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Geotechnical properties of very high moisture content dredged soil lightly cemented with ordinary or portland-limestone cement

By

Mohammed O. A. Bazne

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Geotechnical properties of very high moisture content dredged soil lightly cemented with ordinary or portland-limestone cement

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Sustainable geotechnics warrants exploring beneficial reuse of the large volume of fine grained soils which are produced annually in various forms such as dredged soils and mine tailings. Often these soils are at very high moisture content, and are therefore referred to herein as VHMS for Very High Moisture Soils. These soils exhibit poor engineering properties such as low shear strength and high compressibility.

This dissertation presents results from experiments conducted primarily to assess geotechnical properties over time of lightly cemented VHMS (referred to as LC-VHMS and defined as 5% or less cement by slurry mass). The main objectives of this dissertation are to show that very high moisture dredged soils can be stabilized with low dosages of portland-limestone cement (PLC) or ordinary portland cement (OPC) to achieve useful properties for some beneficial reuse applications such as filling geotextile tubes.

This dissertation's efforts differ from other dredged soil stabilization efforts due to lower cement dosages and property comparisons between traditionally used OPC and the more sustainable PLC. Several different combinations of moisture content, cement type, and cement content were prepared and tested over time on dredged soils collected from disposal facilities near the ports of Memphis and Mobile.

The experiment results indicate that meaningful shear strength improvements were sometimes observed, and pozzolanic strength gain tendencies were documented, which supported the position that LC-VHMS, especially with PLC, is sustainable and can achieve suitable engineering properties for some beneficial reuse applications.

Keywords:

Sustainable Development; Dredged Soil; Stabilization; Portland-Limestone Cement; Beneficial Reuse.

DEDICATION

Firstly, I dedicate this dissertation to my father and mother, my sister and brother (Media and Ahmed), for their love, continuous support and encouragement during my study, and I wouldn't be able to reach this stage without them. Secondly, I would also like to dedicate this to the soul of my late brother. Most notably, Thanks to my wife, Selar, who patiently walked with me tirelessly and sought to care for me throughout the journey to earn this degree. I dedicate this to my lovely son (Adam). Finally, I would like to dedicate this work to all who love me.

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AASHTO	American Association of State Highway and Transportation Officials
AL	Alabama State
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
c_u	Undrained Cohesion
C_{dry}	Cement Content by Dry Soil Mass
D	Deviator Stress
DM	Dredged Material
DOT	Department of Transportation
f_u	Undrained Angle of Internal Friction.
IWS	Initial Moisture Content
LC-VHMS	Lightly Cemented Very High Moisture Soil
ME	Memphis, TN; Where Dredged Soil Collected From USACE Dredge Disposal Facilities
MO	Mobile, AL; Where Dredged Soil Collected From USACE Dredge Disposal Facilities
OPC	Ordinary Portland Cement
PLC	Portland Limestone Cement
q_u	Unconfined Compressive Strength
$\sigma3$	Confining pressures
UC	Unconfined Compression Test

UU	Unconsolidated Undrained Triaxial Test
VHMS	Very High Moisture Soil
τ_u	Undrained Shear Strength
TN	Tennessee
USACE	U.S. Army Corps of Engineers
w_c	Moisture Content

CHAPTER I

INTRODUCTION

1.1 Introduction and Background

Recently, numerous studies are concerned about the production of a large volume of fine grained soil in various forms such as dredged soils. Also, there has been an increased awareness about the environmental impacts of waste dredged soil and potential applications for disposed and recycled dredged soil. Furthermore, more consideration is gradually drawn up for beneficial reuses of dredged soil in sustainable geotechnics. For instance, the use of dredged soil as construction backfill or fill in geotube bags minimizes the environmental impacts by removing contaminated sediment from aquatic environments and by increasing sea navigation and river and lake cleanup (e.g., Howard and Carruth 2015, Grubb et al. 2010, Bazne et al. 2015).

Dredged Materials (DM) are often very high moisture soils (referred to herein as VHMS) and exhibit undesirable engineering properties. Owing to the undesirable properties, the placement of millions of cubic meters of VHMS, from harbors, oceans, and rivers into disposal facilities has resulted in capacity issues at some of these facilities, leading to increased cost of monitoring, and running of these facilities. One appropriate way to enhance undesirable properties of dredged material is stabilization with cement. Cement stabilization is considered a technically a viable option to effectively enhance the properties of the material with no compaction effort demand. Hence, this study intends to show that dredged soil can be stabilized and managed beneficially by lightly cementing VHMS (LC-VHMS) with portland-limestone cement (PLC) or ordinary portland cement (OPC) and still achieve useful properties for some beneficial reuse applications, such as: embankment, fill in geotube, and protection of the coast, cover layer for landfill facilities, subgrade layer and or enhance highway layer, and some other applications. Also, stabilizing VHMS will reduce quantities of waste material as well increase navigation of ports. (e.g., Howard et al. 2014, Vahedifard et al. 2015, Bazne et al. 2016).

1.2 Hypothesis and Focus

The hypothesis in this research is that LC-VHMS can be advantageously applied to different engineering applications to improve river and port transportation routes by reusing DM. An additional focus of this study is to examine an alternative to OPC, such as PLC, which has effective impacts on stabilizing and enhancing undesirable properties of DM. The effective impacts can be characterized by improving the performance of stabilized DM with very low doses of cement.

Cement as a component can be classified into OPC and recently found PLC, it has been demonstrated from further studies that PLC could be considered as a sustainable alternative of OPC in terms of:

- Normally 10 to 12% reduction footprint, pound-for-pound.
- Manufactured simply and produced and supplied with existing equipment.
- Related to the OPC, the same operation regarding mix designs and admixture could be utilized with PLC

Most likely, better performance benefits could be examined such as increase cementitious efficiency, enhance strength and sitting time, increase durability.

The innovative application of utilizing PLC as a more sustainable alternative to OPC was adopted in ASTM C595, C1157, and AASHTO M240. PLC has limestone content of 5 to 15% and has average Blain of 557 m^2/kg, which are much higher than in OPC; therefore, more active flocculation and pozzolanic reaction should be expected as well as high performance of stabilization.

The key points herein are: first, the pozzolanic reaction can vary with respect to cement type based on limestone content. Second, the flocculation and pozzolanic are two paramount reactions which are more contributed to cementing reaction with soil (i.e., the activity of cement components with physical properties of cement). Consequently, the pozzolanic reaction determines the type of cement that reacts impeccably with Silica and or Alumina in the clay mineral of the DM. It should be noted that (1) strength of stabilized soil increases with further increase in the amount of cement, and (2) increasing limestone content in the cement demands more water for reaction, which makes utilizing PLC with VHMS more recommendable.

Various studies show that DM can be stabilized with a wide range of cement content at an extensive range of initial moisture content. Recent investigations (e.g., Chrysochoou et al., 2009; Kim et al., 2009) illustrated that 15 to 30% cement by mass can be mixed with dredged soil at optimum to 250% moisture content in order to enhance the performance of DM. However, there is a lack of information regarding the performance of low dosage of cement stabilization of dredged soil at LL and or 100% moisture content and a lack of information regarding an alternative of the performance of OPC. Therefore, this study is looking for the effective low doses of cement that can be used to stabilize dredged soil at high water content and still achieve enough strength which can be suitable in sustainable geotechnical applications such as embankments and fill in geotextile tubes. Furthermore, PLC should be a sustainable alternative to OPC.

In this study, there are various specific details that would have a significant impact on cement stabilizing dredged soil, such as: (1) properties of the dredged soil (unit weight, initial water content, size of aggregate and fine materials content, activity of clay, organic content, plasticity of soil), (2) activity of the cement (dosage of cement content, type of cement), and (3) technique of stabilizing (way of mixing, preparing soil before stabilizing, maturity temperature and curing period).

The research was started with a preliminary study regarding DM and its beneficial reuses in sustainable geotechnical application, ports and sea transportation, highway projects and other civil engineering applications such as embankments. After a thorough literature review, the first test plan was developed to determine the effective strength of LC-VHMS, and also the capability of PLC to be a sustainable alternative of OPC. It must be noted that for technical purposes and regarding the initial moisture content, stabilization in this study is also done with slightly over light cement content (LC-VHMS is defined as 5% or less cement by slurry mass). A second test plan was developed after reviewing the results from the first test plan. The second test plan includes testing LC-VHMS with 5 different types of PLC and OPC. For each OPC type, an equivalent PLC was tested where they both contain limestone and clinker but with different proportions. The purpose of the second test plan is to further investigate the concept that PLC can provide a sustainable alternative of OPC.

1.3 Objectives and Scope

There are numerous studies on the behavior of cement treated dredged materials for beneficial reuse that have shown that OPC can potentially mitigate undesirable properties (e.g., Azhar et al., 2014; Yusuf et al., 2012; Huang et al., 2011; Rekik and Boutouil, 2009; Wang and Miao, 2009); yet there are still unclear points in terms of effective dosage of cement and initial moisture content, effect of pozzolanic reaction on aging strength, and the development of undrained shear parameter with aging. On the other hand, what have not been studied yet are the effective properties of LC-VHMS and PLC which can be used as the better sustainable alternative product of OPC in terms of LC-VHMS. Therefore, the main objectives of this research are to study the possibility of lightly cementing VHMS and using PLC as an alternative of OPC, which both have effective impacts on increasing the performance of stabilized dredged materials for beneficial purposes in sustainable geotechnical and others civil engineering applications. The research objectives are achieved through a series of intensive laboratory tests to examine:

1. Geotechnical properties of two types of dredged soil, feudalized at LL and 100% moisture content, and stabilized with very low dosages (2.5, 5,10% of dry soil mass) of OPC and PLC.
2. Procedure to enhance the mix proportion with respect to the select cement type (PLC and OPC) with Soil type.

3. Procedure to enhance effective initial moisture content to improve workability and geotechnical properties of lightly cemented VHMS (100% moisture content and 5% cement by slurry mass) with 5 various type of OPC and PLC individually.

1.4 Organization of Study

This dissertation is organized into five chapters. The first chapter is an introduction of the study. The second chapter presents a thorough literature review regarding dredged soils, related issues, beneficial reuse, and general remediation. The second chapter is a peer-reviewed document (Bazne et al., 2015) that had been published in the proceedings of the International Foundations Congress and Equipment Expo 2015 (Geotechnical Special Publication No.189. IFCEE 2015: pp. 2717-2727. doi: 10.1061/9780784479087.253). Chapter three presents results from experiments conducted primarily to assess index and strength properties of LC-VHMS stabilized with PLC and OPC over time. Several different combinations of moisture content, cement type, and cement content were prepared and tested over time on dredged soils collected from disposal facilities near the ports of Memphis, TN and Mobile, AL. Chapter four presents experimental testing results of LC-VHMS from dredged soil samples collected from the port of Mobile source with 5% of various types (I, II, III, IV, and V) of PLC and OPC. Chapter five summarizes research conclusions and provides recommendations for future research. Chapters three and four are formed from two manuscripts prepared for submission to scholarly journals and are currently in various stages of reviewing. It is noted that minor non-technical modifications were done to each peer review chapter research in order to adjust them with the dissertation format and to create one document.

In addition to the above-mentioned peer-reviewed manuscripts, which have been directly used in the current dissertation, this effort has also led to three other publications, including two peer-reviewed conference articles and one technical report submitted to a sponsor. Two peer-reviewed articles from this effort have been accepted for publication in the proceedings of the American Society of Civil Engineers (ASCE) Geo-Chicago 2016: Sustainability, Energy, and the Geoenvironment. The first article's title is "Engineering Properties of Lightly Cemented Dredged Soil", and the second article's title is "Integrating Lightly Cemented Very High Moisture Content Fine Grained Soils into a Vegetated Landscape". Further, a technical report titled "Sustainably Enhancing Intermodal Freight Operation of Ports Using Geotextile Tubes" was submitted to the National Center for Intermodal Transportation for Economic Competitiveness (NCITEC), US Department of Transportation, in March 2016. However, these three documents are not included in this dissertation in order to keep the scope of this dissertation more focused.

CHAPTER II

BENEFICIAL REUSE OF FINE GRAINED SOILS FOR PORT, RIVER, AND SHORELINE APPLICATIONS

This chapter has been published as a conference article in proceedings of the International Foundations Congress and Equipment Expo 2015 (ASCE Geotechnical Special Publication No.189. IFCEE 2015: pp. 2717-2727. doi: 10.1061/9780784479087.253). The original paper may be accessed at http://dx.doi.org/10.1061/9780784479087.253. Furthermore, the paper (Bazne et al. 2015) has been reformatted and replicated herein with minor modifications in order to outfit the purposes of this dissertation.

2.1 Introduction

In recent years, sustainable geotechnics has been emphasized to facilitate maximum built environment opportunities, with minimum environmental impacts. One method of pursuing sustainable geotechnics is through beneficial reuse of fine grained soils. Beneficial reuse during construction, or within the natural environment for enhancement purposes is more desirable than a built disposal area or open water disposal (both of these practices should be minimized for maximum sustainability).

Despite federal, state, and local agencies eager for increased beneficial reuse of dredged materials, millions of cubic meters of potentially useable dredged materials are still disposed of by open-water dumping or confinement. In addition, over the past few years, the Panama Canal expansion has provided even more inertia to dredge ports and Navigation channels along the US Gulf Coast and up the Mississippi River to accommodate increased sized cargo ships.

The objective of this study is to provide guidance for beneficially reusing fine grained **V**ery **H**igh **M**oisture **S**oils (abbreviated VHMS). The study uses a three part approach to provide VHMS guidance. First, properties of dredged soils are presented alongside two promising approaches to fine grained dredged soils to be beneficially reused (i.e. lightly cementing and geotextile tubes). Second, a series of potential applications for stabilized VHMS are provided via literature review. Third, a series of laboratory experiments are presented to highlight stabilized VHMS properties of relevance when used as geotextile tube fill, and to document shear strength of lightly cemented materials over an extended period of time. This study does not address specific environmental treatments for any application presented.

2.2 Dredged soil properties

Dredged soils can vary from coarse grained non-plastic materials to fine grained plastic materials, or any combination in between. Dredged soils with higher proportions of fine grained material are generally more problematic and are the focus of this study. The specific focus is fine grained VHMS, since beneficial reuse of these materials is especially problematic. Initial moisture contents of fine grained dredged materials can easily be 100 to 200% (Table 2.1 from Howard and Carruth 2014). Index properties such as liquid limit (*LL*) can be on the order of 100 (Table 2.1 from Howard and Carruth 2014), and mechanical properties can be minimal since, for example, the soils are highly compressible and have such as portland or slag cement and/or use of geotextile tubes are items that have potential to improve VHMS properties so that they are suitable for beneficial reuse. Techniques to use these materials are discussed in the next section

2.3 Pertinent Methods to Improve Dredged Soil Properties.

2.3.1 Chemical Stabilization

Stabilizing soils of all types using portland cement, slag cement, lime, flyash, kiln dust, or similar has been performed for decades. Hundreds of references are available on soil stabilization, though more attention is generally given to materials with moisture contents below VHMS. Several applications are presented later where materials of pertinence are incorporated, though the cement dosages are generally 5% by slurry mass or higher. Minimal use of cementitious materials is more sustainable, and as a result, what is referred to herein as lightly cemented materials (5% or less by slurry mass) are the focus. Lightly cementing VHMS has the potential to improve properties to levels suitable for beneficial reuse in some applications.

2.3.2 Geotextile Tubes

Geotextile tubes are a versatile technology that is likely to be important in effective soil beneficial reuse in many cases. Filling geotextile tubes with lightly cemented VHMS is a possible vehicle for beneficial reuse. Geotextile tubes have been used for: shoreline erosion control, environmental applications, solutions to difficult construction problems such as wetland dike construction, underwater stability berms, flood control, island construction, and dewatering sediments for eventual disposal.

Geotextile tube use was documented as early as the 1960's, but their use did not gain prominence until the early 1990's. Similarly, innovative fabric uses date back several decades (e.g. Koerner and Welsh 1980), and have continued in recent years (e.g. Solis et al. 2010). For example, Koerner and Welsh (1980) document use of fabrics as underwater containment for pumped cement grout and in erosion prevention applications where concrete filled fabric tubes are placed along slopes. Solis et al. (2010) documented use of sand filled woven polypropylene tubes to support a portion of a pipeline along the Mexico coastline. While these applications do not directly apply to beneficial reuse of soil, they demonstrate versatility and show the likelihood that geotextile tubes can be used for additional applications.

Geotextile tubes have been filled with silt and/or peat using multiple types of equipment (see Marlin 2002 for two example projects). Miki et al. (1996) discussed geotextile tube applications such as restoring collapsed slopes and using river sediments to construct a revetment body to restore natural vegetation. Shin and Oh (2007) present geotextile tube applications filled with dredged material to prevent beach erosion. Howard and Trainer (2011) document twelve applications where geotextile and geomembrane tubes were used for marine and shoreline applications

2.4 Potential Applications for dredged Soils

Several references are cited that have potential relevance for beneficial use of VHMS. Some of the applications presented are beginning to find their way into practice while others are still in the conceptual stage. Several of the projects presented made no mention of geotextile tubes, lightly cemented soils, or both used in combination, but were

Presented as similar future projects might benefit from considering these approaches within their overall design framework.

2.4.1 Port Expansion and Management

Lord (2013) summarized the Panama Canal, and highlighted global commerce implications of the 5.25 billion dollar expansion expected to open in early 2015. The expansion is largely to accommodate larger ships; i.e. ships that can carry three times the cargo of those that can currently pass through the canal. The project requires 130 million m^3 of dredging. The summary quotes the U.S. Army Corps of Engineers (USACE) as viewing the increased traffic as a potential “game changer” for American ports. The summary also notes that some ports are already preparing by performing activities such as dredging their harbors.

2.4.2 River Restoration

Landers (2011) documented a $50 million dollar effort with dredged contaminated sediments from the Buffalo River. Pollution resulted from more than a century of industrial activity. Sewer overflows and non-point-source pollution were also cited as contributing factors. The Buffalo River is 1 of 43 locations throughout the Great Lakes region identified as a location manifesting significant environmental degradation. Four main contaminants were addressed via dredging: polycyclic aromatic hydrocarbons, polychlorinated biphenyls, lead, and mercury. Phase 1 dredged 458,000 m^3 with a clamshell bucket. The material was sent to a confined disposal facility, and phase 1 dredging was expected to cost $5.9 million dollars.

Landers (2012) documented work in New Jersey on the Passaic River in contaminated areas. Polychlorinated biphenyls, dioxin, metals, and many organic compounds were present. Approximately 150,000 m^3 of contaminated sediment is to be removed by two dredging phases. Phase 1 was to remove approximately 30,000 m^3 of the most contaminated sediments, and consist of an excavator on a barge to remove sediment approximately 3.65 m deep. The material was to be screened, mixed with water to create slurry to be pumped approximately 0.4 km to an upland processing facility for additional screening and further processing before eventually being loaded into sealed containers for transport. The water removed was be treated and returned to the river. Phase 1 was scheduled to take ≈ three months and cost ≈ $80 million total dollars. Phase 2 is scheduled to remove approximately 120,000 m^3 of material, with details forthcoming. After the conclusion of phase 2, the EPA plans to propose a plan for capping or removing millions of m^3 of contaminated sediment from a 12.9 km section of the river.

Holm et al. (2012) documented a major restoration effort that has been ongoing for over 30 years within approximately 19.3 km of the Blue River in the Kansas City metropolitan area. At the initiation of construction in 1983, industrial activity and uncontrolled filling had been occurring for ≈ 80 years. Soils were contaminated with materials including polychlorinated biphenyls, and total petroleum hydrocarbon levels were elevated at multiple locations. Contaminated soils were disposed of as per applicable regulations or bypassed by adjusting alignment.

During early years of the Blue River project, no environmental features were incorporated. Aquatic habitat loss eventually resulted in various small features being incorporated. Wildlife enhancement features were added to the project in the later part of

The 2000's such as tree root masses for habitat and plants along channel banks for stability. Large amounts of rip rap have also been used for items such as channel bank stabilization. Holm et al. (2012) noted the Blue River project illustrated the evolution in society's environmental perspective, and demonstrated that channel modification projects can reduce flood risks *and* be environmentally conscious.

2.4.3 Ecosystem Restoration

Howard et al. (2012a) and Karnati et al. (2012) document island construction in Peoria IL on the Illinois River. Geotextile tubes were filled with native unstabilized fine grained sediment. High solids dredging was performed with a patented environmental clamshell bucket that ultimately provided material to a positive displacement pump that transported VHMS into geotextile tubes. VHMS was mostly CH material (*LL*'s of 56 to 72), and a typical moisture content during tube filling was 70%. Around 38,000 m^3 of unstabilized VHMS was used to fill tubes. Three rows of tubes were placed side by side to create the wall with ends in various rows staggered a minimum of 25% of their length. Riprap stone was placed on the outside portions of the wall where there was potential for erosion.

One beneficial reuse consideration is that filling geotextile tubes with fine grained soils usually results in consolidation and in the presence of waves or currents piping may occur. A presentation by Gaffney documented in Howard et al. (2009) discusses the ecosystem restoration Tennessee Drakes Creek project. A U-shaped dike-contained channel was constructed with geotextile tubes filled with dredged material ranging from organics to silty sand to stone. A total of 16,800 m^3 was dredged. Yan and

Chu (2010) documented dike construction that included use of clay filled geotextile bags that formed a smooth slope for grouted geotextile mattresses.

2.4.4 Emergency Construction and Disaster Recovery

The Department of Homeland Security sponsored the SERRI initiative, and one of SERRI's multi-year efforts evaluated chemically stabilized VHMS for emergency construction and disaster recovery applications. Aspects pertinent to beneficial soil reuse that are applicable to this study are briefly summarized in this section.

Howard and Trainer (2011) evaluated geotextile and geomembrane tubes for use after natural disasters (mostly for building temporary walls in a flooded area), and filling geotextile tubes with stabilized VHMS was investigated to some extent.

Howard (2012) documents use of small portable dredges with challenging access circumstances. Howard (2012) also documents cementitious material storage, cementitious material handling, and pugmill mixing equipment for chemically stabilized VHMS. Figure 2.1 is an example flowchart for a construction case that could be useful for a variety of applications; the quantities used are explained in Howard (2012). Note that use of hydraulic dredges coupled with dewatering technologies such as polymers are an option to replace mechanical dredging for exceptionally long pumping distances, though this scenario is not discussed in detail as mechanical dredging aligned more closely with this study's scope

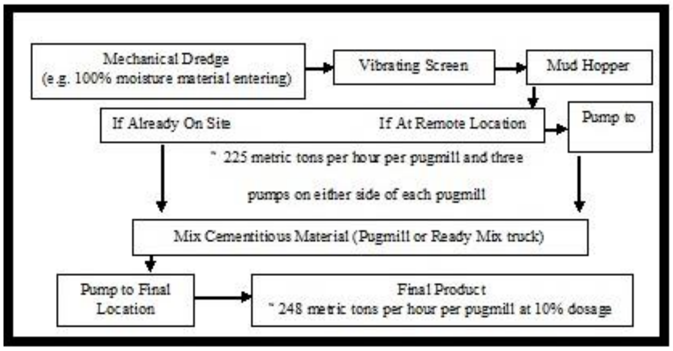


Figure 2.1 Example stabilized VHMS Construction from Howard (2012)

Howard and Carruth (2014) provide shear strengths for up to 7 days curing at room temperature for a range of soil types, cement types, moisture contents, and cement dosages (5 to 15%). The manuscript also cites several studies that provide evidence that pumping VHMS long distance is feasible (over 1 km seems easy feasible for a variety of materials). Longer term shear strengths and dosages below 5% were not evaluated since they are not all that meaningful for disaster recovery.

2.4.5 Lightweight Fill

Beneficial reuse of VHMS has gained momentum outside the US in the form of Super Geo-Material (SGM) or material prepared according to the pneumatic flow mixing (PFM) method (Tanaka et al. 2009; Oota et al. 2009; Nakai et al. 2009). SGM is mixed with clay slurry at a moisture content above the *LL*; 30 to 35% air is typical. The previous references document projects that use 6.8(10^4) to 8.6(10^6) m^3 of SGM or PFM placed in thicknesses of 2.5 to 13.8 m at 2,000 to 25,000 m^3/day for tunnel backfill, the Japan airport (placed in 3 to 8 m deep water), and a shield tunnel. The soils mixed had *LL* values of 58 to 91 and moistures of 85 to 250%. Cement contents were 3.3 to 14.8% by slurry weight (8.7 to 14.8% was used more often than lower dosages), which produced 28 day laboratory mix design shear strengths (s_u) of 1.6 to 3.0 kg/cm^2. Site variability was reported to be considerable, which was the motivation for reducing s_u to a field structural design value (s_{ud}) of 0.6 to 1.0 kg/cm^2.

2.5 Beneficial Soil Re-use Laboratory Experiments

2.5.1 Materials Tested

One geotextile (*GT 500*), two soils (*Soil 1, Soil 3*), one portland cement (*SC6*), and one slag cement (Grade 100) were tested. Howard and Trainer (2011) and Howard et al. (2012b) used these same materials and terms. A small-scale geotextile tube (often referred to as a *pillow*) was used, which has dimensions of ≈ 53 cm by 53 cm and holds ≈ 28,000 cm^3. The *pillow* is manufactured using *GT 500* and conventional seams. *Soil 1* classified as *CL* to *CH*, and *Soil 3* classified as *CH* to *OH*. *SC6* is a specialty grind portland cement with *Type III* fineness but lower SO_3 content.

2.5.1.1 Experiment 1-Volume Change or Settlement Potential Inside Geotextile Tubes

Stabilized VHMS was evaluated that could be pumped into a geotextile tube. Volume change or settlement was of primary interest, though a shear strength index was measured with hand held gages. Volume change associated with filling a geotextile tube with stabilized VHMS was investigated by monitoring height change in a small laboratory scale geotextile tube with time since volume change will dictate the final height of a geotextile tube and has many construction implications.

2.5.1.2 Experiment 1-Test Protocol

An abbreviated protocol is provided, with full details in Howard and Trainer (2011), whose primary intent was disaster recovery. Soil slurry at 233% moisture was mixed with 15% portland cement by total slurry mass, with mixed slurry divided evenly between three buckets. Slurry was in a fluid like state even after cement addition.

A modified *Geotube*® Dewatering Test (*GDT*) was used to test the stabilized slurries. Two types of tests were conducted: emerged (Figure 2.2a) and submerged (Figure 2.2b). The emerged test was to evaluate when the geotextile tube was out of the water, while the submerged tube was to evaluate characteristics when the tube was completely covered with water. Two stands and string were used to measure height change of the *pillow* over time. The lower string was leveled and positioned beneath the *pillow* to serve as the datum for measurements while the upper string was leveled and positioned at the top of the *pillow*. Height was the distance measured between the strings. Change in height is not equivalent to volume change on a percentage basis since the *pillow* is curved when filled.

Slurry mixed with cement was poured into the top of the standpipe (Figure 2.2c) while the standpipe and *pillow* were held slightly above the stand as the first bucket was being poured to ensure proper filling. Immediately after the *pillow* was filled, initial height was measured and recorded using the string apparatus (Figure 2.2d).

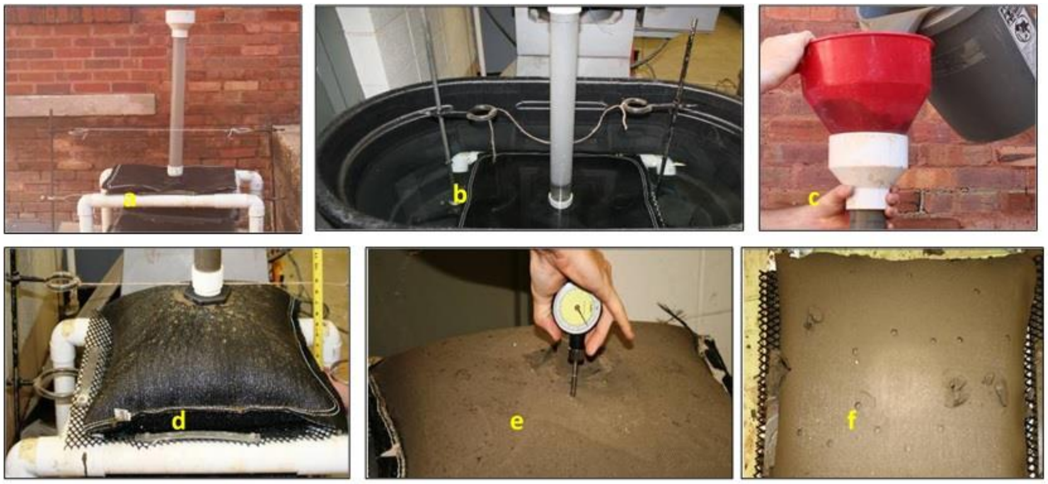


Figure 2.2 Photographs of Experiment 1

(a) Emerged Test Set-Up (b) Submerged Test Set-U c) Slurry Entering Tube d) Measuring Initial Height e) Testing Top Surface Post Dewatering f) Bottom Surface Post Testing

After curing for 24 or 72 hours at approximately 24 C, final height of the *pillow* was recorded and it was cut open. A hand held gage was used to record 20 readings on the top surface (Figure 2.2e) and then on the bottom surface (Figure 2.2f). Hand held gage readings were adjusted to estimated shear strength using companion work provided in Howard et al. (2012b).

2.5.1.3 Experiment 1-Test Results

Table 2.1 provides settlement test results. Height change ranged from 10 to 24% and nearly all changes occurred during the first four hours. This amount of volume change is tolerable for some applications. This volume change would likely be due to entrapped air in addition to water expelled through the geotextile.

The adjusted average *Soil 1* submerged strength at the top and bottom of the *pillow* after 24 hr was 0.27 kg/cm^2 and 0.45 kg/cm^2, respectively. Coefficients of variation were 11 to 17% for submerged testing. Emerged shear strength estimates from the hand held gages were 2 to 3 times the submerged case.

Table 2.1	Result of Modified GDT Test

Soil	Type	Time (hr)	Initial (cm)	Height	Final (cm)	Height	Height (%)	Change
1	Submerged	24	25.4		22.9		10	
1	Emerged	24	25.4		20.3		20	
1	Emerged	24	26.7		22.2		17	
1	Emerged	72	25.4		22.9		10	
3	Emerged	24	21.6		16.5		24	

The data collected indicates cement stabilized VHMS has beneficial reuse potential for some applications when pumped into geotextile tubes. The material tested herein was intended to represent a relatively easily to achieve material that is easily pumped. A variety of strength and fluidity combinations can be achieved; many applications would likely desire reduced cement and moisture contents.

2.5.2 Experiment 2-Lightly Cemented VHMS Strength versus Time

Sixty specimens were prepared and tested over 180 days to determine how much strength could be mobilized within lightly cemented VHMS. Several applications could utilize materials with only modest unconfined compressive strengths (q_u), though measured properties in these conditions do not seem to be nearly as prevalent in literature as materials with higher cement dosages. All experiment 2 testing was performed on *Soil 1* (labeled as group 3 in Howard et al. 2012b).

2.5.2.1 Experiment 2-Test Protocol

An abbreviated protocol is provided as the procedures were essentially the same as Howard et al. (2012b) with minor accommodations for the lower dosage rate of 2.5%. The main difference was a few specimens were capped with Plaster of Paris prior to testing if the top was not level after curing. Figure 2.3 provides specimen preparation photos, which consisted of preparing soil slurry at a target moisture content of 100% (actual values were 97.2 to 98.5% prior to cement addition), mixing cementations materials, and preparing specimens in plastic molds that had porous stones on each end. The material was fluid enough that it filled the 7.6 cm diameter by 15.2 cm molds by lightly tapping the outside. Once the mold was filled with lightly cemented slurry, molds were clamped shut and placed underwater to cure for 1 to 180 days before testing in unconfined compression at a load rate of 0.23 cm/min. After testing, some specimens were oven dried to determine their moisture content. While curing, water temperature was monitored continuously (measured temperatures were 18 to 24 C) and used to calculate a temperature-time factor (TTF) using a linear relationship with units of C-hr. Data reduction was the same as Howard and Carruth (2014).

Figure 2.3 Preparing of Lightly Cemented VHMS test Specimens

2.5.2.2 Experiment 2-Test Results

Figure 2.4 provides experiment 2 results. Half the specimens were prepared with 2.5% portland cement by slurry mass (soil plus water mass), and the other half had 2.5% total cementitious material (0.63% portland cement and 1.87% slag cement, which has become somewhat common for soil stabilization). As seen in Figure 2.4a, portland cement outperformed portland/slag cement by a considerable amount. Even after 180 days of curing, the portland/slag cement blend achieved minimal strength. Portland/slag specimens were erratic and as a result, only their compressive strength with time plot is reported. Based on Figure 2.4a, investigating portland cement seems most logical for lightly cemented VHMS applications and all remaining information presented is for 2.5% portland cement.

A strength versus TTF curve was plotted, which looked similar to Figure 2.4a and resulted in the relationship $q_u = 20.9 \ln(\text{TTF}) - 128.7$ with an R^2 of 0.93. Total density was 1.48 g/cm^3 on average, with a standard deviation of 0.014. Maximum strain was 1.8% on average with a standard deviation of 0.5%. Moisture content of entire specimens oven dried immediately after testing was 89.2 to 91.7% with an average of 90.6%. There were no moisture content trends with time as values remained similar to that just after mixing with portland cement for up to 180 days when submerged in water with porous stones on each end of the specimen. Recall that the target moisture content of 100% was for slurry prior to cement addition (i.e. equal parts soil and water). Figure 2.4b shows a reasonable correlation between q_u and elastic modulus (E) measured from the linear portion of the specimen stress-strain curve. A slope of 64 was similar to *Soil 1* when tested by Howard and Carruth (2014) at several different proportions and higher cement dosages as their testing resulted in slopes of 65 to 84 when data was collected and reduced in the same manner.

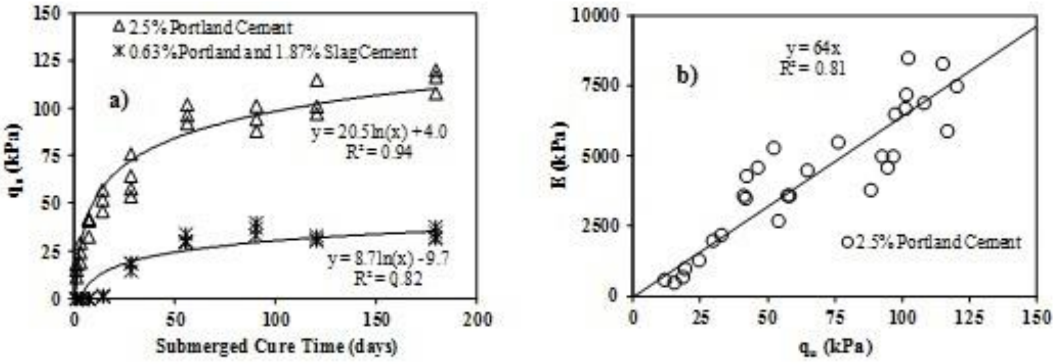


Figure 2.4 Lightly Cemented Unconfined Compression Test Results.

2.6 Discussion

Relatively speaking, characterization of LC-VHMS is not well established as most past efforts have focused on C-VHMS (i.e. higher cementitious dosage rates). There are several needs related to LC-VHMS, such as more detailed strength and consolidation testing as a function of time. Also, moisture gradients and moisture content changes as a function of time (especially in the first few months after initial mixing) need to be better understood for different applications. It is anticipated that LC-VHMS will behave quite differently depending on consolidation and drying potential. Pilot scale demonstration projects are needed where LC-VHMS is pumped into geotextile tubes that are subsequently monitored over time. Strength and stability properties could be monitored, alongside equilibrium moisture content and consolidation states. Mixing uniformity could also be monitored during the demonstrations

2.7 Summary and Conclusions

This study aimed to present concepts and applications for fine grained VHMS for the purpose of increasing and improving soil beneficial reuse. Several applications were presented that either have, or should consider, beneficial reuse. Test data was presented related to using stabilized VHMS as geotextile tube fill that indicates some promise and the need for additional investigation. Additional testing showed lightly cemented VHMS has potential to have properties of use for some applications if cured for longer periods of time before those properties are needed. A considerable amount of additional work needs to be performed on lightly cemented VHMS

CHAPTER III

EFFECTS OF LIGHT CEMENT STABILIZATION ON PROPERTIES OF FINE GRAINED DREDGED SOILS

This chapter has been submitted to the ASCE Journal of Materials in Civil Engineering as a technical paper, and it is under peer review process while this dissertation has been written. This chapter has been reformatted and replicated herein with minor modifications in order to outfit the purposes of this dissertation

3.1 Introduction and Background

In recent years, dredging and the associated dredged material has drawn more attention, due at least in part to the Panama Canal expansion. This attention varies from beneficial reuse in, for example, construction backfill to minimizing environmental impacts by removing contaminated sediment from aquatic environments, to increasing sea transportation, to river and lake cleanup (e.g., Howard and Carruth 2015, Grubb et al. 2010, Bazne et al. 2015). Placing millions of cubic meters of very high moisture content fine grained soil (referred to hereafter as VHMS) from harbors, oceans, and rivers into disposal facilities has resulted in capacity issues at some of these facilities. Thus, beneficial reuse has steadily become more appealing.

VHMS has undesirable properties such as low strength, handling problems, and high compressibility. Stabilization or remediation of dredged soils for beneficial reuse has been the topic of many studies, where some have shown that cement stabilization of dredged soil can potentially mitigate undesirable properties. What has not been studied to a large extent in previous studies is the potential to meet the needs of some types of projects by way of lightly cemented VHMS (referred to as LC-VHMS and defined as 5% or less cement by slurry mass), especially by way of a more sustainable alternative to ASTM C150 Type I portland cement. To this end, the primary objective of this study is to evaluate engineering properties of LC-VHMS for backfilling and embankment applications while comparing properties achievable with traditionally used ordinary portland cement (OPC) described in ASTM C150 to those of portland-limestone cement (PLC) as described in ASTM C595 and C1157.

PLC is a more sustainable alternative to OPC, and as of 2012, Type IL PLC was adopted in ASTM C595 (and AASHTO M240), which was a meaningful step towards acceptance of PLC into the US construction market. Cost et al. (2013) and Cost et al. (2015) provide background information on PLC use worldwide, which has occurred for some time, and also describe the PLC products making their way into the US market that generally have been optimized for synergy behaviors and can generally be described as having higher Blaine finess per percent of added limestone relative to past use of PLC in different countries. Since PLC manufactured for improved synergies in the US market are relatively new to concrete, their applicability in chemical stabilization of soil is even more novel. LC-VHMS produced with PLC would have a particularly low carbon footprint considering the lower dosages of more sustainable cement

This chapter presents results from a series of experiments which were conducted to assess engineering properties of LC-VHMS. Dredged soils were collected from two disposal facilities near the ports of Memphis, Tennessee (TN) and Mobile, Alabama

(AL). For each site, twelve different mixtures were prepared including two moisture contents, two cement types, and three cement contents. A series of index test, unconfined compression (UC), and unconsolidated undrained (UU) triaxial tests were conducted on the specimens. Prior to presenting the experimental plan and results, literature review is provided focusing on applications and relevant properties for stabilized fine grained soils.

3.2 Applications and Relevant Properties for Stabilized Fine Grained Soils

Cement stabilization is considered as an efficient chemical treatment for VHMS which could be used for construction fill applications (e.g., Chew et al. 2004, Horpibulsuk et al. 2005, Sariosseiri and Muhunthan, 2009, Bazne et al. 2015). Others have studied the use of cement stabilization of clayey soft dredged material that could not be used as fill material to enhance shear strength (e.g., Kim et al. 2008). Stabilized VHMS could, or in some cases has been, used for applications including: filling geotextile tubes (Howard and Trainer 2011; Howard et al., 2012; Bazne et al. 2015); backfill materials (Huang et al., 2011); and a variety of general purpose land improvement or land creation applications in and around ports such as shoulder protection (Vervaeke et al., 2003).

Hydration and pozzolanic reactions are possible when cement is mixed into clay soils (Azhar et al., 2014). Hydration reactions have been studied in soil by researchers including (Kim et al., 2009). A series of unconfined compression experiments were conducted to study characteristics of cement stabilized dredged soil, and they showed increasing strength with the time due to pozzolanic reactions.

Grubb et al. (2010) studied properties of 20 stabilizing combinations mixed with dredged soils from Craney Island, Virginia, and showed the effects of pozzolanic reactions between combinations. Howard et al. (2015) performed unconfined compression tests to study chemical properties of VHMS stabilized with cement, and results indicated 20 to 745 kPa UC strength could be achieved after 1-7 days of room temperature curing for various combinations of moisture and cement contents ranging from 100 to 233 and 5 to 15% (of slurry mass), respectively. Grubb et al. (2010b) studied stabilized dredged material classified as CH or OH with in situ moisture of around 130% with various combinations of cementitious materials. The primary finding was that stabilized dredged materials exhibit suitable strength, compressibility, and bulking characteristics to be favorable for large fill and subgrade improvement applications at costs equal to or less than conventional construction materials

3.3 Materials and Methods

3.3.1 Materials Tested

Fine grained soils were collected from two United States Army Corps of Engineers (USACE) dredge disposal facilities. The first soil was sampled in Memphis, Tennessee and is labeled ME. The second soil was sampled from Mobile, Alabama and is labeled MO. Collected soils were tested for index properties as shown in Table 3.1. The dredged soils were tested in conjunction with two cement types: 1) Type GU PLC specified under ASTM C1157; and 2) Type I/II OPC specified under ASTM C150. The PLC used herein had approximately 13% limestone, whereas the OPC had a much lower limestone content of approximately 2%; embodied energy decreases with limestone content increases as ground limestone replaces clinker in the cement

Table 3.1 Average Index Properties of Dredged Soil Collected from Memphis (ME) and Mobile (Mo) Dredged Disposal Facilities

Property	Unit	Test Method	Soil Site	
			ME	MO
Specific Gravity (G_s)	--	ASTM D584	2.66	2.57
Initial Water Content (w_c)	%	ASTM D2216	80	33
Max. Dry Density (γ_{dmax})	g/cm^3	ASTM D698	1.31	1.52
Optimum Moisture Content (ω_{opt})	%	ASTM D698	30	25
Liquid Limit (LL)	%	ASTM D4318	90	70
Plastic Limit (PL)	%	ASTM D4318	32	24
Plasticity Index (PI)	%	ASTM D4318	58	46
Sand	%	ASTM D422	5	18
Silt	%	ASTM D422	58	40
Clay	%	ASTM D422	37	42
Organic Content	%	ASTM D422	12	8
USCS	--	ASTM D2487	CH to OH	CH to OH

3.3.2 Slurry Preparation

Soils were prepared into slurry by mixing dredged material (DM) at initial moisture content (w_c) with water to generate VHMS. The initial moisture contents of soil slurry (IWS) were selected to be liquid limit (LL) and 100% for MO and ME soils.

3.3.3 Testing Matrix and Sample Preparation

Table 3.2 presents the testing matrix for unconfined compression (UC) and unconsolidated-undrained triaxial (UU) testing. The UC testing matrix includes two cement types (PLC and OPC) and three cement contents (C_{dry}) (2.5, 5, and 10% of dry soil mass). Note that some of the 10% C_{dry} dosages modestly exceed the definition of LC-VHMS, but were tested to bracket LC-VHMS yet provide a systematic test matrix. LL is considered the minimum moisture content where soils have a shear strength of approximately zero (absent stabilization), and it is the minimum moisture content meeting the VHMS definition. At 100% moisture, VHMS has 50% solid particles. The majority of the cases tested in this study did not have measurable flow, as defined by ASTM D6103, and as such placement via positive displacement pumps would likely not be as desirable as bucket loaders and trucks.

A total of 12 UC specimens were prepared for each group using a plastic mold (165 mm tall and 76.2 mm diameter) which was fitted with a thin aluminum plate to facilitate specimen removal. Stabilized slurry was added in 3 lifts with the mold being tapped 25 times around the side between each lift to insure uniform specimen production. Specimens were then covered with a plastic cap and stored in a curing room maintained at 100% relative humidity and room temperature (18-25°C).

A total of 12 UU specimens were also prepared for each group. The mixture prepared for each group was first molded in four PVC molds (95 mm tall and 100 mm diameter). Stabilized slurry was added in 3 lifts with the mold being tapped 25 times around the side between each lift to insure uniform specimen production. The UU molds were filled in 3 lifts with the mold being tapped 25 times around the side after placing each lift. The UU models were covered with aluminum sheets (Figure 3.1b) and stored in the curing room, similar to UC specimens. Since the groups with 2.5% C_{dry} showed little or no strength gain during the UC testing, UU tests were not performed for groups containing 2.5% C_{dry} as.

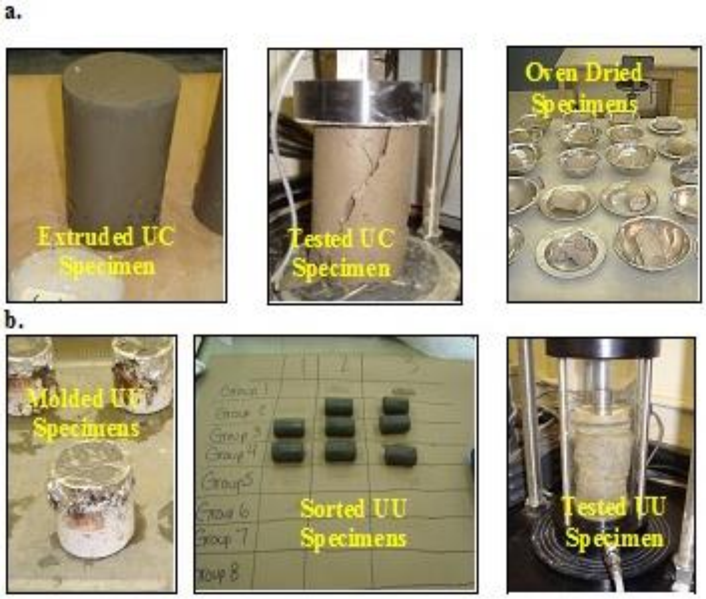


Figure 3.1 Photographs of Specimens and Testing

UC (part a) and UU (part b)

Table 3.2 New Testing Matrix for UC and UU Tests on Each Soil type

Site	Initial w_c (%)	Cement Type	C_{dry} (%) ^{A}	Specimens ^{B}
ME and MO	LL (70% for MO and 90% for ME)	PLC	2.5	UC
			5	UC, UU
			10	UC, UU
		OPC	2.5	UC
			5	UC, UU
			10	UC, UU
	100	PLC	2.5	UC
			5	UC, UU
			10	UC, UU
		OPC	2.5	UC
			5	UC, UU
			10	UC, UU

A: Percentage by dry mass. C_{dry} for UC testing was 2.5, 5, or 10%, while C_{dry} for UU testing was 5% or 10%.
B: UC testing had 2 soils, 2 initial moisture contents, 2 cement types, 3 cement dosages, 3 replicates, 4 test ages (7, 28, 56, 90 days), or 288 total UC specimens. UU testing had 2 soils, 2 initial moisture contents, 2 cement types, 2 cement dosages, 3 confining pressures, 1 replicate, 4 test ages (7, 28, 56, and 115 days), or 192 total UU specimens. Confining pressure varied depending on the specimens being tested with specimens with higher strength generally being exposed to higher confining pressure at later ages. Due to logistical factors, UU tests originally planned for 90 days were conducted after 115 days of curing

3.3.4 Soil Property Test Procedures

Average moisture content, dry density and void ratio were measured for the three replicate UC test specimens after 90 days of curing. UC specimen testing is discussed in the following section. Void ratio was determined using wet density and dry density while moisture contents were evaluated for each specimen tested. Atterberg limits samples were cured for 90 days, allowed to air dry for 3 days, pulverized and passed through sieve No 40 according to ASTM D4318 (multi-point procedure).

3.3.5 Unconfined Compression Test Procedures

After curing, the UC specimens were extruded from the molds and tested (Figure 3.1a). The UC tests were conducted according to ASTM D2166 with a strain rate of 1% /min, 0.5% strain past the maximum force, and using the corrected area for stress and strain determination.

3.3.6 Unconsolidated Undrained (UU) Triaxial Test Procedures

Three specimens (70.28 mm tall and 35 mm diameter) were extruded from each UU mold and tested. UU tests were performed according to ASTM D2850. Confining pressures ranged from 10 to 120 kPa. The maximum deviator stress was considered as the failure point for specimens tested. The UU models and specimens are shown in Figure 3.1b. After curing, UU specimens were sampled from their respective curing molds and sorted in a logical order based on test type, group and sample prepared. Sorting molds prior to testing, makes it simpler to recognize data and logically select the cured mold.

3.4 Test Results and Discussion

3.4.1 VHMS Property Modifications

A decrease in initial moisture content occurred immediately after cement addition. Moisture contents following 90 days of near sealed curing in 100% relative humidity are presented in Figure 3.2. As shown in Figure 3.2a, moisture contents for Memphis soils were reduced from 90% by 2 to 8% and from 100% by 7 to 17%. Figure 3.2b presents data for Mobile soils, which were reduced from initial moisture contents of 70% by 4 to 12% and 100% by 7 to 17%. The magnitude of water reduction increases with additional cement content, and the relationship between final moisture content and cement content is not linear. These results were generally expected as others have reported similar types of results (e.g., Kamon et al., 1991; Chew et al., 2004).

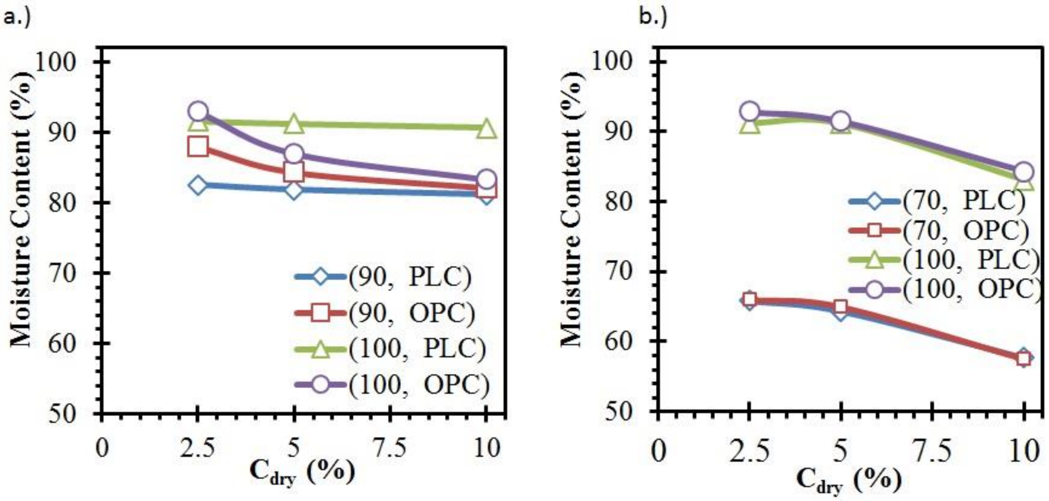


Figure 3.2 90 Day w_c vs. C_{dry}

a.) Memphis b.) Mobile

It is worth noting that PLC seems to have produced marginally more moisture content reduction for Memphis soils. When comparing the 12 combinations of soil source, initial moisture content, and cement content, PLC generated more moisture reduction for 8 of the 12 combinations presented in Figure 3.2. Water reduction may be attributed to increased dry mass, hydration, and/or pozzolanic reactions. Furthermore, Ca^{++} concentrations may be higher in PLC than in OPC, and Ca^{++} can bond with SiO_2 and Al_2O_3 in clay particles when in the presence of water to form pozzolanic bonds. In these conditions, there would be more cementitious bonds formed through pozzolanic reactions. Relative pozzolanic behavior of OPC versus PLC is largely unexplored in soil and should be investigated further.

Dry densities were evaluated for each UC specimen presented herein (Figure 3.3). As shown in Figure 3.3.a, Memphis dry densities ranged from 0.74 to 0.82 g/cm^3. Figure 3b presents dry densities recorded for Mobile specimens, which ranged from 0.70 to 1.00 g/cm^3. For both soils, the dry density after 90 days of curing increased with cement content and decreased for higher initial moisture contents. It is also worth noting that for most circumstances, dry densities were higher for specimens treated with PLC than for similar specimens treated with OPC.

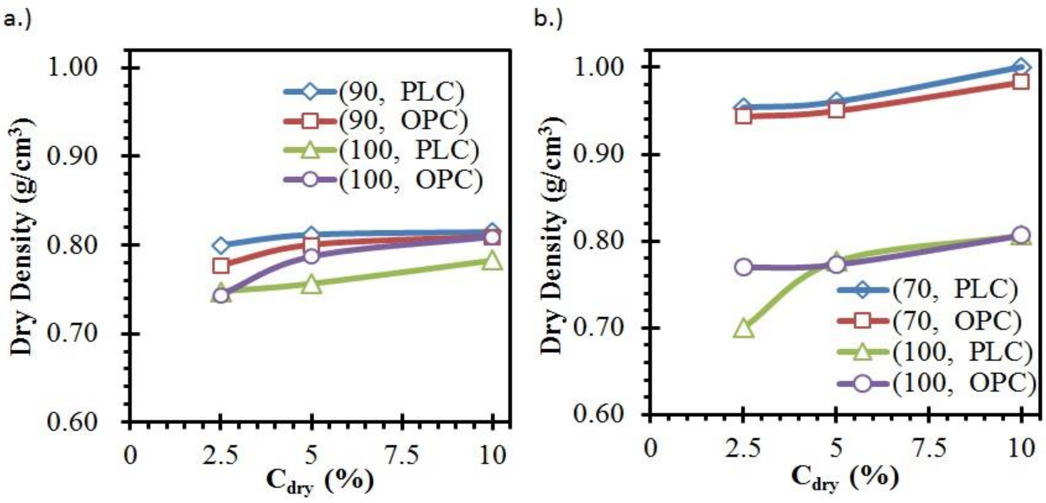


Figure 3.3 90 Day Dry Density vs C_{dry}

a.) Memphis b.) Mobile

Void ratios were determined using wet and dry unit weights. According to Figure 3.4, void ratios ranged from 0.57 for Mobile soil treated with 10% OPC by dry mass at an initial moisture content of 70% to 0.93 for Memphis and Mobile soils treated with 2.5% OPC at initial moisture contents of 100%. Based on Figure 3.4, void ratios for Memphis (Figure 3.4a) and Mobile (3.4.b) soils tend to consistently decrease as cement content is increased for PLC and OPC. This is expected because an increase in cement content causes an increase in the number of solid particles per unit volume. Bergado et al. (2006) found similar results when stabilizing soil from Bangkok at 100% and 130% initial moisture content with 10% and 15% cement.

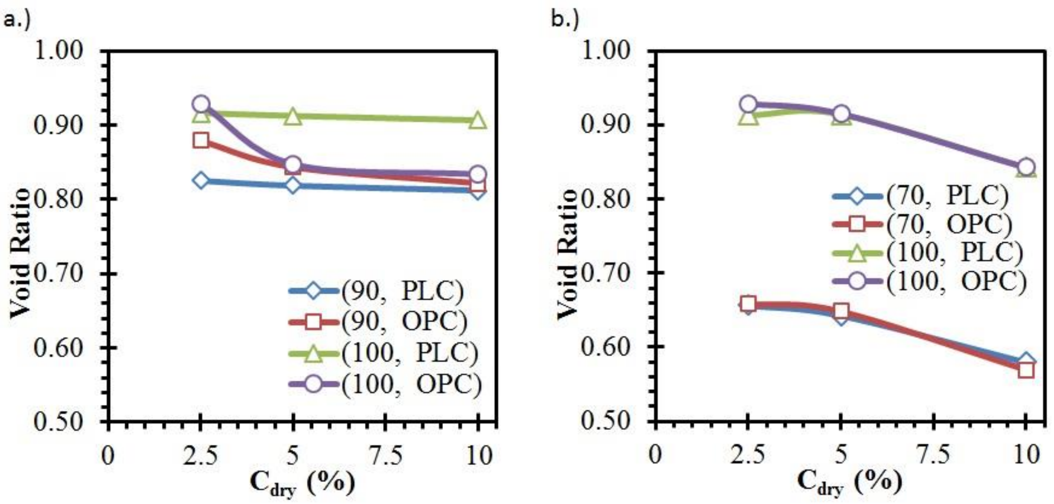


Figure 3.4 90 Day Void Ratio vs C_{dry}

a.) Memphis b.) Mobile

Results of Atterberg limit testing for stabilized Memphis and Mobile soils are shown in Figures 3.5 and 3.6, respectively. As shown, LL decreased noticeably and PL increased marginally to cause a decrease in PI for each initial moisture content, soil source, and cement type combination when dosed with 2.5% cement. It is known that cationic exchange between Ca^{++} from cement with Na^{+} and K^{+} from clay particle surfaces causes a decrease in LL (Mitchell, 1976). However, LL remained essentially constant for additional increases in cement for Memphis soils. After initial reductions in LL for Mobile soils, LL increased by 1.25% on average when increasing cement content to 5% and increased by an additional 5.25% on average when cement content was raised to 10%. High LL is attributed to large spaces between double layer particles, and further cement addition may have contributed to increasing the distance between double layers.

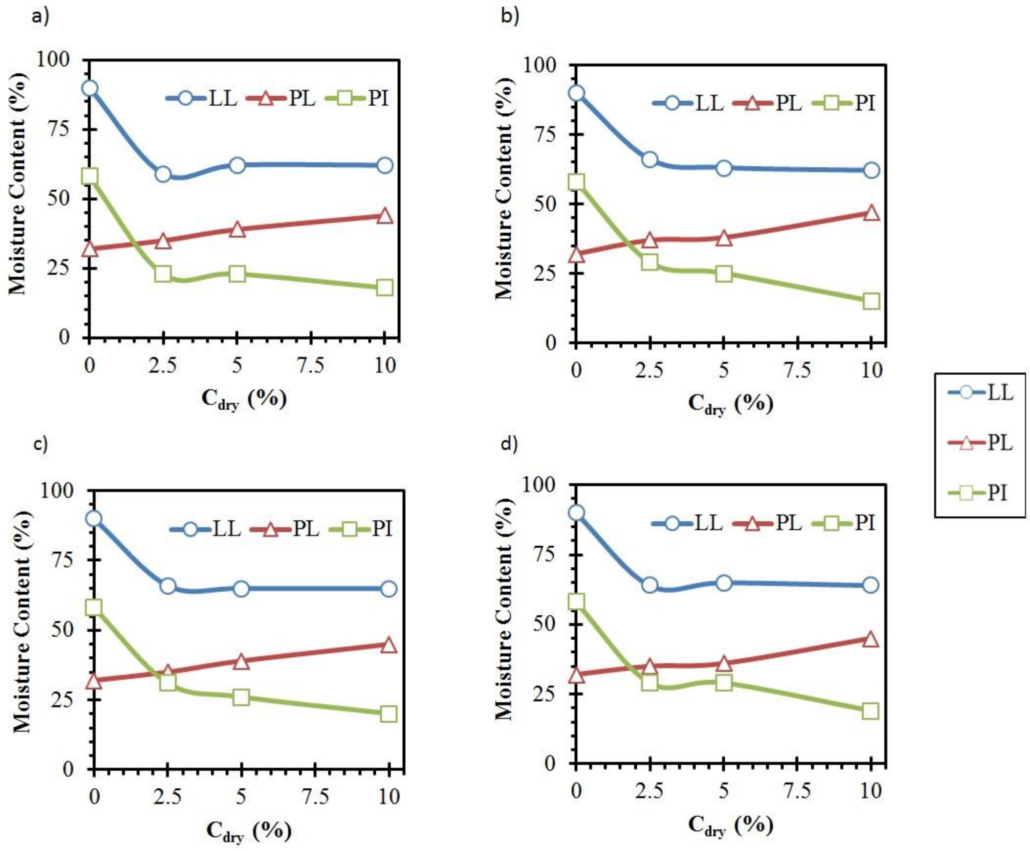


Figure 3.5 90 Day Atterberg Limits for Memphis Soils vs Cement Content

a.) 90% wc and PLC b.) 90% wc and OPC c.) 100% wc and PLC d.) 100% wc and OPC

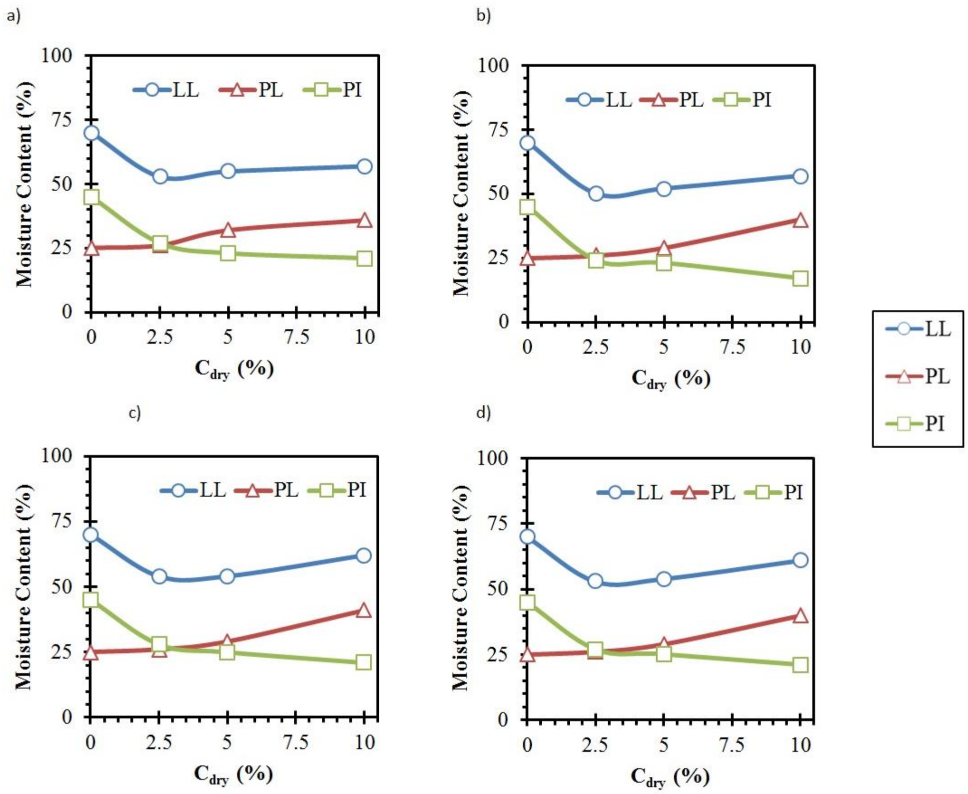


Figure 3.6 90 Day Atterberg Limits for Mobile Soils vs. Cement Content

a.) 70% wc PLC b.) 70% wc OPC c.) 100% wc PLC d.) 100% wc OPC

3.4.2 UC Test Results

Average relationships between unconfined compressive strength (q_u) of stabilized VHMS, cement type, cement content, initial moisture content, and soil type are presented in Figures 3.7 and 3.8 for Memphis and Mobile soils, respectively. When evaluated after the different cure time, q_u increased with cement content and curing time, and decreased with initial moisture content.

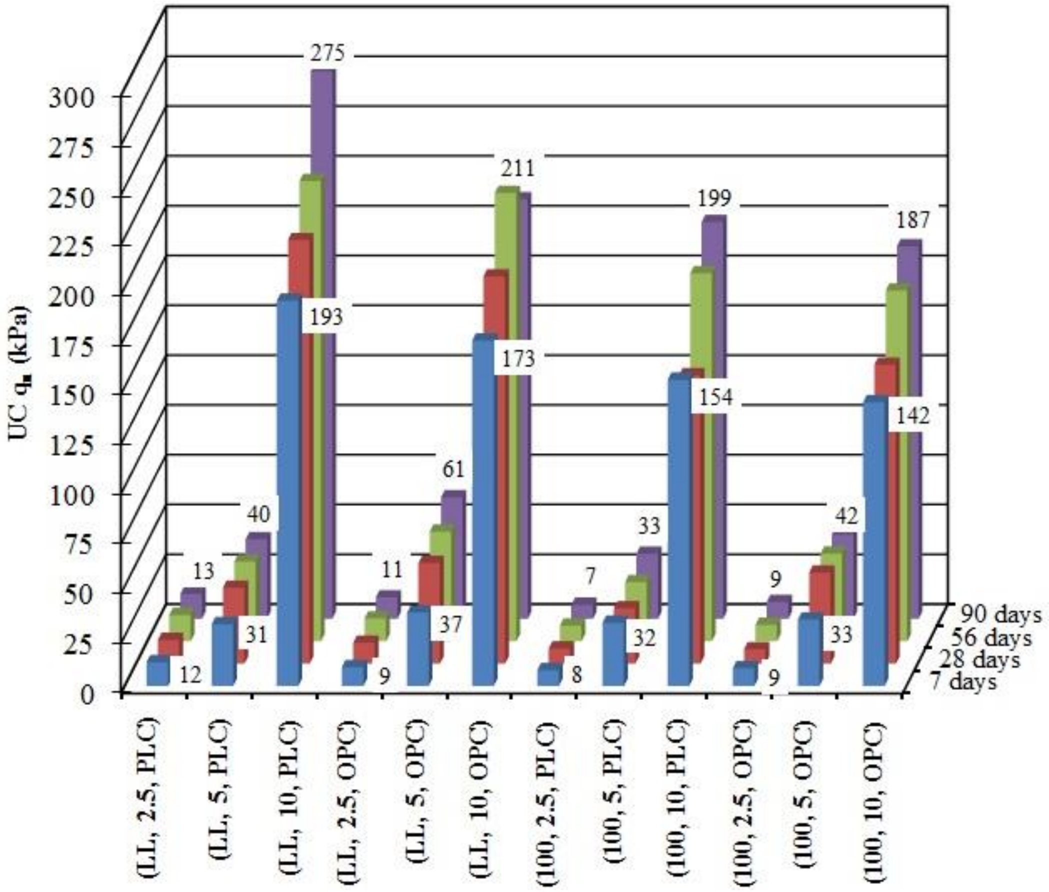


Figure 3.7 Unconfined Compressive Strengths for Memphis Specimens with Initial Moisture Content at LL and 100%

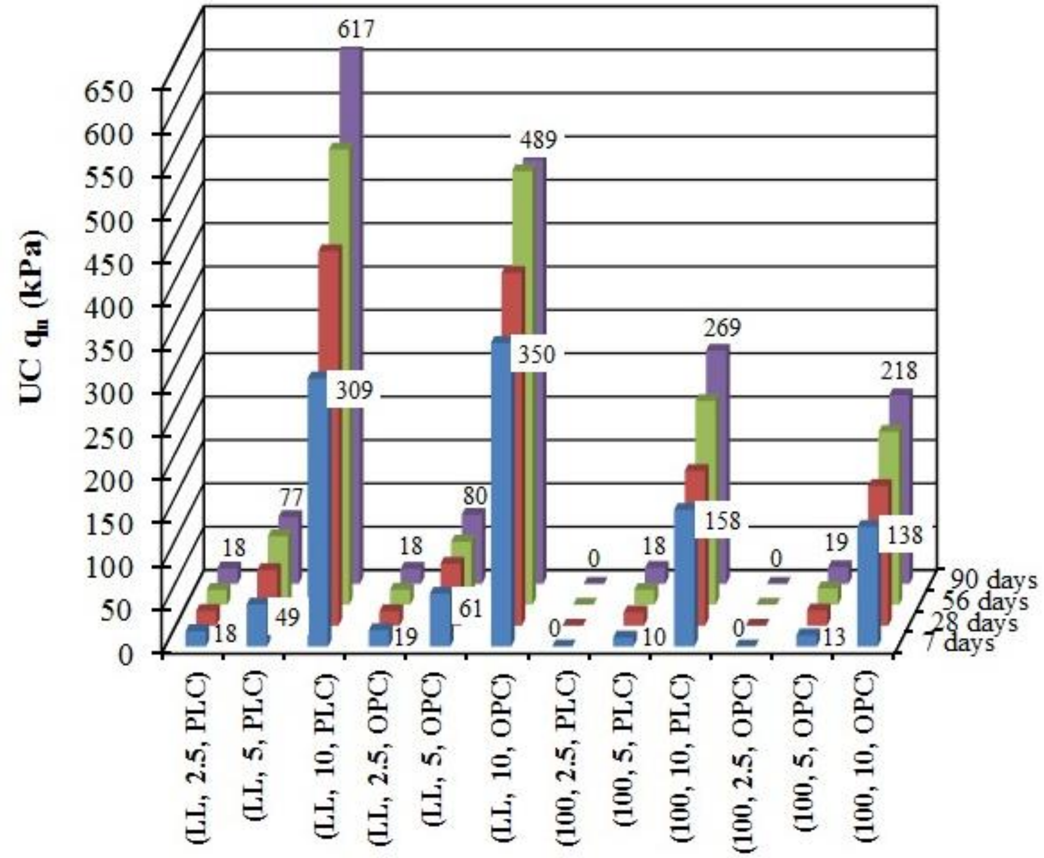


Figure 3.8 Unconfined Compressive Strengths for Mobile Specimens with Initial Moisture Content at LL and 100**%**

As shown in Figure 3.7, modest strengths were obtained by Memphis soil when treated with 2.5% and 5% cement, regardless of cement type. At 5% cement, OPC outperformed PLC by modest to noticeable margins. Much higher strength gains were observed for Memphis soil treated with 10% cement for both cement types and initial moisture contents evaluated. Interestingly, PLC specimens cured for 90 days had consistently higher q_u than OPC for both initial moisture contents considered for Memphis soils.

Data from Howard and Carruth (2015) was used to benchmark Figures 3.7 and 3.8. Soil 3 tested by Howard and Carruth (2015) was from Mobile and had similar properties to the Mobile soil tested in this study. Unconfined compressive strengths at 100% moisture and 10% cement by dry mass was 100 to 150 kPa for 7 different cements after 7 days of curing. These results are in reasonable agreement with the 150 ± 15 kPa strengths provided for 10% cement and 100% moisture in Figure 3.8.

As shown in Figure 3.8, there was no strength gain for Mobile specimens treated with 2.5% cement and 100% initial moisture content and very little strength gain with 5% cement and 100% moisture. Modestly useful strengths were produced with 5% cement at 70% moisture (LL). OPC produced strengths higher overall, but not statistically different than PLC. Strength gain that was easily a half-order of magnitude more than 5% cement was observed for Mobile soils treated with 10% cement at 70% or 100% initial moisture. Noticeably higher q_u was observed for Mobile soils treated with 10% PLC at 70% initial moisture contents. Mobile specimens had higher compressive strengths for PLC specimens than for OPC specimens for both initial moisture contents evaluated at 10% cement.

The statistical approach used herein was based on analysis of variance (ANOVA) with factorial arrangements of treatments and a response variable q_u. Most calculations were performed using the statistical package SAS. Different cure times were considered as block effects while factors of cement content, cement type, and initial moisture content were considered as treatments. Results of ANOVA analysis are shown in Table 3.3

Table 3.3 New ANOVA for q_u from UC Test Results of LC-VHMS

	Memphis			Mobile		
Source	df	p-value	Sig?	df	p-value	Sig?
Total (corr)	143			141		
Cure Time	3	<0.0001	Yes	3	<0.0001	Yes
Cement Cont. × Cement Type × Water Cont	2	0.1501	No	2	0.8855	No
Cement Cont. × Cement Type	2	<0.0001	Yes	2	0.0224	Yes
Cement Cont. × Water Cont.	2	<0.0001	Yes	2	<0.0001	Yes
Cement Type × Water Cont.	1	0.1870	No	1	0.7957	No
Cement Cont.	2	<0.001	Yes	2	<0.0001	Yes
Cement Type	1	0.4844	No	1	0.0809	No
Water Cont.	1	<0.0001	Yes	1	<0.0001	Yes
Error	129			127		

Before investigating factorial impacts, investigation into interaction between factors was evaluated. For cases where interaction was shown to be present, analysis of single factor impacts was not appropriate as interaction may alter the effects of one factor as the values of other factors change. However, individual treatment groups may still be evaluated for significant differences when interaction prevents trends analysis.

Based on Table 3.3, different cure times produced statistically different q_u for specimens exposed to the same treatment combinations (an expected result). Also, two factor interactions were significant for cement content and cement type as well as cement content and moisture content for Memphis and Mobile soils. Therefore, it is inappropriate to perform trends analysis based on individual treatments considered herein. However, multiple comparison procedures may be used to statistically rank treatment groups (Table 3.4).

Table 3.4 New Ranking of Cement Content, Cement Type, and Initial Water Content with Respect to q_u from UC Test Results of LC-VHMS

Memphis					Mobile				
Cement Type	C_{dry} (%)	Water Cont.	Mean q_u(kPa)	t - group	Cement Type	C_{dry} (%)	Water Cont.	Mean q_u(kPa)	t- group
PLC	10%	90%	228.0		PLC	10%	70%	479.8	
OPC	10%	90%	200.8	B	OPC	10%	70%	436.4	B
PLC	10%	100%	170.6	C	PLC	10%	100%	210.0	C
OPC	10%	100%	163.8	C	OPC	10%	100%	179.0	C
OPC	5%	90%	50.8	D	OPC	5%	70%	71.2	D
OPC	5%	100%	41.3	DE	PLC	5%	70%	67.2	D
PLC	5%	90%	37.2	E	OPC	2.5%	70%	17.6	E
PLC	5%	100%	30.4	E	PLC	2.5%	70%	17.4	E
PLC	2.5%	90%	12.4	E	OPC	5%	100%	17.2	E
OPC	2.5%	90%	10.5	E	PLC	5%	100%	15.3	E[1]
OPC	2.5%	100%	8.2	E	OPC	2.5%	100%	0.0	E[1]
PLC	2.5%	100%	7.6	E	PLC	2.5%	100%	0.0	E

[1]: With such a large range of values these cases were not statistically different, but they are practically different detailed caption, notes, reference, legend information, etc here

As shown in Table 3.4, LC-VHMS specimens treated with 10% cement exhibited statistically higher q_u than specimens treated with 2.5% or 5% cement for all soil source and initial moisture content combinations, as expected. However, it is interesting to see that for both soil sources, specimens treated with 10% PLC produced statistically higher q_u than specimens treated with 10% OPC when initial moisture contents were equal to the respective liquid limit of the soil tested. This difference could be the result of pozzolanic tendencies between OPC and PLC, which is discussed in the following paragraphs.

Hydraulic and pozzolanic behaviors can be evaluated by comparing compressive strength results from 7 days to 28 days and 56 days to 90 days, respectively. For cases where 28 day compressive strengths are meaningfully different from 7 day strengths, hydraulic reactions are likely. For cases where 56 day compressive strengths are very similar to 90 day compressive strengths, long term compressive strengths are less likely to rely on pozzolanic bonds. Further, statistical evaluations were performed to evaluate pozzolanic versus. hydraulic tendencies for OPC and PLC specimens. These evaluations are described in the following paragraph.

To evaluate trends of q_u with curing time, four completely randomized statistical evaluations were performed. Cement content was held constant at 10% for all evaluations of cure time trends. Soil source and cement type were held constant for each evaluation, producing four evaluations. Tables 3.5 and 3.6 provide ANOVA summaries for statistical evaluations for these four additional evaluations.

Table 3.5 New ANOVA for Cure Time Investigation Based on UC Test Results (PLC)

	Memphis			Mobile		
Source	df	p-value	Sig?	df	p-value	Sig?
Total (corr)	23			21		
Cure Time × Water Content	3	0.2858	No	3	0.0598	No
Cure Time	3	<0.0001	Yes	3	<0.0001	Yes
Water Content	1	<0.0001	Yes	1	<0.0001	Yes
Error	16			14		

--10% cement was evaluated

Table 3.6 New ANOVA for Cure Time Investigation Based on UC Test Results (OPC)

	Memphis			Mobile		
Source	df	p-value	Sig?	df	p-value	Sig?
Total (corr)	23			23		
Cure Time × Water Content	3	0.7090	No	3	0.0001	Yes
Cure Time	3	0.0064	Yes	3	<0.0001	Yes
Water Content	1	0.0005	Yes	1	<0.0001	Yes
Error	16			16		

--10% cement was evaluated

Tables 3.7 and 3.8 provide results of multiple comparison procedures where cure time and initial moisture content combinations are ranked based on q_u

Table 3.7 New Ranking of Cure Time Based on q_u from UC Test Results of LC-VHMS

Memphis (10% PLC)			Mobile (10% PLC)		
Cure Time (days)	Mean q_u (kPa)	t-group	Cure Time (days)	Mean q_u (kPa)	t-group
90	237.1	A	90	442.9	A
56	207.8	B	56	351.0	B
28	178.7	C	28	305.0	B
7	173.5	C	7	218.2	C

Table 3.8 New Ranking of Cure Time and Water Content Based on q_u from UC Test Results of LC-VHMS

Memphis (10% OPC)			Mobile (10% OPC)			
Cure Time (days)	Mean q_u (kPa)	t-group	Cure Time (days)	Water Cont.	Mean q_u (kPa)	t-group
56	200.5	A	56	70	500.0	A
90	198.8	A	90	70	489.0	A
28	172.2	B	28	70	406.7	B
7	157.8	B	7	70	350.0	C
---	---	---	90	100	217.5	D
---	---	---	56	100	199.3	D
---	---	---	28	100	161.0	E
---	---	---	7	100	138.0	F

Note: Two-way interaction of treatments prevented analyzing results for Mobile specimens based solely on Cure Time

As shown in Table 3.5, there is no significant two-way interaction between cure time and moisture content for Memphis or Mobile soils stabilized using PLC. Also, cure time and moisture content have significant effects on q_u. Based on these results, it is appropriate to rank treatment combinations through multiple comparison procedures based on cure time alone.

As shown in Table 3.6, there is no significant two-way interaction between cure time and moisture content for Memphis specimens stabilized using OPC, and cure time and moisture content have significant effects on q_u for LC-VHMS specimens from Mobile treated with OPC. However, there is significant two-way interaction between cure time and moisture content for Mobile specimens stabilized with OPC. Thus, it is appropriate to rank treatment combinations using multiple comparison procedures based on cure time alone for Memphis specimens treated with OPC. However, the effects of moisture content must be considered when ranking treatment combinations for Mobile specimens stabilized with OPC.

As shown in Tables 3.7 and 3.8, neither circumstance had 10% OPC specimens gaining significant q_u after 56 days, but there was significant strength gain after 56 days for both circumstances where 10% PLC specimens were tested. The relative behaviors of OPC and PLC at 10% by dry soil mass are interesting. PLC showed evidence of pozzolanic and hydraulic reactions, where OPC seemed to be mostly benefitting from hydraulic reactions since there was no meaningful strength gain between 56 and 90 days for LL and 100% moisture at 10% cement for both soils evaluated. Overall, q_u for PLC specimens exceeded that of OPC specimens by around 10% when moisture contents were equal to LL.

3.4.3 UU Triaxial Test Results

Figures 3.9 and 3.10 present average relationships between maximum deviator stresses (D) of stabilized VHMS, cement type, cement content, initial moisture content, and soil type for Memphis and Mobile soils, respectively. It should be noted that D in Figures 3.9 and 3.10 is average of three tests with three different confining pressures (σ_3). As shown in these figures, σ_3 is varied from 10 to 120 kPa in the text, depending upon the cement content and curing age. It is noted that confining pressures differed by cement content at 115 days of curing so Figures 3.9 and 3.10 data should not be compared between cement contents. The results show that at the same confining pressure, D increases meaningfully with increased cement content. Also the results indicate that D increases with increased curing time and decreases with increased initial moisture content. Furthermore, D increases meaningfully with increase in σ_3. Wang and Miao

(2009) indicate that cement content has a significant effect on increasing shear strength and increasing confining pressure increases shear strength due to increase friction between particles

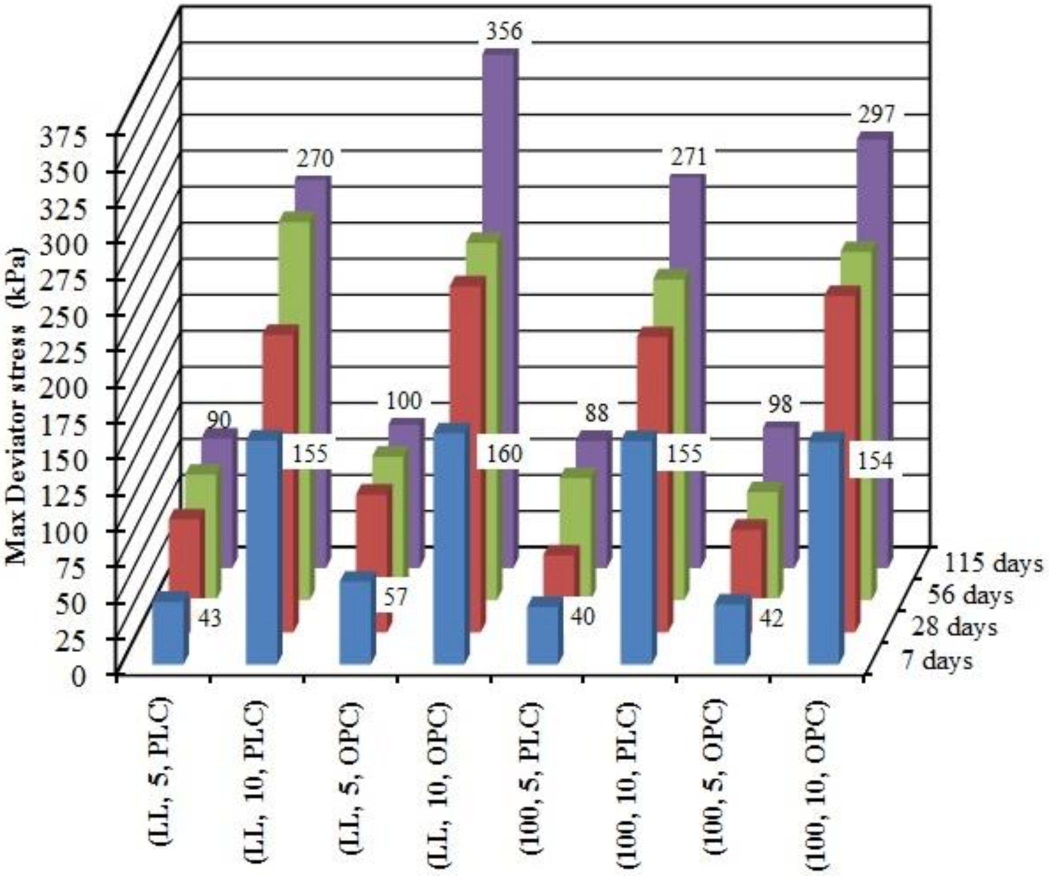


Figure 3.9 UU Triaxial Results (Maximum Deviator Stress): Memphis soil

Confining pressures tested: a) 10, 20, and 40 kPa for all mixes for 7-day specimens; b) 15, 30, and 45 kPa for all mixes for 28-day and 56-day specimens; c) 15, 30, and 45 kPa for 5% C_{dry} at 115-day specimens; and d) 15, 60, and 120 kPa for 10% C_{dry} at 115-day specimens

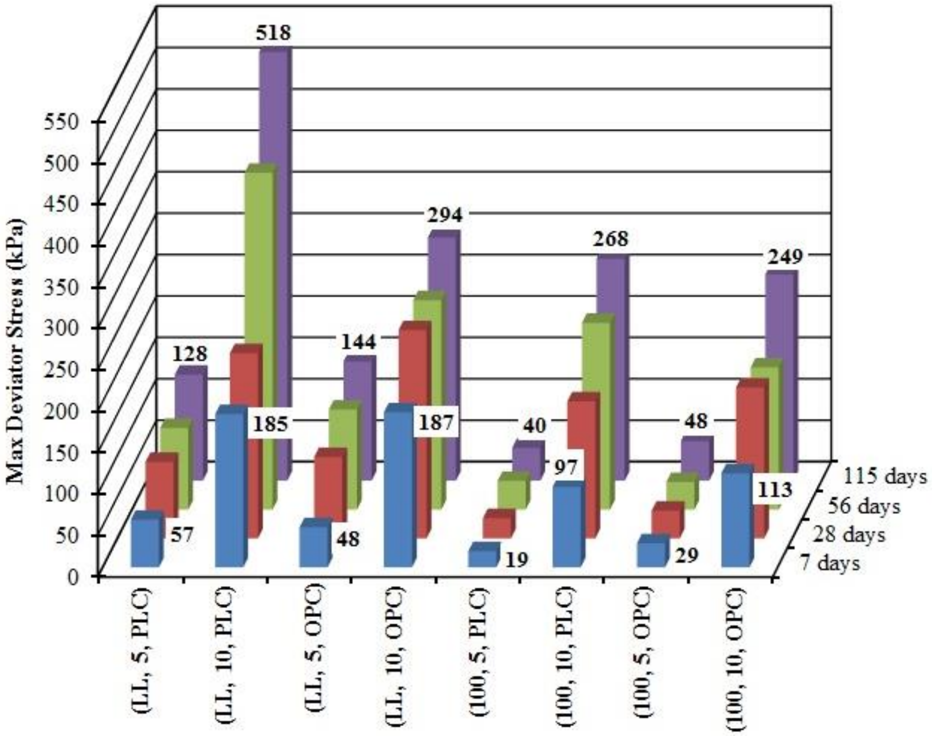


Figure 3.10 UU Triaxial Results (Maximum Deviator Stress): Mobile soil

Confining pressures tested: a) 10, 20, and 40 kPa for all mixes for 7-day specimens; b) 15, 30, and 45 kPa for all mixes for 28-day and 56-day specimens; c) 15, 30, and 45 kPa for 5% Cdry at 115-day specimens; and d) 15, 60, and 120 kPa at 10% Cdry for 115-day specimens

Mohr-Coulomb (M-C) failure envelopes were plotted for each set of specimens, to determine undrained cohesion (c_u) and the undrained angle of internal friction (ϕ_u). Further details about the UU test results including M-C failure envelope for each test can be found (Vahedifard et al. 2015). Table 3.9 shows results of c_u and ϕ_u for Memphis and Mobile soil. The results indicate that c_u increased with increased curing time, cement content, and decreased initial moisture content at a given curing time. Cement addition had a meaningful effect on increasing cohesion, but Table 3.9 shows that ϕ_u ranges from 0° to 14°, and it is related to interaction between fine particles and does not always increase with cement content increases. These results were generally expected as others have reported similar types of results (e.g., Okyay and Dias 2010; Miao et al. 2012).

Table 3.9 New Variation of Undrained Cohesion and Friction Angle of Memphis and Mobile Soils With Different Curing

Site	I D	Cured 7 Days		Cured 28 Days		Cured 56 Days		Cured 115 Days	
		c_u (kPa)	ϕ_u (°)	c_u (kPa)	ϕ_u (°)	c_u (kPa)	ϕ_u (°)	c_u (kPa)	ϕ_u (°)
ME	(LL, 5, PLC)	22	0	30	8	39	4	42	2
	(LL, 10, PLC)	77	0	93	5	107	9	132	1
	(LL, 5, OPC)	26	2	46	1	41	7	33	13
	(LL, 10, OPC)	80	0	97	9	124	0	158	5
	(100, 5, PLC)	19	1	27	0	36	5	41	3
	(100, 10, PLC)	78	0	91	5	100	5	114	6
	(100, 5, OPC)	19	2	29	6	33	4	36	10
	(100, 10, OPC)	76	1	82	14	108	5	143	1
MO	(LL, 5, PLC)	29	0	46	0	45	3	42	14
	(LL, 10, PLC)	77	8	92	9	204	0	196	12
	(LL, 5, OPC)	19	7	42	5	54	4	70	1
	(LL, 10, OPC)	94	0	95	12	116	4	138	2
	(100, 5, PLC)	7	6	12	0	16	2	18	2
	(100, 10, PLC)	50	0	83	0	111	0	107	8
	(100, 5, OPC)	15	0	11	7	14	4	19	5
	(100, 10, OPC)	58	0	88	1	86	0	96	9

Shear strength (τ_u) for UU test results are presented in Figures 3.11 and 3.12 for Memphis and Mobile soils, respectively. The figures are plotted for a normal stress (σ) of 150 kPa, which can be considered a representative normal stress for low ground pressure construction applications. As expected, Figures 3.11 and 3.12 show increasing shear strength with cement content increases. Also, the results indicated differences in shear strength with curing time (7, 28, 56, or 115 days), and the differences are noticeable at 10% cement, and initial mixing moisture content equal to the soil's liquid limit.

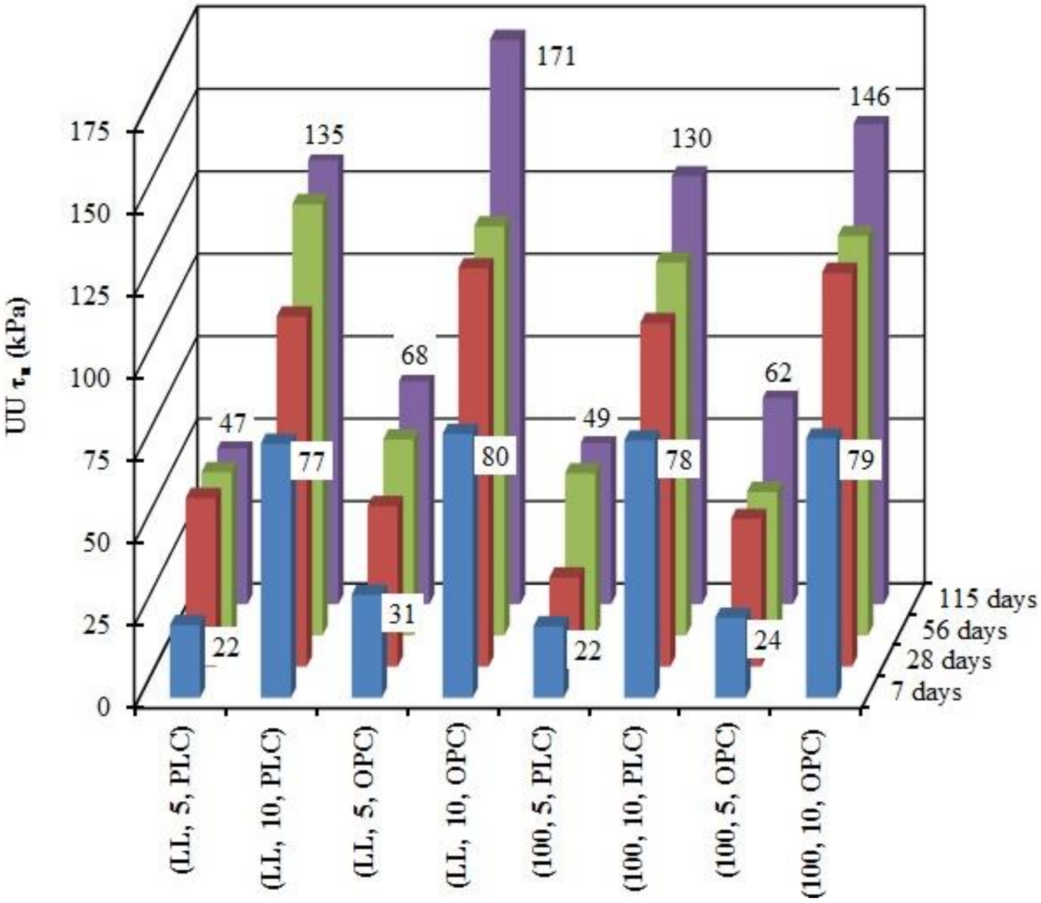


Figure 3.11 Shear Strengths for Memphis Specimens with σ =150 kPa

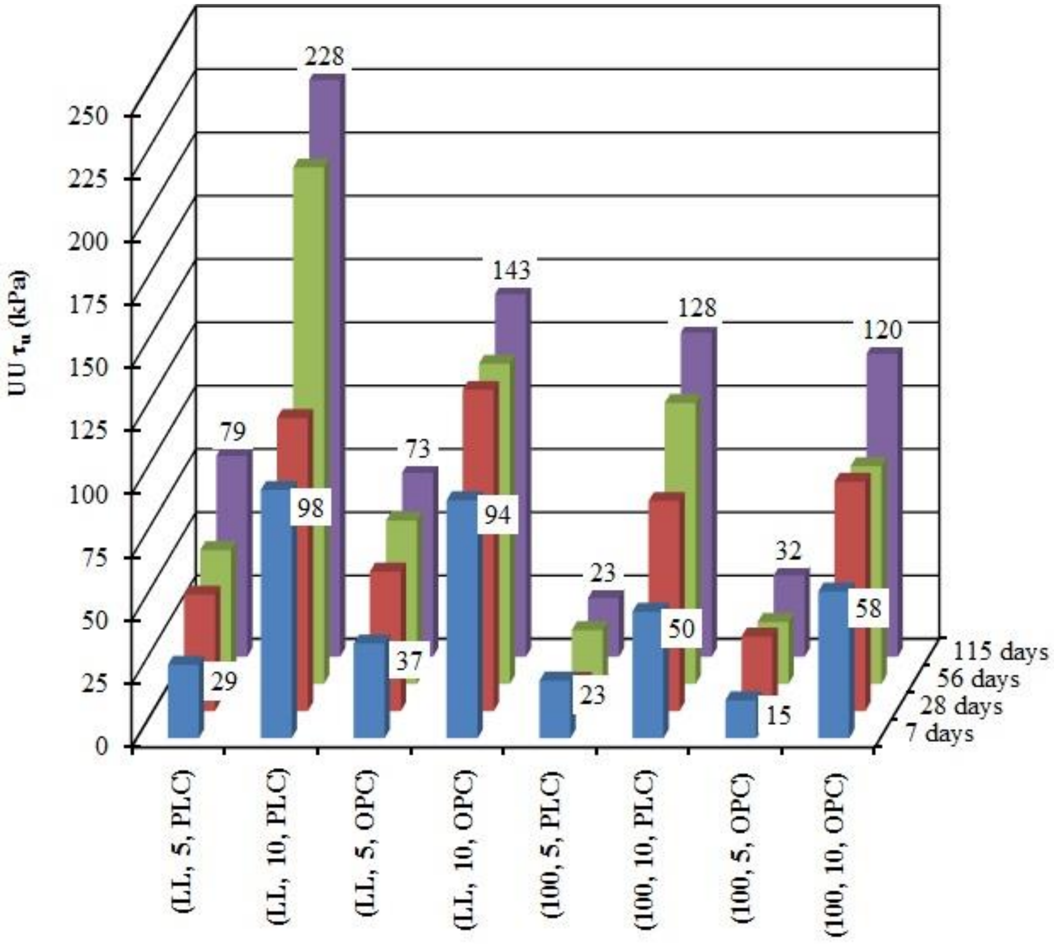


Figure 3.12 Shear Strengths for Mobile Specimens with σ = 150 kPa

It can be seen from Figures 3.11 and 3.12 that specimens treated with 10% cement by dry soil mass exhibited higher τ_u than specimens treated with 5% cement for all soil source and initial moisture content combinations, as expected. At 5% cement, OPC produced greater shear strengths than PLC for Memphis soil, and as much or more shear strength for Mobile soil. The UU findings at 5% cement generally agree with UC findings presented in Figures 3.7 and 3.8. Interestingly, findings at 10% cement did not fully agree between UC and UU testing as discussed in the next paragraph.

Mobile soil treated with 10% PLC produced higher late age shear strength than Mobile soil treated with 10% OPC, whereas 10% OPC produced higher early age shear strength. Memphis soil treated with 10% cement resulted in higher strengths at early and late ages from OPC (at early ages, strengths were only slightly higher with OPC). UC strengths in Figures 3.7 and 3.8 did not align with these results and suggested PLC outperformed OPC by a noticeable margin at 10% cement. These discrepancies may be attributed to the effect of confining pressure, though more investigation is needed before suitable answers can be provided for relative behavior of OPC versus PLC as this is an area that is largely unexplored for PLC being supplied to the southeast US marketplace since the ASTM and AASHTO test method modifications in 2012. Regardless, the potential for very useful pozzolanic behavior to be gained from PLC was documented, as was PLC's ability to, at a minimum, be competitive performance wise with ASTM C150 Type I OPC for stabilization of very high moisture content fine grained dredged soils while being more sustainable due to less embodied energy during manufacturing.

3.5 Conclusions

Lightly cemented VHMS can, as expected, be effectively produced with ordinary portland cement (e.g. ASTM C150), but the more sustainable alternative of portland-limestone cement (i.e. ASTM C1157 or C595) also showed considerable potential. The data presented utilized lower cement loadings than are typical when stabilizing fine grained dredged soil at moisture contents greater than or equal to their liquid limit. A key finding from this study is that portland-limestone cement (PLC) is promising as a sustainable stabilization agent for fine grained dredged soil and deserves further study, in particular for the potential to enhance pozzolanic (or late age) strength gain. There are applications that can make use of material having properties of some of the blends produced in this study.

Unconfined compression and unconsolidated undrained triaxial tests were performed and results indicated that mixing VHMS with varying percentages of cement up to 10% by dry soil mass reduced plasticity, void ratio and moisture content, while increasing dry density. As expected, strength increased with cement content. Effects of curing over time were much greater for specimens treated with 10% cement by dry soil mass while strength gain over time was less pronounced at lower cement contents. Moreover, what seem to be largely pozzolanic reactions were powerful enough to produce further strength after 56 days of curing in PLC in unconfined compression tests while OPC strength gain after 56 days was negligible for OPC specimens in unconfined compression testing. However, this behavior was not observed in unconsolidated undrained triaxial tests performed after 115 days of curing. It is possible that these differing trends could be the result of confining pressures applied during unconsolidated undrained triaxial testing. Overall, pozzolanic tendencies between OPC and PLC are inconclusive since UU and UC behaviors did not follow the same trends. Regardless, PLC performed at least comparable to OPC for LC-VHMS, which is the most important finding in this chapter since PLC is gaining acceptance in the marketplace due to its performance and sustainability benefits in concrete

CHAPTER IV

STABILIZED VERY HIGH MOISTURE DREDGED SOIL: RELATIVE BEHAVIOR OF PORTLAND-LIMESTONE CEMENT AND ORDINARY PORTLAND CEMENTNT

This chapter has been submitted to the ASCE Journal of Materials in Civil Engineering as a technical paper, and it is under peer review process while this dissertation has been written. This chapter has been reformatted and replicated herein with minor modifications in order to outfit the purposes of this dissertation.

4.1 Introduction and Background

Recently, dredged soils have been more at the forefront of several engineering, science, and operations discussions due at least in part to the recent expansion of the Panama Canal and the associated dredging that resulted along subsequent freight routes, ports and harbors. The most desired approach for handling dredged soils is to use them in a manner that supports the sustainability triple bottom line of economics, environment, and social well-being. The ability to achieve an economical, yet environmentally conscious solution that enhances well-being for society, however, is much more daunting than merely stating the desired approach. One avenue to beneficial reuse of dredged materials is chemical stabilization, which has been shown promising for large scale projects (e.g. Grubb et al. 2010a; 2010b). Chemical stabilization of dredged sediments also seems to have possible operational and sustainability benefits for ports and harbors as documented in Smith et al. (2016). Bazne et al. (2016) is a companion effort to this study and therein a literature review focusing on applications for lightly cemented-very high moisture content fine grained soils (abbreviated LC-VHMS) is provided that is not repeated herein. In essence, there are many applications that could make use of large quantities of dredged soil (e.g. backfill and embankments) stabilized with a modest amount of cement.

From a stabilization viewpoint, one of the most promising options to improve sustainability, and also to improve other aspects of the aforementioned triple bottom line, is to adopt portland-limestone cement (PLC) such as specified in ASTM C595, ASTM C1157, or AASHTO M240 in place of ordinary portland cement (OPC) such as specified in ASTM C150. PLC has been produced worldwide for several years, but as documented later in this study, products being produced for the southeast US construction market since 2012 have properties that differ from more traditional uses of uncalcined limestone in cement (e.g. higher Blaine fineness and consideration of limestone content to fineness relationships). While PLCs manufactured for improved synergies in the US market are relatively new to the concrete industry (ASTM C595 and AASHTO M240 were modified in 2012), their applicability in the chemical stabilization of soil is even more novel. LC-VHMS produced with PLC would have a particularly low carbon footprint considering the lower dosages of more sustainable cement.

Considering the aforementioned and longstanding issues with handling and using dredged material as well as recent PLC marketplace factors, this study’s primary objective is to characterize the behavior of PLC versus OPC in LC-VHMS to determine if PLC is a sustainable alternative to OPC for VHMS stabilization. This objective was met by way of testing five matched pairs of PLCs and five OPCs from four different cement manufacturing facilities. In three instances, OPC and PLC were produced from similar clinker and were only available for this study because of a ready mixed concrete study. Relative behavior of OPC and PLC produced from similar clinker based on the requirements in ASTM C595 (AASHTO M240) that were modified in 2012 from multiple cement sources is a rare opportunity, and one facilitated by previous ready mixed concrete work at the Mississippi State University (MSU) Construction Materials Research Center (CMRC). Several of the cements tested herein were produced and collected for a multi-year effort to demonstrate performance and sustainability benefits of PLC when used in ready mixed concrete with ample use of supplementary cementitious materials (SCMs). Interactions between PLC and SCM's can be pozzolanic in nature, which as first observed in Bazne et al. (2016), may also be a useful attribute of PLC's use in fine grained soils that can have pozzolanic potential because of their mineralogy.

In the following section, properties of the dredged soil and cements tested are presented, but in addition, rationale is presented for the cements tested in terms of their properties and also in terms of where the corresponding testing fits into existing literature related to uncalcined limestone additions to cement. Thereafter, the experimental program is presented that makes use of oven curing to simulate a wide range of ages to investigate hydraulic and pozzolanic behaviors of the various cements and their ability to stabilize VHMS. Testing consisted primarily of Atterberg Limits, Unconfined Compression (UC), and Unconsolidated Undrained (UU) triaxial protocols. Test results are then presented alongside discussion of the implications of these results couched in terms of marketplace acceptance and the triple bottom line of environment, economics, and social well-being.

4.2 Properties of and Rationale for Materials Tested

4.2.1 Dredged Soil

One dredged soil was evaluated in this study, which was taken from the US Army Corps of Engineers (USACE) in their South Atlantic Division (SAD) division and Mobile District (SAM). USACE delivered the material in super sacks in November of 2013, which was all from one location and said to be a mid-range material with respect to their dredged disposal sites in that area (i.e. there is coarser material near the inlet, but finer material near the outlet wier). The samples tested in this study was taken midway between the dredging inlet and water outlet of the disposal facility, which was a 100 acre site. USACE indicated the dredged material delivered was representative of the upper end of Mobile Harbor. Table 4.1 provides index properties of this soil, which is abbreviated MO for Mobile. This soil was also one of the materials utilized in Bazne et al. (2016) and Vahedifard et al. (2015).

Table 4.1 New Index Properties of Dredged Soil from Mobile (MO) Disposal Facility.

Property	Unit	Test Method	Average Value
Specific Gravity (G_s)	--	ASTM D584	2.57
Initial Water Content (w_c)	%	ASTM D2216	33
Max. Dry Density (γ_{dmax})	g/cm^3	ASTM D698	1.52
Optimum Moisture Content (ω_{opt})	%	ASTM D698	25
Liquid Limit (LL)	%	ASTM D4318	70
Plastic Limit (PL)	%	ASTM D4318	24
Plasticity Index (PI)	%	ASTM D4318	46
Sand	%	ASTM D422	18
Silt	%	ASTM D422	40
Clay	%	ASTM D422	42
Organic Content	%	ASTM D422	8
USCS	--	ASTM D2487	CH to OH

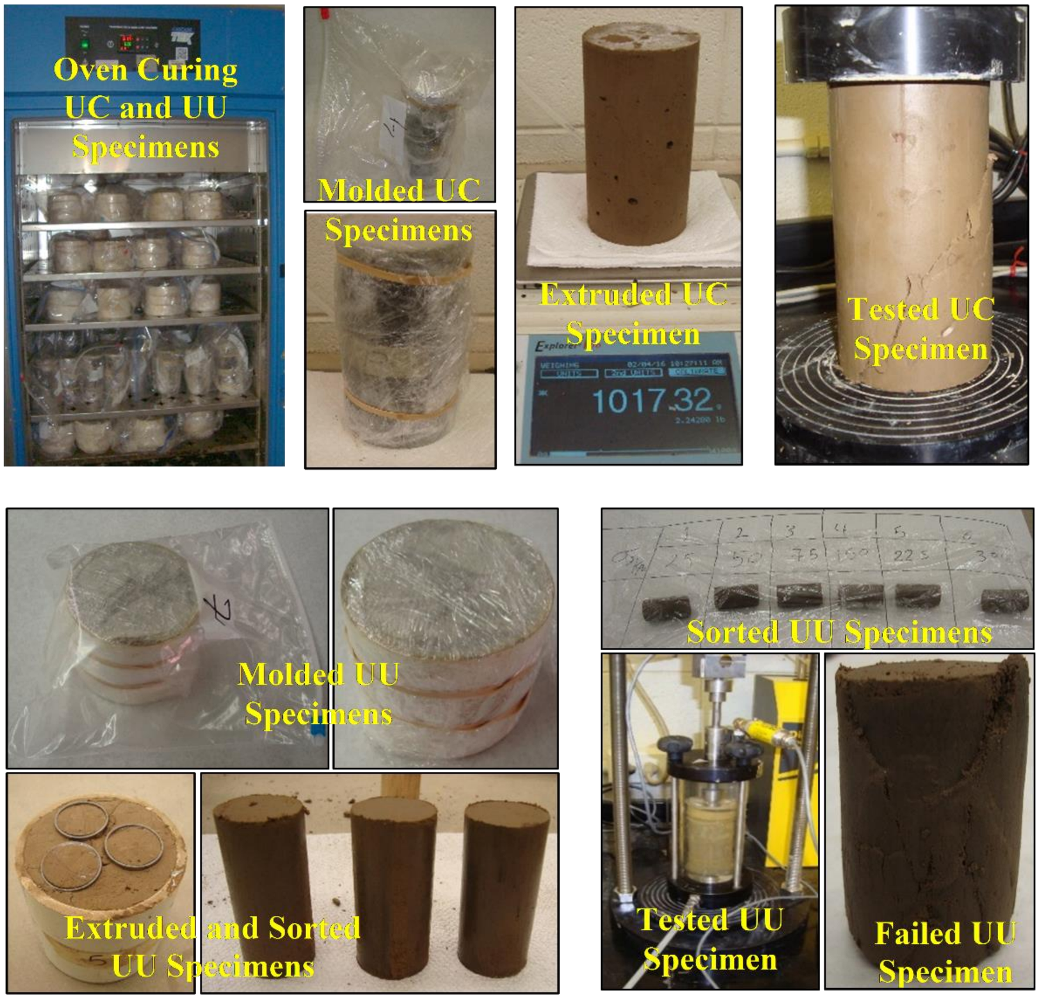


Figure 4.1 Photograph of Specimens, Curing, and Testing.

4.2.2 Cements

In this study, the term cement generically refers to OPC or (PLC, but does not refer to supplementary cementitious materials (SCMs) such as fly ash or slag cement. Five OPCs and five PLCs were utilized in this research that were taken from four different cement plants owned by four different companies, and their properties are provided in Table 4.2. The OPC samples represent a range of products, but also represent the ASTM C150 Type I or II cements normally produced at these plants. The PLC samples include a range of characteristics within the newly modified ASTM C595 specification. Before describing properties of these cements, some basic characteristics of cement manufacturing relative to these cements are presented.

The most recognizable aspect of cement manufacturing is the kiln, which is where several raw ingredients are introduced, heated to extreme temperatures, and clinker is produced. Most of the embodied energy in cement is from clinker, and as such, reducing clinker content (assuming equal performance) reduces greenhouse gas emissions and enhances sustainability. Clinker properties can vary somewhat over time, and clinker can be stored (or used immediately) at a cement plant while producing finished cement. The second major step of cement manufacturing is finish mill grinding. Clinker, gypsum, grinding aids (if included), and uncalcined crushed limestone (if included) are introduced into the finish mill, and ground to the desired level (measured as Blaine fineness) to produce the final cement product. Clinker makes up 90%(+) of the mass of typical OPC, but PLC as specified by ASTM C595 can contain up to 15% limestone (as of 2012) and as such, can have less than 90% clinker. Note that greenhouse gas emissions are reduced roughly by the limestone content used in the finish mill. That is, emissions are reduced roughly by the clinker content removed from the finish mill.

Table 4.2 New Properties of Cements Utilized for Laboratory Experiments

Cement ID	**OPC 1**	**PLC 1**	**OPC 2**	**PLC 2**	**OPC 3**	**PLC 3**	**OPC 4**	**PLC 4**	**OPC 5**	**PLC 5**
Al_2O_3 (%)	4.8	4.2	5.0	4.2	4.4	4.0	5.5	5.3	4.6	4.0
CaO (%)	64.1	64.3	64.2	64.9	63.1	63.1	63.9	63.4	63.1	63.9
SiO_2 (%)	19.9	18.2	20.3	17.9	20.3	17.9	19.1	17.8	19.0	16.7
Limestone (%)[1]	1.7	12.8	0.1	13.0	0.3	14.0	2.2	8.8	4.1	15.7
Blaine (m^2/kg)	405	538	403	579	421	556	422	522	407	681
Vicat Initial (min)	90	135	115	95	140	100	95	95	105	90
Vicat Final (min)	170	190	190	155	250	225	170	160	205	175
fc-1 D (MPa)[2]	16.6	20.4	18.0	18.7	15.2	17.1	18.2	19.9	15.0	20.1
fc-3 D (MPa)	28.6	31.0	25.9	29.5	27.0	27.4	29.7	31.8	25.8	29.2
fc-7 D (MPa)	35.2	39.2	31.6	34.1	30.2	32.3	34.6	38.0	31.8	35.6
fc-28 D (MPa)	44.7	45.6	44.0	42.8	39.3	39.7	41.4	42.8	42.1	41.2

OPC 1, PLC 1, OPC 2, and PLC 2 all came from the same plant, but were sampled several months apart. OPC 1 and PLC 1 were used in Vahedifard et al. (2015).

[1] Percent limestone reported for each cement sample was determined with split-loss type calculations as might be used in ASTM C150 reporting, though this is not a required method for reporting under ASTM C595. These values (and some chemical analysis results listed) are shown for comparative information only, and it should be noted that calculated values often slightly over-estimate actual limestone content due to trace amounts of carbon present in gypsum or other components. No samples exceeded Type IL specification limits for limestone content based on production data.

[2] fc = mortar cube compressive strength measured via ASTM C109 at test day (D) shown

Cements used in this study are paired in Table 4.2. For example, OPC 1 matches PLC 1 and OPC 5 matches PLC 5. Pairs 1 and 2 come from one cement plant. Two pairs were included from this plant for two reasons. First, OPC 1 and PLC 1 were used in the companion work of Vahedifard et al. (2015) and Bazne et al. (2016) so their inclusion in a much more detailed study from the cements perspective provides continuity. OPC 1 and PLC 1 were produced from clinker produced several months apart. Second, this cement plant was included in the CMRC ready mixed concrete work with PLC described earlier, where OPC 2 and PLC 2 were included. These two cements, however, were not produced with clinker from the same time period as they were produced several months apart. The PLC produced with the same clinker as OPC was depleted during the original study and as such was not available for this study. The remaining three pairs of cements (pairs 3, 4, and 5) were produced from similar clinker and were only available for this study because of the multi-year CMRC concrete study (Shannon 2015; Shannon et al. 2015; 2016). Having five pairs of cements that have been extensively used for characterization purposes (in particular with ample use of SCMs), with three of them having clinker from the same time period, is a key component of this research which distinguish it from previous similar studies.

Cost et al. (2013) and Cost et al. (2015) provide background information on PLC use worldwide in ready mixed concrete, which has occurred for some time, and also describe the PLC products making their way into the US market that generally have been optimized for synergy behaviors and can generally be described as having higher Blaine finess per percent of added limestone relative to past use of PLC in different countries. Until the past five years, many of the studies evaluating limestone influences when combined with SCMs came from Europe or other parts of the world, but those cements are typically coarser (i.e. lower Blaine fineness) than those currently being used in the southeast US cement market. Limestone is softer than clinker, and as such grinds more easily, making limestone particles finer than clinker particles in finished cement. When the amount of limestone is properly proportioned into an overall cement fineness (PLC total fineness needs to exceed OPC total fineness) that grinds clinker and limestone particles appropriately, there are considerable synergy potentials from PLC with ample SCMs supported by the changes to C595 and M240 in 2012.

Howard et al. (2015) was one of the first efforts to document the behaviors described in the previous paragraph in the southeast US when the expansion and renovation of Davis Wade Stadium (DWS) successfully used PLC with 50% cement replacement with SCM's. DWS had concrete with up to 70% replacement, but only OPC was used during the project for these cases. Shannon et al. (2016) investigated some of these 70% replacement concrete mixtures from DWS with PLC and found that there were some cases at these exceptionally high replacement rates where OPC outperformed PLC.

Successful outcomes from PLC over a period of 3 to 4 years led the Mississippi Department of Transportation (MDOT) to allow (and even incentivize) use of PLC statewide. As documented in Howard et al. (2016), PLC's use in the southeast construction market has grown dramatically over the past five years, which in and of itself makes the study of PLC in stabilizing VHMS important to dredging and similar industries. This is because, generally speaking, the cements used by the ready mixed concrete industry in a given region are the most logical cements for soil stabilization if their performance is reasonable since cement supply and logistics are governed by ready mixed concrete demand.

PLC's use in clay soil is largely unexplored, as Bazne et al. (2016) is one of the first efforts to do so with cements produced since 2012 to the knowledge of the authors. There is reason from literature to suggest PLC has potential in clay soil because of the favorable interaction with SCMs presented earlier in this section. It is well documented that the finely ground limestone particles in PLCs contribute to hydration efficiency both mechanically and chemically through improved particle packing, establishment of nucleation sites, formation of calcium carbo aluminates, and possibly other chemical interaction mechanisms (Tennis et al. 2011; De Weerdt et al. 2011). The availability of aluminate compounds beyond those supplied by clinker is also mentioned as a factor driving enhanced strength development in systems with SCMs (De Weerdt et al. 2011).

From the perspective of soil, hydration and pozzolanic reactions are possible when cemetitious material is blended into clay (e.g. Azhar et al. 2014; Kim et al. 2009). Basic principles of these reactions are documented in Howard et al. (2016) and summarized as follows. When cement hydrates, two main families of products are produced: 1) calcium silicate hydrate (CSH); and 2) a group of water soluble products generically referred to herein as freelime. Freelime is needed for pozzolanic reactions; for example pozzolans in the SCM fly ash provide silica to react with free lime. In soil, freelime can react with silica to form CSH, or with aluminate compounds to form calcium aluminate hydrate (CAH). CSH and CAH both lead to durable and strength producing bonds. Silica and/or alumina can be supplied by clay minerals under proper conditions (e.g. pH > 12). Overall, this is potentially meaningful relative to PLC because the finely ground limestone particles coupled with silica and/or alumina in soil could produce a sustainable and well performing cement system that makes use of a cement that is becoming more readily available

4.3 Experimental Program

4.3.1 Sample Preparation and Testing Matrix

Table 4.3 presents the testing matrix for UC and UU testing. A total of 300 specimens were tested, including 60 specimens for UC and 240 specimens for UU. Index properties of the tested specimens were also measured.

For all tests, dredged soil samples collected from Mobile were prepared into slurry by mixing soil with water to generate VHMS at 100% initial moisture content (w_c = 100%). UC specimens were prepared using plastic molds (165 mm tall and 76.2 mm diameter). A thin aluminum plate was placed at the bottom of each model to facilitate specimen removal. Stabilized slurry was added in 3 lifts with the mold being tapped 25 times around the side between each lift to insure uniform specimen production. Specimens were then covered with a plastic cap, surrounded with saran plastic wrap and kept in a plastic freezer bag (Figure 4.1) to minimize moisture loss. UU specimens were prepared by placing material in PVC molds (95 mm tall and 100 mm diameter). Stabilized slurry was added in 3 lifts with the mold being tapped 25 times around the side between each lift to insure uniform UU specimen production. The UU molds were covered with aluminum foil fitted with a cover, surrounded with saran plastic wrap and kept in a plastic freezer bag (Figure 4.1) to minimize moisture loss. Once fully prepared, UC and UU specimens were cured in a force draft oven at 60 °C (Figure 4.1).

Table 4.3 New UC and UU Testing Matrix

Site	**Initial w_c (%)**	**C_{dry} (%)^A**	**Cement ID PLC/OPC**	**Specimens**
MO	100	10	1	UC^B, UU^C
			2	
			3	
			4	
			5	

A: cement dosage was 10% by dry soil mass, which at 100% moisture is 5% dosage by slurry mass.
B: UC testing had 1 initial moisture content, 10 cements (5 PLC, 5 OPC), 1 cement dosage, 2 test ages (9, 95 days), and 3 replicates for 60 total UC specimens.
C: UU testing had 1 initial moisture content, 10 cements, 1 cement dosage, 4 test ages (3, 9, 27, and 95 days), 6 confining pressures (25, 50, 75, 150, 225, and 300 kPa), and 1 replicate, for a total of 240 UU specimens

Prior to oven conditioning of the actual tested specimens, a trial run was performed with LC-VHMS prepared as part of a parallel effort. Immediately after cement addition, the LC-VHMS used for the trial run had a moisture content of 132%. This moisture content decreased to 122% after approximately 2 weeks of 60 °C oven curing. This level of moisture loss, while not ideal, was deemed acceptable for these experiments since OPC and PLC were treated identically in a blocked experiment where the goal of the investigation was to compare OPC to PLC. Readers should view test results with the understanding that there is some moisture loss with time that affects measurements over time but that OPC to PLC comparisons are not affected.

4.3.2 Index Properties

Average moisture content, dry density, and void ratio were measured for UU test specimens after 3, 9, 27 and 95 days of curing. Moisture content was also measured prior to adding cement (denoted "Initial w_c%" in Figure 4.2), and immediately after adding cement (denoted "Adding C" in Figure 4.2). The void ratio was determined using wet and dry density, while moisture contents were evaluated for each specimen tested. Atterberg limits and organic content were determined for each UU test group that cured for 3, 9, 27 and 95 days. Atterberg Limit samples were prepared by pulverizing soil from a given UU group sample that had passed through the No 40 sieve and air dried for few hours to reduce moisture content. Decreasing moisture was performed in four stages, the first three stages were allowed to run liquid limits test while the last stage of air drying allowed to run plastic limits test. According to ASTM D4318 (multi-point procedure) were followed regarding determining Atterberg limits.

Organic content was determined according to ASTM D2974- Test Method D by subtracting the percentage of ash content from 100% of the soil sample. The percentage of ash content was determined by evaluating the remaining of soil sample after igniting the oven-dried sample from the moisture content determination in a furnace at 750°C.

4.3.3 Unconfined Compression Test Methods

After curing, the UC specimens were extruded from the molds and tested (Figure 4.1). UC tests were conducted according to ASTM D2166 with a strain rate of 1% /min, 0.5% strain past the maximum force, and using the corrected area for stress and strain determination.

4.3.4 Unconsolidated Undrained Test Methods

For each group of UU testing, six specimens (70.28 mm tall and 35 mm diameter) were extruded from two UU molds (three specimens from each mold) and tested. UU tests were conducted according to ASTM D2850 and confining pressures were 25, 50, 75, 150, 225 and 300 kPa. The maximum deviator stress was considered as the failure point for the specimens tested. The UU molds and specimens are shown in Figure 4.1. After curing, UU specimens were sampled from their respective curing molds and sorted in a logical order based on test type, group and sample prepared. Sorting molds prior to testing made it simpler to recognize data and logically select the cured mold.

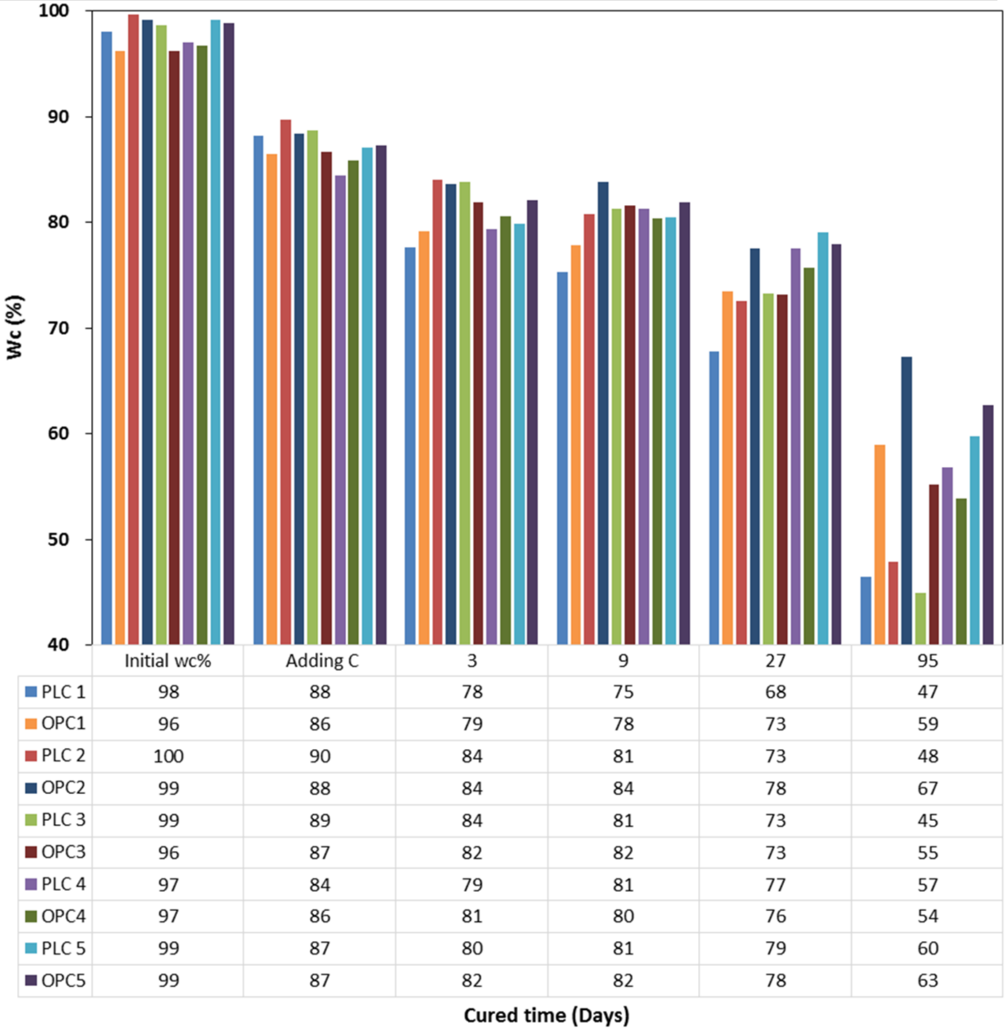
4.4 Test Results

4.4.1 Index Property Results

Figure 4.2 shows moisture content progressions with time. A decrease in initial moisture content occurred immediately after cement addition (i.e. compare between “Initial wc%” and “Adding C” in Figure 4.2). As shown in Figure 4.2, average moisture contents for treated soil were reduced from 98 to 87% immediately after addition cement. Also, the magnitude of water reduction increases with curing time and the relationship between final moisture content, curing time and groups of cement type is not linear.

These results were generally expected as others have reported similar types of results (e.g. Kamon et al., 1991; Chew et al., 2004). There were no meaningful overall differences in moisture content based on average readings for OPC relative to PLC until 95 days of curing, where samples treated with PLC showed more moisture reduction (51% on average) than samples treated with OPC (60% on average).

Avg-All	**98**	**87**	**81**	**80**	**75**	**55**
Avg-OPC	**97**	**87**	**81**	**81**	**76**	**60**
Avg-PLC	**99**	**88**	**81**	**80**	**74**	**51**



	Initial wc%	Adding C	3	9	27	95
■ PLC 1	98	88	78	75	68	47
■ OPC1	96	86	79	78	73	59
■ PLC 2	100	90	84	81	73	48
■ OPC2	99	88	84	84	78	67
■ PLC 3	99	89	84	81	73	45
■ OPC3	96	87	82	82	73	55
■ PLC 4	97	84	79	81	77	57
■ OPC4	97	86	81	80	76	54
■ PLC 5	99	87	80	81	79	60
■ OPC5	99	87	82	82	78	63

Figure 4.2 Moisture content results versus time

Figure 4.3 presents dry densities that were evaluated for each group of UU specimens. Dry densities ranged from 0.8 to 0.9 g/cm^3. For each treatment group, dry density increased with increased curing time. When all Figure 4.3 data is averaged for OPC and PLC, OPC densities were slightly less than 0.01 g/cm^3 heavier than PLC, which is not a meaningful difference

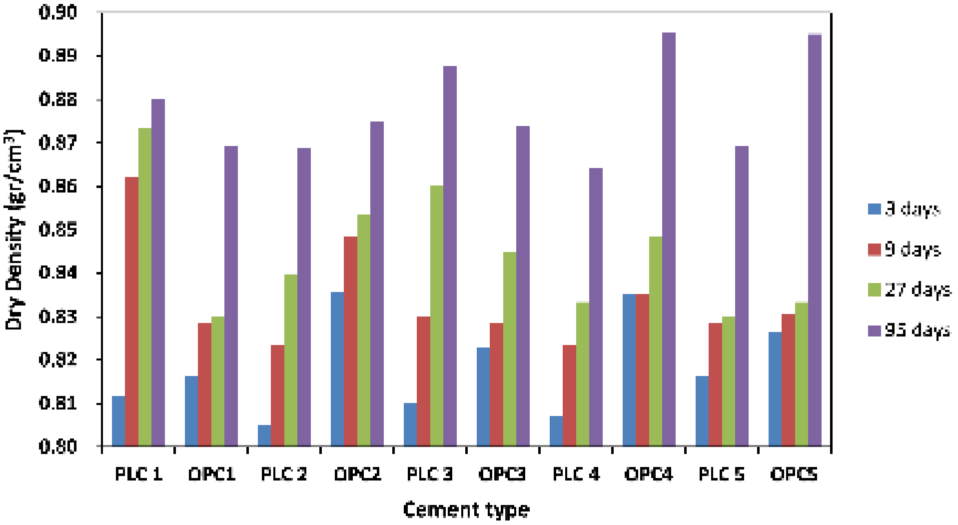


Figure 4.3 Dry density versus cement type at different curing time

Void ratios were determined using wet and dry unit weights from each group of UU specimens. Figure 4.4 displays the determined void ratios which ranged from 1.89 to 2.22. Based on Figure 4.4, void ratios tend to consistently decrease as curing time is increased for the selected soil treated with groups of PLC and OPC, which is expected. Bergado et al. (2006) found similar results when stabilizing soil from Bangkok at 100% and 130% initial moisture content with 10% and 15% cement.

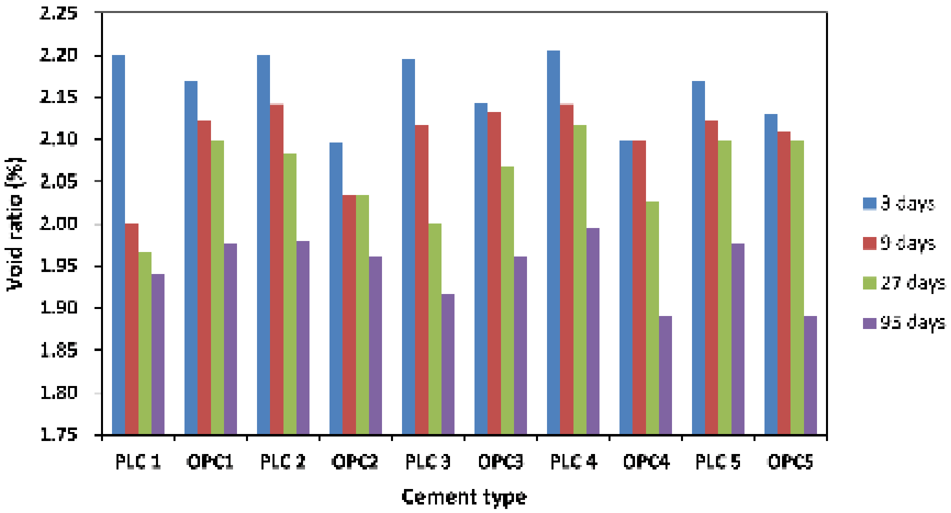
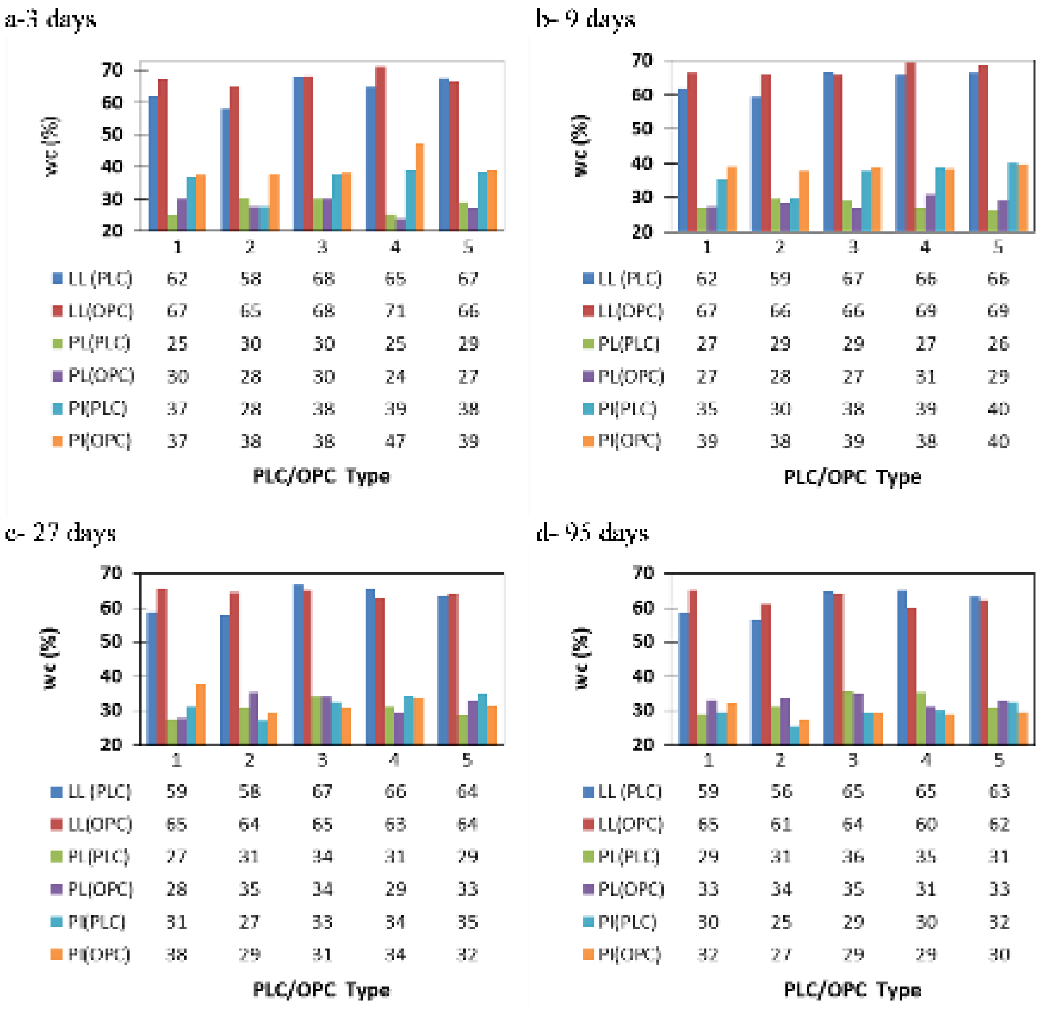


Figure 4.4 Void ratio versus cement type at different curing times

Figure 4.5 shows results of Atterberg Limits testing. By lightly cementing the soil, LL decreased noticeably and PL increased marginally to cause a decrease in PI. Paired two tail *t*-testing at a 5% level of significance was performed on LL and PL with the following results. The average difference in LL between OPC (65.5) and PLC (63.0) was statistically significant (*p-value* of 0.01). The average difference in PL between OPC (30.3) and PLC (29.6) was not statistically significant (*p-value* of 0.28). Practically, an average liquid limit change of 2.5% and an average plastic limit change of 0.7% OPC to PLC is not especially meaningful relative to marketplace acceptance (either cement type was practically the same over several sources).



a-3 days

	1	2	3	4	5
LL (PLC)	62	58	68	65	67
LL(OPC)	67	65	68	71	66
PL(PLC)	25	30	30	25	29
PL(OPC)	30	28	30	24	27
PI(PLC)	37	28	38	39	38
PI(OPC)	37	38	38	47	39

b- 9 days

	1	2	3	4	5
LL (PLC)	62	59	67	66	66
LL(OPC)	67	66	66	69	69
PL(PLC)	27	29	29	27	26
PL(OPC)	27	28	27	31	29
PI(PLC)	35	30	38	39	40
PI(OPC)	39	38	39	38	40

c- 27 days

	1	2	3	4	5
LL (PLC)	59	58	67	66	64
LL(OPC)	65	64	65	63	64
PL(PLC)	27	31	34	31	29
PL(OPC)	28	35	34	29	33
PI(PLC)	31	27	33	34	35
PI(OPC)	38	29	31	34	32

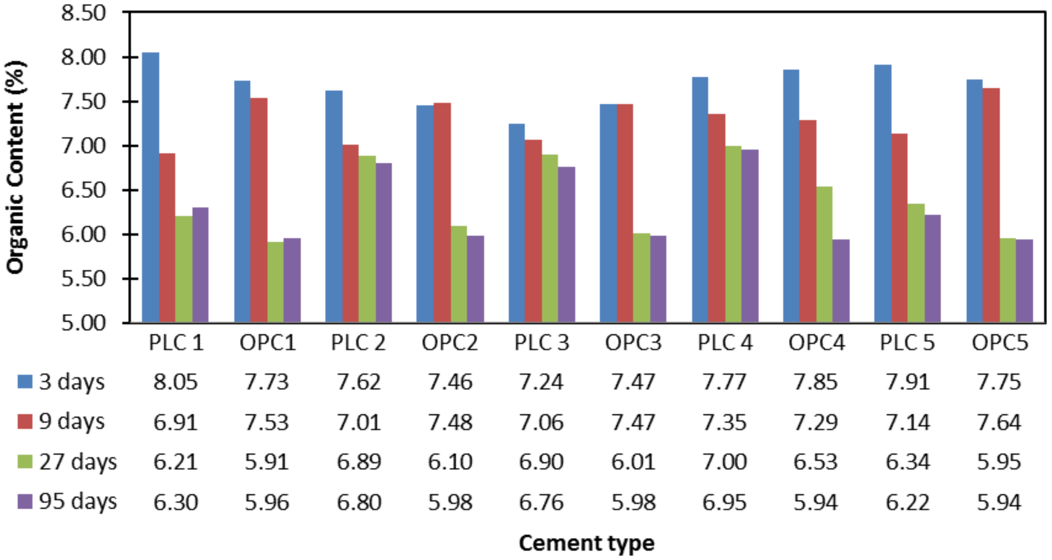
d- 95 days

	1	2	3	4	5
LL (PLC)	59	56	65	65	63
LL(OPC)	65	61	64	60	62
PL(PLC)	29	31	36	35	31
PL(OPC)	33	34	35	31	33
PI(PLC)	30	25	29	30	32
PI(OPC)	32	27	29	29	30

Figure 4.5 Atterberg limit versus cement type at different curing time

Figure 4.6 shows organic content reduced with cement addition and cure time as expected. Decreasing organic content could be the result of an increase in the inorganic content from adding cement, as well as hydraulic and pozzolanic reactions that reduce the influence of organic matter. Chen and Wang (2006) demonstrated that a cement component (calcium sulphate) restricts organic content's impact by allowing soil particles to crystallize and limit the organic component's influence. Paired two tail *t*-testing at a 5% level of significance showed the average difference in organic content between OPC (6.8) and

PLC (7.0) was not statistically significant (*p-value* of 0.057). Practically, these organic contents are the same. Overall, there were, at best, modest differences between OPC and PLC for several marketplace cements indicating that use of PLC in place of OPC would have no meaningful performance effects with regard to index properties

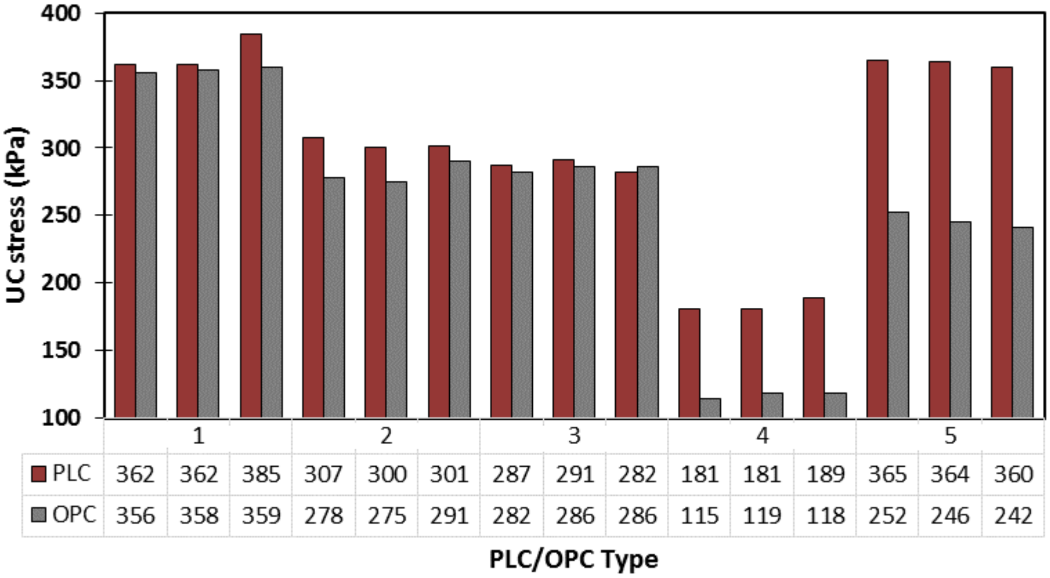


	PLC 1	OPC1	PLC 2	OPC2	PLC 3	OPC3	PLC 4	OPC4	PLC 5	OPC5
🟦 3 days	8.05	7.73	7.62	7.46	7.24	7.47	7.77	7.85	7.91	7.75
🟥 9 days	6.91	7.53	7.01	7.48	7.06	7.47	7.35	7.29	7.14	7.64
🟩 27 days	6.21	5.91	6.89	6.10	6.90	6.01	7.00	6.53	6.34	5.95
🟪 95 days	6.30	5.96	6.80	5.98	6.76	5.98	6.95	5.94	6.22	5.94

Figure 4.6 Organic content versus cement type at different curing times

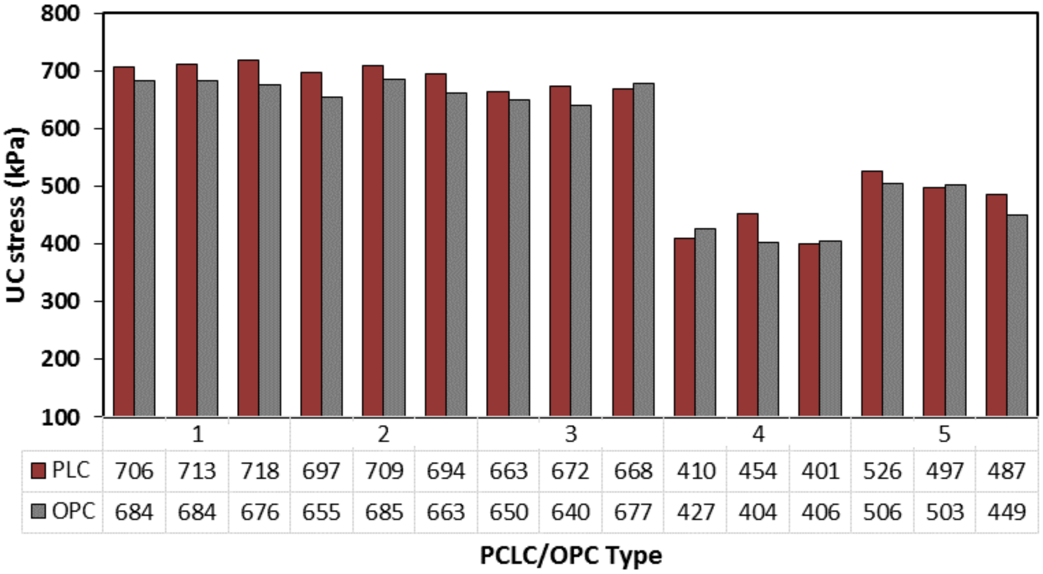
4.4.2 Unconfined Compression Test Results

Figures 4.7 and 4.8 present UC strength (q_u) results. Figure 4.7 (9 days oven cured) shows that VHMS treated with PLC’s 1 to 3 are slightly stronger than those treated with OPC, but that PLC’s 4 and 5 are considerably stronger than OPC. Figure 4.8 (95 days oven cured) shows that OPC and PLC strengths converged to a large degree as PLC is only slightly stronger than OPC. On average, PLC’s had an unconfined compressive strength of 301 kPa after 9 days of oven curing, whereas OPC had an average strength of 258 kPa (a 17% difference). After 9 days of oven curing, PLC ranged from 4 kPa weaker to 118 kPa stronger. The 17% average strength increase from PLC was largely driven by PLC 4 and 5, which interestingly have the highest and lowest limestone contents evaluated (15.7, 8.8%), but also have correspondingly different Blaine fineness values. After 95 oven curing days, VHMS treated with PLC's average strength was 601 kPa, which exceeded OPC's average strength of 581 kPa by a modest 3%. After 95 days of oven curing, PLC ranged from 17 kPa weaker to 50 kPa stronger.



	1			2			3			4			5		
🟥 PLC	362	362	385	307	300	301	287	291	282	181	181	189	365	364	360
■ OPC	356	358	359	278	275	291	282	286	286	115	119	118	252	246	242

Figure 4.7 Unconfined compression strength for specimens treated with PLC and OPC for 9 days



	1			2			3			4			5		
🟥 PLC	706	713	718	697	709	694	663	672	668	410	454	401	526	497	487
▩ OPC	684	684	676	655	685	663	650	640	677	427	404	406	506	503	449

Figure 4.8 Unconfined compression strength for specimens treated with PLC and OPC for 95 days

Paired two tail *t*-testing at a 5% level of significance for all UC data showed the average PLC strength of 451 kPa was significantly different than the average OPC strength of 419 kPa (*p-value* of 4e-5). Figure 4.9 is an equality plot comparing PLC and OPC unconfined compressive strengths. Figure 4.9 shows that PLC was noticeably stronger in a few cases, but never noticeably weaker than OPC. Regression through the origin (RTO) of all Figure 4.9 data showed PLC to be 5% stronger than OPC (R^2 of 0.95). UC testing showed PLC, overall, to be a better strength producing cement than OPC in fine grained VHMS. However, this strength improvement was fairly modest overall, especially considering that changing cement source (e.g. source 1 versus source 4) was far more meaningful for strength development

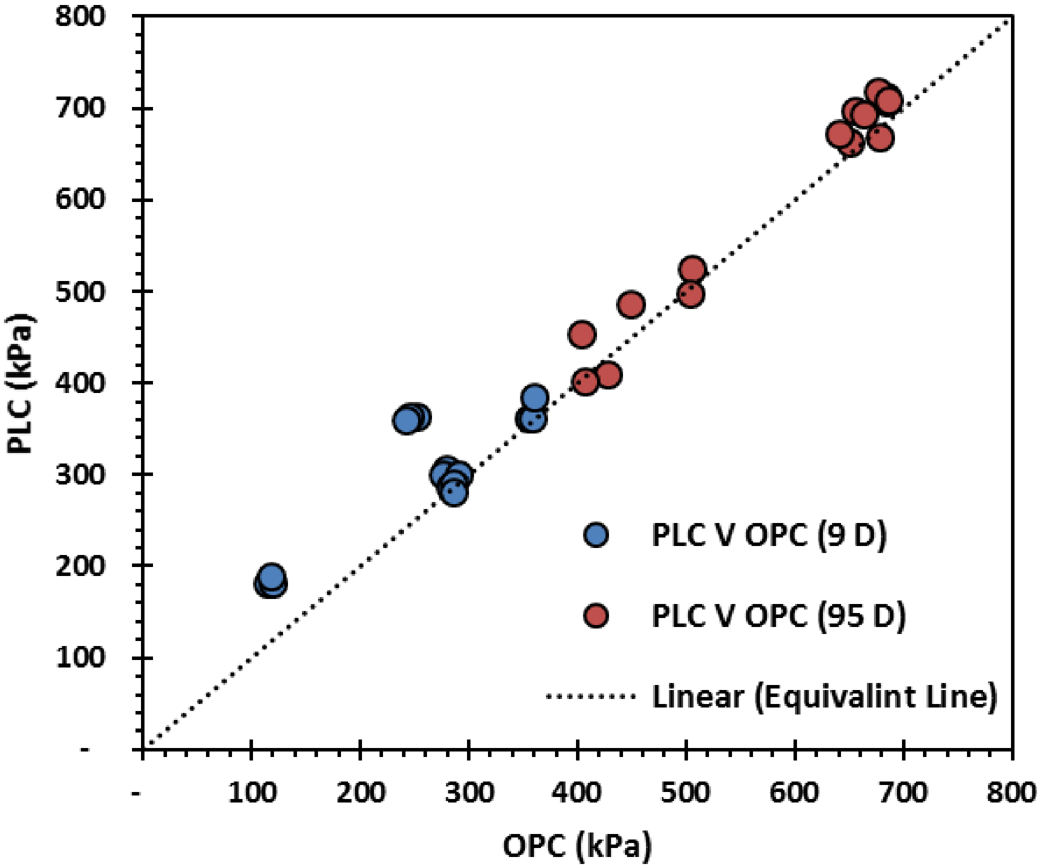


Figure 4.9 Unconfined compression strength for specimens treated with PLC versus OPC for 9 and 95 days

4.4.3 Unconsolidated Undrained Test Results

Table 4.4 shows the maximum deviator stress (D) results from triaxial testing. As expected, strength growth occurred from increased cure time or confining pressure. Figure 4.10 provides example plots as a function of confining pressure. The influence of confining pressure was more pronounced over time. Other studies (e.g., Sariosseiri and Muhunthan 2009; Wang and Miao 2009) indicated that increasing confining pressure increases shear strength due to increased friction between particles.

Table 4.4 New Maximum deviator stress (D) for LC-VHMS with both groups of PLC and OPC individually and at varied curing time in days (d)

Cement Source	Confining Pressure (σ_3) (kPa)	PLC	OPC	PLC	OPC	OPC	OPC	PLC	OPC
		3d (kPa)		9d (kPa)		27d (kPa)		95d (kPa)	
1	25	143	161	404	439	589	720	1,021	1,009
	50	147	191	429	465	602	800	1,144	1,327
	75	170	215	463	494	789	928	1,238	1,454
	150	204	242	581	620	941	999	1,687	1,587
	225	216	277	633	670	987	1,113	2,046	1,786
	300	265	327	704	743	1,090	1,280	2,205	2,077
2	25	225	190	374	397	609	689	998	913
	50	234	224	406	429	631	787	1,190	1,038
	75	241	270	432	435	695	840	1,402	1,304
	150	308	297	488	539	824	912	1,828	1,393
	225	326	302	552	573	984	967	2,170	1,723
	300	358	341	572	676	989	1,099	2,504	1,924
3	25	172	248	329	451	536	747	1,041	1,266
	50	183	261	354	463	653	789	1,090	1,417
	75	226	299	385	465	759	876	1,165	1,620
	150	269	335	416	541	866	1,146	1,522	1,871
	225	285	360	479	598	1,010	1,179	1,794	2,205
	300	324	388	509	605	1,061	1,265	1,989	2,516
4	25	109	138	297	138	425	430	720	837
	50	125	147	305	147	432	471	870	952
	75	161	159	327	159	501	492	935	1,083
	150	192	170	339	170	570	593	1,359	1,268
	225	203	208	359	208	737	648	1,579	1,627
	300	247	216	431	216	750	676	1,825	1,746
5	25	255	205	419	452	606	580	914	810
	50	268	202	451	465	663	683	1,030	939
	75	271	222	484	483	739	772	1,139	1,118
	150	312	232	554	512	823	849	1,396	1,464
	225	322	273	577	606	872	999	1,741	1,717
	300	354	312	599	647	936	1,006	1,889	1,803

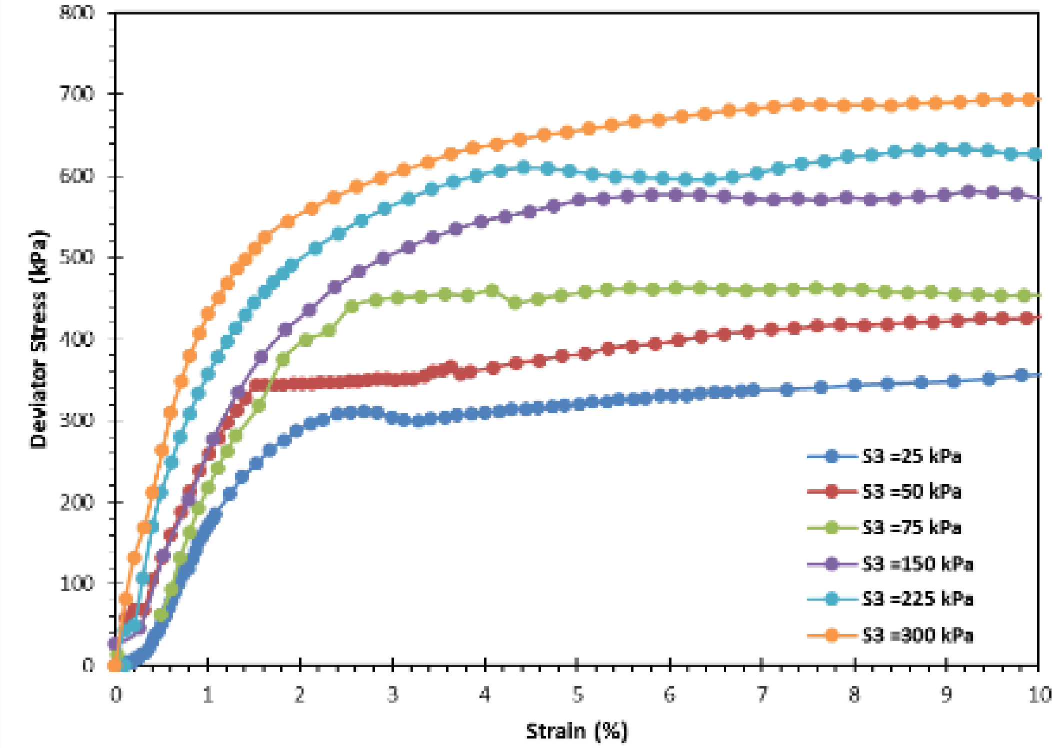
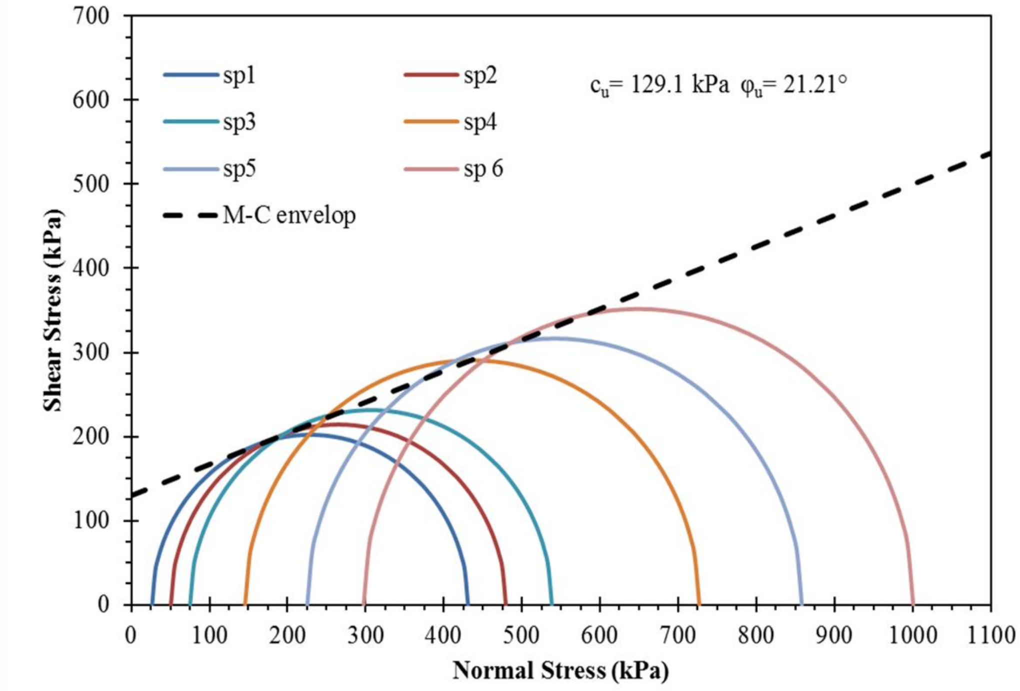


Figure 4.10 Deviator stress versus strain
(UU test PLC1-9 days)

Figure 4.11 shows example Mohr-Coulomb (M-C) failure envelopes that were plotted for each set of specimens, to determine undrained cohesion (c_u) and the undrained angle of internal friction (ϕ_u). Figures 4.12 and 4.13 present c_u and ϕ_u results and show c_u and ϕ_u increasing with curing time. Miao et al. (2012) and Okay and Dias (2010) provide complimentary data. Figure 4.14 presents shear strength (τ_u) calculated at a normal stress (σ) of 150 kPa, which can be considered a representative normal stress for low ground pressure construction applications

a) PLC 1 – 9 day cure



b) OPC 1 – 9 day cure

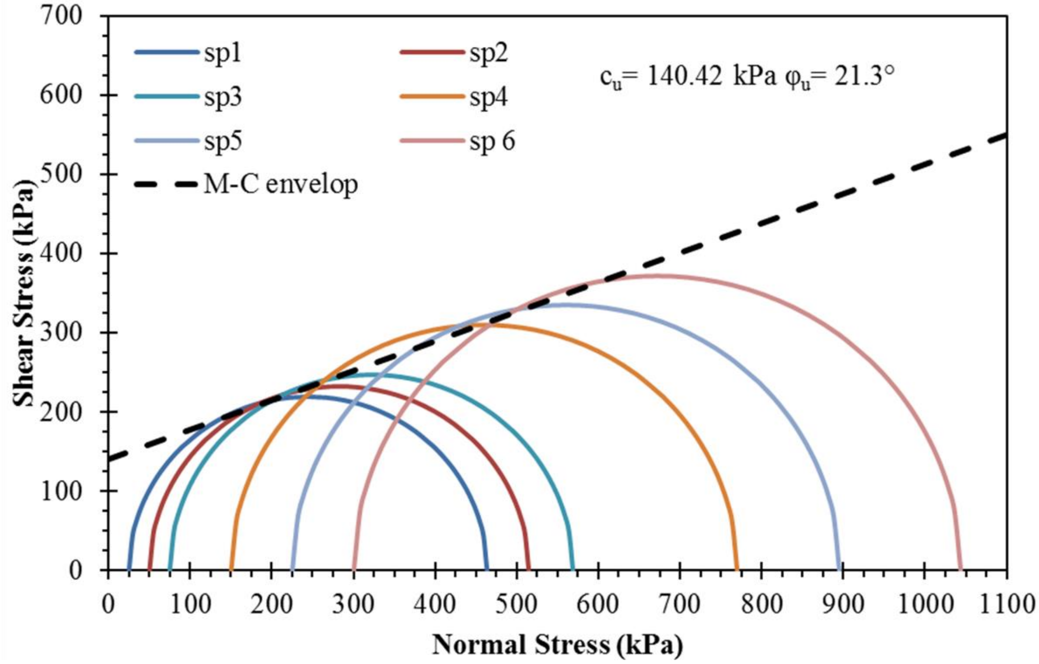
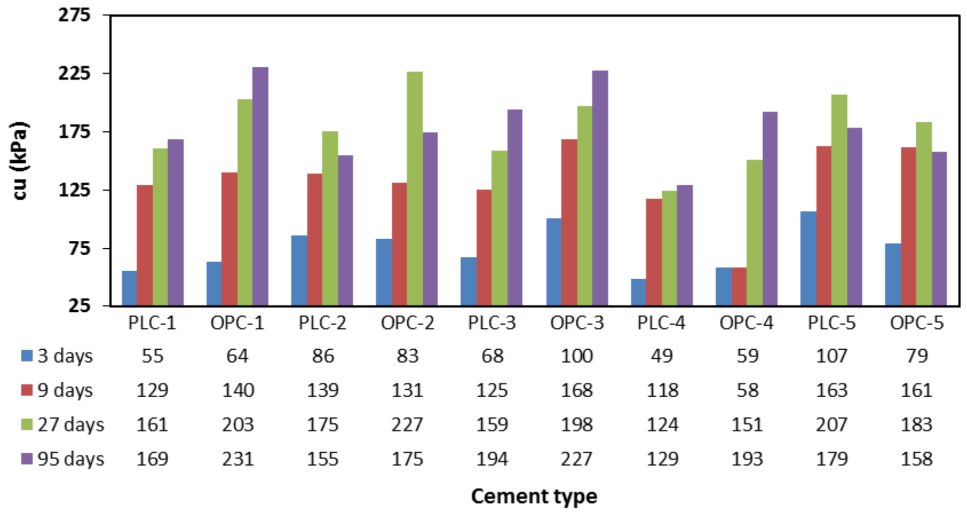
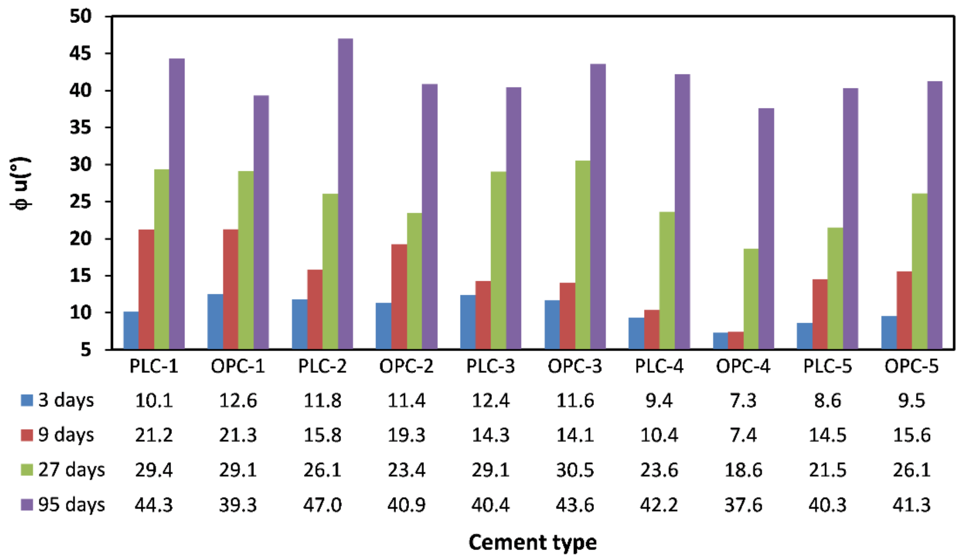


Figure 4.11 Example Mohr-Coulomb failure envelopes



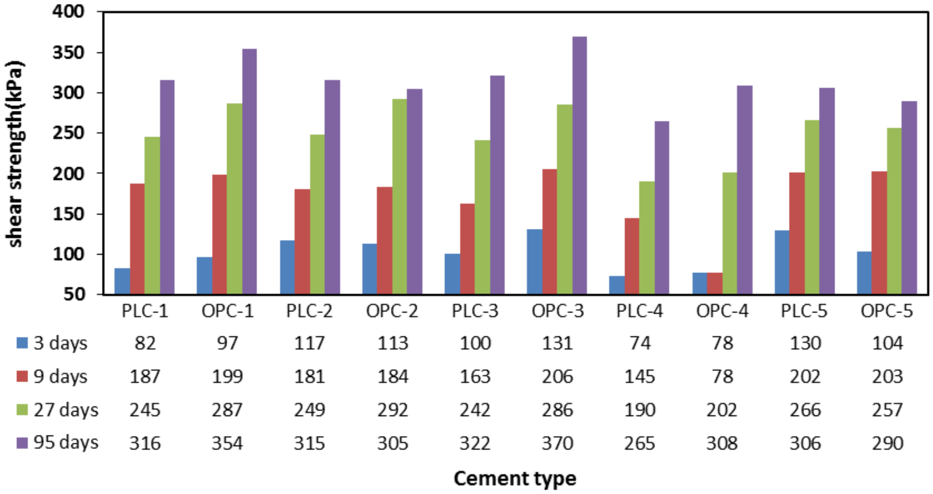
	PLC-1	OPC-1	PLC-2	OPC-2	PLC-3	OPC-3	PLC-4	OPC-4	PLC-5	OPC-5
🟦 3 days	55	64	86	83	68	100	49	59	107	79
🟥 9 days	129	140	139	131	125	168	118	58	163	161
🟩 27 days	161	203	175	227	159	198	124	151	207	183
🟪 95 days	169	231	155	175	194	227	129	193	179	158

Figure 4.12 Undrained cohesion versus cement type at different curing times.



	PLC-1	OPC-1	PLC-2	OPC-2	PLC-3	OPC-3	PLC-4	OPC-4	PLC-5	OPC-5
🟦 3 days	10.1	12.6	11.8	11.4	12.4	11.6	9.4	7.3	8.6	9.5
🟥 9 days	21.2	21.3	15.8	19.3	14.3	14.1	10.4	7.4	14.5	15.6
🟩 27 days	29.4	29.1	26.1	23.4	29.1	30.5	23.6	18.6	21.5	26.1
🟪 95 days	44.3	39.3	47.0	40.9	40.4	43.6	42.2	37.6	40.3	41.3

Figure 4.13 Undrained friction angle versus cement type at different curing times



	PLC-1	OPC-1	PLC-2	OPC-2	PLC-3	OPC-3	PLC-4	OPC-4	PLC-5	OPC-5
■ 3 days	82	97	117	113	100	131	74	78	130	104
■ 9 days	187	199	181	184	163	206	145	78	202	203
■ 27 days	245	287	249	292	242	286	190	202	266	257
■ 95 days	316	354	315	305	322	370	265	308	306	290

Figure 4.14 Undrained shear strength versus cement type at different curing times. Shear strength is based on normal stress of 150 kPa

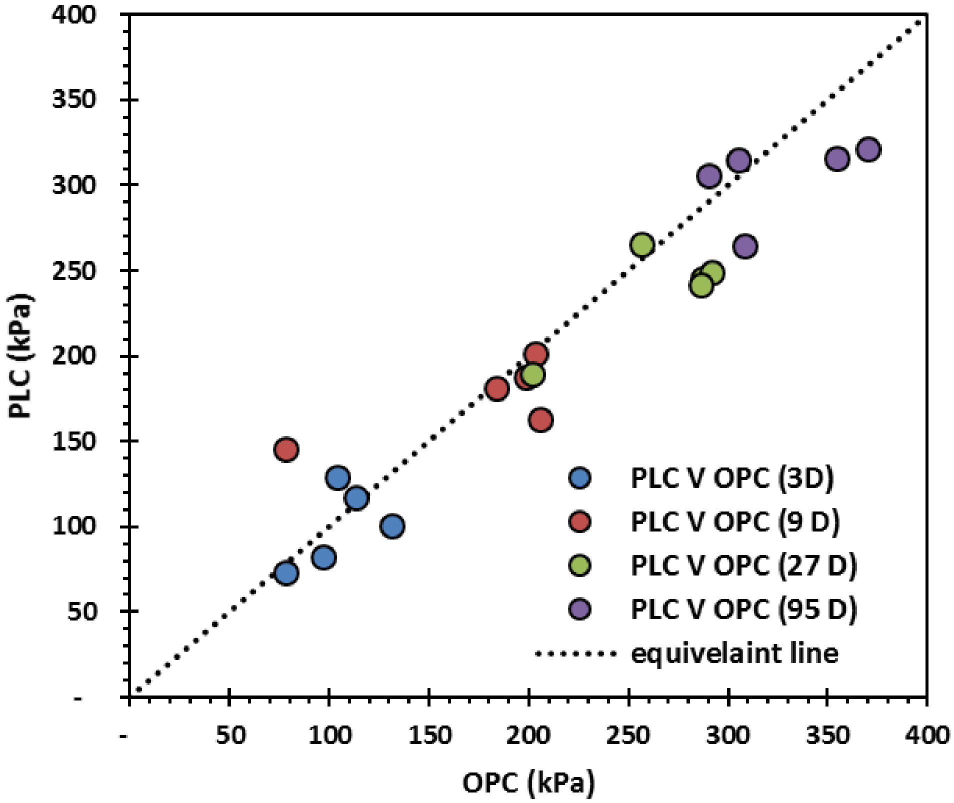


Figure 4.15 Shear strength for soil stabilized with PLC versus OPC.

Shear strength is based on normal stress of 150

Figure 4.15 is an equality plot of the Figure 4.14 data where each test day is shown. Overall, shear strength calculated from UU data showed VHMS treated with OPC being modestly stronger than those treated with PLC, as RTO showed PLC at 92.5% of OPC's strength (R^2 of 0.89). Stated another way, PLC was around 8% weaker than OPC from an overall perspective. When viewed by cement source, RTO showed distinct trends. The following list provides PLC to OPC source comparisons: pair 1 – PLC was 11% weaker (R^2 of 0.99); pair 2 – PLC was 4% weaker (R^2 of 0.93); pair 3 – PLC was 15% weaker (R^2 of 0.99); pair 4 – PLC was 7% weaker (R^2 of 0.70); pair 5 – PLC was 5% stronger (R^2 of 0.97). Figure 4.15 does not agree with Figure 9 trends wise as UC data (Figure 4.9) showed PLC modestly, but clearly, outperforming OPC, whereas Figure 4.15 showed more scatter and 4 of the 5 cement pairs favoring OPC over PLC by modest values. Bazne et al. (2016) often showed this same trend with multiple soils, water contents, and cement dosages.

4.5 Discussion and Implications of Results

Atterberg limit results were comparable to those found in literature (Brandl 1981; Chew et al. 2004; Horpibulsuk, 2012; Yi et al. 2013). Also, Federico et al. (2015) found increasing plastic limit and decreasing liquid limits with increased cure time. The implication of the phenomenon may be attributed to the physical reaction due to increased solid particles (cement) and the chemical reaction (flocculation) that result from the cationic exchange between Ca^{++} from cement with Na^+ and K^+ from clay. Consequently, cement causes reduction in the space between double layers soil particles. As presented earlier, on average, PLC had liquid limits that were 2.5% lower than OPC.

Because the proportion of Ca^{++} in PLC is higher than OPC, the slightly more pronounced liquid limit reduction of PLC is not surprising.

Chen and Wang (2006) and Jacobson et al. (2005) provide information regarding cement influences and organic matter. Jacobson et al. (2005) demonstrated that cement contained sulphate which reduces solubility of organic matter. PLC and OPC have almost identical capacity to reduce solubility of organic matter, and as test results presented earlier show, PLC and OPC both reduced organic matter, but there were no meaningful differences between them in this regard.

The primary item warranting discussion was the different behavior of OPC and PLC with regard to UC and UU determined strengths. Chen and Lin (2009) is a resource for additional information regarding the behaviors discussed in the remainder of this section. UU test results illustrated that LC-VHMS undrained shear strength increases linearly with confining pressure (PLC or OPC). Confining pressure has the potential to increase compressibility, consequently increasing solidification and undrained shear strength (Chen and Lin 2009; Hung et al. 2011). It is speculation that LC-VHMS stabilized with PLC may react differently than OPC to confinement during UU testing as performed herein. With such high void ratio specimens cured a prescribed amount and then confined (not realistic of most actual loading conditions), it is possible that cementitious bonds were broken during UU confinement. If that occurred, conglomerate particles would form and the failure planes produced from damage during confinement would likely dictate behavior during shear.

Figure 4.16 demonstrates hypothetical differences between UC and UU conditions that could explain some of the differences observed in this research and in

Bazne et al. (2016). For UC testing (Figure 4.16(a, b and c)), the mode of failure was shearing absent any pre-determined weak planes from confinement. For UU testing (Figure 4.16(d, e and f), failure modes might shift if there were pre-determined failure planes induced during confining. As noted earlier, this is speculation, as imaging (or similar) techniques were not employed due to the scope of these efforts

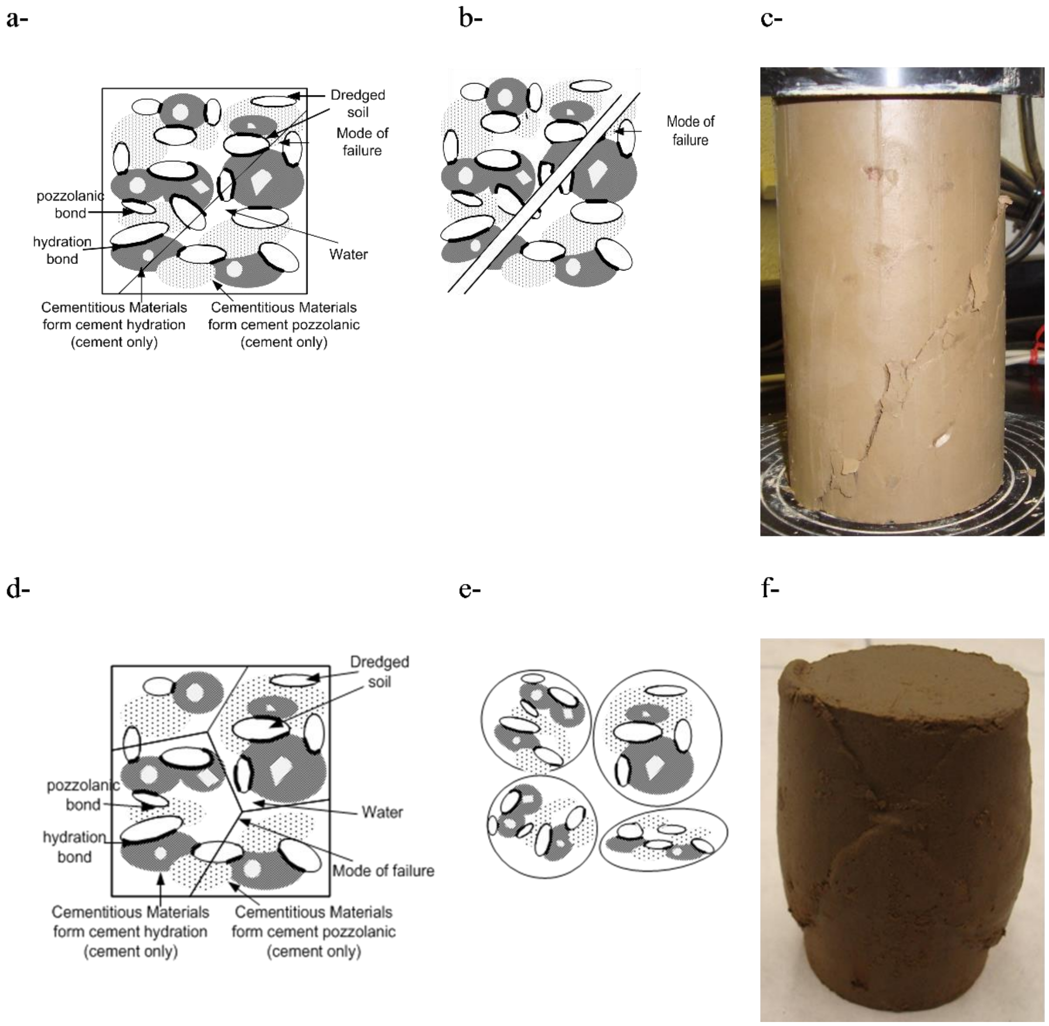


Figure 4.16 Hypothetical schematic of bonding and failure

4.6 Summary and Conclusions

This research's primary objective was to characterize behavior of portland-limestone cement (PLC) versus ordinary portland cement (OPC) in lightly cemented very high moisture content fine grained dredged soil (LC-VHMS) to determine if PLC is a sustainable alternative to OPC for dredged soil stabilization. For this purpose, a set of experimental tests was performed on ten diffetnt mixtures of LC-VHMS, inclduing five PLCs and five OPCs from four different cement manufacturing facilities. Three of these five pairs of cements were from similar clinker made possible by a recently completed ready mixed concrete study. With PLC being implemented into the ready mixed concrete industry, it is important to determine how this cement with less embodied energy than OPC behaves in terms of index and strength properties.

This research's objective was met as the findings clearly show PLC as a sustainable alternative to OPC. Marketplace factors in the region where the authors are located suggest PLC and OPC economics are comparable. Embodied energy clearly favors PLC, and engineering properties presented are not compelling for or against PLC. All cements considered, index properties were practically the same OPC to PLC, unconfined compression test results slightly favored PLC (around 5% better), while unconsolidated undrained triaxail test results modestly favored OPC (around 8% decrease in properties with PLC). Cement source variations were more pronounced than OPC to PLC comparisons suggesting that if PLC were the baseline marketplace cement, that projects making use of stabilized dredged soils could continue as they have in the past, only with a cement embodying less energy, which is positive to the environment.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONSD

5.1 Conclusions

The object of this study was to explore ways to sustainably improve engineering properties of dredged soil for beneficial reuse applications such as sustainably enhancing sea transportation, reduction of disposal facilities' area, river restoration, reduction of environmental impacts, and shoreline protection by fill in geotextile tube with dredged materials. Therefore, this study has been conducted to show that very high moisture dredged soils can be stabilized with low dosages of portland limestone cement (PLC) or ordinary portland cement (OPC) to achieve useful properties for some beneficial reuse applications. Throughout the study, experimental results other conclusions were made which can be described as follows:

- The experimental results suggested that using PLC in LC-VHMS can provide a sustainable alternative to OPC while leading to comparable engineering properties.
- The strength increased with increasing cement content. 10% of dry mass of cement, considered the lowest cement content, could be blended with dredged soil at 100% moisture content in order to stabilize VHMS to the level that meets the required compressive strength for some geotechnical applications.

- LC-VHMS treated with PLC showed better performance than those treated with OPC in terms of the unconfined compressive strength. Therefore, dredged soil stabilized with PLC (ASTM C595 or C1157) is a sustainable option since PLC has less embodied energy than the commonly used OPC specified by ASTM C150.
- Mixing VHMS with varying percentages of cement reduced plasticity, void ratio and moisture content, while increasing dry density.
- LC-VHMS exhibit brittle behavior and this behavior is more pronounced with PLC than OPC, and this brittle behavior increases with higher cement doses.
- Effects of curing time were much greater for specimens treated with 10% cement by dry soil mass while strength gain over time was less pronounced at lower cement contents.
- Triaxial testing results showed that higher shear strength can be achieved by increasing confining pressure.
- Mixing PLC and OPC with 10% of dry mass dredged soil at 100% moisture content is flowable enough to be pumped after mixing directly
- The UC test results showed the strength of the PLC samples to exceed the OPC samples by 5%, whereas UU showed OPC strength to exceed PLC strength by 8%.

5.2 Recommendations for Future Research

This study is considered first in the use of lightly cemented dredged material with PLC to enhance the undesirable properties of dredged soil. Therefore, there is ample range for more study and investigations or development. Based on the findings of this study, the following recommendations could be made for future research in this field:

- Collecting undisturbed sample of dredged soils for testing.
- Further study in order to determine shear behavior while samples are fully consolidated.
- Use lightly cemented dredged soils for filling geotextile tube and perform small scale and full scale experiments to monitor the behavior of geotextile tube versus time.
- Perform further study to determine the influence of mixing and transferring mixture on shear strength.
- Perform further study regarding the influence of temperature of mixing.
- Further study regarding consolidation behavior of lightly cemented dredged soils.
- Study beneficially reused and stabilized dredged soil for highway and road applications (sub-base and sub-grade).

Further study the influence of compaction on the performance of LC-VHMS while utilizing PLC and OPC

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