

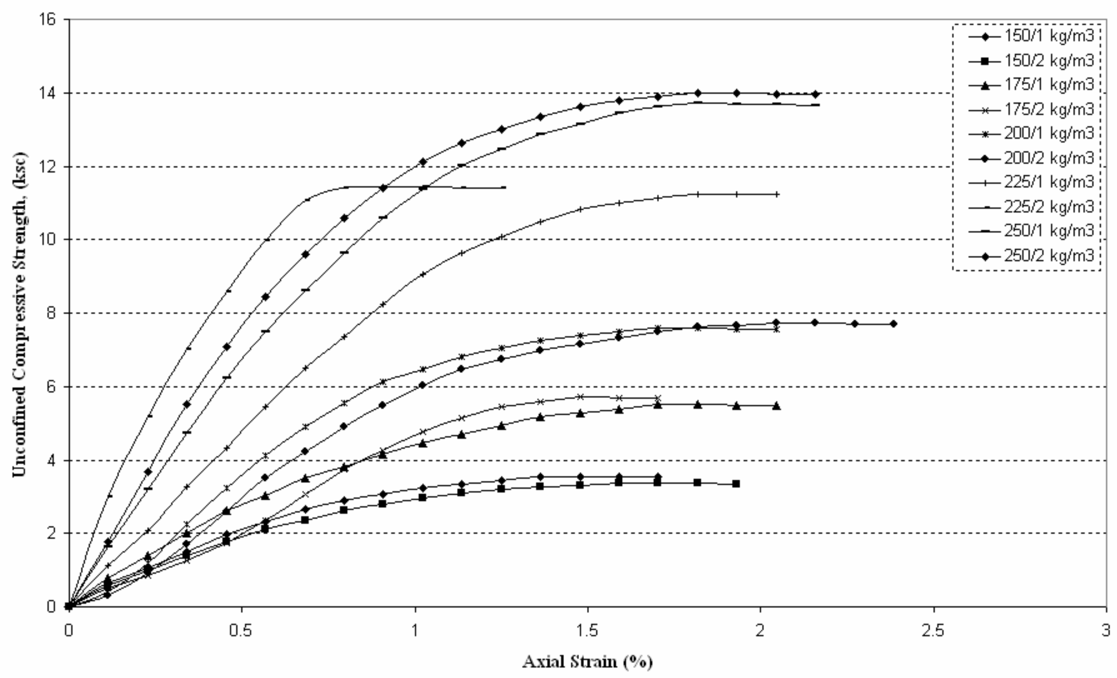
APPENDIX A



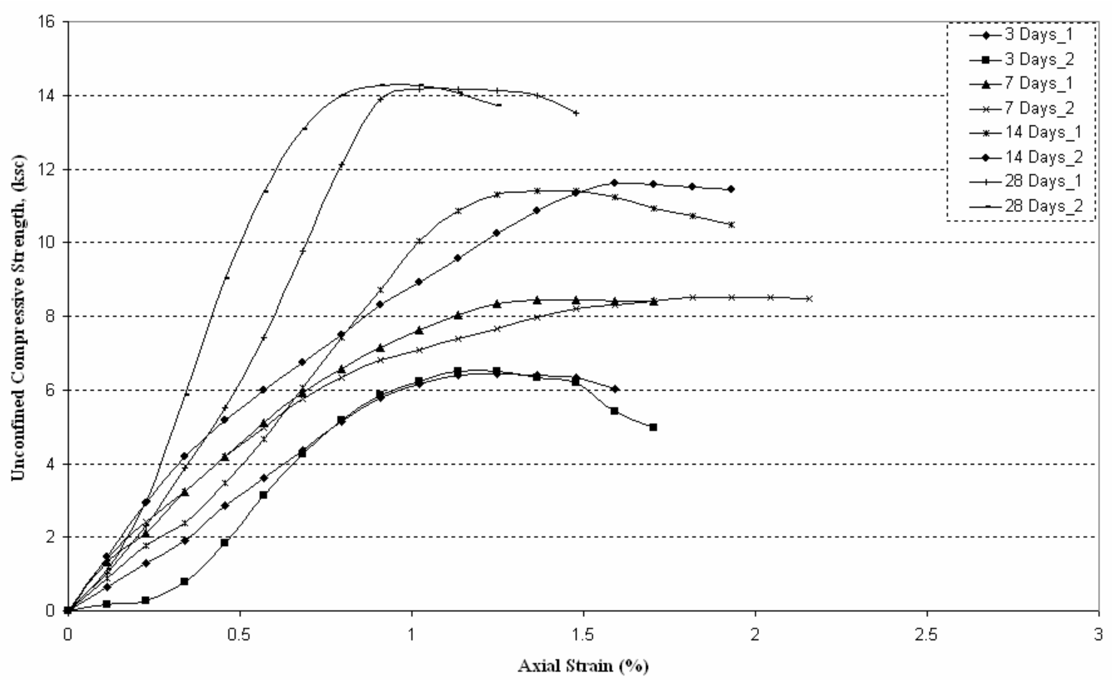
Appendix Figure A1 Stress – Strain Characteristics of cement content at 140% water content



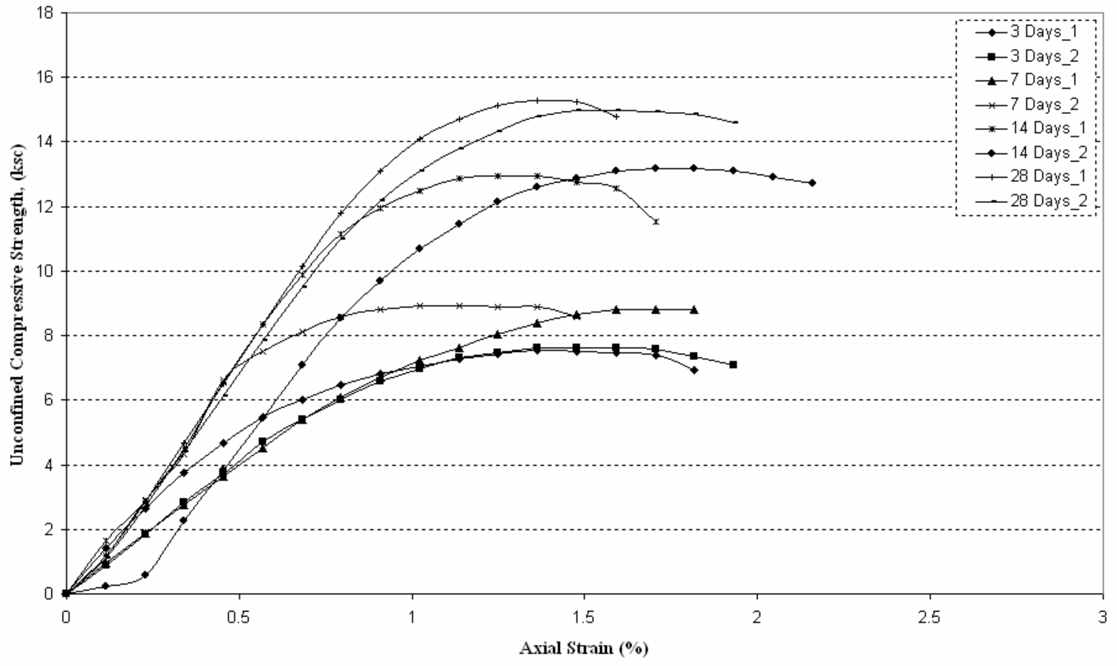
Appendix Figure A2 Stress – Strain Characteristics of cement content at 160% water content



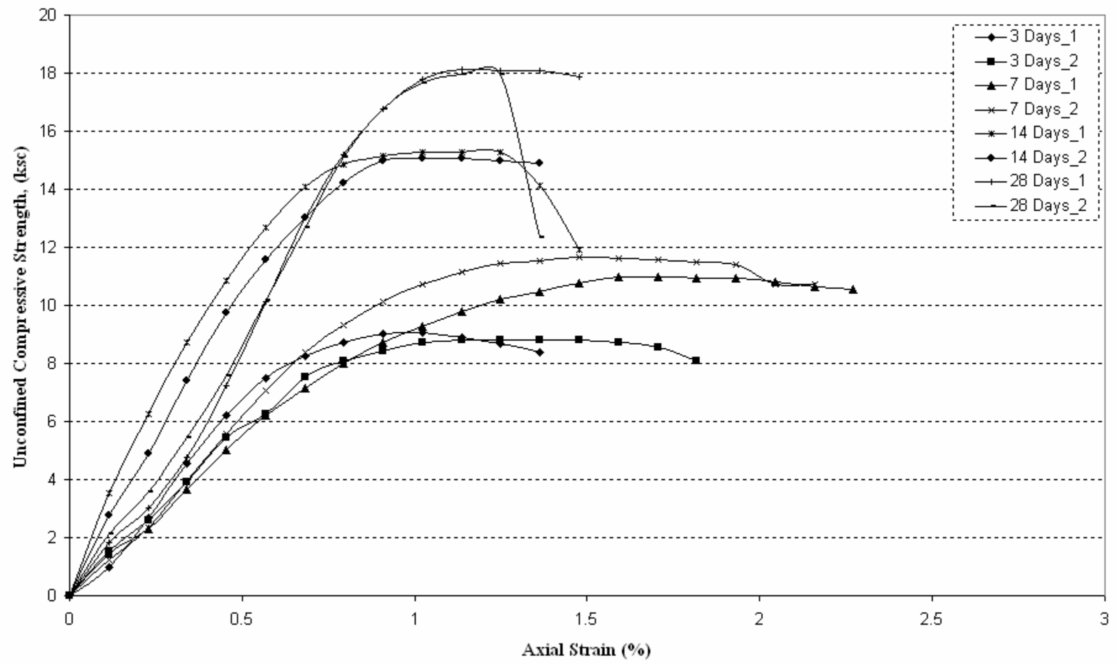
Appendix Figure A3 Stress – Strain Characteristics of cement content at 180% water content



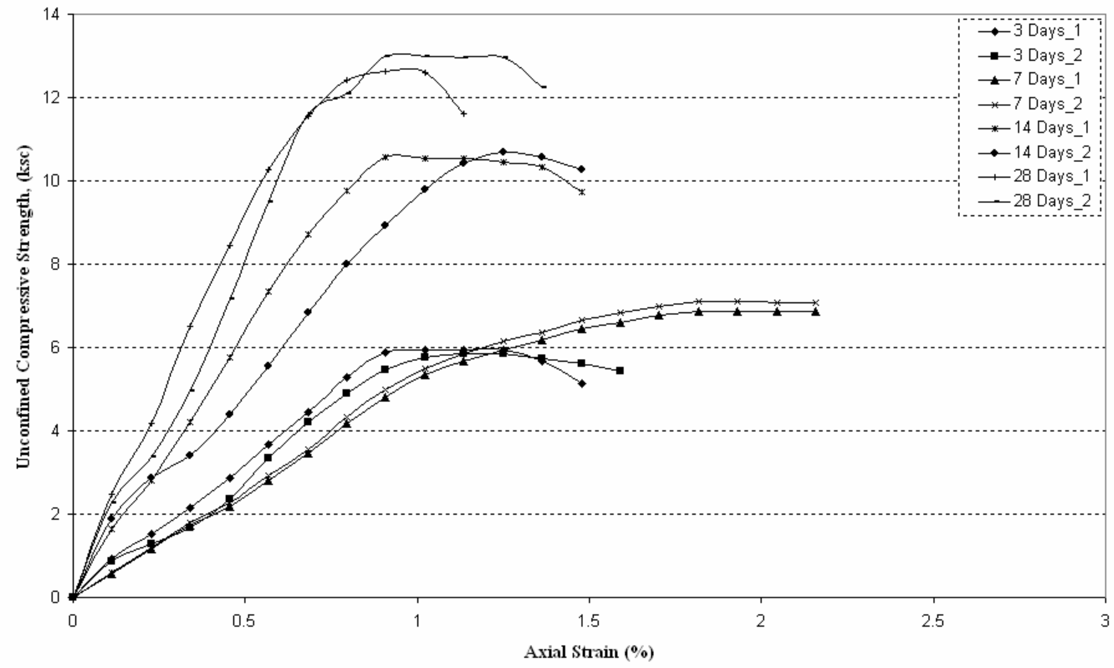
Appendix Figure A4 Stress – Strain Characteristics of unsoaked Mix 1



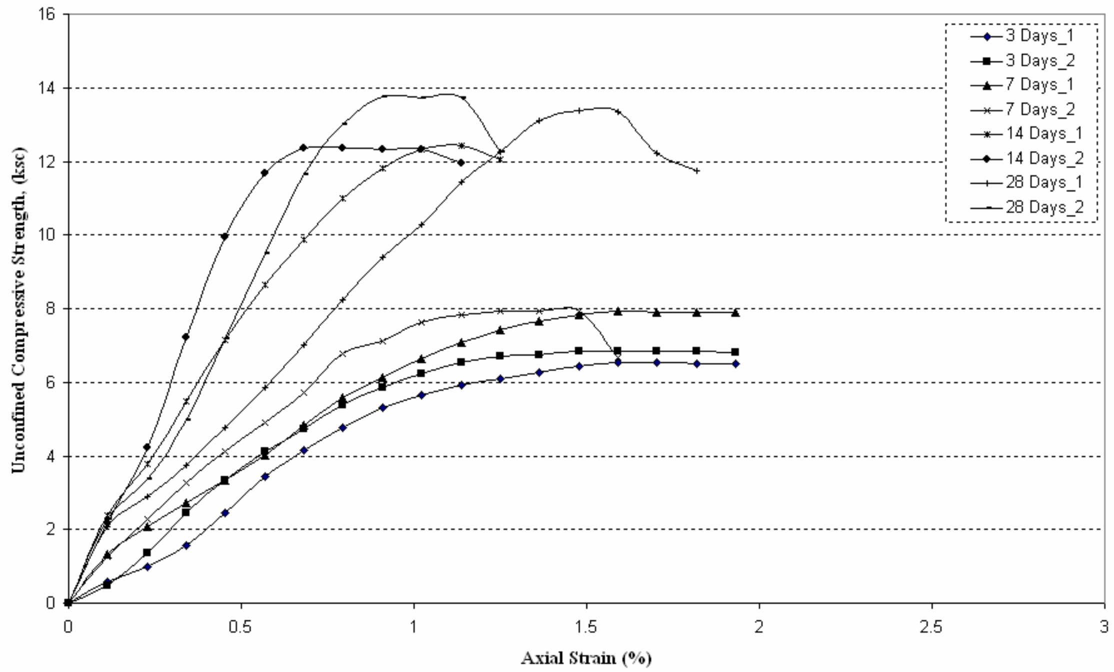
Appendix Figure A5 Stress – Strain Characteristics of unsoaked Mix 2



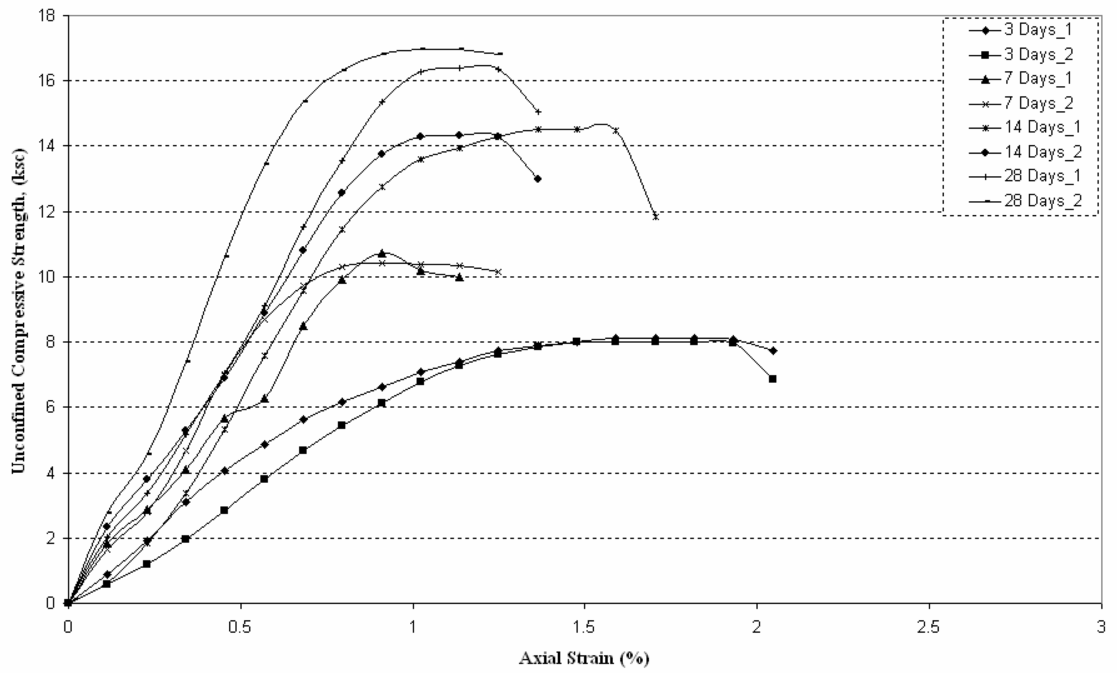
Appendix Figure A6 Stress – Strain Characteristics of unsoaked Mix 3



Appendix Figure A7 Stress – Strain Characteristics of soaked Mix 1

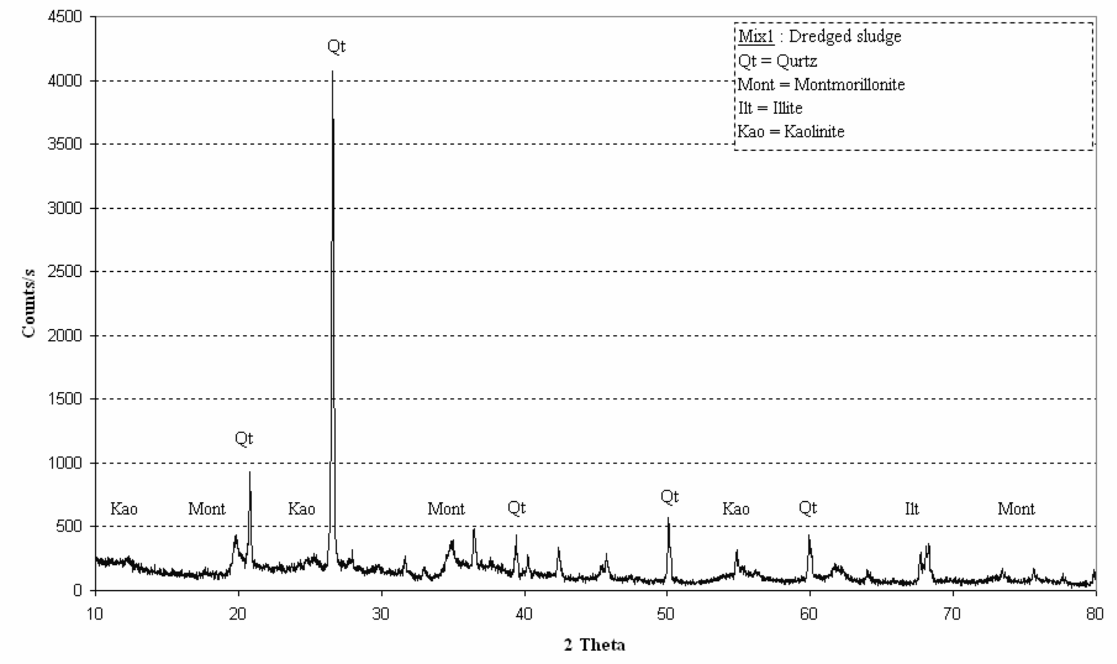


Appendix Figure A8 Stress – Strain Characteristics of soaked Mix 2

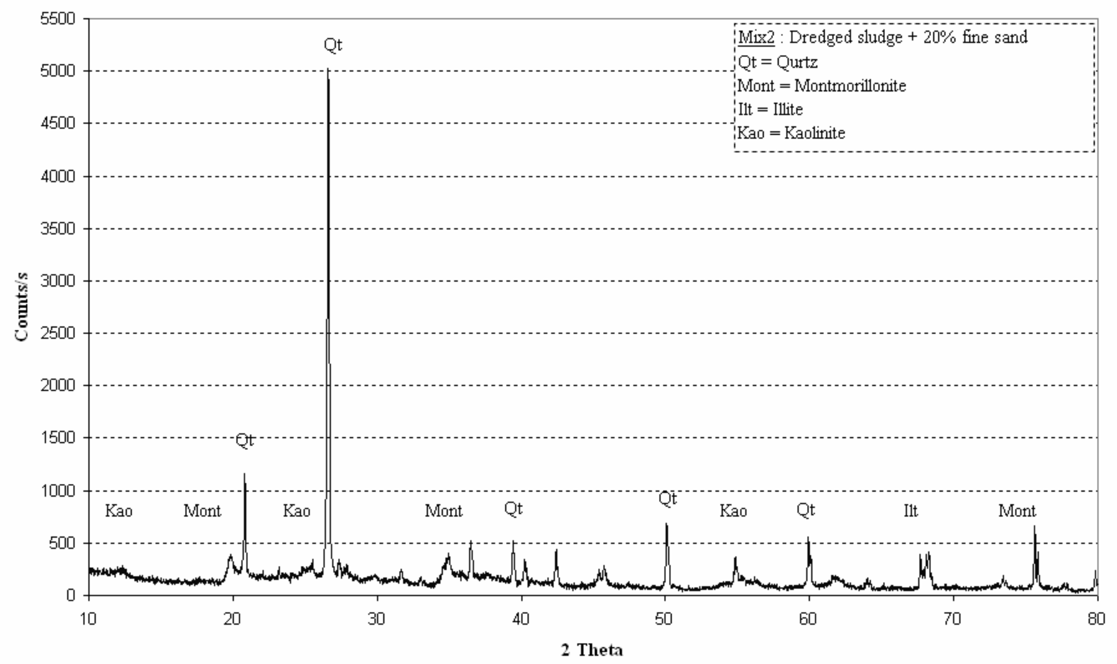


Appendix Figure A9 Stress – Strain Characteristics of soaked Mix 3

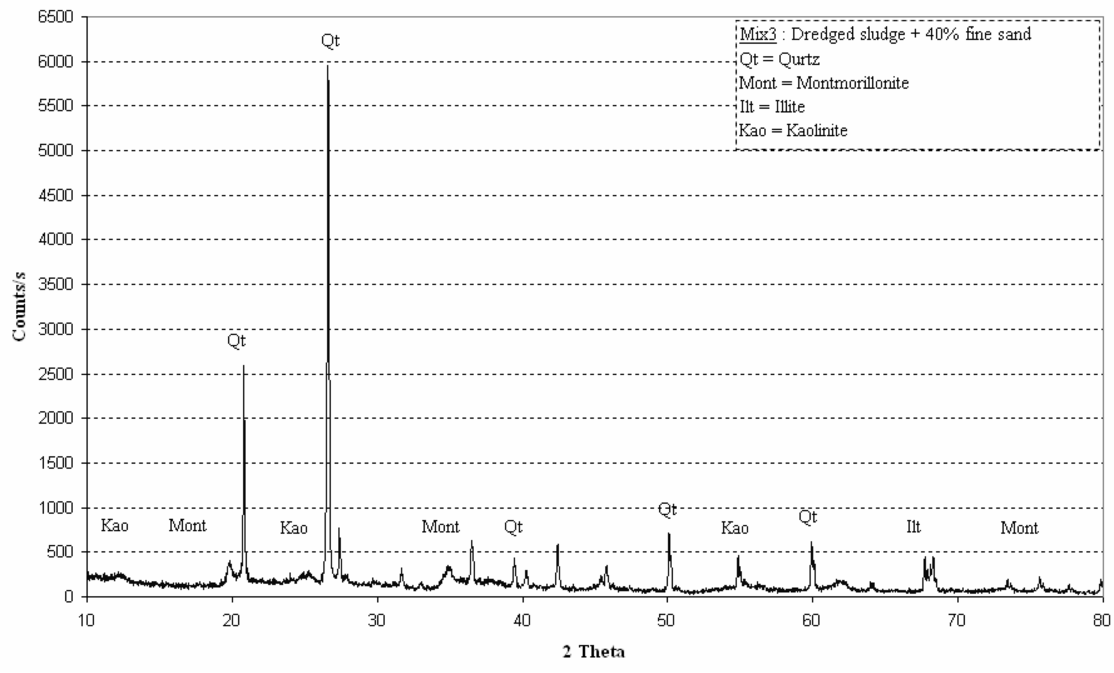
APPENDIX B



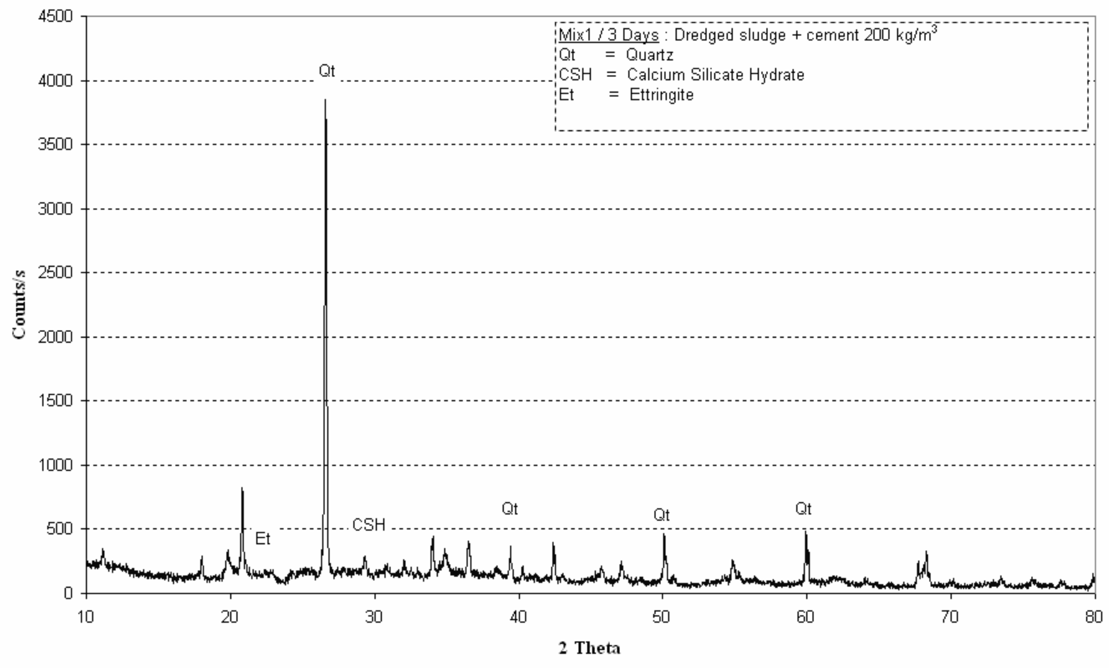
Appendix Figure B1 X-ray diffraction patterns of untreated Mix 1



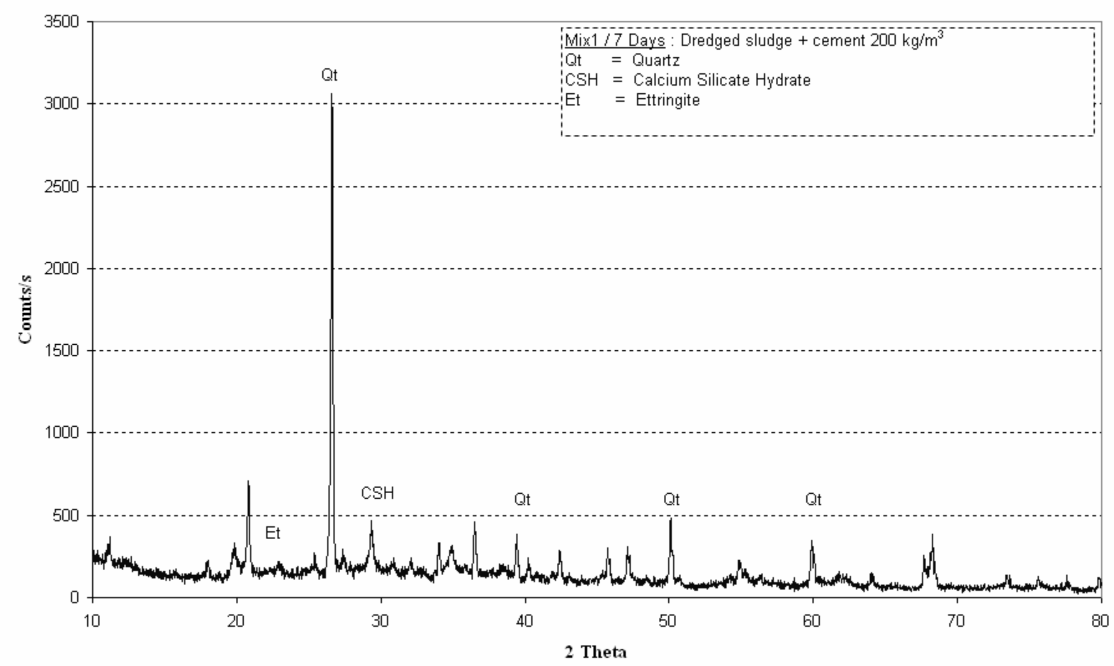
Appendix Figure B2 X-ray diffraction patterns of untreated Mix 2



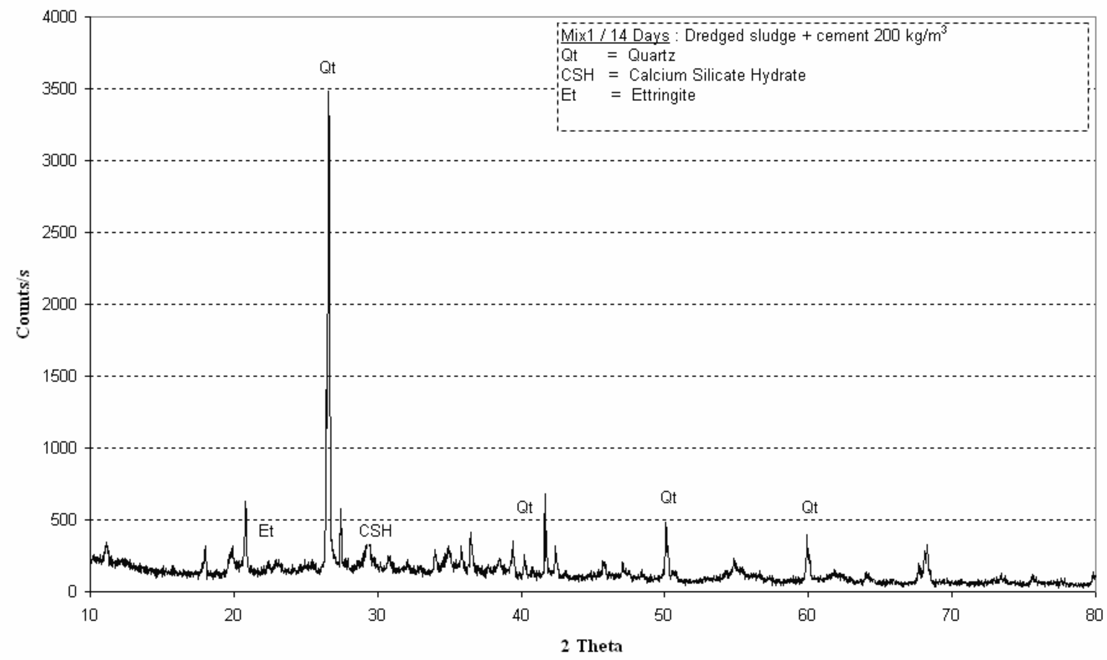
Appendix Figure B3 X-ray diffraction patterns of untreated Mix 3



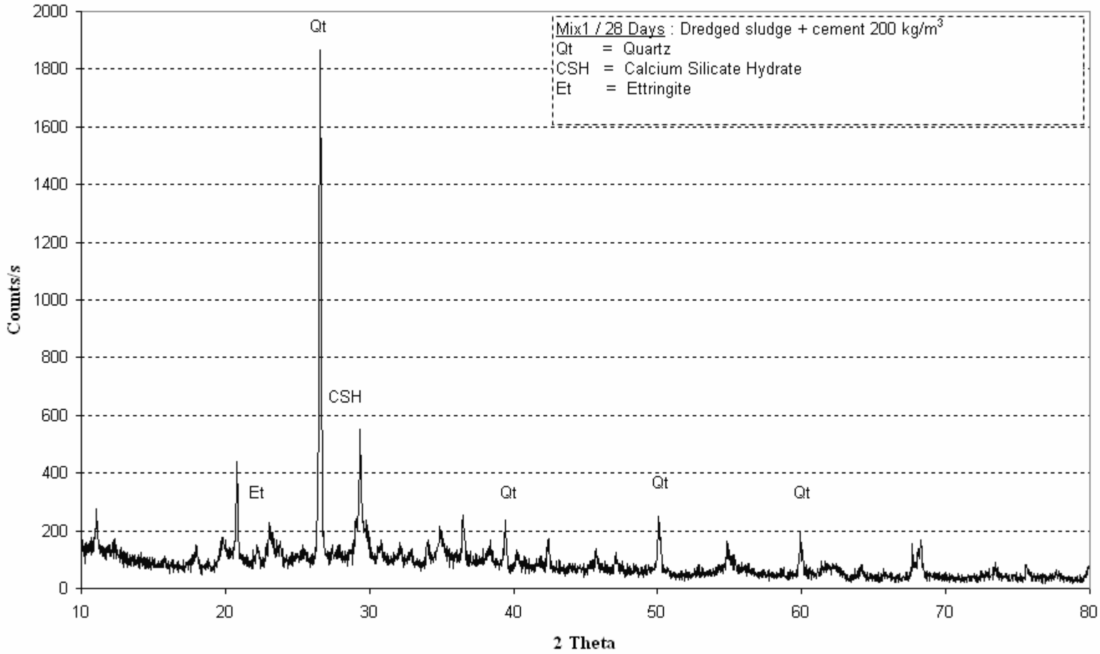
Appendix Figure B4 X-ray diffraction patterns of unsoaked unconfined compressive strength Mix 1 at 3 days curing time



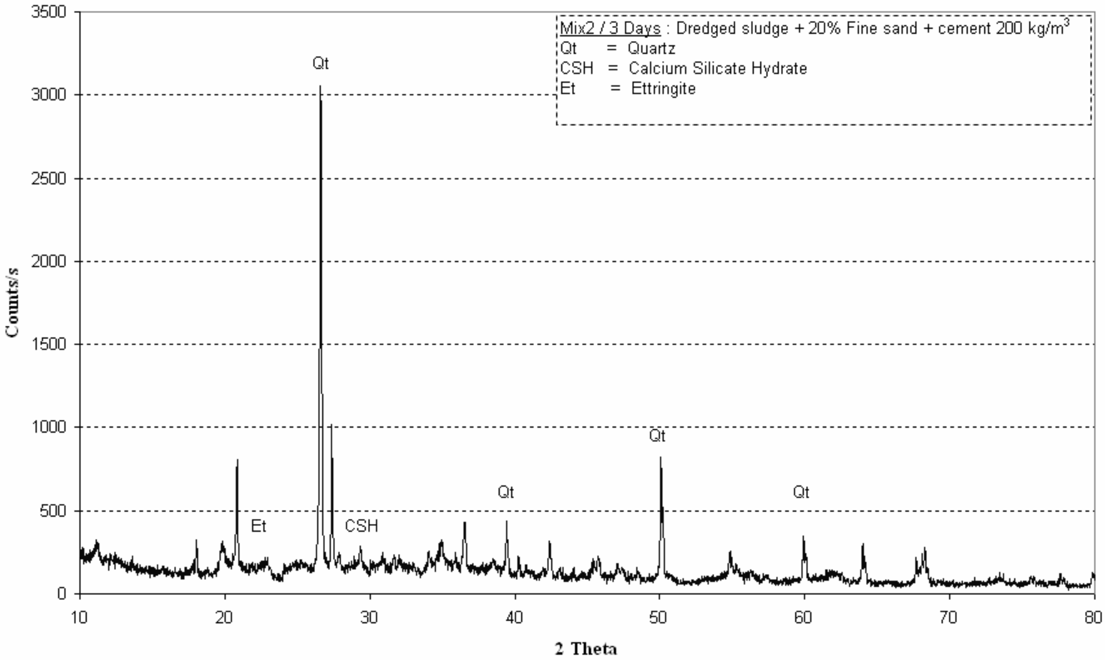
Appendix Figure B5 X-ray diffraction patterns of unsoaked unconfined compressive strength Mix 1 at 7 days curing time



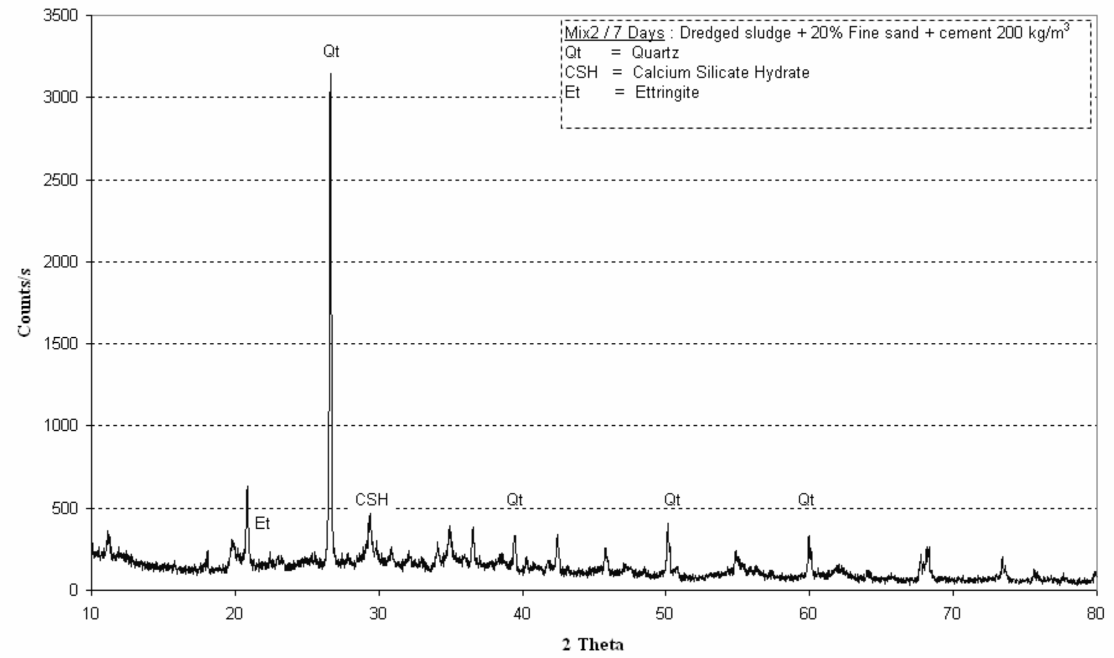
Appendix Figure B6 X-ray diffraction patterns of unsoaked unconfined compressive strength Mix 1 at 14 days curing time



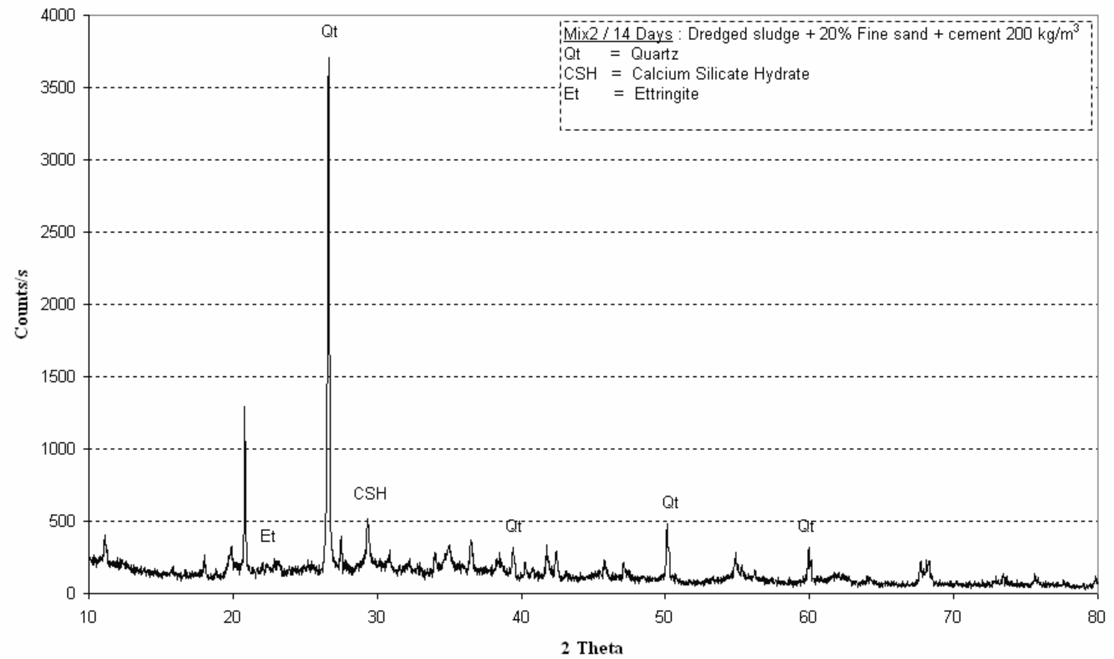
Appendix Figure B7 X-ray diffraction patterns of unsoaked unconfined compressive strength Mix 1 at 28 days curing time



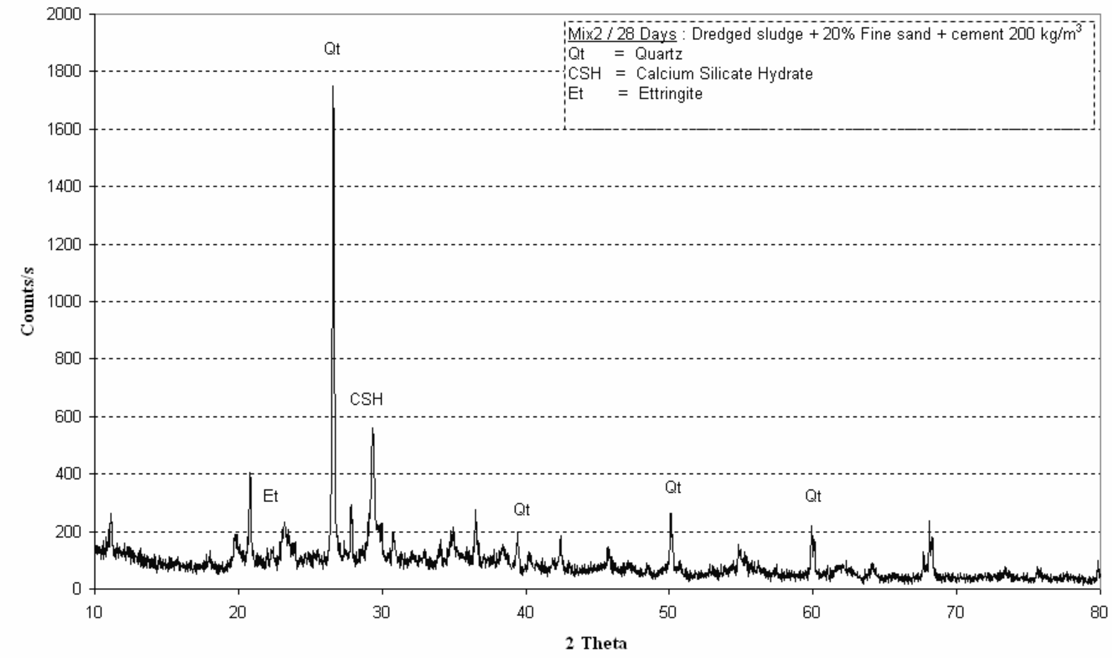
Appendix Figure B8 X-ray diffraction patterns of unsoaked unconfined compressive strength Mix 2 at 3 days curing time



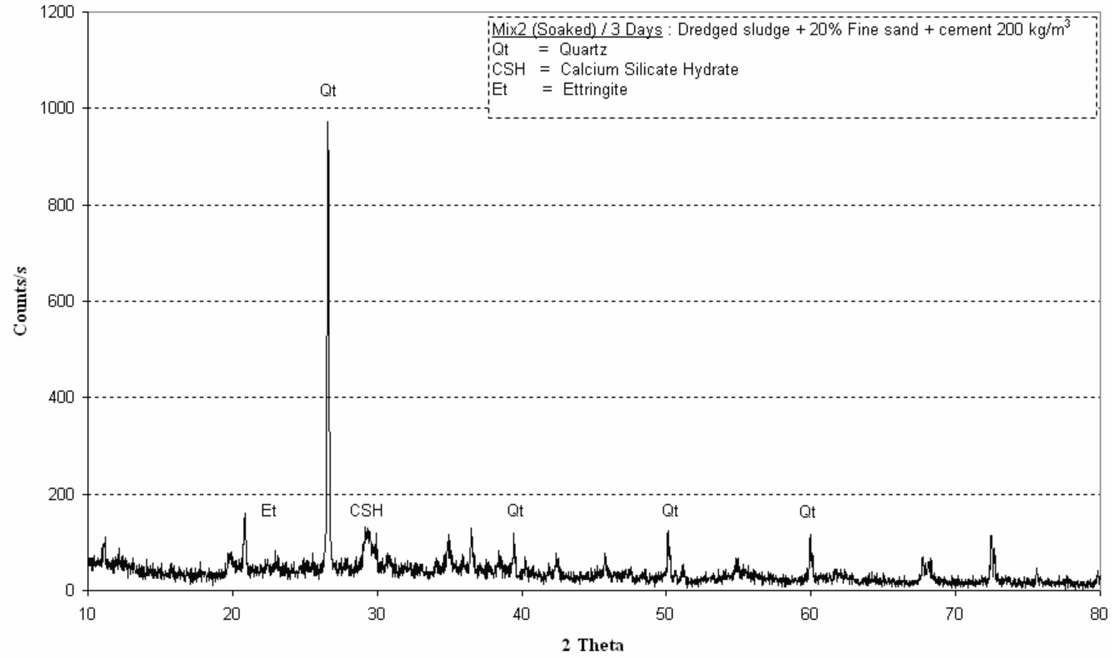
Appendix Figure B9 X-ray diffraction patterns of unsoaked unconfined compressive strength Mix 2 at 7 days curing time



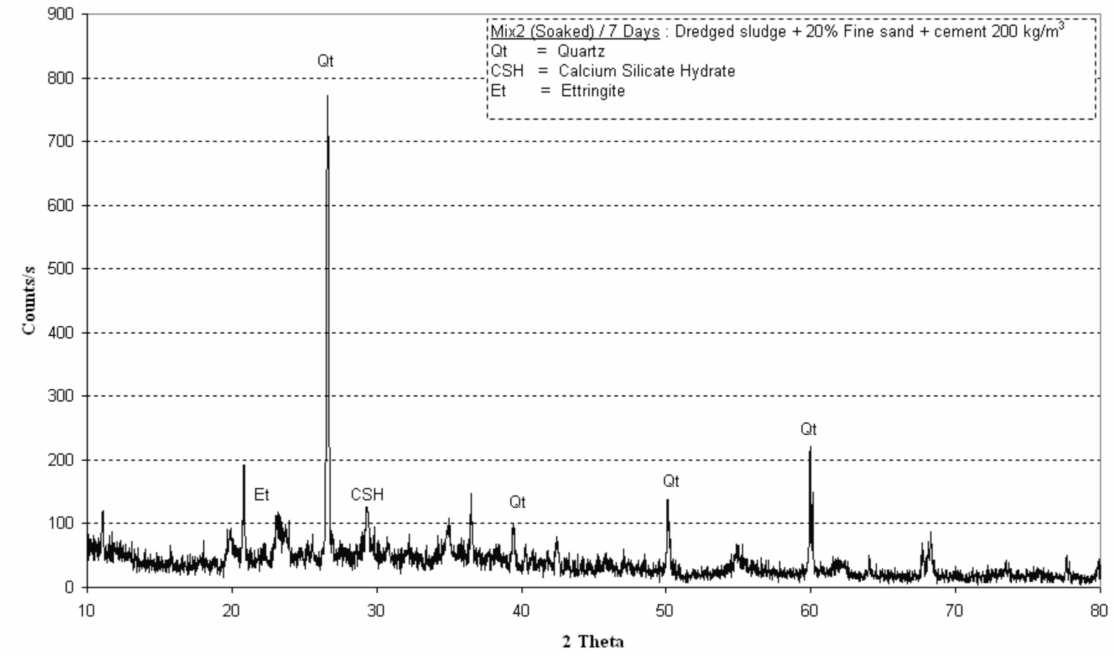
Appendix Figure B10 X-ray diffraction patterns of unsoaked unconfined compressive strength Mix 2 at 14 days curing time



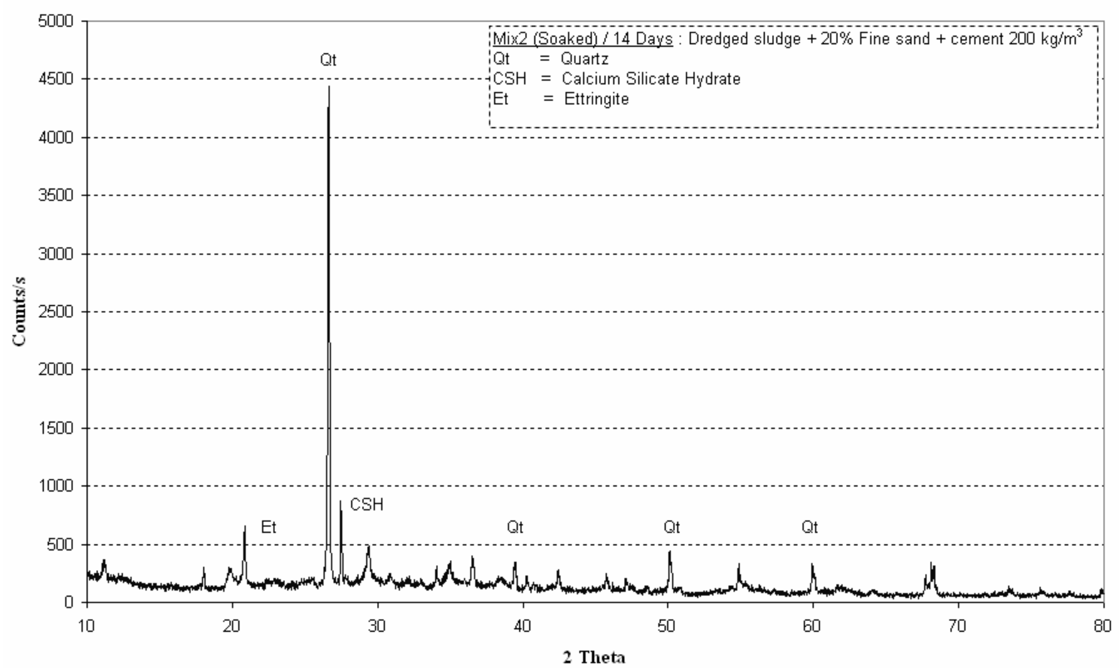
Appendix Figure B11 X-ray diffraction patterns of unsoaked unconfined compressive strength Mix 2 at 28 days curing time



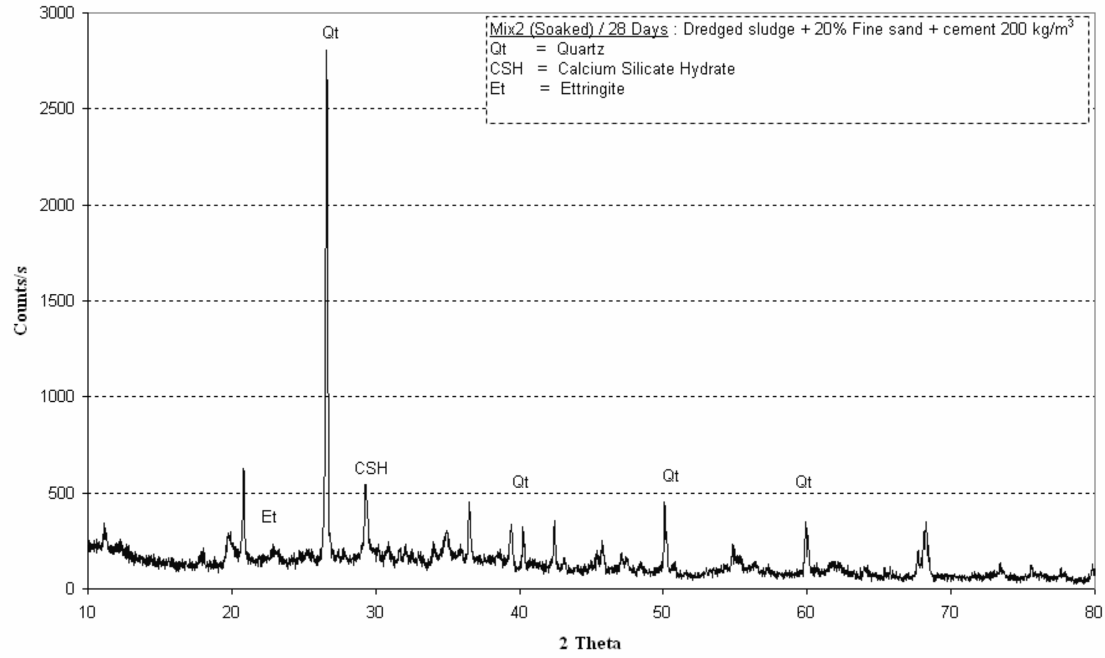
Appendix Figure B12 X-ray diffraction patterns of soaked unconfined compressive strength Mix 2 at 3 days curing time



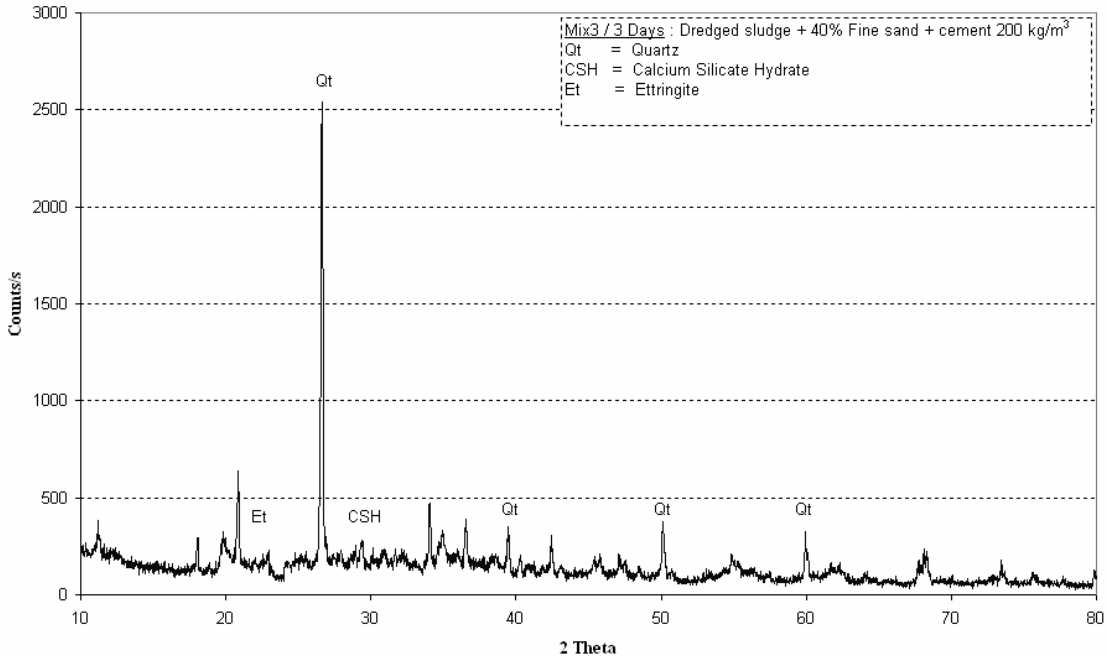
Appendix Figure B13 X-ray diffraction patterns of soaked unconfined compressive strength Mix 2 at 7 days curing time



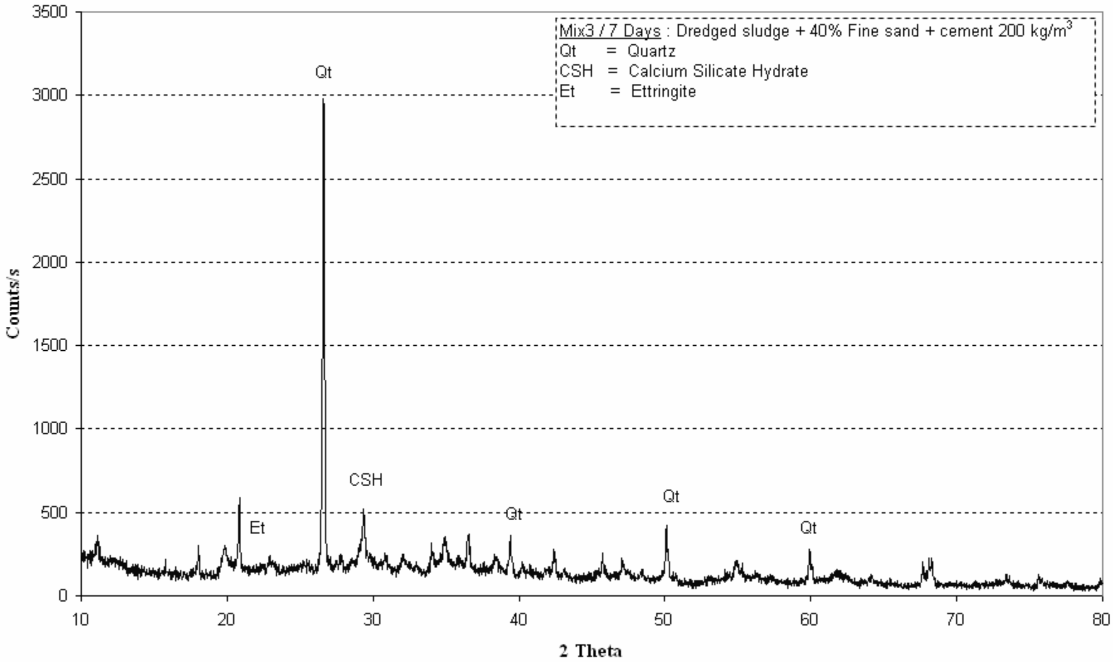
Appendix Figure B14 X-ray diffraction patterns of soaked unconfined compressive strength Mix 2 at 14 days curing time



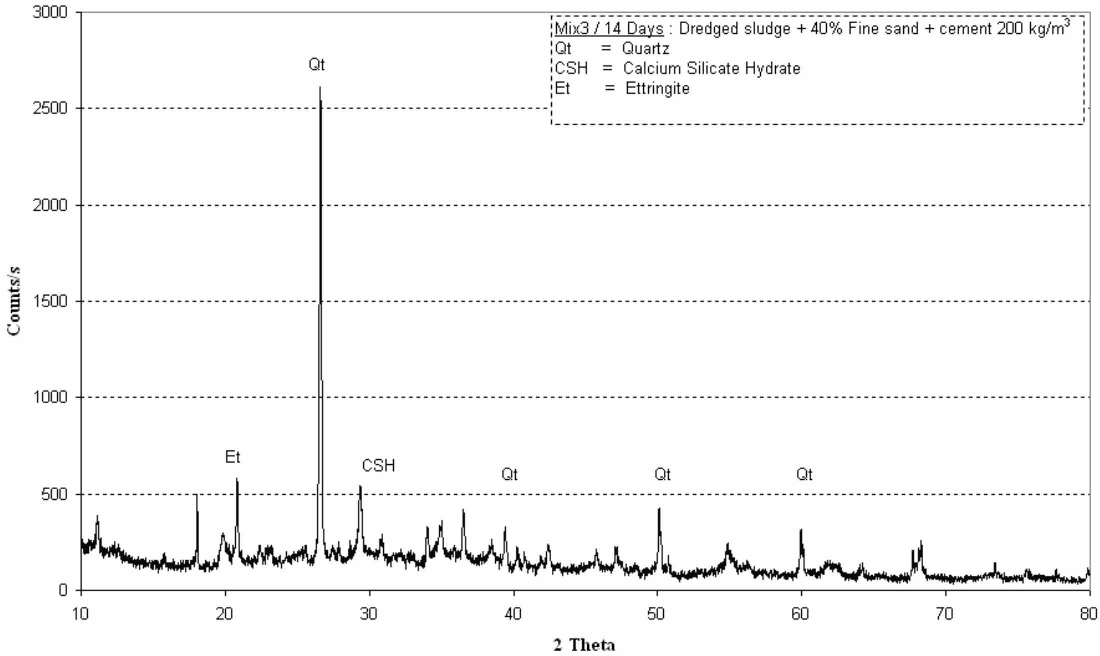
Appendix Figure B15 X-ray diffraction patterns of soaked unconfined compressive strength Mix 2 at 28 days curing time



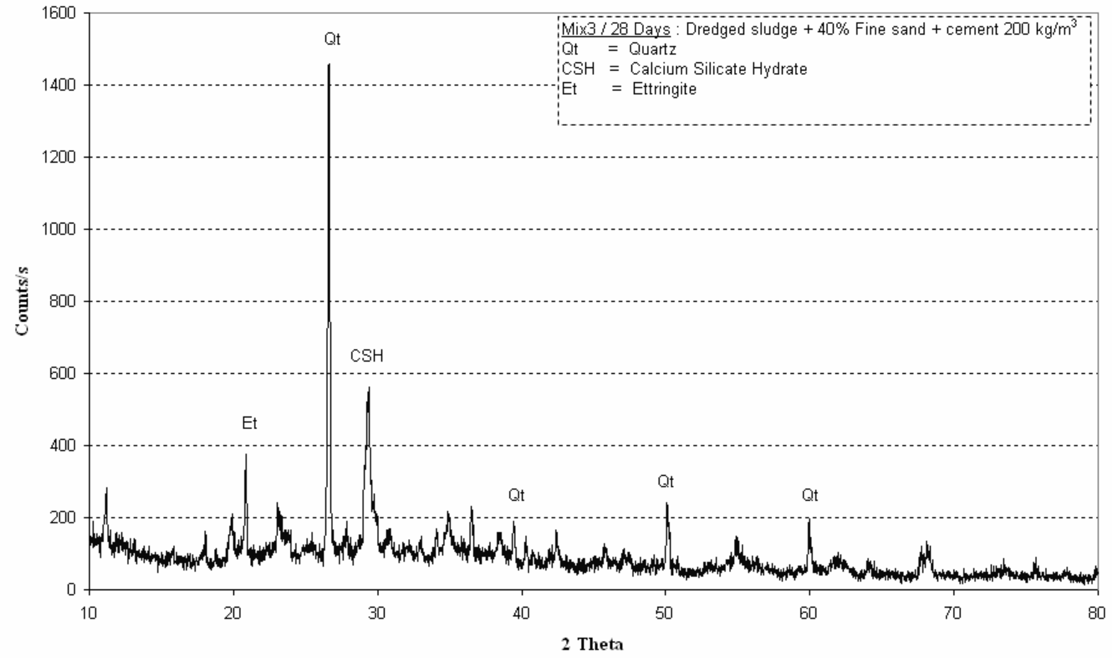
Appendix Figure B16 X-ray diffraction patterns of unsoaked unconfined compressive strength Mix 3 at 3 days curing time



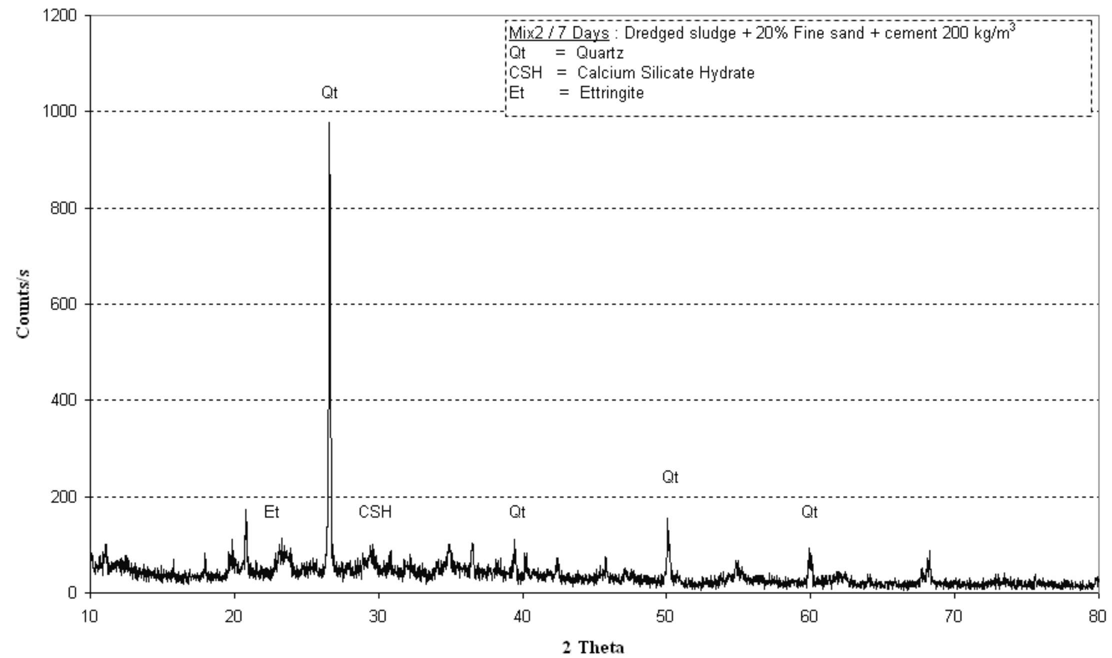
Appendix Figure B17 X-ray diffraction patterns of unsoaked unconfined compressive strength Mix 3 at 7 days curing time



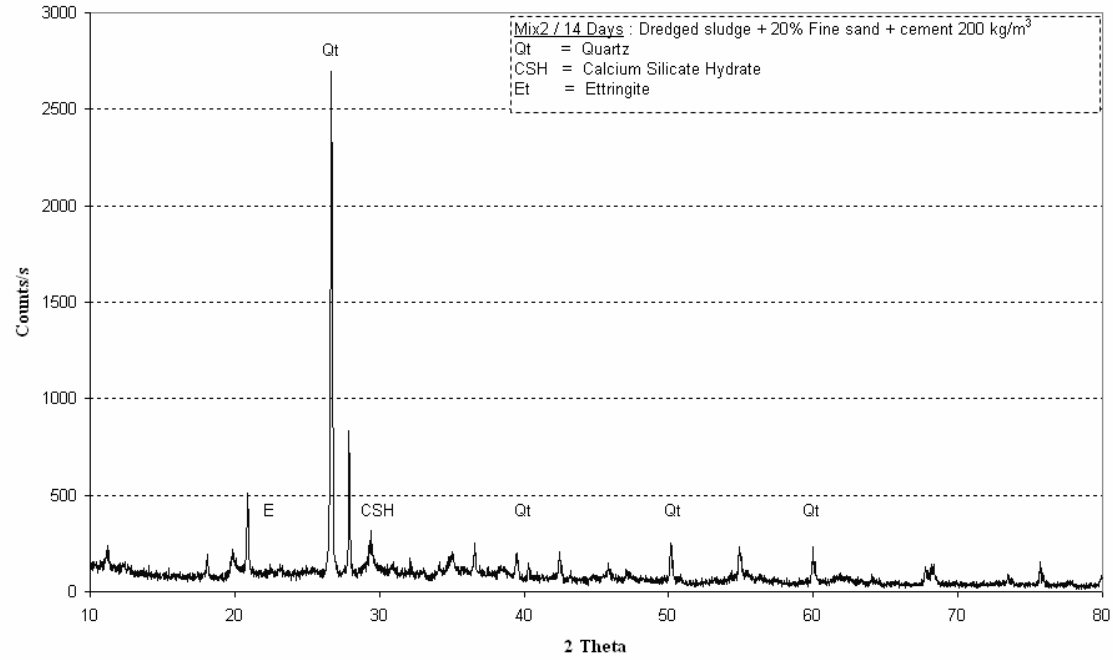
Appendix Figure B18 X-ray diffraction patterns of unsoaked unconfined compressive strength Mix 3 at 14 days curing time



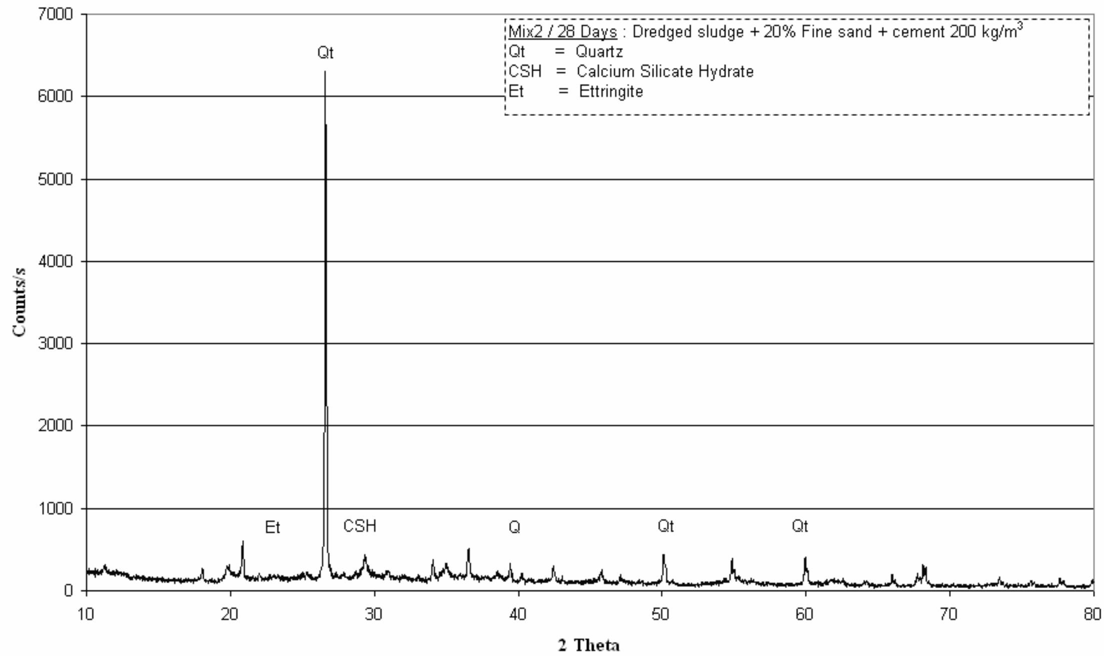
Appendix Figure B19 X-ray diffraction patterns of unsoaked unconfined compressive strength Mix 3 at 28 days curing time



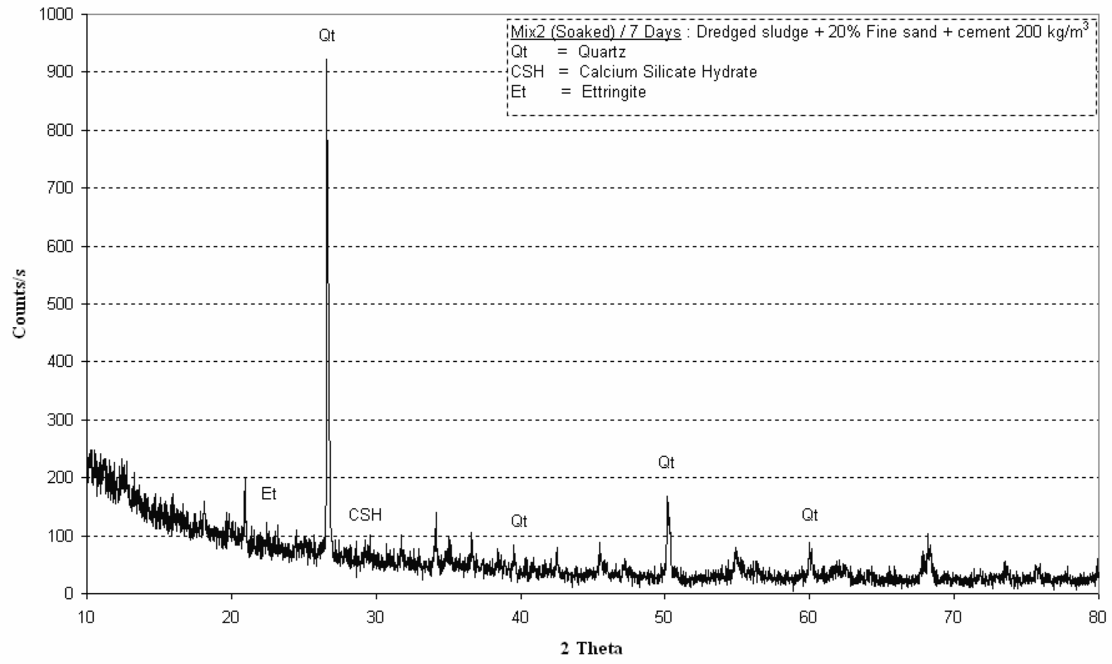
Appendix Figure B20 X-ray diffraction patterns of unsoaked CBR Mix 2 at 7 days curing time



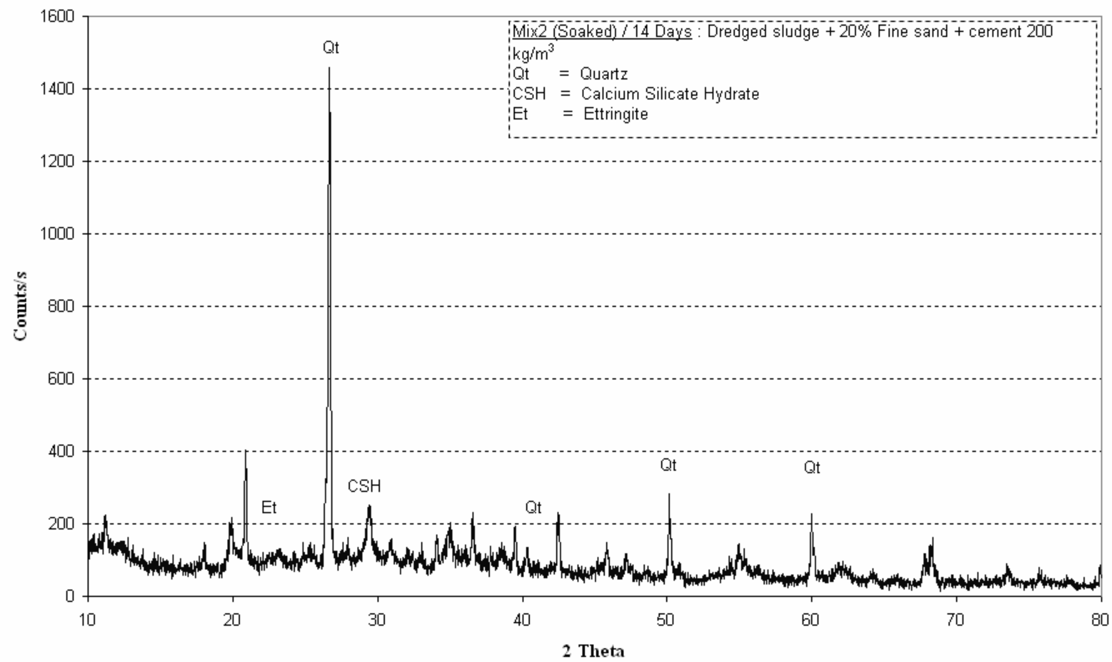
Appendix Figure B21 X-ray diffraction patterns of unsoaked CBR Mix 2 at 14 days curing time



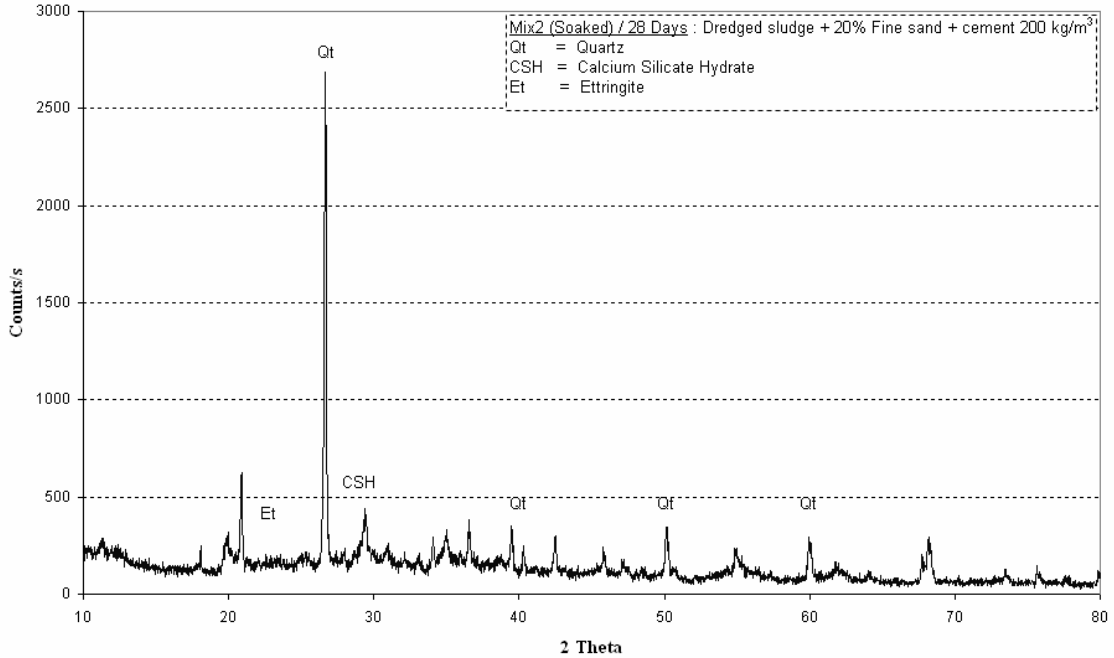
Appendix Figure B22 X-ray diffraction patterns of unsoaked CBR Mix 2 at 28 days curing time



Appendix Figure B23 X-ray diffraction patterns of soaked CBR Mix 2 at 7 days curing time

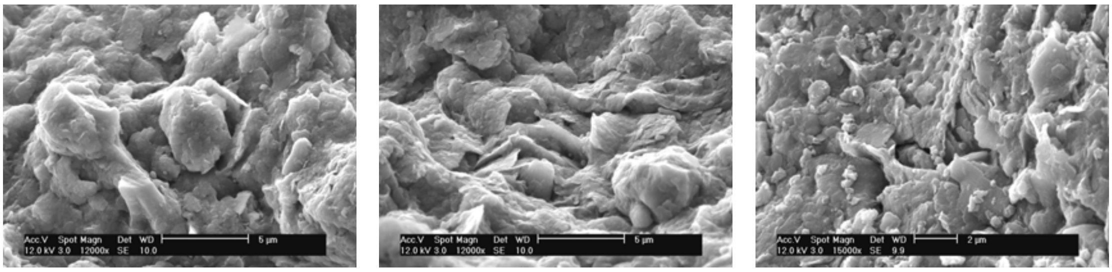


Appendix Figure B24 X-ray diffraction patterns of soaked CBR Mix 2 at 14 days curing time

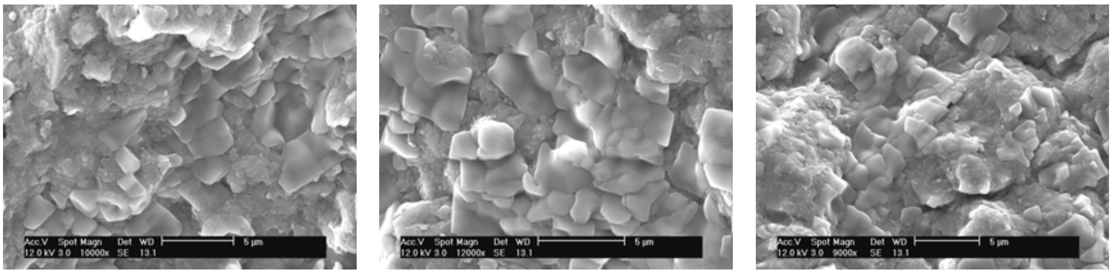


Appendix Figure B25 X-ray diffraction patterns of soaked CBR Mix 2 at 28 days curing time

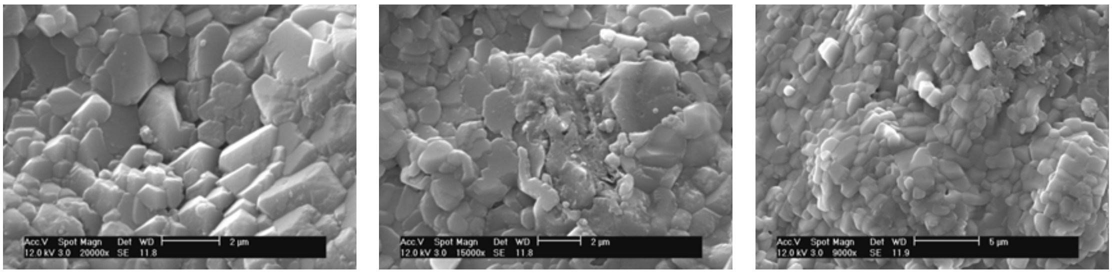
APPENDIX C



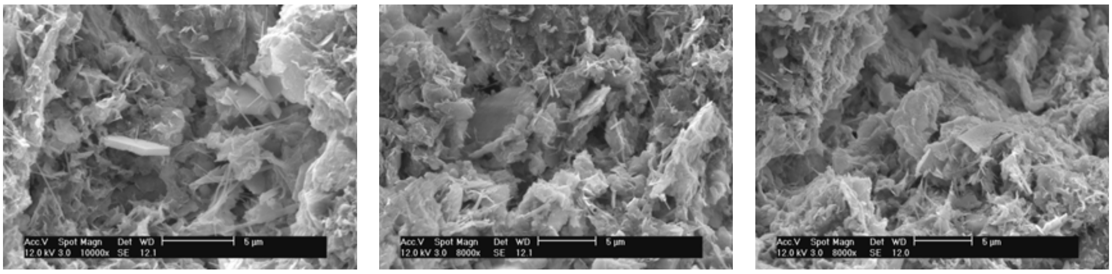
Appendix Figure C1 SEM micrographs of untreated Mix 1



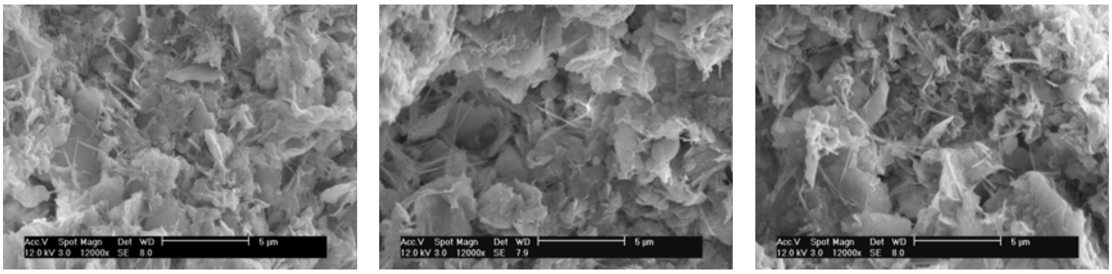
Appendix Figure C2 SEM micrographs of untreated Mix 2



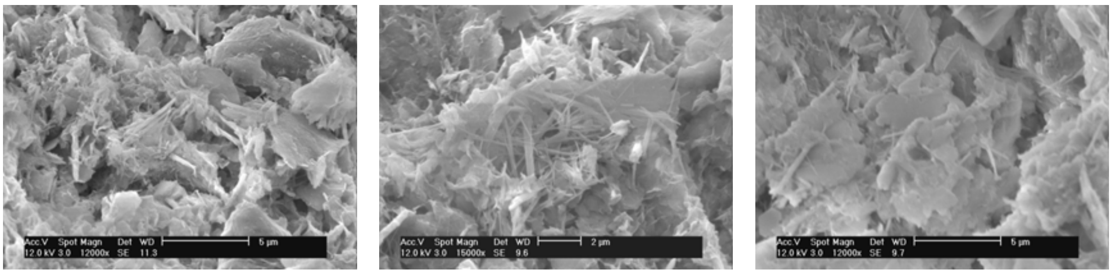
Appendix Figure C3 SEM micrographs of untreated Mix 3



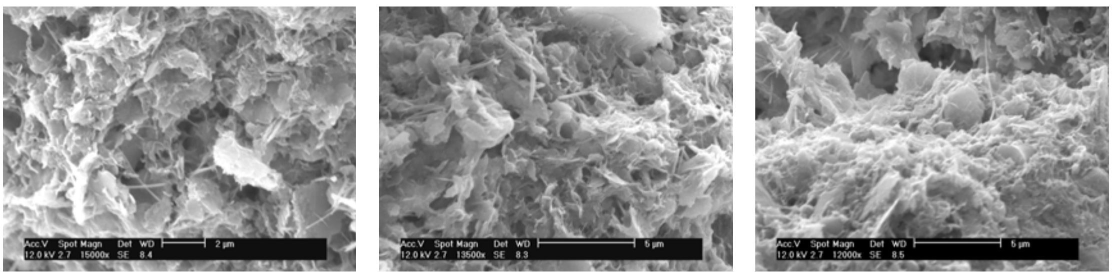
Appendix Figure C4 SEM micrographs of unsoaked unconfined compressive strength Mix 1 at 3 days curing time



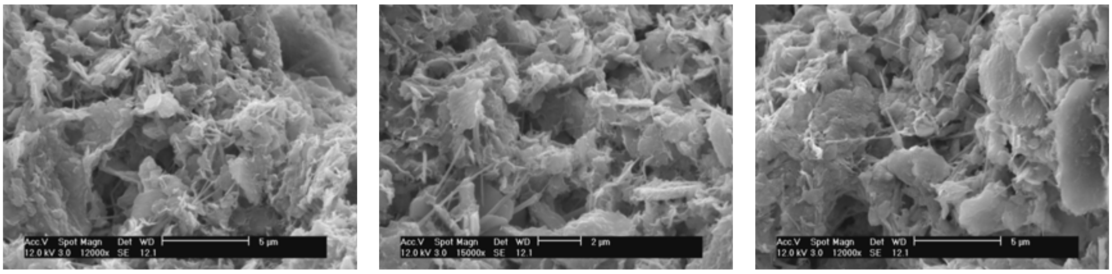
Appendix Figure C5 SEM micrographs of unsoaked unconfined compressive strength Mix 1 at 7 days curing time



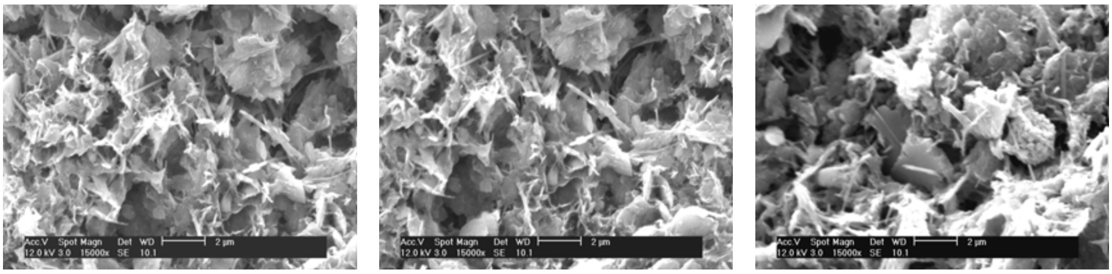
Appendix Figure C6 SEM micrographs of unsoaked unconfined compressive strength Mix 1 at 14 days curing time



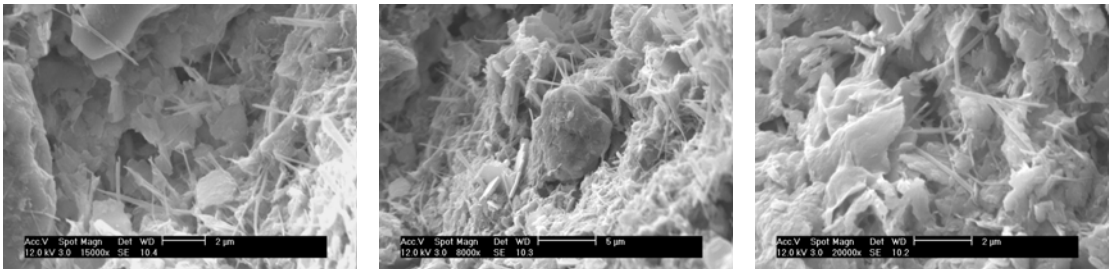
Appendix Figure C7 SEM micrographs of unsoaked unconfined compressive strength Mix 1 at 28 days curing time



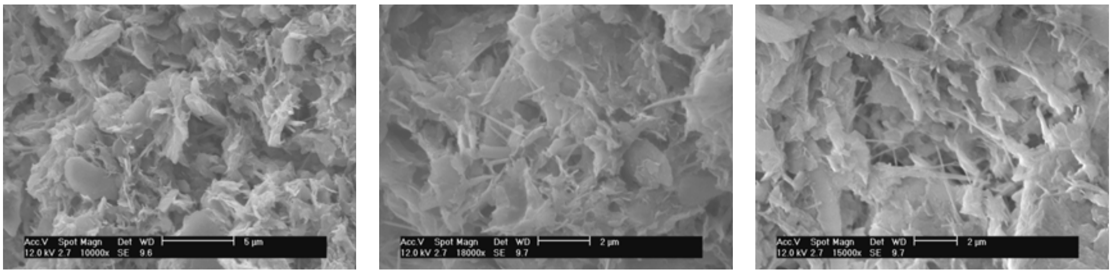
Appendix Figure C8 SEM micrographs of unsoaked unconfined compressive strength Mix 2 at 7 days curing time



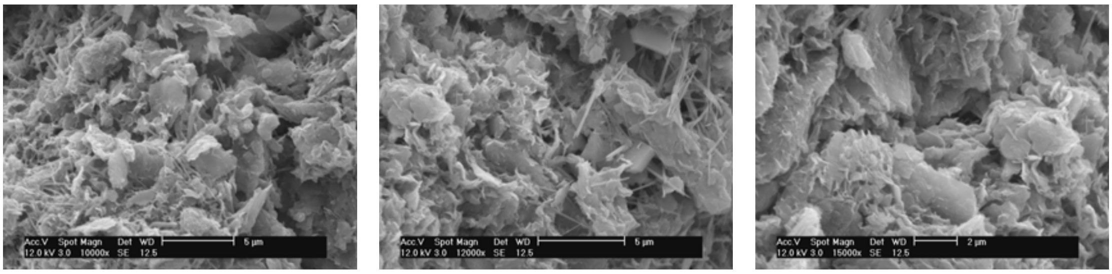
Appendix Figure C9 SEM micrographs of unsoaked unconfined compressive strength Mix 2 at 14 days curing time



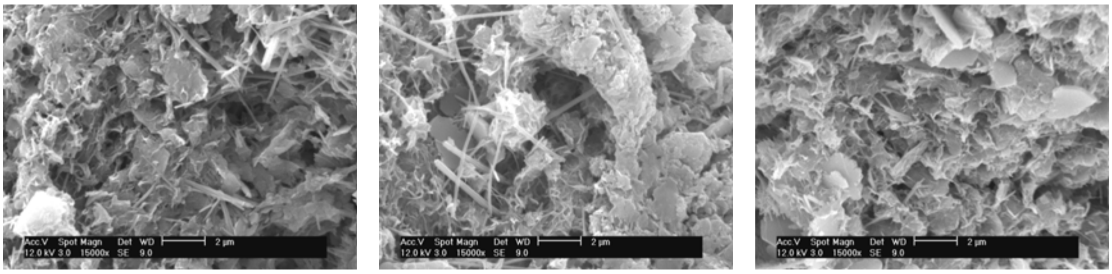
Appendix Figure C10 SEM micrographs of unsoaked unconfined compressive strength Mix 2 at 14 days curing time



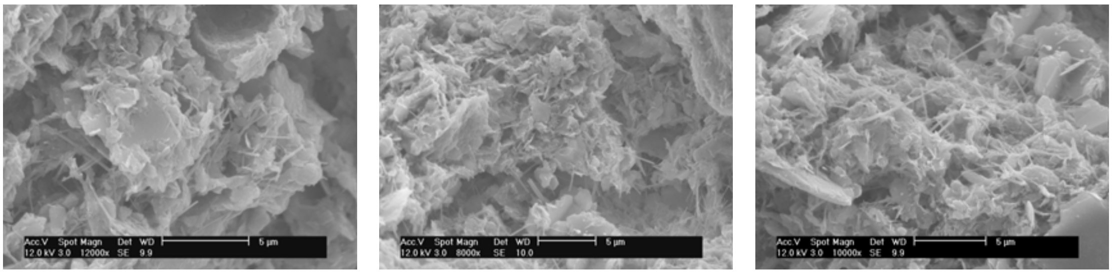
Appendix Figure C11 SEM micrographs of unsoaked unconfined compressive strength Mix 2 at 28 days curing time



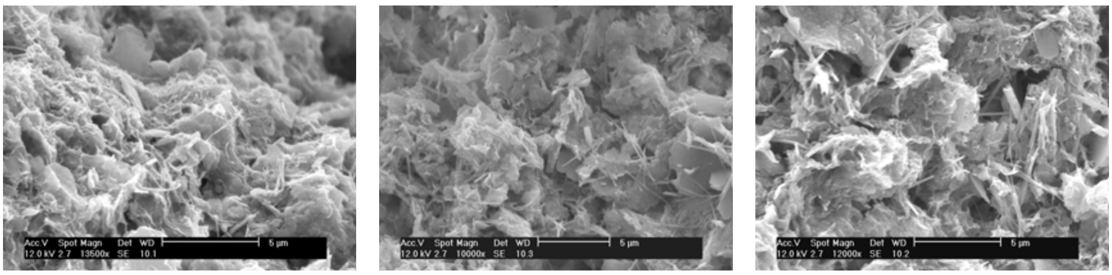
Appendix Figure C12 SEM micrographs of soaked unconfined compressive strength Mix 2 at 3 days curing time



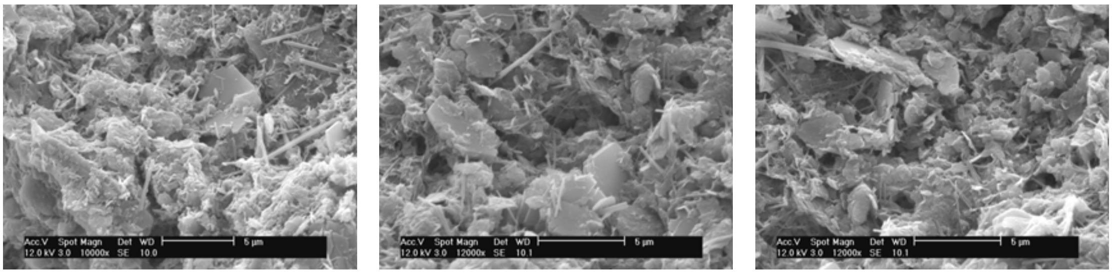
Appendix Figure C13 SEM micrographs of soaked unconfined compressive strength Mix 2 at 7 days curing time



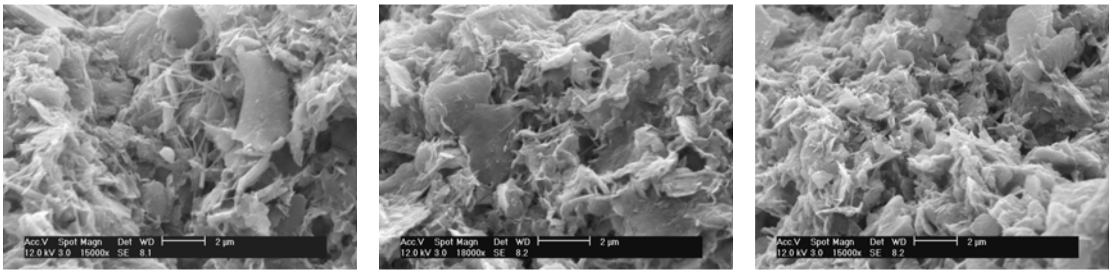
Appendix Figure C14 SEM micrographs of soaked unconfined compressive strength Mix 2 at 14 days curing time



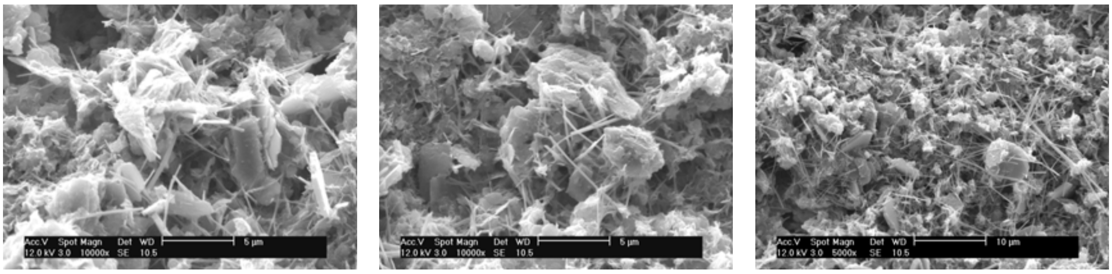
Appendix Figure C15 SEM micrographs of soaked unconfined compressive strength Mix 2 at 28 days curing time



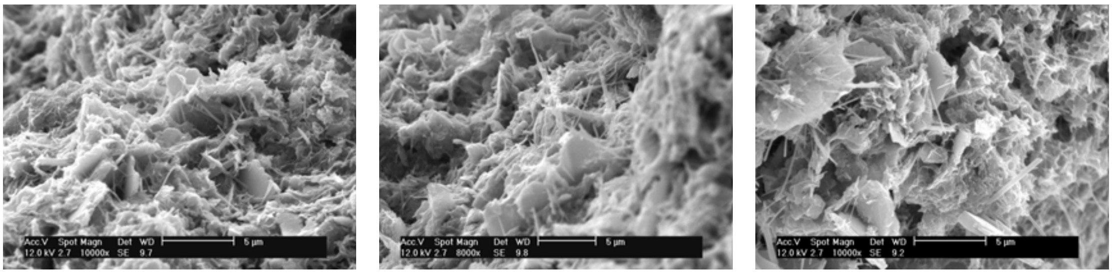
Appendix Figure C16 SEM micrographs of unsoaked unconfined compressive strength Mix 3 at 3 days curing time



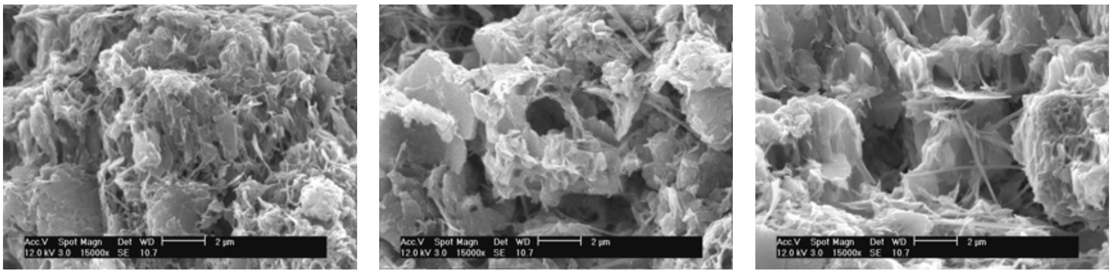
Appendix Figure C17 SEM micrographs of unsoaked unconfined compressive strength Mix 3 at 7 days curing time



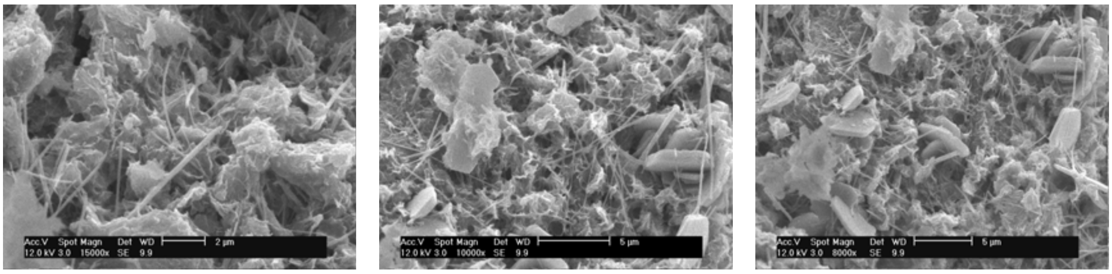
Appendix Figure C18 SEM micrographs of unsoaked unconfined compressive strength Mix 3 at 14 days curing time



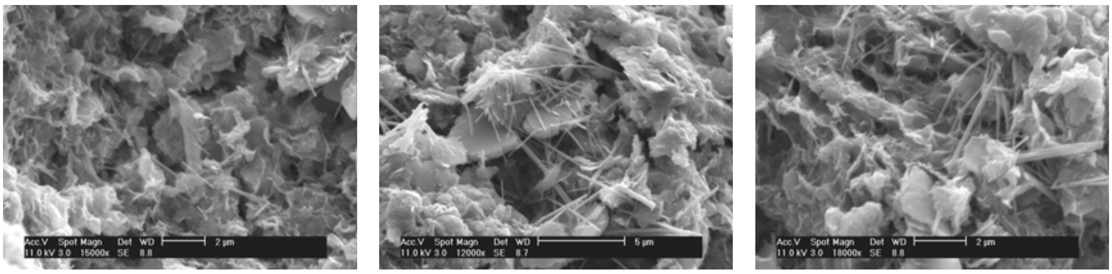
Appendix Figure C19 SEM micrographs of unsoaked unconfined compressive strength Mix 3 at 28 days curing time



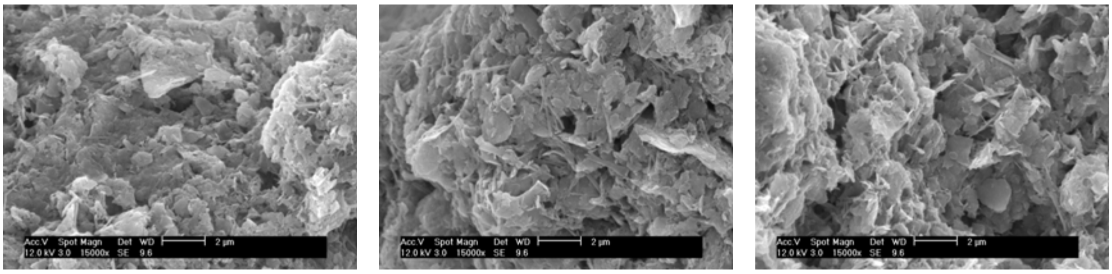
Appendix Figure C20 SEM micrographs of unsoaked CBR Mix 2 at 7 days curing time



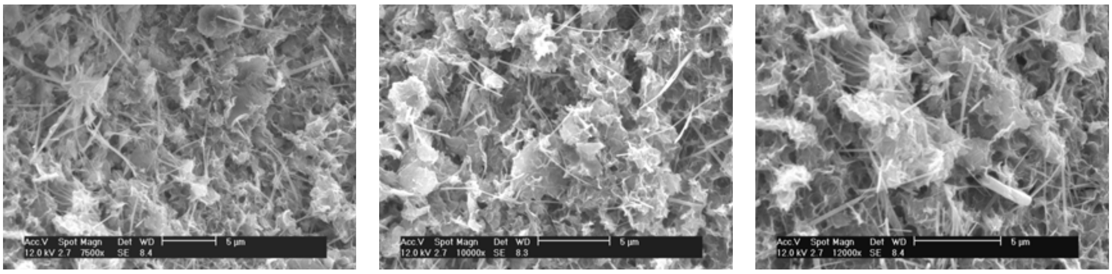
Appendix Figure C21 SEM micrographs of unsoaked CBR Mix 2 at 14 days curing time



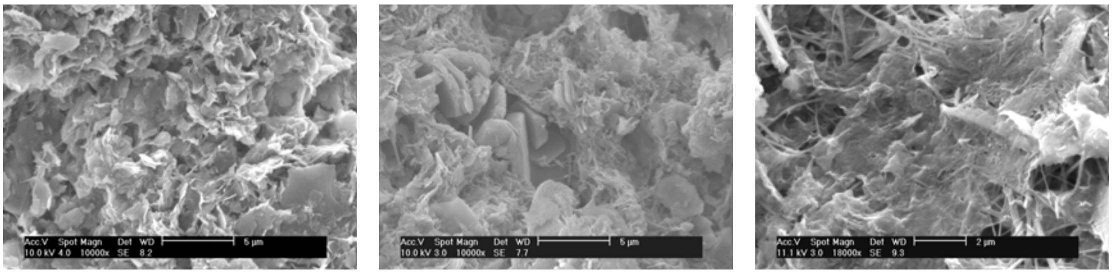
Appendix Figure C22 SEM micrographs of unsoaked CBR Mix 2 at 28 days curing time



Appendix Figure C23 SEM micrographs of soaked CBR Mix 2 at 7 days curing time



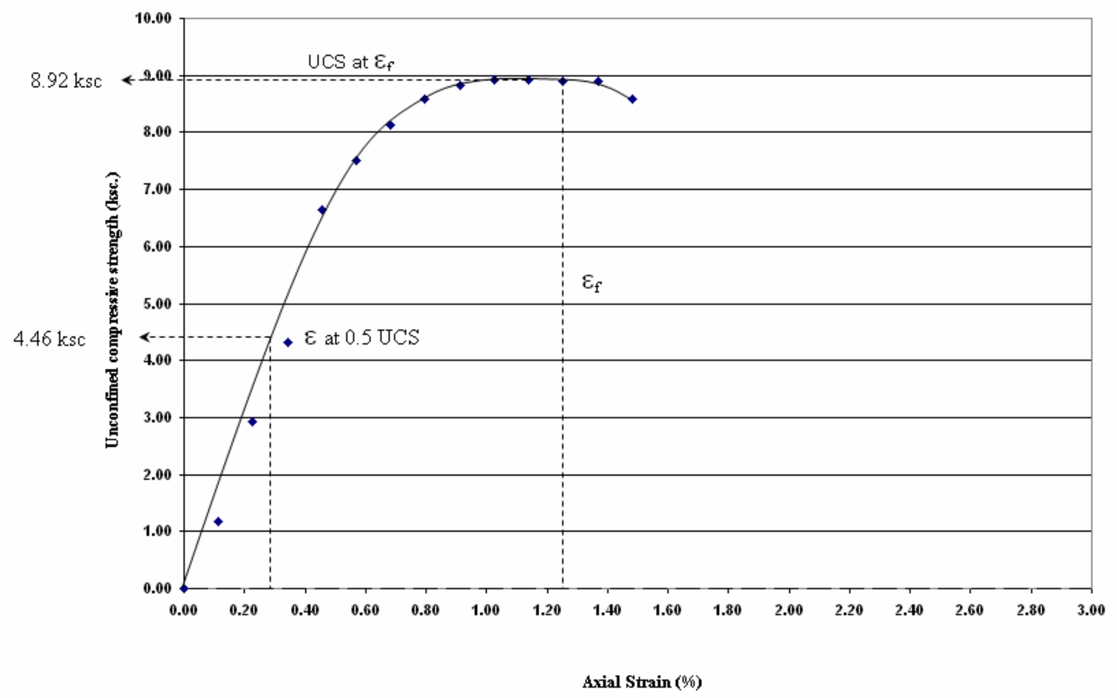
Appendix Figure C24 SEM micrographs of soaked CBR Mix 2 at 14 days curing time



Appendix Figure C25 SEM micrographs of soaked CBR Mix 2 at 28 days curing time

APPENDIX D

Example for evaluate Modulus of Elasticity (E_{50})



Appendix Figure D1 Example of Stress – Strain Characteristics curve for evaluate E_{50}

According to Stress – Strain Characteristics curve

UCS at ε_f	=	8.92	ksc.
0.5 UCS at ε_f	=	4.46	ksc.
At 0.5 UCS at ε_f	=	1.22	%
Modulus of Elasticity (E_{50})	=	0.5 UCS at ε_f / at 0.5 UCS at ε_f	
	=	4.46 / (1.22/100)	
	=	365.57	ksc.