Civil and Environmental Engineering Department

Sustainably Enhancing Intermodal Freight Operation of Ports Using Geotextile Tubes

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16. Abstract

The primary objective of this report was to study use of geotextile tubes filled with cementitiously stabilized very high moisture content fine grained dredged soils for beneficial reuse. The purpose of doing so was to sustainably enhance intermodal freight operation of ports. A material of key emphasis in this report was lightly cemented very high moisture content fine grained soil (LC-VHMS), which by definition in this report contained 5% or less cement by slurry mass (soil plus water). A cement of key interest in this study was portland-limestone cement (PLC), which is a more sustainable alternative to ordinary portland cement. The project's research and educational plan had four components summarized as follows: 1) evaluate engineering properties of geotextile tubes filled with LC-VHMS; 2) develop methodologies to help ports include geotextile tubes more readily; 3) study sustainability and economic competitiveness of LC-VHMS filled geotextile tubes; 4) educate students and the engineering community on the potential benefits of LC-VHMS filled geotextile tubes. The overall conclusion of this report is that LC-VHMS should be considered as geotextile tube fill for some applications and LC-VHMS could have some value absent geotextile tubes in other applications in and around ports and harbors. Engineering With Nature (EWN) applications could make use of lightly cemented materials as they have the potential to improve properties to levels suitable for low strength applications.

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CHAPTER 1 - INTRODUCTION

1.1 General and Background Information

Ports are a key component to any intermodal freight system. In some senses, ports define the true nature of intermodal activities as they are the transfer point that connects ships or barges to rail lines and trucks. Typically freight is transferred in containers that do not require handling of the freight within the containers.

Efficient port and river operations are important to freight movement and subsequent economic competitiveness. Efficient port and river operations, however, are challenging. For example, in 2011 the Mississippi River flooded and in 2012 there was a drought along the same river. During 2012, the Vicksburg District of US Army Corps of Engineers (USACE) had their dredging operation running around the clock for around 4 months from Cape Girardeau, MO to the Gulf of Mexico.

Dredging is a key component of efficient port and river operations. Maintaining and improving operation of ports along the Gulf Coast and along the Mississippi River up to Memphis, TN requires almost continuous dredging. The materials dredged vary greatly and range from clean sand suitable for beach replenishment to very high moisture content fine grained soils. The later can be costly in terms of disposal. Beneficially using fine grained soils with elevated moisture contents can be challenging, and is a key item of emphasis in this report.

Geotextile tubes filled with fine grained very high moisture content fine grained soils that have been chemically treated are the main focus of this report. Geotextile tubes are versatile products that have found their way into many applications including sediment containment, shoreline protection, and breakwaters. Chemically stabilized soils have a long history of successful use. Attempting to pair these two items is promising.

A few terms are important with regard to this report and are used multiple times. The first is VHMS, which is an abbreviation for Very High Moisture Soils. VHMS, as defined in this report, is a soil moisture content at or above the soil's liquid limit (LL). The second term is cemented (C), which is a term meaning a soil has been dosed with 5% or more cementitious material by total mass (i.e. soil plus water mass). For example, C-VHMS refers to a soil having a moisture content above its liquid limit that has been dosed with 5% or more cement by soil plus water mass. The third term, which is somewhat associated with research performed at Mississippi State University (MSU), largely in conjunction with this project, is lightly cemented (LC). LC is a term meaning a soil has been dosed with 5% or less cementitious material by total mass. For example, LC-VHMS would be appropriate to describe a soil with LL of 50 that was stabilized with 3% portland cement by slurry mass while at a moisture content of 70%. Note that C or LC can be used to describe a 5% dosage by slurry mass.

1.2 Objectives

The primary objective of this report was to study use of geotextile tubes filled with cementitiously stabilized very high moisture content fine grained dredged soils for beneficial reuse. The purpose of doing so is to sustainably enhance intermodal freight operation of ports. This project's research and educational plan had the following components, which were accomplished as per the scope presented in the next section:

1. Evaluate engineering properties of geotextile tubes filled with very high moisture content fine grained soils stabilized with more sustainable cementitious materials such as portland-limestone cement (PLC).
2. Develop methodologies that could allow ports to include geotextile tubes more readily into their design, construction, and operations decisions.
3. Study sustainability and economic competitiveness of geotextile tubes filled with cementitiously stabilized materials, and where appropriate compare their attributes to alternative approaches.
4. Educate students and the engineering community on the potential benefits of using cementitiously stabilized fine grained soils as geotextile tube fill.

1.3 Scope

To accomplish the project's objectives, ports were considered in seven states along the US Gulf Coast and up the Mississippi River to Memphis, TN. Some of the busiest ports in the US are located on the Gulf Coast, and the region around Memphis, TN is a key intermodal hub. Most testing herein was performed for LC-VHMS, though some testing was performed at C-VHMS conditions where cementitious dosage rates were only slightly above the 5% threshold. The projects scope was accomplished by dividing activities into tasks as described below.

<u>Task 1: Literature Review and Collecting Relevant Data From Ports:</u>
Chapters 2 and 3 contain a literature and practice review, alongside a survey sent to several ports. Findings from these endeavors shaped some of the research performed. More emphasis was placed on items that seemed more relevant to ports and vice versa.

<u>Task 2: Experimental Study of Engineering Properties of Stabilized Dredged Soils:</u>
Communication with several individuals in the relatively early stages of this project led to the authors collecting soil (sampled from two dredged disposal facilities near ports), cement (sustainability was a consideration relative to the cementitious materials utilized), ash, scaled geotextile tubes, and grass seed as described in Chapter 4. Combinations of these materials were utilized to study engineering properties of stabilized soils (mostly LC-VHMS), with a primary intention of these materials being used in applications where they would serve as geotextile tube fill. Information gained from Task 1 was used to guide the selection of engineering properties. Ultimately, the properties evaluated were: strength (unconfined compression, shear), strain to failure, density, elastic modulus, plasticity (i.e. Atterberg limits) consolidation, shrinkage (evaluation was based on observation of experiments, not detailed measurements), and water pH as it exited scaled geotextile tubes. These properties were used for later tasks to assess use of LC-VHMS filled geotextile tubes for applications in and around ports and harbors. Experimental methods and results from the engineering property investigations are provided in Chapter 5, Chapter 6, and Chapter 7.

Task 3: Assessing Construction Details:

All pertinent information in chapters 2 to 7 was used to assess construction in and around ports and harbors that made use of geotextile tubes filled with LC-VHMS. Stacked geotextile tubes were a point of emphasis where construction sequencing and geotextile tube fill consistency (i.e. strength/stability) with time were considered. Construction was assessed for the more promising applications identified in chapters 2 and 3 based on engineering properties in chapters 5 to 7. Construction assessments are provided in Chapter 9.

Task 4: Studying Sustainability of Geotextile Tubes in Ports:

Chapters 8 and 9 address sustainability aspects of using geotextile tubes in and around ports and harbors. Discussion is provided regarding applications where geotextile tubes filled with LC-VHMS could be used in a more sustainable manner than conventional construction materials that allows better integration with the natural landscape. As with other aspects of this report, feedback obtained from ports (Chapter 3) was coupled with the literature and practice review performed (Chapter 2) to address the most relevant sustainability aspects possible within the scope of this research. Chapter 8 presents experiments and results to determine whether vegetation could be established in LC-VHMS inside geotextile tubes, as well as outside of geotextile tubes.

Task 5: Economic Competitiveness of Geotextile Tubes Used at Ports:

An item evaluated in Task 5 was relative economics of LC-VHMS filled geotextile tubes versus alternative scenarios. The relative merits of geotextile tubes to serve as walls/slopes (especially when stacked) was investigated for potential applications in and around ports and harbors. Chapter 9 presents economic competitiveness information.

Task 6, Task 7, and Technology Transfer: Reporting and Findings:

Quarterly reports were written, and this report is the culminating effort of the work presented. Chapter 10 describes all technology transfer activities that have occurred to date. Chapter 11 provides the project's conclusions and recommendations, while Chapter 12 is a list of all references utilized herein.

CHAPTER 2 – LITERATURE AND PRACTICE REVIEW

2.1 Overview of Literature and Practice Review

A review of literature and practice was performed related to several issues that ultimately relate to economic competitiveness of ports and harbors. Economic competitiveness and ports often go hand in hand. Dredging and dredged sediment was a central element of the literature review. The review also investigated factors associated with the recent expansion of the Panama Canal, geotextile tubes, chemically stabilized dredged material, vegetation establishment, and sediment handling.

2.2 Sustainability and Beneficial Use or Reuse

Essentially all aspects of this report have some relation to sustainability and/or beneficial use or reuse. In that the focus of this report is ports and harbors, sustainability and beneficial use or reuse items pertaining to dredged materials was of primary interest. As described in the following paragraph, views of dredged material have changed considerably over the years.

The study of dredged materials has occurred for decades. Around four decades ago, Bartos (1977) assembled data for classifying and determining engineering properties of dredged material for USACE. The key finding relative to this project was that dewatered and dredged material is a soil and can be treated as such. The report encouraged productive use of dredged material as a natural resource, which, generally speaking did not gain much momentum for many years after the report was written. In present day (August 2015), however, USACE has a website devoted to beneficial use of dredged material (http://el.erdc.usace.army.mil/dots/budm/budm.cfm).

The 2005 World Summit provided a formal definition of sustainability that can be seen on pages 11 to 12 of UN (2005), quoted as: "These efforts will also promote the integration of the three components of sustainable development – economic development, social development, and environmental protection – as interdependent and mutually reinforcing pillars…". In recent years organizations such as ASCE have referred to these items as the triple bottom line (i.e. economics, environment, and social well-being). Others have informally referred to these three sustainability pillars as people, planet, profit.

Puppala and Chittoori (2014) note that the higher the overlap between social, environmental, and economic impacts, the more sustainable the project. The authors also note that geotechnical engineering often forms an important interface between the man-made and natural environments. It was also stated that a major part of the sustainability-related research in geotechnical engineering focused on reuse of materials such as ashes (fly ash, bottom ash, and other types of ashes). Ports provide an excellent opportunity for overlap of the aforementioned sustainability components.

One item of interest in recent years that is indirectly associated with the efforts of this project is land loss in areas such as Louisiana. In that ports and harbors are along coasts and rivers, it is possible that beneficial use of dredged material taken from in and around ports and harbors could be useful with regard to mitigation of land loss. Ghose-Hajra et al. (2015) discussed Louisiana's land loss, noting that since 1932, more than 22% of the marshland that existed has disappeared. Concepts were described by Ghose-Hajra et al. (2015) that make use of dredged material to create new land.

Joffrion et al. (2015) also describes the challenges the state of Louisiana is facing regarding land loss. The authors report that since the 1930's, Louisiana has lost 1,880 sq. mi of land and stands to lose 1,750 sq. mi more over the next 50 years if action is not taken. One reason for the observed land loss is levees and other features constructed to protect people and property from major floods can prevent rivers from depositing their sediments in the floodplain. A $50-billion master plan encompassing 50 years has been developed that includes five primary objectives including flood protection and promoting a sustainable ecosystem by way of harnessing natural system processes. The plan includes projects such as barrier island restoration, marsh creation, and creation of oyster barrier reefs, and some of these projects stand to use dredged soils according to Joffrion et al. (2015).

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, MO metropolitan area. At the initiation of construction in 1983, industrial activity and uncontrolled filling had been occurring for around 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.

2.3 Panama Canal

The Panama Canal, and more specifically activities associated with the canal's expansion, have potential relevance to the activities of this report. Brown (2014) provides a historical summary of the Panama Canal, and how it is one of the greatest engineering achievements of all time. The Panama Canal opened in August of 1914, and the original construction required 262 million yd^3 of earth and rock to be moved. Original construction activities spanned 30 years and cost around $639 million dollars (not adjusted to present day). Brown (2014) concluded by noting the Panama Canal expansion commenced in 2007.

The Panama Canal expansion has garnered attention in a variety of venues, evidencing its enormous impact potential (e.g. Bentley 2013; TR News 2013; Petroski 2014). The American Society of Civil Engineers (ASCE) held a *Global Engineering Conference* in Panama City in October of 2014. The 2014 calendar year marks the 100^{th} anniversary of the Panama Canal's opening.

With regard to the expansion, cost, dredging quantity, and completion date information varies according to the source referenced. Irrespective of source, the project cost billions of US dollars and required millions of m^3 to be dredged. As of August of 2015, Canal de Panama (http://micanaldepanama.com/expansion/) served as a source of information for the project and reported the project as 93% complete as of August of 2015. Project costs of $5.2 to $5.5 billion US dollars were the most common among the sources reviewed, with other numbers occasionally reported (e.g. $6.2 billion reported by Rodrigue and Notteboom 2015a). The Canal de Panama website reported 56.6 million m^3 of dredging for the Atlantic entrance, Pacific entrance, Gatun cut, and Culebra in September of 2015. Lord (2013) stated the entire project is to require 130 million m^3 of dredging.

According to ASCE, up to 15,000 ships cross the Panama Canal annually. 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. A considerable amount of the dredging being performed is to accommodate Post-Panamax ships. Prior to the expansion, the limiting ship size that could pass through the canal's locks was referred to as a Panamax vessel. Post-Panamax vessels are those that have evolved over the period since the original canal opened, which were too large to travel the canal prior to expansion. Petroski (2014) states that as of fall 2014, 37% of the world's fleet is a Post-Panamax vessel. The February 2013 issue of *Prism* magazine has a summary article that quotes the U.S. Army Corps of Engineers as viewing the increased traffic from the Panama Canal expansion 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. Rodrigue and Notteboom (2015a) stated the expansion accommodates containerships of 12,000 to 15,000 TEUs (20-foot equivalent units) that draft 50 ft; as a reference prior containerships that could use the canal were 4,500 TEUs with a 42 ft draft.

The expansion of the Panama Canal can be grouped into categories: Pacific Access Channel, new set of locks, dredging along the waterway, and raising Gatun Lake. The new locks increase the length of ships passing through the canal from 294.3 meters to 366 meters and increase the depth of the ships to 15 meters. The larger ships, in turn, lead to decisions of ports and harbors relative to their response to an altered freight pattern. According to Frittelli (2011) and USACE (2012), many harbors and channels that could be affected by the Panama Canal expansion are not adequately maintained to meet current or expected demand.

TR News (2013) reported that deep-draft ports along the Gulf Coast and East Coast are investing in landslide and waterside infrastructure capacity to qualify as gateways for the new cargo. Contributions to expedite dredging projects in conjunction with intermodal connectivity is also occurring. Two examples were provided. The first was a Florida-Miami-multimodal investment strategy, where a dredging project was receiving $70 million for what is being referred to as the Miami tunnel (connects seaport to I-95). The second was in Georgia; $231 million to the Savannah Harbor Expansion. This project expanded the main intermodal container facility and has funded multiple, intermodal connector road projects for the port.

Rodrigue and Notteboom (2015b) discuss the Panama Canal with a focus on the expansion. The authors noted that after the 2007 announcement that the canal was to be expanded that most US East and Gulf Coast port decision makers began considering the readiness of their respective facilities to accommodate the larger ships. It was stated that many of these decision makers concluded their current infrastructure/capacity would put them at a competitive disadvantage. A dredged depth of 50 ft is the general post expansion target for ports as that matches the draft of the Panama Canal expansion; 42 ft was a general draft target prior to the expansion for most East and Gulf Coast ports. Rodrigue and Notteboom (2015b) summarized information taken from websites and press releases of 13 port authorities from New Orleans to Boston, where channel clearance was one of the three items of primary interest. Responses varied considerably, including: completed dredging harbor channel to 50 ft, depths were already at 50 ft, discussions to dredge from 50 to 55 ft, plans to dredge up to 47 ft. Timelines varied from completion dates in 2014 to planned completions up to 2019 to no specific plan or timeline.

2.4 Ports, Freight, and Economic Development

There is little question that the freight handled by ports is essential for economic development. Landers (2013d) notes the U.S. transportation system moves 17.6 billion tons of goods valued at $16.8 trillion in 2011, but noted future demands are likely to be higher. EC (2014) reported that there were 3.7 billion tons of freight handled in European ports in 2012, and that vessels of 10,000 TEU or more make up 48% of the new containership order book. According to Lovelace (2014), approximately 6 million yd^3 of material is removed from the Mobile Harbor navigation project alone, costing around $25 million annually.

TRB (2013) describes critical issues in transportation and indicates the US depends on transportation to compete globally. It also notes how freight transportation systems must adapt to growth in gross domestic product projected at 80% in the next 25 years. The Transportation Research Board (TRB) Executive Committee compiled a list of critical transportation issues for the 2013 calendar year. One of these issues was that “transportation exerts large-scale, unsustainable impacts on energy, the environment, and climate.” The source also stated that ports and waterways lead to more than $1 trillion in annual commerce in the 12 largest ocean ports, and that over 9,000 vessels and 30,000 barges move 157 billion ton miles annually on the 25,000 navigable channel miles of the Inland Waterway System. It was also noted that “Many ocean ports are seeking deeper channels and harbors in response to possible shifts in logistics and in port calls after the widening of the Panama Canal and the possibility of Asian imports arriving directly to East Coast ports instead of crossing North America by rail.”

Meitzen (2013) discusses freight infrastructure routes and how smoothly functioning freight transportation is part of the U.S.’s critical infrastructure. It was noted that in 2007, 11,000 ton-miles of freight was carried per person in the U.S. It was noted that in 2008, 4.5 million U.S. people were employed in transportation and warehousing. The main item discussed in the paper, however, was land use around freight corridors and facilities. Ports were not all that was discussed, though they do apply to at least a portion of the discussion. It was stated that several aspects of economic growth have led to increased competition for land resources around freight corridors and facilities. The article referenced NCHRP Report 16, and that it provides a perspective on freight transportation’s importance and presents tools and strategies to resolve (or minimize) conflicts between freight and non-freight land uses. Of particular interest to the work of this report would be to beneficially reuse dredged materials to improve land’s useability in and around ports.

Bomba (2015) discusses Gulf Coast ports and their role in the energy sector, with emphasis on how energy sector trends impact ports and private terminals in the Gulf of Mexico. Discussion was provided on issues such as impacts of landside oil and gas exploration (e.g. hydraulic fracturing), crude oil supply, and so forth. It was stated that approximately half of the nation’s annual total of foreign waterborne commerce is handled at ports and private marine terminals in the Gulf of Mexico. With regard to the Panama Canal expansion, discussion was provided regarding liquefied natural gas (LNG) and how hydraulic fracturing has increased U.S. natural gas production. In that the draft of most LNG tanker vessels is deep, over 90% could not fit into the Panama Canal locks prior to the expansion, but over 90% are able to fit after the expansion. LNG world markets coupled with the Panama Canal expansion is anticipated by many in the shipping and petroleum industries to LNG a significant export commodity from the Gulf of Mexico.

Frittelli (2011) presented a comprehensive assessment of the Harbor Maintenance Trust Fund. The Harbor Maintenance Tax (HMT) was enacted by Congress in 1986 for operation and maintenance (O&M) cost recovery noted to be mostly dredging of harbor channels to their authorized dimensions (revenues are deposited into the Harbor Maintenance Trust Fund, or HMTF). Generally, coastal and great lakes ports are taxed.

Geological differences result in ports varying greatly in their required amount of dredging (Frittelli 2011). Gulf and East Coast ports, as a group, require considerably more dredging than West Coast ports. The relationship between most U.S. ports is competitive (not complementary), which contrasts the HMT's creation of a national pool of funds that are re-distributed between ports. Some ports receive less than 1% of their contributions. Since the HMTF provides a national pooled fund for dredging (as opposed to port specific funding), naturally deep harbors subsidize shallower ports. A port-specific funding system would favor heavier used ports over those that are underutilized. In the 111th Congress, multiple bills were introduced to modify tax rates or how the revenues from these taxes are spent.

Alternative tax approaches such as a Harbor Services User Fee (HSUF) were discussed where carrier, as opposed to shipper who currently pays HMT, pays the tax (Fritelli 2011). It was stated that the HSUF has the advantage of requiring ship owners to internalize costs associated with deploying larger ships as they increase port costs due to requiring deeper channels and berths (they are more economical on their ocean leg).

HMTF funds are for maintenance dredging (work performed to maintain congressionally authorized widths and depths), not for new construction (work to increase width or depth) as that requires an act of congress and is funded by other means. Over the past decade, maintenance dredging was reported to account for around 84% of the total material dredged and 70% of dredging expenditures. About 80% of maintenance dredging is performed by private contractors. On a unit volume basis, construction dredging was reported to be over twice as expensive as maintenance dredging. Maintenance dredging costs (in constant 2000 dollars) were reported by USACE to be $3.19/yd^3 in 2008. Significant factors for determining O&M costs are sand and silt quantities moved by water (river flow or by coastal wave action), channel length, and the number of locks. The most expensive channel is the Mississippi River from Baton Rouge to the Gulf of Mexico, and Mobile Harbor in Alabama is the second most expensive. These two projects used 8.3 and 3.5% ($569 and 238 million) of the HMTF expenditures between FY 1999 and 2008, respectively (Fritelli 2011).

Landers (2013e) provided a policy briefing regarding the Water Resources Development Act (WRDA). Items discussed included identification of projects related to flood risk reduction, storm damage reduction, and ecosystem restoration. Measures that can protect the coast and simultaneously benefit the environment were noted in the briefing. Several million dollars were requested to repair projects damaged by Hurricane Sandy and to conduct emergency dredging at inlets, harbors, and channels. An important component for the USACE was stated to be projects that promote long-term sustainability of coastal ecosystems and communities with minimum cost and risk associated with large storms.

Landers (2015b) discussed design phase activities associated with the Charleston, South Carolina harbor where most channels are to be improved and deepened from 45 to 52 ft, since 45 ft is too shallow to support the largest cargo ships of the day. The project's estimated cost is $521 million. A key part of the project is deepening the harbor's 17 mile long entrance channel and extending the channel 3 miles seaward. It is estimated that on the order of 40 million yd^3 of material will be dredged and require disposal. Of this total, around 6 million yd^3 is to be placed in existing upland confined disposal facilities, 29 million yd^3 is to be placed in an ocean dredged material disposal site, and the remainder is envisioned to be limestone that is scheduled for beneficial use as part of artificial reef construction.

Landers (2014) documents an example at the port of Miami where decreasing traffic congestion was a key motivation for a public-private partnership to provide additional access to the port through a roadway and tunnel system. Overall costs of the project were reported at nearly $1-billion, and the project was in operation as of August 2014. Bomba (2015) reports that the Port of Mobile, a port that receives around 2/3rds of its revenue from coal exports, is considering a $140 million expansion near a coal terminal.

Shafer et al. (2013) discussed design and construction of a new berth capable of handling ships with a 50 ft draft for the Port of Baltimore. According to Shafer et al. (2013), Baltimore was one of only two East Coast ports with a federally mandated channel of 50 ft deep. Most of the details of this project are not directly applicable to this report, but it is important to note that the new berth was, at least partially, in response to the Panama Canal expansion. It is also noteworthy that the project was built on a former disposal site with around 3 million yd^3 of excavated marine material that resulted in significant design challenges from soil conditions. While not discussed in the article, it is worth mentioning that had this material been improved slightly over time (e.g. LC-VHMS) it might have been useful for this project. It is also interesting that the new berth's design considered 14,500 TEU capacity ships with a 50.9 ft draft (New Panamax ships are only 12,000 TEU, whereas Panamax ships were much smaller at 4,200 TEU's). TEU is 20 ft equivalent unit.

2.5 Relevant Geotextile Tube Applications

This section summarizes some applications where geotextile tubes were used that have relevance to the efforts in this report. Note that there are some additional uses of geotextile tubes presented in other sections of this chapter in situations where the studies overall scope is more appropriately described within another heading. The following paragraphs describe potentially relevant applications of geotextile tubes.

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. Innovative fabric uses date back several decades and have continued in recent years. 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 the versatility of fabrics and more specifically geotextile tubes.

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. Pimentel et al. (2014) evaluated submerged breakwater concepts that utilized geotextile tubes. Information presented indicates that proper use of geotextile tubes as submerged breakwaters can result in proper accumulation of sand and effective coastal protection. ACE (2014) documents geotextile tubes used along the edge of fill material for a breakwater project. The tubes were stacked four high, though they were largely resting on interior fill. Sand was used throughout this project.

Bygness (2015) summarizes the award winning Fort Pierce city marina project in Florida where a stacked unwashed quarry sand filled geotextile tube structure formed the perimeter of the largest island. Geotextile tubes were surrounded by stone. The geotextile tube fabric was a sand color composite designed to contain the sand fines, minimize turbidity, and have a high angle of friction to minimize the possibility of slippage. During the project, minimal turbidity was observed, and no slippage or construction damage was observed. The artificial island system was Florida’s first project to replicate the natural barrier islands and it permits habitat and recreation to coexist while also helping to mitigate storm events. Oyster shells and lime rock were also used at lower elevations to promote establishment of oyster beds and other essential fish habitats.

An example of fine grained soil being used to fill geotextile tubes in a permanent application is Drakes Creek in Tennessee. A dike was constructed using around 640 m of 13.7 m circumference geotextile tubes, and this project was presented during the *2008 Geotextile Tubes Workshop* documented in Howard et al. (2009). Geotextile tubes were filled with unstabilized dredged material containing organics, silty sand, and stone for the US Army Corps of Engineers (USACE). A total of 16,800 m^3 was dredged. The dike was constructed in 2000 and was still in service as of 2008.

Yan and Chu (2010) document use of clay slurry filled geotextile mats to construct land reclamation dikes in China in 2001. Clay slurry filled geotextile mats made up the interior of the dike, which was armored with a grouted geotextile mattress. Geotextile mats are relatively flat compared to geotextile tubes. The soil filling geotextile mats classified as SC-CL and had a liquid limit of 20 with 55% fines. The soil was selected so it could be pumped into the geotextile mats and consolidate relatively fast under the conditions inside the mats. The designed height of the dike was 4.8 m (including the grouted mattress), the width of the bottom mat was 22 m, and 9 layers of geomats were used (after settlement, each mat was 0.4 to 0.5 m thick). Mats were filled with clay slurry pumped into the mats (few details were provided regarding pumping procedures other than a 20-30 kPa pressure was applied). It was concluded that low plasticity clay was suitable to be used as material to fill geotextile mats in slurry form and that the field trial showed a dike built with the proposed approaches is stable.

Tseng et al. (2014) summarizes a project in Taiwan where 8.6 m circumference geotextile tubes were stacked in a pyramid (two tubes on bottom row and one tube on top of them) in the middle of a sandbar (i.e. sand was on either side of the tubes). The tubes were filled with silt, and the accumulated height was around 3 m. The authors reported that geotextile tubes provided a fast repair method that avoided use of concrete blocks by using in situ material.

Howard et al. (2012) documents alternative geotextile tube fill materials for marine applications. A point of discussion in the paper was replacing sand as geotextile tube fill for some types of permanent (i.e. not dewatering) applications. Four case studies were presented where imported sand was used as geotextile tube fill. Discussion of the possibility of three of these projects having potential to be improved using materials native to the project site was presented. A fifth case study presented was a project in Peoria, IL where an island was created at Lower Peoria Lake using geotextile tubes filled with unstabilized fine grained sediment native to the project site. This project was also documented in Karnati et al. (2012).

Three rows of geotextile tubes were placed side by side to create the island perimeter. High solids dredging was performed with a patented environmental clamshell bucket, and after passing over a vibrating screen, the sediment was pumped into the geotextile tubes with a positive displacement pump. The soil pumped into the geotextile tubes was mostly CH material with liquid limits of 56 to 72 and as pumped moisture contents on the order of 70%. Around 38,000 m^3 of fine grained sediment was pumped into geotextile tubes during the project. Karnati et al. (2012) reported that a stage II construction is to involve addition of a geotextile tube on top of the lower three tubes and that dredged material is going to be used to fill the interior of the island to an elevation around 1 m above the top of the fourth geotextile tube. Riprap stone was placed on the outside portions of the wall where there was potential for erosion.

Zhu and Beech (2015) present information related to geotextile tube dewatering in applications where tubes are stacked. The authors stated that it was becoming more and more common to utilize geotextile tubes for dewatering and subsequently containing contaminated materials (e.g. dredged contaminated sediment, municipal or agricultural waste, coal mine slurries). Three example projects were provided where just over 7 million m^3 of contaminated sediments were dewatered using geotextile tubes (New York, Ohio, and China). One project had a 10 m high stack of geotextile tubes, one had four layers of geotextile tubes, and one had ten layers of geotextile tubes. Two other projects were also presented: 1) biosolids in Mississippi where 3 or 4 layers of geotextile tubes were stacked; and 2) coal mine waste in Alabama where four layers of geotextile tubes were stacked. Discussion was provided regarding several possible failure modes, and it was noted that relationships of shear strength versus moisture content can be developed and used to determine when upper layers of geotextile tubes can be placed on lower layers (i.e. after they have dewatered enough to gain sufficient strength to support an additional row of tubes).

Zhu and Beech (2015) presented a case history of the Savanna Street Wastewater Treatment Plant in Mississippi where four rows of 3 stack or 4 stack geotextile tubes were constructed. Slope stability analysis was performed focusing on shear strength of the sludge in the tubes. Laboratory testing led to an undrained shear strength ratio of 0.3 and a total unit weight of 11.8 kN/m3 for 25% or greater solids. Offsets were selected as 1.5, 3, and 6 m from the bottom of the stack to the top. An estimated cost savings of $3 million dollars was estimated from use of geotextile tubes.

All content in the remainder of this section was provided by TenCate™. A considerable amount of the information relevant to this project is contained in TenCate™ (2013), which is a publically available set of case studies assembly by the company. Only select parts of the numerous case studies assembled are relevant to this project. Additionally, other information was provided in the form of presentations, meetings, and similar unpublished manners. In some instances, a case study provided in TenCate™ (2013) was supplemented with additional unpublished information. Unless stated otherwise, the summary information pertinent to this project presented in the remainder of this section came from TenCate™ (2013).

Company literature (TenCate™ 2012) reports that Geotube® technology has been used in more than 50 countries. Example applications provided in TenCate™ (2012) include wetlands and island creation. Wetlands creation (e.g. Shamrock Island off the Texas coast) has incorporated considerable amounts of sand pumped behind filled geotextile tubes. Island creation (e.g. Amwaj Island in Bahrain) has incorporated stacked geotextile tubes (2 layers high) with sand backfilled behind the tubes. The stacked tube configuration can be covered with riprap, soil, or possibly other materials.

Several of the projects presented in TenCate™ (2013) incorporated high quantities of contaminated sediments. Some of the projects, such as offshore disposal (e.g. filling a geotextile tube then placing it in the ocean via a split bottom barge), are not of interest to this research. It was stated prior to presenting the case studies that five major types of contaminants within sediments are of concern:

1. <u>Nutrients, Raw Sewage:</u> phosphorus, nitrogen compounds (e.g. ammonia or organics)
2. <u>Organic Hydrocarbons:</u> oil and grease
3. <u>Halogenated Hydrocarbons and Pesticides:</u> DDT, PCB, dioxins
4. <u>Polycyclic Aromatic Hydrocarbons:</u> e.g. petroleum and petroleum byproducts
5. <u>Heavy Metals:</u> e.g. iron, lead, cadmium, zinc, mercury, arsenic

Connor Creek in Michigan involved 130,000 m^3 of contaminated sediments. During dewatering, once 50% solids were achieved, another layer of geotextile tubes were stacked and dewatering continued. At the project's conclusion, sediment was taken from the tubes and landfilled.

Tianjin Eco-City in China was a lake remediation project where a wastewater impoundment was transformed into a wetland and recreational lake. Contaminated sediments were dewatered and used as fill for a landscaped mound (9 m high with a footprint of around 12 ha) by remaining in the geotextile tubes after dewatering. A total of 2,400,000 m^3 of contaminated sediments were dredged, dewatered, and beneficially used to construct the landscaped mound. A total dredging capacity of 3,000m3/hr filled geotextile tubes that were allowed to dewater for a few days before being filled again to the target height. Filling and subsequent dewatering occurred in 6 or 7 cycles before a layer of geotextile tubes was stacked on top of the current layer (tubes were stacked 4 layers high). Note that filling geotextile tubes multiple times is fairly common. Effluent discharge water from the geotextile tubes was released back into the lake. The geotextile tubes has HDPE geomembrane surrounding them (top and bottom), and the mound was capped with 1.5 m of enriched topsoil.

The two Svartsjon lakes in Sweden had mercury contaminated sediment, and the dewatering strategy was to use geotextile tubes encased in situ within a landfill-based barrier system to house 300,000 m^3. This approach removed the need to transport contaminated sediments off site along narrow roads post dewatering. Adjacent to dewatering, a water treatment plant was constructed. Dredging was at about 300 m3/hr at 5% solids, and after 3 to 4 months, solids concentrations had increased to 20%. After dewatering, the geotextile tubes were capped and geomembrane lined before placing a topsoil cover and vegetation.

Lake Dianchi in China had contaminated sediments and in 2009 a contract was awarded to dredge 3.4 million m^3 of contaminated sediments. Containment dykes for two lagoons were constructed by filling geotextile tubes with the contaminated sediment. These tubes were initially filled to a 2.5 m height, and after a week of dewatering another filling and dewatering cycle occurred, which was repeated for about 10 cycles to achieve a design height of 2.5 m. Once the containment dykes were in place, a geomembrane liner was installed, sediment was pumped into the interior of both lagoons, drying occurred naturally over an extended period, and thereafter the dyke walls were demolished and contaminated sediments were landfilled.

Lake Sorte So in Denmark was a temporary dewatering application were geotextile tubes were stacked three high before the tubes were cut open and dewatered sediment removed. Grubers Grove Gay in Wisconsin contained heavy metals within its sediment, which was dewatered with geotextile tubes. The multi-layer dewatered geotextile tubes had 30 to 40% solids concentration after dewatering. After dewatering, geotextiles tubes were capped with a 0.9 m thick soil layer that was subsequently vegetated.

Canal do Fundao in Brazil requird the dredging of 600,000 m^3 of contaminated sediment that was dewatered with GT 500 geotextile tubes. The dewatered tubes were capped and vegetated to become part of the natural landscape of Fundao Island. Solids retention was in excess of 99% within geotextile tubes and effluent water was of high enough quality to return directly to the canal. Polymers were injected during dewatering, and the geotextile tubes were 2.1 m tall after dewatering. Three layers of geotextile tubes were stacked.

Embraport is a container terminal in Brazil that was recently constructed at the Port of Santos. This project has been documented in multiple venues (TenCate™ 2013; TenCate™ 2014; Stephens and Melo 2014). The following paragraphs summarize relevant aspects of this project obtained from multiple sources and include supplemental information provided by TenCate™ that is not necessarily contained in the three aforementioned publications. The total Embraport investment was reported to be $1.15 billion.

Construction required 1.5 million m^3 of fill and dredging of 600,000 m^3 of contaminated sediments to accommodate the New Panamax container ships (dredging and upland sediment disposal was originally a condition for obtaining the project's construction license). Ultimately, innovative use of 36.5 m circumference by 65 m long GT 500 geotextile tubes allowed the 600,000 m^3 of contaminated sediments to be beneficially reused, reducing the amount of imported fill needed by 30%. Upland disposal of dredged materials would have required the purchase of more land or a footprint reduction for the project (either was said to threaten the project's economic model). Beneficial reuse was accomplished by dewatering sediments under the proposed container storage area, leaving the dewatered geotextile tubes in place, and then placing fill and a pavement structure over the tubes. Major design challenges with this approach were: 1) can a geotextile tube based system securely contain and dewater the sediments; 2) can the effluent water be treated and returned to the native environment; 3) can a stable platform be developed capable of storing ocean container units stacked up to seven layers high and supporting heavy port traffic loads; 4) can the site be constructed to have a 40+ year design life.

Impermeable berms (referred to as containment dykes in some documents) were installed around the project's perimeter to an elevation of 4.5 m, while internal berms were installed to an elevation of 2.5 m to divide the site into several dewatering cells. Contaminated sediments were cutter head hydraulically dredged at 1,400 m^3/hr, dosed with an organic polymer, and pumped into geotextile tubes at around 20% solids. Each geotextile tube was filled multiple times. The final dewatered tube height was 1.8 m, and each tube contained around 2,145 m^3 after dewatering, resulting in around 446,160 m^3 of fill in the 208 geotextile tubes, or 30% of that needed. Effluent water was collected in channels and treated onsite to precipitate any dissolved heavy metals or other solids (pH was raised to precipitate dissolved solids), the pH was neutralized to 7, the then the water was released back to the natural environment. The tube captured 99.9% of all suspended solids during dewatering,

Once dewatered (55% solids or more), a drainage layer was placed over the tubes, and thereafter up to 8 tonne/m^2 overburden was placed. After overburden consolidation was complete, part of the overburden fill was removed. A minimum compacted fill thickness of 20 cm remained over the consolidated geotextile tubes (some documents referred to this as bedding sand). The pavement placed over the compacted fill consisted of 70 cm of well graded gravel, and a surface made of concrete pavers that were 8 cm thick (some documents said the pavers were 10 cm thick). The project also had two layers of reinforcing geotextile to help facilitate load distribution and minimize differential settlement.

Site development costs (some documents referred to this as earth fill platform costs) were reduced 20 to 30% by adopting the approach featuring geotextile tubes (the owner was reported to have realized a savings exceeding $50 million US dollars). The project's carbon footprint was said to have been reduced by around 7,900 metric tons of CO_2 equivalents via geotextile tubes. The Embraport website suggests the project is operational and has been successful (http://www.terminalembraport.com.br/en/).

Marine composite fabrics are relatively new and of potential interest to this project. They are produced in tan and green colors, and can be used to create sand filled mattresses and Geotube® containers. A case study of Gan International Airport, Maldives, was provided to the authors from unpublished information where sand filled GT 550 MC tan marine composite fabric was utilized as coastal erosion protection in the 2013 to 2014 time frame. The Republic of Maldives lacks sufficient erosion protection materials, making this a good application for geotextile tubes. This project, in and of itself, is outside the scope of this report, but it does show coastal applicability of marine composite fabrics. It is conceivable that marine composite fabrics could be used in conjunction with LC-VHMS for beneficial reuse applications, though this has not been explored to the knowledge of the authors.

TenCate™ provided unpublished information (a presentation and a write up by Edgar Westerhof) and TenCate™ (2013) on a project for revitalizing an industrial harbor in an area referred to as De Mars on the river IJssel in the city of Zutphen, Netherlands. During harbor refurbishment, dredging was performed to improve ship access and riverbanks were restored to prevent the harbor frim re-filling with sand and sludge over time. The harbor was contaminated with 18,000 to 25,000 m^3 of polluted sludge and presentation photos showed the river banks were heavily damaged. River bank refurbishment would traditionally call for virgin materials to raise embankment levels, but instead GT 500 geotextile tubes were filled with the polluted sludge at 10% solids and a flocculent via dredging at 400 m^3/hr to raise the river banks (65% solids were in the tubes after 4 days). Tubes were filled mostly side by side within four sheet pile compartments (for tubes per compartment) that stabilized the geotextile tubes during and after filling, and allowed water escaping the tubes to be collected in an adjacent compartment for testing prior to controlled river discharge. Water quality was suitable for discharge after being aerated. Compared to traditional construction, overall savings were estimated to be 30%. After the geotextile tubes dewatered, a rock revetment was placed to protect the slope from future erosion, and earth fill was placed over the tubes and vegetated. Photos taken 1 year after geotextile tube installation showed the area vegetated and conforming to the local landscape. When providing this data, TenCate™ noted that there was initially an alternate and more economical proposal to the sheet pile; use GT 750 M geotextile tubes filled with sand to form the barrier for the compartments.

2.6 Relevant Applications for Sediment Beneficial Reuse in and Around Ports

This section presents applications that might be suitable for sediment beneficial reuse in and around ports. Some of the information presented was not collected in and around points, but future applications that are similar could be in and around ports. Creating or restoring coastal habitat are potentially appealing for beneficial use of sediment, though these applications would often require non-contaminated sediments (Section 2.7 discusses beneficial use of contaminated sediments). Another concept of possible interest is improving properties of sediment through stabilization to a level that makes them more suitable for some permanent construction applications than local materials. This would be especially useful in an area experiencing lots of development (e.g. Lake Charles, LA area as of the writing of this report). Wetlands creation is a possible application, though this often requires small elevation increases, which would usually prohibit use of conventionally sized geotextile tubes. Smaller tubes, or sediment absent tubes (with or without stabilization), however, still have potential to be useful.

Some applications benefit from mass stabilization of fine grained soils via hydraulic (e.g. portland) cements. In some cases, a key attribute of these projects is to beneficially use on site soil after improvement as opposed to hauling these soils out and importing alternate materials. In a large number of cases, the sites of interest are near navigable waterways and were previously a dredged material placement area (DMPA). Many of these types of applications would target relatively low unconfined compressive (UC) strengths (e.g. 300 kPa or less) after curing for 2 to 4 weeks. Some of these types of applications stabilize very large soil quantities measured in hundreds of thousands of cubic meters.

Schifano (2013) presented a discussion of future needs and noted that because of the scale of the degraded and marginal land problem that significant innovation is needed. One area highlighted was beneficial reuse of dredged sediments (they were noted to have persistent pollutants). Quoting the author: "Use of dredged sediments for coastal and waterfront projects such as marine facilities expansion, ewt, land creation and restoration, levee maintenance and construction, and land reclamation for compensation of flooded land, requires improvements in the engineering and technology of these materials."

Lightweight backfill over compressible soils is of potential interest in and around ports and harbors. Tsuchida et al. (2001), while producing lightweight backfill, successfully collected mud from the seabed with a floating barge and bucket dredge, mixed mud with cementitious materials, and pumped the mixed material into place.

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 exceeding the soil's liquid limit and 30 to 35% air is typical in these mixtures. The previous references document projects that use $6.8(10^4)$ - $8.6(10^6)$ 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 had liquid limits of 58 to 91 and moisture contents of 85 to 250%. Cement contents were 3.3 - 14.8% by slurry weight (8.7 - 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.

Zele et al. (2014) reported on a study in Flanders, Belgium aimed at protecting the Flemish part of the Scheldt estuary that was part of the European PRISMA program and is described in the next three paragraphs. Monitoring of the estuaries sediment quality revealed that at least 80% is chemically suitable for re-use in infrastructure, but the materials are poor geotechnical quality. A full pilot scale project was conducted for dike construction with 100% re-use of dredged sediment. The dike was 800 m long, had slopes of 20/4, a 7 m crest width, and 4.5 m height. The dike is a dividing structure between a tidal area with controlled reduced tide and an area that only floods due to storm surge; A minimum threshold of 60% of the dike's total volume of 100,000 m^3 was to be dredged material. The dredged sediment used was not contaminated material having a fine sandy loam texture, 3.7% organic matter, 62% sand, 24% silt, 14% clay (finer than 2 μm), and a PI of 12.

Dike design requirements were: permeability less than 1e-7 m/s, undrained shear strength of 35 kPa, angle of internal friction of 25^o, and cohesion of 4 kPa. To meet design requirements, several additives were pilot scale tested including portland cement, quick lime, fly ash, bottom ash, slag cement, and sodium silicate. Specimens were prepared, sealed, and cured at ambient temperature over time before testing with a motorized laboratory vane apparatus. To produce 35 kPa undrained shear strength at 28 days, 4 to 14% additive by slurry mass was required at moisture contents from 50 to 150%. Ultimately, an unspecified blend of portland cement and fly ash was selected as the best performing additive combination. At 52% moisture, 28 day shear strengths with the unspecified proportion of portland cement and fly ash were approximately 18 kPa (3.6% dosage), 50 kPa (4.8% dosage), 65 kPa (6.1% dosage), 100 kPa (7.3% dosage), and 180 kPa (9.1% dosage).

During construction, sediments were mechanically dredged, loaded onto barges (typical loads of 300 - 550 m^3), transported to the site, unloaded with an excavator, placed over a vibrating sieve (double mesh, 150 mm and 50 mm diameters), captured in a buffer, and piston pumped to the stabilization plant. The plant contained two independent mixers, each with a calibrated additive dosing systems. Once mixed with the additives, stabilized sediment was loaded into dump trucks that placed the materials directly into the berm of the dike construction location. After curing around 5 days, a low-impact excavator leveled the stabilized sediments. Quality control operations utilized a vane tester to estimate undrained shear strength. In place vane measured strengths ranged from 35 to 105 kPa. Undisturbed samples were tested and the angle of internal friction was 34 to 40^o, and the cohesion was 8 to 34 kPa. In situ strengths were well above minimum requirements used in design.

To protect the dike's surface from erosion, vegetation was installed. A pre-test experiment concluded that classic techniques (surface roughening, seeding, and rolling) would not result in fast sprouting due to dry weather and harsh subsoil (low permeability, high alkalinity). The 35,000 m^2 of dike slopes was performed by hydro-seeding (fescue at 300 kg/ha). Water, mulch, a starch based binder, and a polymer water retaining agent were used. Slopes were watered every four days for two weeks, and after two weeks seed germination was noticed. After six weeks a tight vegetation cover was established.

2.7 Beneficial Reuse of Contaminated Sediments

Contaminated sediments are not uncommon in and around ports and harbors, or in other water bodies. El Mohtar (2013) discusses geoengineering of contaminated sediments and states there is over a billion yd^3 of contaminated sediments in rivers, lakes, and oceans. The author also makes the point that geotechnical and geoenvironmental engineers must play a much larger role in contaminated sediment remediation.

Not all sediments are contaminated, but those that are often lead to hesitancy in considering beneficial use applications. Contaminated sediments need evaluated in a comprehensive manner and utilized only after appropriate engineering, environmental, public safety, and other relevant factors are considered, though the remainder of this section shows this is feasible for multiple types of applications. Portland cement stabilization is one approach to beneficial use of contaminated sediments. Portland cement stabilization is intended to immobilize contaminants, and reduce contaminant leachability allowing reuse (e.g. engineered fill, landfill cover) or disposal in a non-hazardous waste landfill. This approach is considerably more economical than other alternatives in many cases.

Austin and Wilk (2004) reported on portland cement treatment of dredged material from the Port of San Diego. The authors stated that dredged material disposal costs are significant to maintenance dredging, and that cases with contaminants further increase costs as the contaminants prohibit ocean disposal and require up-land disposal. Approximately 12,600 m3 (16,500 yd^3) was dredged for the project reported, which had below hazardous contaminate levels that prevented normal ocean disposal. Contaminated sediment is often placed in confined disposal facilities (CDFs), which were noted to often be located near areas being dredged that, when near port areas, is precious land. For the project reported, cement based solidification/stabilization (S/S) was used so that the dredged sediment could be disposed in a local municipal solid waste landfill (MSWL). A clamshell dredge was used to load sediment onto barges, and free water captured during dredging was pumped back into the dredge area that was contained within a silt curtain. Thereafter, a S/S blending head mounted on equipment with a long reaching arm was used to mix a portland cement slurry resulting in 2 to 5% portland cement dosage (dosage basis was not reported). A few hours after mixing, the stabilized dredged sediment was transferred by a clamshell into a holding area, then put into trucks with lined beds for transport to the MSWL. Disposal criteria at the MSWL were a pH of 2 to 12, and no free liquids per a Paint Filter Test. Around 27 barge loads of material were stabilized, with all activities associated with one barge load of material taking an average of 3 days.

Matthews and Wilk (2004) described a land creation project where dredged sediment containing PCBs was used after stabilization with 13% portland cement by mass. S/S technology was used at the New Bedford Harbor Superfund site to create two acres of useable land. Soft dredged sediment was pugmill mixed with cement and stockpiled until a workable consistency was reached (this required a minimum of 24 hours and up to 3 months). Once suitable for use, the material was compacted in lifts behind the bulkhead. Significant cost savings were realized by using treated dredged material as structural fill; around 9,000 m^3 of sediment was treated.

Arora et al. (2006) reported on portland cement treatment of sediment contaminated with dioxin in Gulfport, MS. Some of the contaminated soils were incinerated and produced soil ash, while others were not incinerated. Soil ash, contaminated sediment, and portland cement were mixed in some cases, and contaminated sediment and portland cement were mixed in other cases. Portland cement dosages rates ranged from 4.7 to 14% depending on the reuse application (pavement subbase or base layer). A suite of dioxin leachability tests indicated the effectiveness of portland cement stabilization; the project covered an area of approximately 13 acres (5.3 hectares).

Schifano (2013) discusses soil mixing and its potential to restore degraded and marginal land. One of several items mentioned was confined disposal facilities for contaminated dredged sediment that often contain large volumes of material with complex composition and behavior. Use of soil mixing or S/S were both discussed in the article. Incorporating hydraulic cements was noted for its ability to physically bind or enclose contaminants within the stabilized mass. The author noted that there are a variety of laboratory test methods available to assess leachability, which is an important parameter for applications where contaminants are present.

It should be understood that not all contaminated sediments are treated with portland cement. Landers (2013b) describes contaminated sediment efforts on the Grasse River in Massena, New York. Significant quantities of PCB's were present and the remediation plan consisted of dredging and capping. Dredging occurred for 109,000 yd^3 of near shore sediments that were sent to a landfill. Capping occurred for main river channel sediments.

Landers (2013c) describes an EPA plan for cleaning up the Gowanus Canal in New York City (a Superfund site). A considerable amount of dredging is part of the plan, and the total project cost is estimated at $467-$504 million and nine years of working time. Approximately 590,000 yd^3 of contaminated soil is to be dredged from the canal. Highly polluted material is proposed to be treated via thermal desorption off site, and thereafter be beneficially reused elsewhere. Less contaminated material was proposed to likely be stabilized and reused off-site. Dredging and treatment costs are expected to be $179 - $216 million.

2.8 Properties of Dredged Material and Stabilized Fine Grained Soils

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 report. Initial moisture contents of fine grained dredged materials can easily be 100 to 200%. Index properties such as liquid limit (LL) can be on the order of 100, and mechanical properties can be minimal since, for example, the soils are highly compressible and have low shear strength. In the aforementioned conditions, these soils are not suitable for beneficial reuse applications (e.g. backfill) without treatment. Chemical stabilization is a logical method to employ.

Nordin and Queen (1992) reported that changes occurred in the Mississippi River bed gradations between Illinois and Louisiana from 1932 to 1989. Hundreds of locations were sampled for bed material from the thalweg of the river along a 955 mile reach. In 1989 there was less: coarse sand, very fine sand (0.062 - 0.125 mm), and gravel. In parts of the river (upstream) the bed was generally finer than in 1932 (i.e. mean and medial diameters were generally smaller in 1989 than in 1932), while downstream was about the same. The authors reported key changes in the Mississippi River since 1932: 1) sediment inflow to the river has been reduced into the reach studied by almost 50%; 2) extensive bank protection works have reduced bank erosion as a fine sediment source by a considerable amount; 3) meander cutoffs have shortened the reach and increased the overall slope between Cairo, IL and the Gulf. It was originally speculated that based on the three aforementioned factors that thalweg sediments in 1989 would be coarser than they were in 1932, which did not turn out to be the case. Gravel mining is a possible explanation for some of the particle size issues. Suspended sediment reduction, while well documented, is not well understood relative to how much suspended sediments change bed sediment sizes.

Stabilizing soils of all types using portland cement, slag cement, lime, flyash, kiln dust, or similar has occurred for decades. Hundreds of references are available on soil stabilization, though more attention is generally given to materials with moisture contents below VHMS levels. Several applications are presented later in this section 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 lightly cemented (LC) materials, which are the focus of this investigation, do not appear to be commonly used.

Howard and Trainer (2011) and Bazne et al. (2015) document volume change (or settlement) experiments performed during work as part of the Southeast Region Research Initiative (SERRI) program. Volume change associated with filling a geotextile tube with C-VHMS was investigated by monitoring height change in a geotextile pillow (see chapter 4) since volume change affects the final height of a geotextile tube and has many construction implications. Emerged and submerged tests were conducted where height change was measured over time (1 to 3 days); note since pillows are curved, height change does not correspond directly with volume change. Height change ranged from 10 to 24% and nearly all changes occurred during the first four hours.

Howard et al. (2012) sampled the fine grained soil used to fill geotextile tubes at Peoria, IL (project described elsewhere in chapter 2) and tested strength over time at the in situ moisture content of 70%. After 3 days of submerged room temperature curing, shear strengths were 0.5, 2.6, and 7.0 kg/cm^2 for dosages of 75, 150, and 250 kg/m^3 of portland cement. After 7 days of room temperature curing, shear strengths were 0.7, 3.6, and 9.4 kg/cm^2 for the same cement dosages.

Howard and Carruth (2014) studied C-VHMS dewatered with polymers. Shear strength improved 25%, on average, due to polymer inclusion. Shear strength was 1.5 kg/cm^2 or less, and the materials tested has been dewatered to 233% moisture and were stabilized with 15% portland cement.

Carruth et al. (2014) evaluated effects of water type on C-VHMS produced with soils having liquid limits ranging from around 50 to 100. Fresh (tap with no salinity), brackish (Lake Pontchartrain with 5 parts per thousand salinity), and salt (Florida coast with 40 parts per thousand salinity) water sources were used at 100 or 233% moisture with cement dosages of 10 or 15%. Water salinity appeared to have some effect on strength gain, yet the effect was not consistent with water or soil type. The use of C-VHMS with brackish or salt water did not appear to be prohibitive.

Howard and Carruth (2015) performed around 1,200 unconfined compression tests on VHMS produced with three soils having liquid limits of around 50 to 100, cement loadings of 5 to 15%, and moisture contents of 100 or 233% (15% cement was only tested at 233% moisture). Testing occurred after submerged curing at room temperature for 1 to 7 days, and shear strengths ranged from 0.1 to 3.8 kg/cm^2 for the entire data set. The data set of interest to the current work was testing at 5% cement by slurry mass and 100% moisture (i.e. *w/c* ratio of 10). After 1, 3, and 7 days of curing, s_u ranged from 0.29 - 0.75, 0.36 - 1.11, and 0.37 - 1.25 kg/cm^2, respectively.

Zhang et al. (2014) investigated long term effects of curing temperature on strength behaviors of cement stabilized clay by performing unconfined compression tests for up to one year of curing at temperatures ranging from 20 to 50 ^oC. It was noted that most strength testing of cement stabilized clay is after curing for a period of time in the 20 to 25 ^oC range, though it was noted that in tropical areas such as Singapore that measured temperatures within fill can reach 38 ^oC. This temperature gap is not considered in most current design practices. Temperature was the main focus of this investigation, with a key item being curing temperature effects and how they might differ between hydration and pozzolanic reactions (reactions between clay particles and hydration products). It was noted that concrete or mortar commonly experience a crossover behavior with respect to temperature, which was contrary to literature and data presented where cement stabilized clays experienced higher early and higher relatively mature age strengths with increasing temperature. An interesting experimental finding of Zhang et al. (2014) was that higher curing temperatures led to higher short-term and higher long-term strengths. Singapore clay with a liquid limit around 90, <6% organics, and a CH classification was tested. The combination of most relevance to this project was OPC at 11.8% of dry soil mass (4.2% of slurry mass) incorporated into Singapore clay with 180% moisture. Curing at 23, 37, 48 ^oC resulted in unconfined compression 90 day strengths of 180, 215, and 265 kPa, respectively. A key point brought up is that the dissociation of SiO_2 and Al_2O_3 (necessary for pozzolanic reactions) is dependent on pH and at higher temperatures, a lower pH can dissociate SiO_2 and Al_2O_3 provided acids from organic content are not prevailing in the system.

Grubb et al. (2010a) is a companion to two other papers published regarding stabilized dredged material. It focuses on treatability by way of twenty combinations of mostly pozzolanic materials (lime, cement kiln dust, high alkali portland cement, slag cement, and fly ash). The soil considered came from a confined disposal facility in Virginia, had 130% in situ moisture, an average liquid limit of 62, and classified as CH/OH. Specimens were tested in unconfined compression at 7, 28, and 180 days, at moisture contents from 80 to 150%. The lowest dosage rate utilized was 5% lime (total dredged material mass basis), with extremely high dosage rates used in some cases (e.g. 2.5% lime, 17.5% cement kiln dust, and 75% fly ash, which produced a 28 day strength of 784 kPa. With a 5% dosage of lime, 30 kPa unconfined compressive strength was achieved at 28 days. This was the only blend with 5% dosage or less.

Grubb et al. (2010b) is a companion to two other papers published regarding stabilized dredged material. A geotechnical evaluation of six stabilized dredged material (SDM) blends was performed where various combinations of cementitious materials were investigated. The dredged material classified as CH/OH and had an in situ moisture of around 130%. The primary finding was that SDM exhibits 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. The activities performed were for stockpiled SDM mellowed for a period of time (e.g. 3 days) that is compacted in place (i.e. it is not VHMS). It was reported that for SDM fill to be trafficable and constructible with low ground pressure equipment, a 28 day unconfined compressive strength of 138 kPa is needed.

A 2007 cost basis economic assessment was performed that considered DM source costs, DM bulkhead offloading, cementitious materials and delivery, DM processing, and SDM placement. Regionally estimated values were DM source costs (3.65/m^3), DM bulkhead offloading (1.08/m^3), cementitious materials and delivery (7.67/m^3 for 5% Type 1E portland cement and 10% fly ash on a wet DM basis if only trucking was paid for the fly ash), and SDM placement ($3.32/$m^3$). For SDM containing 5% Type 1E portland cement and 10% fly ash on a wet DM basis, combined costs were estimated to be around $13 to 16 per m^3. It was noted that the upper end of this range was comparable to the lower end of the metro New York City region processing costs for upland disposal, and also comparable to construction fill costs in several US east coast cities and urban areas.

A primary conclusion from Grubb et al. (2010b) was that expansion of port facilities is an excellent opportunity to showcase beneficial use on an unprecedented scale. The authors further state that ports are often faced with high costs of importing large quantities of select materials not locally available. Additionally, large volumes of DM and pozzolans are readily available, with pozzolanic availability coming from power plants and bulk terminals used by utility and cement industries.

Chrysochoou et al. (2010) is a companion to two other papers published regarding stabilized dredged material. This work suggested that USCS classification alone may be inadequate to assess a soil's reactivity since actual mineralogy controls stabilization potential and the classification can be misleading on the implied or actual soils mineralogical behavior. Silica and alumina in the presence of calcium with alkaline conditions are the main elements necessary for CSH or CAH formation (these formations lead to strength development). Data showed maintaining high pH is important for long term strength gain and that procedures relying on 7 or 28 day test data may not fully document advantages of long-term pH control. The authors suggested that consideration of 6 month (or longer) data may provide key insight or offer opportunities for enhanced design. The authors performed X-ray diffraction (XRD) with rietveld quantification analysis (RQA) as part of a detailed mineralogical analysis and did not find a direct correlation between mineralogy and engineering parameters. It was concluded that a pH below was associated with unconfined compression strengths below 300 kPa, and was also concluded that a persistent pH above 12 by itself was inadequate to produce high 28 day strengths because of limited availability of soluble silica and alumina in SDM blends.

2.9 Sediment Handling

Documenting the ability to successfully handle sediment is important for beneficial use in and around ports. There are some misconceptions regarding geotextile tubes and settlement handing. For example, Zele et al. (2014) reported that geotextile tubes have the disadvantages of: 1) needing high volumes of transport water, and 2) settlement assessment difficulties. Literature cited elsewhere in this chapter demonstrates successful settlement prediction, and lower moisture content sediment filling is documented in the remainder of this section. Additionally, Howard (2012) provides review of several additional references related to pumping or otherwise handling fine grained sediments. Most of this content was not repeated in this report for brevity since Howard (2012) is publically available. Therein, it is clearly documented, in addition to the additional references in this section, that sediment handling at lower moisture contents than, for example, in hydraulic dredging is feasible, even when filling geotextile tubes. This section also has additional information related to sediment handling not specifically dealing with lower moisture content transport.

Emery (1980) documented field trials where a chute was constructed to allow excavated sludge to be fed into a typical concrete ready-mix truck, while stabilization additives were incorporated via a small conveyor belt. The ready-mix truck system was reported to be so efficient that a large stabilization plant was passed over in favor of using multiple trucks.

Oota et al. (2009) indicated it is possible to convey dredged material over 1.5 km. Marlin (1999, 2002, 2003) presents considerable and relevant work to convey high moisture content fine grained soils. Therein, pumping fine grained soils in pilot tests, small island creation, and similar activities are documented. A pilot pumping experiment indicated that the materials under consideration could be pumped 3.2 km horizontally.

PRISMA (2012) documents field trials within a project titled Promoting Integrated Sediment Management (PRISMA), which aimed to achieve sustainable sediment management. Centrifugal (submersible) pumps were attempted initially, but were not successful. Thereafter, piston (concrete) pumps were successfully used to move dredged sediment (undiluted) as described in the reminder of this paragraph. It was stated that use of concrete pumps could allow sediment transport via pipeline, which would enable the Broads Authority to deposit sediment beyond the reach of a crane/excavator, and ultimately the report stated their goal was to fill geotextile bags with undiluted sediment via concrete pumps. A Putzmeister BSA 1407-D pump (4,200 kg weight) was used for the field trials, and a vibrating screen was used for some of the field trials. Sediment transport distances of 12 to 120 meters were investigated. A sizeable bespoke hopper was needed to send the sediment into the concrete pump without spillage. The sediment had considerable larger debris, which led to some issues, and it was determined that a vibrating screen was needed to remove debris. Later trials used a top screen of 75 mm and a bottom screen of 48 mm, with vibrating motion, and debris problems seemed to be alleviated. With proper screening for debris removal, the project reported successful use of the concrete pump for sediment transport.

Malasavage and Doak (2015) presented an innovative dredge referred to as “Pecos” that was reported to be a one-of-kind device that could operate in shallow draft environments and measure fill depth in real time. The dredge is around 100 ft long, can operate in 2 ft of water, and uses a 12 in diameter cutter head hydraulic dredge.

2.10 Vegetation Establishment

This section highlights efforts to establish vegetation within construction projects. Some of the projects are not applicable in and around ports and harbors, but they are presented since components of these efforts are potentially applicable to this report. Vegetation can be very important when attempting to establish harmony between the natural and built environments, and vegetation can also be valuable for performance of some projects as it can, for example, assist with erosion control.

Youssef et al. (2012) performed wind tunnel testing that showed vegetation to significantly reduce windblown mass loss by reducing wind-flow turbulence. Peryea (1999) discusses gardening on lead and arsenic contaminated soils in the state of Washington, and states the pH range of natural Washington soils is about 4 to 9. Amending acidic soils with agricultural lime (calcium carbonate or dolomite) is noted as an option to increase pH above

7. It was noted that it is difficult to reduce pH of soils containing free lime that have a pH of 8 or more. Acidic fertilizers (e.g. containing nitrogen as ammonium or urea) help reduce pH over time.

Marlin (2003) documents large scale demonstrations aimed at handling Illinois River sediments. The main purpose of the demonstration was sediment handling, but at the conclusion of the sediment handling activities, vegetation experiments were performed. For example, sediment was placed onto natural ground in 20 by 40 ft mounds that were 0.5 ft or 1 ft thick. Investigations occurred such as seeding, roto tilling, and leaving as placed. Details regarding the vegetation experiments were not plentiful, but well established grass was reported for at least some of the conditions encountered. It was reported that grass could protect sediment fields from erosion while the material was weathering. Generally speaking, the expectation for the material was to be placed, undergo considerable drying shrinkage resulting in polygons with wide cracks separating adjacent polygons, and then undergo weathering that would break down the polygons into a typical soil mass.

Marlin and Darmody (2005) discuss beneficial reuse of river sediment within a framework referred to as returning the soil to the land. The project's central premise was to return displaced soil eroded from farm fields and stream banks into the Illinois River back to beneficial use locations (soils were often transported long distances). It was suggested river soils are valuable, though out-of-place resource. The study noted that dredged material from urban and industrial areas is often heavily contaminated and warrants the caution of confined disposal. It was also noted that there is a growing recognition that sediment derived primarily from rural, freshwater areas, has potential value for applications such as fill, landscaping, soil amendment, and topsoil (strip mines, old industrial sites, or other). The Illinois River sediment was reported to have favorable chemical properties including elevated pH said to encourage growth of most farm and garden crops. Several field and greenhouse demonstrations showed plants (including grasses) grew readily in weathered sediment from the Illinois River. One example is in mid-September a low-ground pressure bulldozer spread soil from the Illinois River (after drying for a couple of months) to a depth of 0.6 – 1.2 m and seeded the soil with rye grass. By December, the grass was well established. Other examples of vegetation establishment were provided in the document, but the key item was readily established vegetation.

Howard et al. (2009) summarizes findings of a workshop and there are two presentations that provide vegetation evidence in conjunction with geotextile tubes. The first is on page 86 and shows vegetation growth out of the tube after 30 days, and the second is Drakes Creek (pages 170-175) where vegetation is shown some time after project completion. Few tangible details are provided for either case regarding vegetation.

Coulet et al. (2014) presented a comprehensive study where geotextile tubes filled with fine grained sediment were used as part of a retaining structure and eventually vegetated to create a wetlands habitat in Norfolk and Suffolk Broads, UK. The project was framed with an alternate sediment reuse framework where "working with nature" philosophies were incorporated. The desire was to turn two problems into a win-win situation while reducing operational costs. Sediment was mechanically dredged, transported by barge, emptied on site with an excavator, and placed into geotextile tubes with a Putzmeister 1407 positive displacement pump after being placed over a vibrating screen with 74 mm openings. Sediment was pumped around 170 m through a 127 mm diameter pipe. The paper reported that the Broads Authority is actively looking for alternative uses of sediment such agricultural soil improvement, flood defense, general earthwork, land raising, habitat restoration, and restoration of eroded areas. The Broads Authority has been involved with PRISMA (described elsewhere in Chapter 2), which officially commenced in June of 2011 and ended June 2014. Soft organic soils were present (around 40% organics and 18% dry solids). TenCate GT500D tubes were used that were covered with nonwoven TenCatePolyfeltTS70 to reduce disturbance of fine grained particles. Sediment was dredged and pumped with no increase in moisture content. Full scale activities showed sediment was evenly distributed within the tubes, and the pump had enough power to pump the sediment sideways after entering the tubes. The number of filling cycles depended on tube location, subsoil settlement, and fill material consolidation. The calculated primary settlements of 0.5 m and secondary settlement of 0.6 - 0.9 m approached reality. Once the geotextiles were placed, the area behind them was filled intermittently over a 16 week period. This project removed 12,000 m3 of accumulated sediment from the river.

While geotextile tubes were being filled, sediment was placed onto the geotextile tubes to form a vegetation growing media. Reed-bed vegetation was desired. Dormat vegetation was scraped from a donor site near the project in March of 2013. Before vegetation was placed, a pocket was created to provide continuous damp conditions and wave protection. After placement onto the geotextile tubes, vegetation was covered with TenCate GS20/20 geogrid to hold the material in place until it was sufficiently rooted. In addition to scraped vegetation, plug plants and seeds were also spread over the site to encourage wetland and reed-bed establishment. By August of 2013, over 30 vegetation species were recorded. Strong vegetation growth was recorded from the scraped vegetation.

Gerhardt-Smith and Banks (2014) is a summary of a USACE workshop held in 2013 dealing with Regional Sediment Management (RSM) and Engineering With Nature (EWN). RSM was defined as a systems-based approach to change focus from managing projects and sediments on local scales to regional scales. EWN is a program to enable more sustainable delivery of economic, environmental, and social benefits affiliated with water resources infrastructure and operations. Five of the more than two dozen bulleted items listed in the workshop summary are summarized below as they have potential relevance to the work presented in this document.

- Dredged sediments related to navigation business must be recognized as a resource and improved coordination is needed to ensure the sediments are beneficially used when feasible
- Dredged material should be stockpiled for future use
- Dredged material from projects in a maintenance status could be used as a reliable material source for adding lifts over marshes and wetlands to maintain the emergent elevations desired.
- Awareness should be increased of commercial or industrial used for dredged sediments and policies should be encouraged that permit sediment to be transferred from USACE to private entities for their use.
- Vegetation and other biodegradable materials (e.g. burlap) should see increased use for stabilization of banks and wetlands.

Guo et al. (2015) performed a fairly comprehensive vegetation experiment on low volume road shoulders where ryegrass and tall fescue were utilized. Rational for the study was that having vegetation on unpaved shoulders helps to reduce suspended air particles, thus reducing air pollution. The value of vegetation, however, was countered with the value that stabilization brings to a roadway shoulder, and thus this effort's primary emphasis was to provide stabilization and vegetation growth by way of geocell use. The author's noted they were not aware of another study where the impacts of geosynthetics on shoulder vegetation has been reported.

Several meticulous details were included to simulate the slope and drainage conditions of a typical roadway shoulder. Eight test sections with different soil profiles that were 1.5 m square were created inside plywood frames with the bottom open to the ground. Topsoil with a liquid limit of 48 and 19% organics (D2974) was used, which was sometimes mixed with aggregates. Tall fescue was applied at 5.2 g/m^2 as per Kansas DOT seeding requirements for shoulders. Evaluations included grass density, leaf blade length (non-destructive), population density (non-destructive), root length, soil volumetric moisture content, temperature, and dry biomass measurements. Fertilizer was only applied during sowing, and sections were watered for up to the first week. Grass was not mowed for the first twelve months of the study. Monitoring occurred from August 2013 through August 2014 (13 months). The study was successful from the perspective that there was no evidence of geocell reinforcement limiting vegetation growth in unpaved shoulders.

Guo et al. (2015) cited United States Department of Agriculture (USDA) information about Kentucky-31 type of tall fescue. It was noted this grass has been planted on a widespread basis for items such as erosion control due its ease of establishment, long life cycle in harsh conditions, and mistreatment tolerance.

Malasavage and Doak (2015) describe a project to deepen the Oakland Inner and Outer Harbors from elevation -42 to -50 ft to accommodate post-Panamax container ships. A total of 12.8 million yd^3 of material needed moved for the project. Approximate half of the material moved to deepen the harbor was placed adjacent to the deepening site and referred to as the Middle Harbor Enhancement Area (MHEA). The MHEA perimeter included sheet pile wall and stone-armored jetties, and a considerable amount of the final grades are sub-tidal. The MHEA intended to provide conditions suitable for propagation of eel grass, and construction was staged with around three years between stages to allow for foundation consolidation and strength gain. Bulk filling of the MHEA site included clean sands and silt/slay mixtures.

2.11 Materials of Specific Interest

2.11.1 Ash Materials

Coal is used by some power plants to generate electricity by being burned, and bottom ash is a product of the coal that remains after burning. Ash materials have potential relevance to this report because it is fairly common for these types of materials to be produced near bodies of water, or even close to ports and harbors. Industrial activity requiring considerable amounts of freight (e.g. coal) often locates relatively close to ports, rail lines, harbors, or interstate highways. There is thus a potential opportunity for this project to investigate engineering properties of ash materials mixed with sediments and stabilized for beneficial use (leachate or groundwater issues were not considered in this report).

Landers (2013a) describes legislative efforts related to coal ash facility permitting programs. It is noted in the article that coal ash that is not beneficially reused is typically stored in surface impoundments or disposed of in landfills. There are several ongoing discussions related to coal ash and storage.

Landers (2015) discusses the debate about coal ash disposal, largely in the context of the US Environmental Protection Agencies (EPA's) *final rule* that is scheduled to become effective on October 14, 2015. The EPA chose to regulate coal ash disposal under subtitle D of the Resource Conservation and Recovery Act (RCRA), which is a solid waste provision. Additionally, Landers (2015) provided the following information regarding coal ash quantities. Coal ash is one of the largest waste streams in the US; in 2012 there was roughly 110 million tons of coal ash produced in 47 US states and Puerto Rico (around 44 million tons were beneficially reused). Around 53 million tons was disposed of in landfills or surface impoundments. An average size for a landfill is 120 acres with an average depth of 40 ft, and an average size for a surface impoundment is 50 acres with an average depth of 20 ft.

Russell (2015) discussed stabilizing unsurfaced sand roads with wood products and byproducts including paper mill boiler ash. Availability of, for example, paper mill boiler ash could better than gravel in some areas. Around 60% of all paper mill solid waste is landfilled. Boiler ash may consist of bottom ash, fly ash, or both. The study concluded that the paper mill byproduct boiler ash has favorable chemical and mechanical properties and appears to be particularly promising as a road stabilizer and was recommended for further study. While the work of Russell (2015) is not directly applicable to this report, it does show that interest and attempted innovation with ash materials is occurring, and shows a possible application for LC-VHMS (i.e. very low volume road improvements if a dredge disposal facility is near, for example, a forest service road).

2.11.2 Biodegradable Fabrics

Geotextile tubes are, as the name implies, manufactured from geotextiles, which are polymer based synthetic materials. Geotextile tubes are a very useful product for many applications, though consideration should be given to tubes manufactured from materials other than geotextiles for some applications. Biodegradable fibers, such as those used to produce products like burlap could have application for tubes in some beneficial reuse applications of interest to this report as they would be very sustainable. Burlap is a coarse canvas made from largely from jute, and can contain flax, sisal, hemp, and similar. Coir is another biodegradable fiber that has a high lignin content, which makes is degrade more slowly than other natural materials.

Jute is a fiber that, according to (http://www.wildfibres.co.uk/html/jute.html) is second only to cotton in terms of usage production and global consumption. It is mainly grown in India and Bangladesh, and the fibers are part cellulose, part lignin. Typical Jute fiber applications are cases where lower cost is more important than durability. For some of the beneficial reuse applications described later in this report, that could be the case. Products produced with jute fibers often have an open weave fabric, which would be conducive to vegetation growth.

Saride et al. (2014) studied jute geocell reinforced sand subgrades for low volume roads, where jute was obtained from waste gunny bags. The study indicated that the majority of the jute available is not used to make goods, so there is some material available. The study also referenced a few rural road applications referenced by other authors where jute was used in some manner. The jute used to produce geocells had ultimate tensile strengths of around 5 to 6 kN/m, aperture sizes of 1.7 to 2.8 mm, thicknesses of 1.8 to 3.6 mm, and a mass per unit area of around 0.52 kg/m^2. The study concluded that available waste jute bags can be used as pavement reinforcement.

Lovelace (2014) investigated use of tubes made from natural biodegradable fabric for dredged material containment at Gaillard Island disposal area in Mobile Bay, AL. The primary purpose of the project was stated to be testing physical limits and constructability of natural, biodegradable tube materials. Biodegradable structures were stated to have been shown more hospitable to revegetation by deep rooted plants. Use of short term biodegradable structures was said to allow a potentially more desirable alternative, and that the temporary containment for dredged material could allow sufficient time for consolidation and stabilizing vegetation to become established. This project utilized jute burlap and four layers of 10 oz burlap was needed to withstand the pressures required to fill the tubes 4 ft tall when emerged (design fill height was 3.5 ft). Initial flow testing showed hydraulic filling was feasible if the fill contained less than 10% fines (particles between 4 to 63 μm). A submerged hydraulic powered 8 in pump was used alongside intake and outlet lines sized to maintain water pressure suitable of overcoming the tubes dynamic head to fill the tubes with a sandy material. There was substantial loss of fine material through the fabric during filling, resulting in extended fill times. It was concluded that the test project was successful in testing biodegradable containment options for managing sandy and fine-grain dredge material for beneficial use projects. Jute tubes performed similar to synthetic tubes and the finished product was a tube with 100% compacted sand. Pumping time was observed to be a function of the percentage of fines in the sand, with filling times estimated to increase 25 to 40% with higher fines contents. A 20 oz. burlap was recommended for future projects.

2.12 Relevant USACE Dredging and Organizational Information

During the early stages of this project, several individuals from across USACE were contacted, largely for the purpose of selecting dredged disposal sites for sampling and subsequent LC-VHMS testing (see chapter 4). A summary of general information obtained through that process is provided in the remainder of this section. Generally speaking, USACE is organized into eight geographical divisions in the US, with each division having 4 to 7 districts. The two divisions where material was collected and tested for this project were the Mississippi Valley Division (MVD) and the South Atlantic Division (SAD).

As of a few years ago, U.S. Army Corps of Engineers (USACE) handled upwards of 200 million cubic meters of dredged material each year, of which only about 20 to 30 percent is used beneficially (EPA/USACE 2007). Mississippi River ports often leave dredging for USACE. Along the Mississippi River, USACE does mostly hydraulic cutterhead dredging where material is put back into the main channel. A reasonable estimate for dredging along the Mississippi River was stated to be \$2/yd^3. Within MVN, it was stated that most harbor dredging is to move sandy material near the mouths, but that finer material is sometimes encountered in slackwater areas of harbors. MVN did not have but a few fine grained areas of possible interest to this project (most MVN dredged material is sand). Some USACE districts (e.g. Jacksonville) dredge mostly high quality material such as beach sand, and when they do have material selected for disposal they place it in an ocean disposal site. Generally speaking, USACE is responsible for the majority of the dredging that occurs at the typical port or harbor.

CHAPTER 3 – PORTS SURVEY

3.1 Overview of Ports Survey

In that the research being performed, while centered around ports, has multi-disciplinary implications and is to some extent driven by the Panama Canal Expansion, collecting survey information seemed like a worthwhile endeavor. In initial stages, three surveys were considered, two were sent out, and one yielded useful information. The three surveys considered were to ports, dredging contractors, and the USACE. Informal discussion with USACE representatives led to the decision not to conduct a survey within the organization. A survey was sent to dredging contractors in August of 2014, but no responses were obtained and as such the rest of this chapter is solely related to the ports survey and subsequent findings. Note that all that is contained in this chapter are survey details and findings as reported by respondents (with occasional clarification notes by the authors). Interpretation and use of these findings is left for later chapters of this report.

3.2 Survey Description Sent to Ports

A two page document dated July 13, 2014 was sent to several ports. The first page of this document contained the text below, except for minor formatting changes and survey response specifics which are summarized below in brackets with italic text. The description sent to ports was somewhat narrower than the overall research effort as it entailed combined use of geotextile tubes and lightly cemented VHMS (individual use of these items was not mentioned). Respondents could submit information in whatever manner was most convenient for them (e.g. handwritten, scanned, faxed). Respondents were told information received after October 31, 2014 might not be included in the final document. In a few cases, clarification was sought in the late August to early September of 2015 time frame.

Survey Description: Research is underway investigating ports in seven states along the Gulf Coast and inland ports on the Mississippi River as far north as Memphis, TN. The objective is to study use of geotextile tubes filled with cementitiously stabilized very high moisture content fine grained dredged soils for beneficial reuse. Soils of this nature have been termed VHMS for Very High Moisture Soils. The research has an emphasis on sustainability and beneficial reuse of fine grained soils from dredging; most applications are envisioned to use a light dosage of portland cement (e.g. $\leq$ 5%). Increased beneficial reuse of fine grained dredged soils increases sustainability since dredging is a high volume and continual process that often results in disposal needs.

Geotextile tubes are versatile products that have found their way into many applications including sediment containment, shoreline protection, and breakwaters. Typically, geotextile tubes are formed by sewing geosynthetic sheets together that can be filled with a variety of materials. More information on geotextile tubes is available in Howard et al. (2009). Traditionally, sand has been used to fill geotextile tubes for permanent applications. Complimentary research suggests using stabilized fine grained soils in lieu of sand can potentially offer environmental, logistical, and economic advantages for some applications (Howard et al. 2012). This research aims to explore different aspects of using geotextile tubes filled with stabilized dredged soils at ports. Particular areas of interest are engineering properties, construction matters, sustainability, and economic competitiveness of potential applications of geotextile tubes at or around ports. Portland cement stabilization of soils is a very mature technology, though lightly cemented VHMS is not nearly as well established. Coupling lightly cemented VHMS with geotextile tubes is even less common.

This survey is intended to guide the research and to enhance student experiences for those participating in this project. This survey has been sent to dozens of ports in the area previously mentioned, and your voluntary participation would be greatly useful and appreciated. Should you choose to respond, the information provided will be treated as publically available information and may be used in written documents such as articles, theses or dissertations, presentations, educational workshops, university courses, or other as needed. Any questions about the survey (or the research as a whole) can be directed to the undersigned [*undersigned was Isaac L. Howard*]. Responses may be provided via any manner listed below [*email, mail, fax, and phone options were provided*]. If you would like to respond anonymously, you may mail your unlabeled responses to [*address was provided*]. If you only want to answer some of the questions, that is helpful and appreciated as well.

On the second page of the survey, there was a space for contact information to be provided, and a place to forego contact information and request the information provided be anonymous. Ten questions (Q1 to Q10) were asked, and for three of these questions (Q1, Q2, and Q6) a portion of the requested response was a 1 to 10 rating. There was also a space provided where additional comments or suggestions could be provided.

3.3 Ports Surveyed

Initially, the 38 ports listed by state below were the intended survey distribution list. Each port was called and contact information collected for email distribution of the survey. Contact information could not be obtained for three ports (Brownsville, Weedon-Island, and Intracoastal City), and two others declined interest due to lack of application (Offshore Oil Port, and South Louisiana). The remaining 33 ports were sent the survey via email. A total of 12 responses were collected, which is 32% of the intended distribution list and 36% of the ports that received the survey via email. In other words, the survey reflects around 1/3rd of the ports in the region of interest. Survey responses are provided in the next section.

Alabama (2): Decatur, Mobile

Arkansas (1): Helena Harbor

Florida (11): Brownsville, Canaveral, Jacksonville, Manatee, PortMiami, Palm Beach District, Panama City, Pensacola, Port Everglades, Tampa Bay, Weedon-Island

Louisiana (8): Baton Rouge, Fourchon, Intracoastal City, Lake Charles, New Orleans, Offshore Oil Port, Plaquemines Port, South Louisiana

Mississippi (6): Biloxi, Greenville, Gulfport, Pascagoula, Rosedale, Vicksburg

Tennessee (1): Memphis

Texas (9): Arthur, Beaumont, Corpus Christi, Freeport, Galveston, Houston Authority, Lavaca-Port Comfort, Texas City, Victoria

3.4 Survey Results

Table 3.1 summarizes information for the twelve ports that responded to the survey alongside numerical scores where they were applicable. Thereafter, the actual questions asked are provided alongside responses as received from respondents. Note that in a few cases italic text is inserted by the authors in brackets to help readers of this report interpret the responses provided. In a few cases the italic text provided in brackets is based on the authors asking follow up questions to ports in the late August to early September of 2015 time frame to provide clarification regarding some of the original answers obtained.

Table 3.1. Summary of Numerical Responses and Port Contact Information

Port	Respondent	Job Title	Q1	Q2	Q6
Anonymous	Anonymous	Anonymous	3	---	---
AL-Mobile[a]	Robert C. Harris, Jr., PE	Vice-President	5	1	10
AR-Helena Harbor	John C. Edwards	Economic Development Director	5[c]	10	---
FL-Manatee	George F. Isiminger, PE	Senior Director	4	---	1
FL-PortMiami	Becky Hope	Environmental Manager	10	---	10
FL-Palm Beach District	Thomas J. Lundeen, PE	Deputy Port Director/Port Engineer	1	1	1
FL-Tampa Bay	Bruce Laurion, PE	VP of Engineering	3	2	1[e]
LA-Lake Charles	Channing Hayden	Director of Navigation	1	1	2.5[d]
TN-Memphis	Randy Richardson	Executive Director	3	1[b]	3
TX- Beaumont	Bill Carpenter	Deputy Director	2	2	1
TX-Houston Authority	Mark Vincent	Director, Channel Development	10	10	5
TX-Texas City	Jason Hayley	Operations Director	1	1	1
		Average Score	*4.0*	*3.2*	*3.6*

Note: Respondents were told that for 1 to 10 scaled questions, 10 is high (or favorable).
Q1 is related to impacts of the Panama Canal Expansion as a whole on a given port.
Q2 is related to the impacts of only the dredging related to the Panama Canal Expansion.
Q6 is related to beneficial reuse of dredged soil and whether it would improve economic competitiveness.
a: Alabama State Port Authority
b: respondent reported 0
c: estimated future impact of 5
d: response was 2-3
e: respondent said "No.", which was interpreted to be 1

Q1. Has the ongoing expansion of the Panama Canal had any impacts on your operations or it is expected to in the future? If so, what kinds of impacts (social/economic…freight..)? Can you rate your level of impact on a 1 to 10 scale?

Anonymous: Yes: e.g. cooperative agreements/alliances.

AL-Mobile: This is a question every port in the Gulf of Mexico is asking itself. We believe that the amount of freight handled through the port and the economic impact could be significant by allowing larger container ships from Asia that feed our growing automobile industry to transit the Panama Canal.

AR-Helena Harbor: No impact as of this time. We hope that there will be a future impact.

FL-Manatee: No measurable impact yet. Increase in number of port calls, as opposed to size of ships, is expected due to increase in transshipments (larger vessels coming through the canal and transferring cargo to smaller vessels that will fit in ports too shallow for the larger vessels).

FL-PortMiami: In preparation of the ongoing expansion of the Panama Canal (Canal), PortMiami (Port) has improved upon existing operations to include not only the Deep Dredge project, but restoration of on-port rail services, and direct interstate access via the Port Tunnel to facilitate the wide dispersal and accelerated movement of goods into and out of South Florida. These projects highlight the Port's initiative in sustaining it's socioeconomic role as a top economic engine and job creator in South Florida in preparation of playing an even greater role in the global economy when the Canal is completed. Given the positive socioeconomic impact these combined projects will have in tandem with the completion of the Canal it is reasonable to rate the level of impact as a 10.

FL-Palm Beach District: The Port of Palm Beach is not capable of handling post panamax vessels. We may have minor increase in cargo from smaller feeder vessels.

FL-Tampa Bay: This port has 43-foot deep channels. Most new container carriers using the Panama Canal's new locks will not directly visit this port. Instead, they will deliver to their primary hubs like Kingston where the containers would be unloaded and transshipped using feeder carriers to the Gulf Ports.

LA-Lake Charles: No impact.

TN-Memphis: There are many existing obstacles hindering the economical transition of ocean going containers to on-barge shipment. Items such as competing forms of transportation, the low weight of containers, the lack of barges designed to carry large numbers of containers, the oversized engines in current river boats and the height restrictions of existing tow boats and bridges in the inland system just to name a few.

TX-Houston Authority: The expansion has resulted in a program to renovate and improve a large container terminal (>1.2 m TEU annually), continued expansion of a second terminal (>1.0 mil TEU), and non-federal deepening and widening of two federal channels at port expense.

TX-Texas City: No impacts so far. Unable to determine future impacts.

TX-Beaumont: Very little.

Q2. Please rate on a 1 to 10 scale the anticipated impact of only the dredging being performed at your facility in response to the Panama Canal Expansion.

Anonymous: Although the ACP announcement and the potential trades associated factor to economically support some port terminal/channel/terminals facilities infrastructure development, the existing 45 foot channel already accommodated the existing Canal and the authorized 52 foot project dredging shall serve other post-panamax trades/vessels. However, the majority of 45/52 foot terminals/facilities are intended to principally accommodate 45/52 foot project cargos and fleet not specific to the Canal. Nonetheless, even though some significant recent dredging and terminal development projects shall accommodate the possible increase in container trade in part associated with the canal, the 45 foot and 52 foot projects shall accommodate the vessel classes and trades projected to be associated due to the expanded canal.

AL-Mobile: We are not currently planning any dredging that is strictly in response to the Panama Canal Expansion. We are examining a project to widen a portion of the ship channel to our port to allow two large ships to pass one another. Currently the port is limited to one way traffic when a post-panamax ship transits the channel. However, this is in response to current traffic, not additional traffic we foresee as a result of the expansion. Another project being reviewed is a widening and deepening of the entire length of the channel. Again, this is to better handle existing traffic.

AR-Helena Harbor: It would be a positive impact.

FL-Manatee: Either none or substantial, depending on the results of a deepening study currently being performed by our federal partners, USACE. Likely substantial, as the study is likely to support deepening from 40 ft. to 43 or 45 ft. [*Follow up communications revealed that there is no perceived impact if current channels are not deepened. If the channels are deepened, the port will be able to capture larger vessels. It was noted that even if the port does not deepen current channels that indirect traffic from cargo transfer could increase freight through the port. It was also noted that indirect traffic from cargo transfer would not have any impact related to dredging. Any impacts were stated to be assumed to be advantage gained because of the expansion.*]

FL-PortMiami: Referring to A1 [*answer to Q1*] above, a rating cannot be applied to just the Deep Dredge project without including the rail and tunnel projects. However, it is important to note the Port is the largest container port in South Florida and is vital contributor to the local, state and national economy boasting over 180,000 direct and indirect jobs and over $18 billion economic impact on South Florida’s economy.

FL-Tampa Bay: This Port does not see the need to deepen its 43-mile channel, which is already 43-feet deep.

LA-Lake Charles: No impact.

TX-Houston Authority: Non-federal cost of channel improvements is over $85 million.

TX-Texas City: No impact.

Q3. What are your current dredged soil practices, specifically related to the soils final location after dredging?

Anonymous: Typical maintenance placement to DMPAs [*interpreted to be dredged material placement area*] and post placement beneficial reuse (broad definition of BU of DM) where feasible and practicable to the application; new work placement to DMPAs and post-placement beneficial re-use (broad definition of BU of DM) where feasible and practicable to the application or direct BU (broad definition of BU of DM). [*BU and DM interpreted to be beneficial use and dredged material*].

AL-Mobile: It is becoming more apparent every day that the old practice of placing dredged material into a site and leaving for perpetuity is no longer practical and the permitting of new facilities would be extremely difficult, if not impossible. We now take the position that dredged material is a resource rather than a waste and seek to find beneficial uses whenever possible. We no longer allow private terminals to place dredged material into our sites unless they agree to remove an amount equal to two times the volume placed into our site and take it to an offsite location of their choice. We are currently seeking to permit a system at our coal terminal that maintains the sediment in suspension so that it does not accumulate in our berthing areas, thereby reducing the amount of dredging that must be done to maintain our required draft. This system is made by Sedcon Technologies, Inc. Finally, as a last resort, we anticipate having to excavate material and transport it to an offsite disposal site.

AR-Helena Harbor: We have a section of land where dredged material is offloaded.

FL-Manatee: Of two options, upland contained disposal and offshore disposal, we normally go upland due to lower cost.

FL-PortMiami: The beneficial re-use of dredge material, as approved by applicable regulatory agencies, is placing approximately 600,000 cubic yards of dredge material within a portion of a historic dredge/borrow hole to restore approximately 16.6 acres of seagrass beds within the Miami Biscayne Bay Aquatic Preserve. Remaining dredge material is being placed at the federally approved off-shore Ocean Dredged Material Disposal Site.

FL-Palm Beach District: The ACOE [*interpreted by authors to be USACE*] places the dredge material on the beach or near shore disposal area. The dredge material is usually beach quality sand.

FL-Tampa Bay: Currently the Port has two spoil islands within the harbor that will have 20-million cubic yards of capacity once the current levee project is completed in 2015. The Port also has a designated offshore Gulf of Mexico spoil disposal area.

LA-Lake Charles: Placed in Corps of Engineers designated disposal areas along the Calcasieu Ship Channel.

TN-Memphis: Per the federal law that created the Port of Memphis in 1948, we are required to place dredge material in upland sites. [*Follow up communication revealed that by the creation law, the Memphis and Shelby County Port Commission must place material from within the harbor, dredged by USACE maintenance obligations, in an upland site. Alternative requests can be made. The dredge material can be used for project sites as long as they are upland. It was noted that if someone desired to move the dredged material to another location that it was likely this would be approved if all regulatory issues were addressed.]*

TX-Houston Authority: Disposal in CDFs, with those properties used exclusively for dredged material. PHA maintains approximately 6,000 acres of placement areas.

TX-Texas City: Materials are placed in PA [*interpreted by authors to be placement area*] controlled by USACE.

TX-Beaumont: We own our own spoil areas.

Q4. Has your facility considered a beneficial reuse strategy for dredged soil? If so, what kind of strategy?

Anonymous: Yes. Broad consideration of possible multi-purpose outcomes if feasible and practicable.

AL-Mobile: Our port, in cooperation with the Corps of Engineers and numerous natural resource agencies and NGO's has formed an interagency working group to examine opportunities for beneficial use of dredged material. We have identified a potential location for the creation of approximately 1250 acres of marsh habitat. We have conducted screening of the site for potential negative impacts to cultural resources, submerged aquatic vegetation and other issues. We are currently planning to take sediment samples in the designated area for geotechnical analysis to allow us to proceed with preliminary engineering.

AR-Helena Harbor: This has not been considered.

FL-Manatee: Material has been used for island creation in the past. The island has been fashioned into bird habitat. Beneficial use is always considered but has not otherwise been implemented, primarily because the material is not suitable for beach nourishment, construction material because it is too clayey, maintenance material because it is too silty.

FL-PortMiami: Refer to A3 [*answer to Q3*] above.

FL-Palm Beach District: See Q3.

FL-Tampa Bay: No because nothing has been as cost effective as the current spoil disposal practice.

LA-Lake Charles: Yes, but the maintenance quantities involved are too small to make this a practical alternative. Material from dredging of new berths may be used to cap contaminated areas and build wetlands over the cap.

TN-Memphis: Yes, but they are all too expensive. We have looked at shipping the material to other locations in the river system for use and have even tried to reuse the material in other processes such as asphalt with limited success. The problem is the river dredged material is not very consistent on a year to year basis.

TX-Houston Authority: PHA has sponsored construction of approx. 3,000 acres of created marsh. This was done as a demonstration project initially, then as mitigation for the Houston Ship channel deepening program. Confining cells were hydraulically formed using clay, and will then be carefully filled over time to provide a suitable [*clarification was not obtained for this response.*]

TX-Texas City: No consideration at this point in time.

TX-Beaumont: No.

Q5. Do you know of regulations and/or policies in place that may limit the reuse of dredged soil at your facility?

Anonymous: Yes.

AL-Mobile: One of the tremendous benefits of using an interagency working group is that we have been able to work out potential regulatory hurdles among all of the agencies involved, and to achieve consensus, prior to moving to the next step. We do not foresee any regulatory hurdles that cannot be overcome at this time.

AR-Helena Harbor: Not aware of any at this time, but would need to learn more to answer this question with a high degree of confidence.

FL-Manatee: In our case, only those against fines in beach renourishment material and turbidity.

FL-PortMiami: Depending on the potential re-use of the material, both environmental and geotechnical test results of the material may limit its potential re-use per local, state and federal environmental regulations. The Port first evaluates potential beneficial re-use options for all dredge material, then determines the feasibility in accordance with rules and regulations, and community concerns. When beneficial re-use options are exhausted, remaining dredged material is placed at the Ocean Dredge Material Disposal Site.

FL-Palm Beach District: No.

FL-Tampa Bay: No.

LA-Lake Charles: No.

TN-Memphis: Yes, the State of Tennessee office of Environment and conservation does not like the material to be reused in the river system anywhere. It historically has naturally occurring high levels of Arsenic from native soils upriver.

TX-Houston Authority: RCRA (although the goal is to only accept suitable material); state mineral rights over sand, gravel, marl. [*unknown term*] Corps policies (not clearly stated) that limit reuse so as to preserve a source of material for levee raises.

TX-Texas City: New Corps [*interpreted by authors to be USACE*] guidelines specific to the Galveston District only.

TX-Beaumont: No.

Q6. On a scale of 1 to 10, do you feel beneficial reuse of dredged soil might improve your facilities economic competitiveness?

Anonymous: Circumstance dependent.

AL-Mobile: The construction of the previously mentioned marsh habitat project would generate dredged material placement capacity for many years to come. This would eliminate the enormous cost associated with excavation and offsite transport of material placed in our upland dredged material management sites.

AR-Helena Harbor: Need to learn more about the benefits and risks, but it does appear to be something worth further examination.

FL-PortMiami: Beneficial re-use of dredge material not only benefits the costs of dredge projects, it also provides environmental benefits. Both of these elements lead to a plus in the Port's competitiveness and its commitment as a good neighbor.

LA-Lake Charles: Our beneficial use of dredge material is not motivated by economic competitiveness but by construction cost savings and the ability to help address the wetlands loss along the Louisiana coast.

TX-Houston Authority: PHA periodically considers various options for other uses, but none have proven to be viable economically.

TX-Texas City: Don't believe it would improve our economic competitiveness.

Q7. Are there any applications at your facility that you feel might have the potential to be replaced or enhanced by the approaches (or similar approaches) described in the description of this survey?

Anonymous: Maybe.

AL-Mobile: If proven to be feasible, the approach described could be extremely useful in the construction of the marsh habitat to be constructed. We are currently discussing alternatives for the containment of the dredged material in the site. Sand, rip-rap and geotextile tubes have all been discussed as alternatives.

AR-Helena Harbor: It is possible.

FL-Manatee: The approach could replace our existing disposal practices, but the relative cost would certainly have to be a factor.

FL-PortMiami: At this time, there appears to be a limited possibility for this application to be implemented. The Port considers beneficial re-use strategies for dredged material, however, due to property constraints the Port is limited in its ability to store material on-site and stage re-use operations in a timely and cost effective manner without impacting existing tenants (e.g., the Port is active with both cruise and cargo operations occurring on a continual basis). Additionally, the current Deep Dredge project is under way and any change in material disposal at this time would result in a contract change.

FL-Palm Beach District: No.

FL-Tampa Bay: Not sure.

LA-Lake Charles: No.

TN-Memphis: It is possible. The key would be in proving its performance longevity and how it reacts to exposure to fertilizers and other materials typically handled in the inland river system and constant fluctuations between wet and dry climates.

TX-Houston Authority: Not at the present. The Galveston District has used geotubes, but ours is a relatively high-energy environment-riprapped levees close to ship channels, many shorelines bulkheaded, high demand for placement areas results in constructed levees designed for further raises.

TX-Texas City: Unsure.

TX-Beaumont: None.

Q8. Would your group consider the use of geotextile tubes and/or lightly cemented VHMS for any application? If so, please explain.

Anonymous: Use of geotextile tubes have been installed and/or considered in certain settings/circumstances.

AL-Mobile: Until it is proven technology, it would not be suitable for our marsh habitat creation projection. However, the Mobile District of USACE has done some demonstration projects to examine potential alternatives for containment of dredged material. The next step might be one of these demonstration type projects.

AR-Helena Harbor: I think it would be worth considering. I would need to learn more about the issue.

FL-Manatee: Yes. We would be interested in hearing about suggested applications and about how strong the material is.

FL-PortMiami: Refer to A7 [*answer to Q7*] above.

FL-Palm Beach District: It has not been considered.

FL-Tampa Bay: We tried using geotubes for shoreline protection at our spoil disposal island and it was a disaster during construction because of fine silt plugging the pores in the geotubes, and was a failure within two years due to UV degradation and vandalism cutting the fabric. Ultimately the geotubes were replaced with rip-rap.

LA-Lake Charles: Not for the projects that are specific to our facilities. See the comments below for further discussion.

TN-Memphis: It would have to be cost competitive and out last the current methods. Easy enough.

TX-Houston Authority: We would consider it, but do not foresee any applications at present.

TX-Texas City: Only if unable to place material in PA [*placement area*] controlled by USACE.

TX-Beaumont: Not likely.

Q9. Do you have any cost information you could share related to dredging operations, dredged soil disposal facilities, or other dredging operations directly applicable to this project? Examples include how much dredging has been done/is expected, the motivation behind such efforts, alternatives, etc. If you are not comfortable providing specific information, ranges of prices over time (or similar) would be useful as well.

Anonymous: Costs vary widely depending on activity, design, materials, location, etc.

AL-Mobile: Our recent experience is an average cost of around $8 per cubic yard for hydraulic dredging and placement into one of our upland sites. This price is highly dependent upon the quantity dredged as mobilization/demobilization cost can heavily impact the per cubic yard cost of dredging. If excavation, and transport to an offsite disposal site is required, this will add an additional $15 per cubic yard to the cost. That is why it is imperative that we explore beneficial use opportunities.

AR-Helena Harbor: No.

FL-Manatee: Our shoaling rate is about 170,000 CY/yr and it costs about $12/CY for upland disposal and $25/CY for offshore disposal. However, we need to increase our upland disposal capacity at substantial unknown cost. [*CY interpreted as cubic yard, or* yd^3]

FL-PortMiami: The Port's Deep Dredge project is on-going and being managed by USACE. Subsequently, cost breakdown information and other requested information is often not made public and in other instances may be deemed proprietary by the Contractor.

FL-Palm Beach District: No. the ACOE [*USACE*] handles all maintenance dredging.

LA-Lake Charles: Our responsibility is to maintain our dock at a specified depth from the edge of the federally maintained channel to the face of our wharves. To do so we dredge approximately 50,000 to 100,000 cubic yards of material per year, sometimes more and sometimes less. Costs vary depending on market conditions and the proximity of a dredge doing other work. We try to use dredges already working on the channel to minimize mobilization and demobilization costs.

TN-Memphis: The Port budgets $220,000 to $300,000 each year to maintain the 2 placement areas. The corps of engineers spends the money on the dredging. [*Figure 3.1 summarizes information provided to the authors regarding USACE's dredging quantities and expenditures for McKellar Lake, which is the Port of Memphis's primary facility.*]

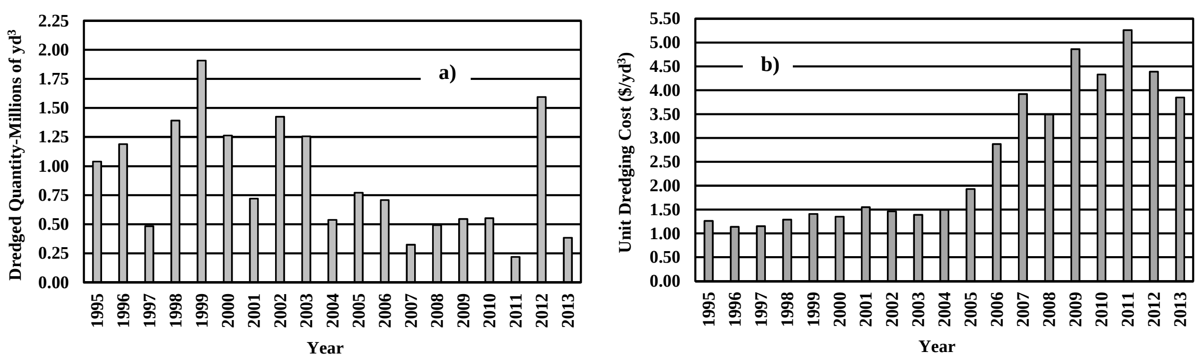


Figure 3.1. McKellar Lake Dredging Summary Provided by the Port of Memphis

TX-Houston Authority: Maintenance dredge costs for federal projects are typically in the range of $5-$8 per yard, after mobilization. Private dredging jobs, including mob, can be higher--$10-$12/yard (hydraulic), with some small jobs running $30-$45 per CY. This does not include tipping fees [*disposal fees*] by PHA or the Corps which can be as high as $9 per cy for placement in a PHA/federal placement area.

FL-Tampa Bay: Possibly, but would need more specific information on what cost data you are looking for.

TX-Port of Beaumont: Not available.

Q10. Does your facility construct walls or slopes as part of port expansion or operations? If so, would you be willing to provide typical costs for typical activities?

Anonymous: Yes, walls and slopes are constructed. Costs vary widely depending on activity, design, materials, etc.

AL-Mobile: I'm not sure I fully understand your question. We construct bulkheads typically with sheetpile. We do not typically construct retaining walls. We do have to construct and protect slopes for some of our projects. Typically these are protected by rip rap. I do not have a typical cost for this, but I can check with our Engineering Division if needed.

AR-Helena Harbor: No walls or slopes have been constructed.

FL-Manatee: We might need new dikes for dredged spoil containment facility construction. Cost was estimated in 2006 to be from $5/CY to $15/CY depending on the source of the material.

FL-PortMiami: The Port's shoreline improvements to expand operations has been through bulkhead construction with costs varying based on design criteria in support of specific needs as they pertain to either cargo (e.g., support the use of front end top loaders, cargo container storage, etc.) and cruise operations (e.g. support the use of fork lifts, pedestrian bridge access to and from vessels, etc.).

FL-Palm Beach District: Yes, we have seawall for our slips. Total project cost $16,500,000 (includes upland improvements). The total length of new seawall is 1750 linear feet ($9,429 per linear ft.).

FL-Tampa Bay: Our berths are constructed with steel bulkheads (either H-Z or Pipe-Z sections), or with breasting dolphins and slopes. We can provide cost data on this.

TN-Memphis: Not for expansions since the original construction in the late 1940's and 1950's.

TX-Houston Authority: Most of our docks are semi-open with steel or concrete bulkhead.

TX-Texas City: Yes. $11,000 per linear foot.

TX-Port of Beaumont: Do not construct slopes, generally drive sheet piles for bulkheads.

Please write in any additional comments or suggestions below.

LA-Lake Charles: The Port of Lake Charles works with the Corps of Engineers and the state of Louisiana to provide funding to beneficially use the material the Corps dredges from the main channel. Some of these projects would benefit from protecting the shorelines from erosion. Geotubes may be useful in this regard depending on cost.

CHAPTER 4 – TEST SITES AND MATERIALS EVALUATED

4.1 Overview of Test Sites and Material Properties

Two USACE facilities were selected as test sites for this project. Overall descriptions of these sites are described in the first two sections of this chapter. Thereafter, properties are provided for the materials utilized for testing in subsequent chapters. The information provided includes properties of the material samples taken from the two USACE facilities that are used to collect data in subsequent chapters.

4.2 Memphis Test Site

The Memphis test site is located in the MVD division and Memphis district (MVM) of the USACE. This site was visited twice by the research team (October 9, 2013 and April 18, 2014) while accompanied by USACE employees. The first visit was to gain understanding of the site's characteristics, and sample small quantities of soil from several locations for initial evaluation. Based on findings from the initial evaluation, the second visit sampled a large quantity of soil from one location for beneficial reuse testing. The area investigated was a slack water harbor; i.e., no current was passing through the area and it was not in the main river stream.

As of the writing of this report, there were four dredge disposal sites adjacent to the Port of Memphis. Figure 4.1a shows part of the port. Sites 1 to 3 were active, whereas Site 4 had not been used in several years. The three active dredge disposal sites are maintained by the Port of Memphis, and USACE performs the dredging into the disposal areas. Table 4.1 summarizes the dredge disposal sites adjacent to the Port of Memphis. Sites 2 and 3 were of most interest since they contained fine grained soils. The remainder of the site visit focused attention on sites 2 and 3.

Figure 4.1. Photos of Memphis Dredge Disposal Site Surroundings

Table 4.1. Summary of Dredged Material Disposal Sites Adjacent to Port of Memphis

Site	1	2	3	4
Description	Treasure Island	East of MS River	McKellar Lake Peninsula	Land Locked
Size (Acres)	229	146	144	110
Material	Mostly Sand & Gravel	Sand to Clay	Sand to Clay	---

Existing site 3 is very grown up in most places (Figure 4.2). The site 3 entry point was sandy, though visually the sand was not very coarse. Considering the extent of large vegetation (including trees) growing over the entire site, it was not deemed an optimal candidate for this research, so the remainder of this investigation focused on site 2.

Figure 4.2. Photos of Memphis Dredge Disposal Site 3 (October 2013)

Site 2 has been actively used for many years, and has considerable amounts of trees growing in the middle of the levee surrounding the disposal facility. Figure 4.3a is an example photo of site 2 showing the trees in the middle of the disposal facility and that there is a fairly wide strip between the levee and the trees where soil is more accessible for beneficial reuse. Site 2 is several meters higher in elevation than the Mississippi River on its west side or the woods on the southeast side. Continual raising of site 2 requires the levee around its perimeter to continually be raised.

In October of 2013, five locations around the perimeter of site 2 were sampled for visual assessment and a modest amount of rudimentary laboratory testing (Table 4.2). Figures 4.3b to 4.3f are photos of the five locations sampled. A modest sample was taken from each location (25 kg or less). The purpose of these samples was to determine which one location was most suitable for obtaining a large bulk sample. Ultimately, the large bulk sample was taken near sample location 3, and its properties are provided in Section 4.4.1. The large bulk sample was taken on April 18, 2014 (Figure 4.3g and 4.3h). Soil was very soft (compressible) in the area where the large sample was taken.

Dredged material was placed into site 2 between the October 2013 and April 2014 visits as follows. Water gets a minimum of 0.6 m deep during dredging and can get 1.8 to 2.4 m in some locations. Once solids settle, all water runs out the weir box where sample 2 was taken. It takes 1 to 2 weeks for the site to drain. Dredging is with cutter head hydraulic dredge at around 10% solids.

Table 4.2. Site 2 Initial Sampling Locations: Small Quantity Samples

Sample	1	2	3	4	5
Description	One Dredge Pipe Inlet	At Outlet Weir Box	A few feet after getting up on levee from entry gate	North end near bend around mid-way	South side around mid-way

--Ash sample described in Section 4.4.3 was taken across from sample 5.

Figure 4.3. Photos of Memphis Dredge Disposal Site 2

4.3 Mobile Test Site

The Mobile test site is located in the SAD division and Mobile district (SAM) of the USACE. This site was not visited by the research team. Instead, SAM had two super sacks of soil delivered to MSU in November of 2013. Both super sacks were from the same location and were said to be a mid-range material with respect to their sites. SAM representatives indicated they have some material that is coarser closer to the inlet, but they also have finer material near the outlet weir. The sample provided to MSU for evaluation in this project was midway between the dredge discharge pipe (south end of the 100 acre site) and the decanting weir (north end of the site). The material was stated to be a representative sample for the upper end of Mobile Harbor. Properties of the bulk sample are provided in Section 4.4.1

4.4 Properties of Materials Utilized for Testing

4.4.1 Soil Properties

Table 4.3 provides properties of the three soils evaluated as determined by MSU. Properties shown for Memphis and Mobile are for the bulk samples utilized for testing presented in later chapters. Table 4.4 provides comparative test results determined by Burns Cooley Dennis, Inc. (BCD) for Memphis and Mobile soils since they were of primary interest in this report. Properties were in reasonable agreement between the two laboratories.

Table 4.3. Average Properties of Soils Tested

	Soil		
Property	**ME**	**MO**	**NO**
Origin	Memphis, TN	Mobile, AL	New Orleans, LA[1]
D698 γ_d (pcf)	82.2	95.7	98.6
D698 γ_d (g/cm^3)	1.32	1.53	1.58
D698 OMC (%)	30	23	18
D4318 LL (%)	90	70	55
D4318 PL (%)	32	24	17
D4318 PI (%)	58	46	38
D854 G_s	2.67	2.57	2.67
D1140 P_{200} (%)	97	82	94
D2974 P_O (%)	12	8	6

1: Material was left over from a previous study (Howard et al. 2012) and referred to therein as *Soil 1*.

Table 4.4. Comparative Properties of Memphis and Mobile Soils Tested by BCD

	Memphis (ME) Soil				Mobile (MO) Soil			
Property	**Sample A**	**Sample B**	**Sample C**	**Avg**	**Sample A**	**Sample B**	**Sample C**	**Avg**
Sample ID	ME-28	ME-28	ME-28	---	MO-1-22	MO-1-22	MO-1-22	---
USCS	CH	CH	CH	*CH*	CH	CH	CH	*CH*
D4318 LL	82	86	103	*90*	64	67	73	*68*
D4318 PL	25	29	35	*30*	21	25	26	*24*
D4318 PI	57	57	68	*60*	43	42	47	*44*
D2974 P_O (%)	10.9	12.2	12.5	*11.9*	8.0	8.2	8.2	*8.1*
D698 γ_d (pcf)	82	---	---	*82*	92.5	---	---	*92.5*
D698 OMC (%)	33.1	---	---	*33.1*	25.2	---	---	*25.2*
D1140 P_{200} (%)	99.6	---	---	*99.9*	88.4	---	---	*88.4*

--Proctor parameters:4 in mold, 5.5 lb hammer falling 12 in, 3 layers, 25 blows/layer. Method A, Standard.
--One 5-gallon bucket full of material was provided as sampled (i.e. near in-situ moisture) and three random samples (A, B, and C) were taken from each bucket for testing.
---Po = percent organic content via method D with a 750 ^{o}C muffle furnace.
--Memphis soil was described as tan and dark grey clay, and Mobile soil was described as tan and grey clay.

4.4.2 Cement Properties

Table 4.5 provides properties of the three cements incorporated into this experimental program. A fourth cementitious material was also incorporated (ASTM C989 Grade 100 slag cement from Holcim (US), Inc. in Birmingham, AL). Properties were measured in one laboratory (Theodore, AL) on actual samples provided for testing, albeit at different times. All Table 4.5 cements were produced in Theodore, AL.

Table 4.5. Cement Properties as Supplied by Holcim (US), Inc.

Cement ID	SC6	OPC	PLC
ASTM Designation	C150[1]	C150	C1157
Cement Type	SG	I/II	GU
Blaine Fineness (m^2/kg)	555	405	538
Limestone Content (%)	---	1.7	12.8
Percent Finer than 45 μm	98.1	96.9	99.5
Initial Vicat (min)	80	90	135
Final Vicat (min)	155	170	190
CaO (%)	64.2	64.1	64.3
AL_2O_3 (%)	4.9	4.8	4.2
SiO_2 (%)	19.3	19.9	18.2
1 Day Mortar Cube Strength (MPa)	23.5	16.6	20.4
3 Day Mortar Cube Strength (MPa)	31.3	28.6	31.0
7 Day Mortar Cube Strength (MPa)	39.4	35.2	39.2
28 Day Mortar Cube Strength (MPa)	---	44.7	45.6
d_{50} (μm)	---	---	11.3

1: SC6 resembles a C150 Type III cement, though it has a low SO_3 content of 3.5%.

Note: SG refers to specialty grind portland cement, which is referred to elsewhere as SC6.

Note: The target limestone content during the spring 2014 time period at the cement plant was generally 10%.

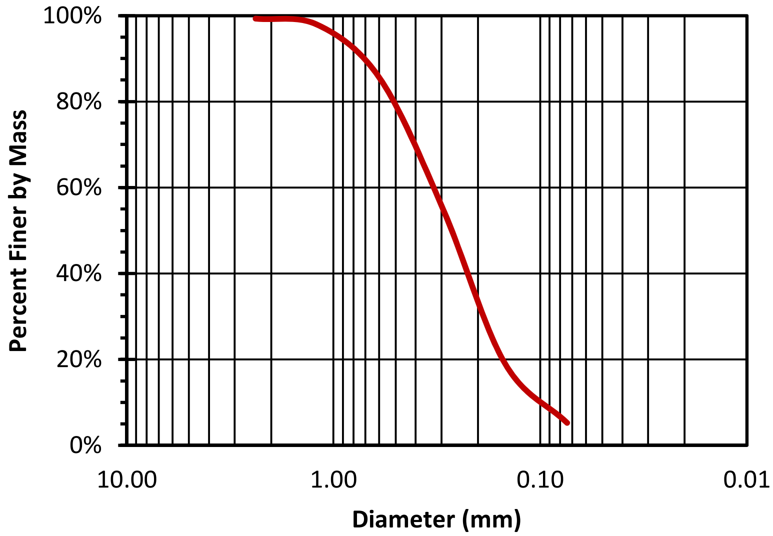
Note: Limestone (%) was measured using cement carbon measurements performed with a LECO carbon/sulfur analyzer.

Note: d50 is the diameter where 50% of the material is smaller than the size indicated as measured with a laser diffraction particle-size analyzer.

4.4.3 Ash Properties

As mentioned previously, the Memphis dredge disposal sites are adjacent to a considerable amount of industrial activity. As of October of 2013, there were coal fired energy generating units in the area, which produce coal combustion by-products (CCBs) such as bottom ash. Figure 4.4 shows an area adjacent to dredge disposal site 2, where a sample of ash was taken to assess the possibility of combining soil from the dredge disposal area with the ash for beneficial reuse purposes. The sample was analyzed by the Holcim (US), Inc.'s Theodore, AL laboratory with an X-ray machine not calibrated for ash, which provides reasonable, but not especially precise results in all cases. X-ray evaluation resulted in 38% SiO_2, 14% Al_2O_3, 22% Fe_2O_3, and 4% CaO. The calcium content was found to be relatively low, while the alkali potential was relatively high (could be useful for pozzolanic activity). Figure 4.5 provides the gradation of the ash material sampled.

Figure 4.4. Photos of Ash Adjacent to Memphis Dredge Disposal Facilities



Sieve Size (mm)	Passing (%)
2.36	99.3
1.18	97.8
0.60	85.3
0.30	55.5
0.15	19.3
0.075	5.2

Figure 4.5 Gradation of Ash Adjacent to Memphis Dredge Disposal Facilities

4.4.4 Geotextile Properties

Three types of geotextile fabrics were utilized in this report to produce small-scale geotextile tubes having dimensions on the order of 53 cm by 53 cm and holding around 28,000 cm^3 of material. These small-scale tubes are often referred to as a *pillow*, and this terminology is used hereafter in this report. Properties of the three geotextile fabrics are provided in Table 4.6. All *pillows* were supplied by TenCate™ Geotube®.

Table 4.6. Properties of Geotextile Fabrics

Property	Method	Units	GT 500	GT1000M	GC 1200MB
Wide Width Tensile Strength-at ultimate-MD	D4595	kN/m	79	200	---
Wide Width Tensile Strength-MD	10319	kN/m	---	---	55
Wide Width Tensile Strength-at ultimate-CD	D4595	kN/m	109	200	---
Wide Width Tensile Strength-CD	10319	kN/m	---	---	55
UV Resistance-strength retained after 500 hr.	D4355	%	80	85	100
Mass/Unit Area	D5261	g/m^2	585	1119	---
Mass/Unit Area	9864	g/m^2	---	---	1200
Apparent Opening Size (AOS)	D4751	mm	0.43	0.60	---
Water Flow Rate	D4491	$l/m^2/s$	13.6	13.6	---
Water Permeability – 50 mm head	11058	$l/m^2/s$	---	---	15.0

Note: properties provided are typical and are from manufacturer data sheets.
Note: test methods beginning with "D" are from ASTM, all others are ISO.
Note: MD = machine direction and CD = cross direction.

4.4.5 Grass Seed Properties

Representatives from MVM provided guidance regarding typical grasses in their district, with Fescue and Bermuda grass being common for applications such as levee slopes. It was noted that drainage districts often use native grasses on stream banks such as little blue stem, big blue stem, or other prairie grass varieties. In this report, the grasses used were: 1) KY 31 Fescue Tall with Endophyte (referred to hereafter as Fescue); and 2) Bermuda coated-hulled (referred to hereafter as Bermuda).

CHAPTER 5 – Portland vs Portland and Slag Cement Stabilization

5.1 Overview of Portland vs Portland and Slag Cement Stabilization

Early in the project, specimens were prepared with materials remaining from a previous project and tested for properties over a 180 day curing period. The leftover soil was not from a dredge disposal facility, but its properties were such that it was reasonable to use them to represent something on the order of something that might come from a disposal facility. In a similar manner, the portland and slag cement used were leftover from the same project. The portland cement used would not be recommended for a beneficial reuse application, but its properties are close enough to portland cement products that would be utilized for beneficial reuse that it was considered an acceptable material. The slag cement utilized would be the same as one that might be recommended for a beneficial reuse project. All materials were leftover from the SERRI work documented in Howard et al. (2012b). The soil is denoted NO in this report (Table 4.3), and this same soil was denoted *Soil 1-Group 3* in the original work. The portland cement is denoted SC in this report, while it was denoted SC6 in the original work. Only one slag cement source was used for both endeavors, so there are no meaningful nomenclature items.

The authors elected to begin these experiments within a few weeks of the project's initiation with materials on hand so data could be collected during the time frame where literature was being assembled, communication was being made regarding appropriate dredge disposal facilities, and so forth. Having properties earlier for LC-VHMS assisted in developing the test plan for the detailed LC-VHMS evaluation (Chapter 6), assisted with technology transfer (Chapter 10), and it also allowed determination of the potential usefulness of slag cement within LC-VHMS. If slag cement when combined with portland cement exhibited potentially useful properties in LC-VHMS, more detailed investigation could be performed thereafter, including incorporating slag cement and PLC into LC-VHMS.

5.2 Portland vs Portland and Slag Stabilization Test Protocol

Sixty specimens were prepared and tested over time to determine how much strength could be mobilized within LC-VHMS. Unconfined compressive strength (q_u) was the primary parameter of interest, though elastic modulus (E), maximum strain (ε_{max}), and specimen wet density (p_s) were also of interest. An abbreviated protocol is provided in this report as the procedures were essentially the same as Howard et al. (2012b) with minor accommodations for the lower dosage rate of 2.5%. Unconfined compression (UC) specimens were nominally 7.6 cm diameter by 15.2 cm tall. Molds were fabricated from PVC pipe that allowed a 6.35 mm thick porous stone to be placed on each specimen end to allow continuous water access during curing. Measurements just after fabrication were used to calculate p_s.

The primary difference between the protocols used in Howard et al. (2012b) and those incorporated herein was a few specimens herein were capped with Plaster of Paris prior to testing if the top was not level after curing. Figure 5.1 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 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 ^{o}C) and used to calculate a temperature-time factor (TTF) using a linear relationship with units of ^{o}C-hr. Data reduction was the same as Howard and Carruth (2015).

Figure 5.1. LC-VHMS Specimen Preparation-Portland vs. Slag/Portland Cement

5.3 Portland vs Portland and Slag Stabilization Test Results

Figure 5.2 provides results that compare portland cement only to portland and slag cement stabilized LC-VHMS. Half of 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 5.2a, portland cement outperformed portland/slag cement by a considerable margin. Even after curing for 180 days, 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 5.2a, investigating portland cement seems the most logical for LC- 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 5.2a and resulted in Equation 5.1.

$$q_u = 20.9 \ln(TTF) - 128.7 \qquad R^2 \text{ of } 0.93 \qquad (5.1)$$

Total specimen density (ρ_s) was 1.48 g/cm^3 on average, with a standard deviation of 0.014. Maximum strain (ε_{max}) 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 portland cement mixing 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 5.2b shows a reasonable correlation between q_u and E measured from the linear portion of the specimen stress-strain curve. A slope of 64 was similar to NO soil when tested by Howard and Carruth (2015) 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.

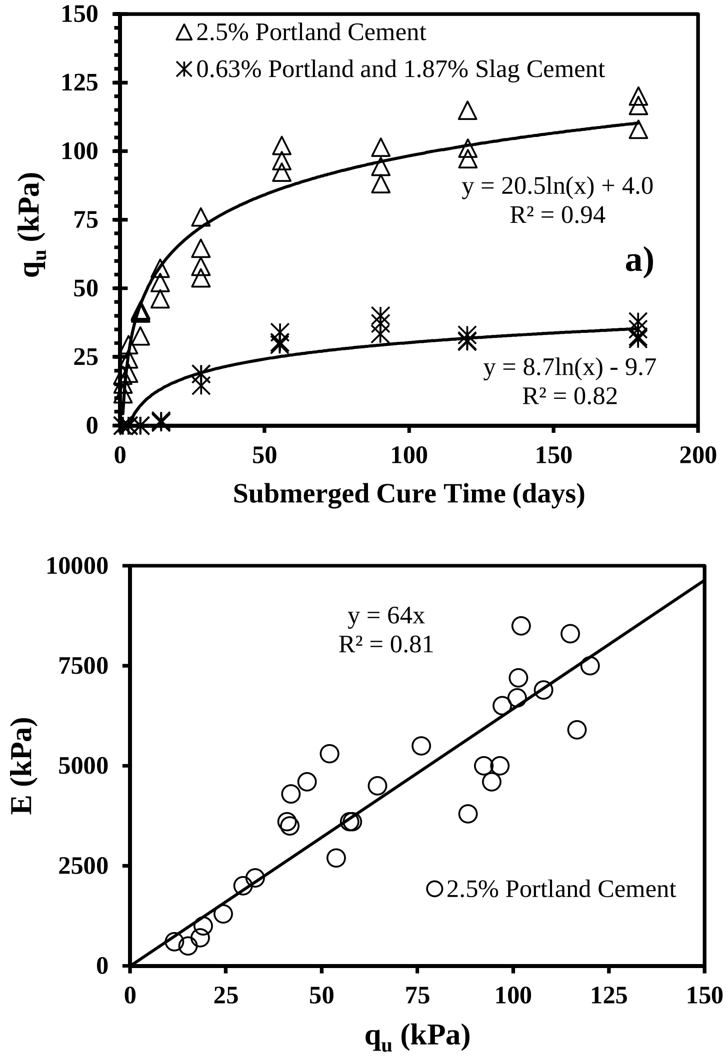


Figure 5.2. LC-VHMS Test Results-Portland vs. Slag/Portland Cement

5.4 Portland vs Portland and Slag Stabilization Discussion of Results

Portland cement was able to achieve around 100 kPa unconfined compressive strength at later ages; 97 kPa after 56 days and 115 kPa after 180 days. These values exceeded the portland and slag cement LC-VHMS by around a factor of 3 at all later ages (the time when slag cement is expected to perform best). This finding led to the remainder of this report focusing efforts away from slag cement for LC-VHMS purposes. Prior to collecting the Figure 5.2 data, testing PLC in conjunction with slag cement was envisioned, but based on Figure 5.2, those efforts were deemed more useful elsewhere. Originally, it was thought that studying PLC in conjunction with slag cement at light dosages might reveal interesting synergies. The findings in this chapter suggested more value was likely from studying LC-VHMS stabilized with either OPC or PLC absent slag cement. This report also showed a 2.5% dosage on a slurry mass basis could produce measurable strength, which was utilized in planning the chapters 6 and 7 test matrices.

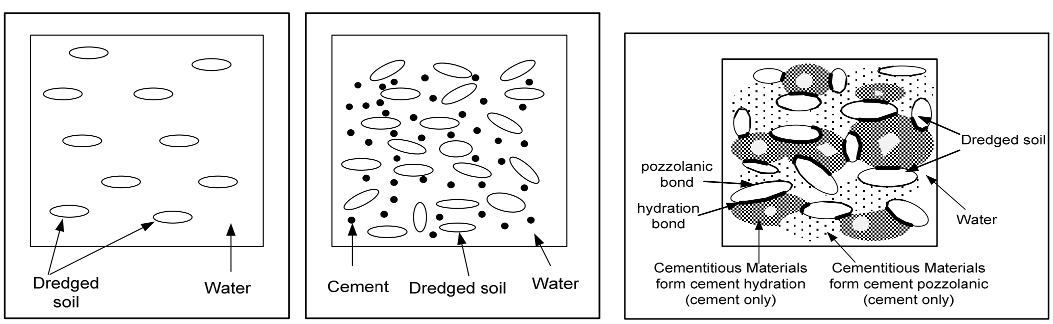
CHAPTER 6 – DETAILED EVALUATION OF STABILIZED TEST SITE SOILS

6.1 Overview

In recent years, dredging of soils (some contaminated) has drawn more attention. 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 VHMS from harbors, oceans, and rivers into disposal facilities has resulted in capacity issues at these facilities. Thus, beneficial reuse has steadily become more appealing.

Large volumes of dredged soils, as a type of VHMS, are encountered annually and must be managed in an environmentally sound manner. Stabilization or remediation of dredged soils for beneficial reuse has been the topic of many studies. VHMS has undesirable properties such as low strength and high compressibility. However, many studies have shown that cement stabilization of dredged soil can potentially mitigate these properties. Some consider cement stabilization as an efficient chemical treatment for soil 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 and increase shear strength (e.g., Kim et al. 2008).

Figure 6.1 is a schematic diagram of unstabilized dredged soil, the influence of cement on particle distribution, and the effects of bonds formed from cement reactions. The effects of modestly reducing very high water content and developing chemical bonds, which enhance solidification and unconfined compressive strength (q_u), are shown in Figure 6.1. Hydration and pozzolanic bonds are possible reactions when cement is mixed into clay soils.



Unstabilized VHMS Modification Chemical Stabilization Reaction

Figure 6.1. Schematic Diagram of VHMS Stabilization Process

Grubb et al. (2010) studied properties of 20 stabilizing combinations mixed with dredged soils from Craney Island, Virginia, and the study showed 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 0.1-3.8 kg/cm^2 shear strength (20 to 745 kPa UC strength) could be achieved after 1-7 days of room temperature curing for various combinations of moisture and cement content ranging from 100 to 233 and 5 to 15% (of slurry mass), respectively. Stabilized VHMS could be used for several applications including: filling geotextile tubes (Koerner et al., 2006; Howard et al., 2012), backfill materials (Huang et al., 2011), fill in disposal areas to reduce the influence of contaminates (Vervaeke et al., 2003), land creation, or land use or development activities near ports and harbors.

A key component of this project was to study engineering properties of stabilized dredged soils. Dredged soils are generally very high moisture content soil (referred to as VHMS) and exhibit poor engineering properties. Stabilization with cement can facilitate the possibility of beneficial reuse for large amounts of dredged soils. This chapter presents results from a series of experimental tests which were conducted to assess engineering properties, largely of lightly cemented VHMS (referred to as LC-VHMS). Some testing was conducted at cement dosages modestly above LC-VHMS levels. A key aim of this chapter was to show that VHMS can be stabilized with low dosages of cement and still achieve useful properties for some applications. Dredged soils were collected from two dredged disposal facilities near the ports of Memphis, TN, and Mobile, AL. For each site, several different combinations of properties were prepared including two water contents (equal to Liquid Limit and 100%), two cement types (portland-limestone cement and ordinary portland cement), and three cement contents (2.5, 5.0 and 10% of dry soil mass). A series of index, unconfined compression (UC), unconsolidated undrained (UU) triaxial, and consolidation tests were conducted on the specimens. The UC and UU tests were performed at various ages of curing to investigate strength gain of LC-VHMS with time.

6.2 Materials and Methods

6.2.1 Materials

Fine grained soils were collected from two USACE dredge disposal facilities. The first soil was sampled in Memphis, TN and is labeled ME. The second soil was sampled from Mobile, AL and is labeled MO. Collected soils were tested for index properties as described in Section 4.4.1 and the results are shown in Table 4.3. Test results showed ME with an average liquid limit (LL) of 90% and an organic content of 12%, while MO had LL of 70% and organic content of 8%.

The dredged soils were tested in conjunction with two cement types: 1) Type GU portland-limestone cement (PLC) specified under ASTM C1157 (note PLC is now also contained in ASTM C595); and 2) Type I/II ordinary portland cement (OPC) specified under ASTM C150. Use of PLC, and subsequent comparison to OPC, is one of the more notable components of this effort. PLC is a more sustainable alternative to OPC, which has been gaining acceptance in the ready mixed concrete market in recent years. The PLC used herein had approximately 13% limestone, whereas the OPC had a much lower limestone content of approximately 2%.

6.2.2 Slurry Preparation

Soils were prepared into slurry by mixing dredged soil with water to generate VHMS (Figure 6.2). PLC and OPC were introduced with cement dosages of 2.5%, 5%, and 10% of dry soil mass. The initial water contents of soil slurry were specified as liquid limit (LL) and 100%.

Figure 6.2. Preparation of VHMS

6.2.3 Laboratory Test Matrix

Table 6.1 presents the testing matrix used for UC testing based on previously mentioned variations. LL is considered the minimum water content where soils have a shear strength of approximately zero, and it is the minimum moisture content meeting the VHMS definition. At 100% moisture content, VHMS has 50% solid particles. The majority of the cases tested in this chapter did not have measurable flow (see Chapters 7 and 9). Note the relationship between dry mass cement contents (C_{dry}), water content (w_c) and slurry mass cement contents (C_{slurry}) is shown in Equation 6.1. All units considered are in percent. For example, a mixture initially at 100% w_c containing 10% C_{dry} would have C_{slurry} of 5%. C_{dry} choices were selected to investigate the minimum cement dosage that can make a meaningful improvement in VHMS properties. Equation 6.1 is provided since other portions of this report (and a large part of the literature review) make use of slurry mass when discussing cement content.

$$C_{slurry} = \frac{C_{dry}}{100\% + w_c} 100\% \qquad (6.1)$$

Table 6.1. Testing Matrix used for UC Tests on Each Soil Type

Site	Initial w_c (%)	Cement Type	C_{dry} (%)[3]	Group No	Spec. Prepared	Specimens Tested After 7 days	28 days	56 days	90 days
ME and MO[1]	LL[2]	PLC	2.5	UCG1	12	3	3	3	3
			5.0	UCG2	12	3	3	3	3
			10	UCG3	12	3[4]	3	3[4]	3
		OPC	2.5	UCG4	12	3	3	3	3
			5.0	UCG5	12	3	3	3	3
			10	UCG6	12	3	3	3	3
	100	PLC	2.5	UCG7	12	3	3	3	3
			5.0	UCG8	12	3	3	3	3
			10	UCG9	12	3	3	3	3
		OPC	2.5	UCG10	12	3	3	3	3
			5.0	UCG11	12	3	3	3	3
			10	UCG12	12	3	3	3	3

[1] The same set of specimens were produced and tested for each site. For example, ME-G1 and MO-G1 represent Group G-1 for the soils collected from Memphis and Mobile dredge disposal facilities, respectively.
[2] Average LL values for ME and MO soils were 90% and 70%, respectively.
[3] Percentage by dry mass.
[4] Three specimens were made, but only two specimens were tested for MO soils for this treatment combination.

Table 6.1 describes 12 mixture groups that were prepared for each site (total of 24 groups between two sites). A total of 12 specimens were prepared for each group for UC tests 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 similar test matrix was developed for UU tests as described in Table 6.2. However, UU tests were not performed for groups containing 2.5% C_{dry} as groups with 2.5% C_{dry} showed little or no strength gain during the UC testing.

Table 6.2. Testing Matrix used for UU Tests on Each Soil Type

Site	W_{cs} (%)	Cement Type	C_{dry} (%)	Group No.	Spec. Prepared	Specimens Tested After 7 days	28 days	56 days	90 days
ME and MO	LL	PLC	5.0	UUG1	12	3	3	3	3
			10.0	UUG2	12	3	3	3	3
		OPC	5.0	UUG3	12	3	3	3	3
			10.0	UUG4	12	3	3	3	3
	100	PLC	5.0	UUG5	12	3	3	3	3
			10.0	UUG6	12	3	3	3	3
		OPC	5.0	UUG7	12	3	3	3	3
			10.0	UUG8	12	3	3	3	3

Table 6.3 shows 4 mixture groups which were prepared for performing Incremental One-Dimensional Consolidation Testing (IC). The test specimens for the IC tests were

fabricated by placing stabilized soil from the Mobile site, which were prepared previously at 100% moisture content, into 90-mm-long and 100-mm- diameter PVC molds. Similar to the procedure used for the UC and UU test molds, 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 specimens were then covered with a plastic cap and stored in a curing room at 18-25°C for 7 days in order to gain enough strength for samples to be extruded.

Table 6.3. Testing Matrix used for IC Tests on Mobile Soil Type

Site	Initial w_c (%)	Cement Type	C_{dry} (%)	Group No
MO	100	PLC	5.0	G1
			10	G2
		OPC	5.0	G3
			10	G4

6.2.4 Soil Property Test Procedures

Moisture content, dry density, and void ratio tests were performed on UC test specimens after 90 days of curing. The testing process for UC specimens 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. Moisture contents are averages of individual specimen moisture contents.

Atterberg limits after 90 days of curing were measured according to ASTM D4318. Liquid limits were determined by using the multi-point procedure. Specimens were air dried (i.e. not oven dried) prior to testing.

6.2.5 Unconfined Compression Test Procedures

After curing, specimens were extruded from molds and UC tests were performed (see Figure 6.3). Unconfined compression tests were conducted according to ASTM D2166 with a strain rate setting of 1% /min, 0.5% strain past the maximum force, and using the correction area for stress and strain determination.

Figure 6.3. UC Specimen preparation and Testing

6.2.6 Unconsolidated Undrained (UU) Triaxial Test Procedures

A series of 96 UU triaxial tests (8 mixtures × 3 replicates × 4 curing days) were performed for both soils herein according to ASTM D2850. Thus, 192 specimens were stabilized and tested. Confining pressures ranged from 15 to 120 kPa. The maximum deviator stress was considered as the failure point for specimens tested. UU specimens were fabricated in a similar manner as UC specimens. However, molds for UU specimens were as shown in Figure 6.4 rather than like those shown for UC specimens in Figure 6.3. After curing, UU specimens were sampled from their respective curing molds and sorted prior to testing.

Figure 6.4. UU Specimen Testing

6.2.7 Incremental Consolidation Test Procedures

Figure 6.5 shows samples with 63 mm diameter and 25.4 mm height which were used for Incremental Consolidation (IC) testing. The specimens were cured for 7 days before testing. A series of 4 consolidation tests were performed herein according to ASTM D2435. The specimens were placed in an oedometer device with a seating pressure 5 kPa. The sample was first allowed to swell by submerging it in water and to reach equilibrium with the swelling pressure. The test was then conducted by applying incremental loading pressures of 12.5, 25, 50, 100, and 200 kPa, followed by unloading steps of 50 and 12.5 kPa. Each loading/unloading step was sustained for 24 hours. IC tests were performed for 4 different mixtures (2 cement types × 2 cement dosages).

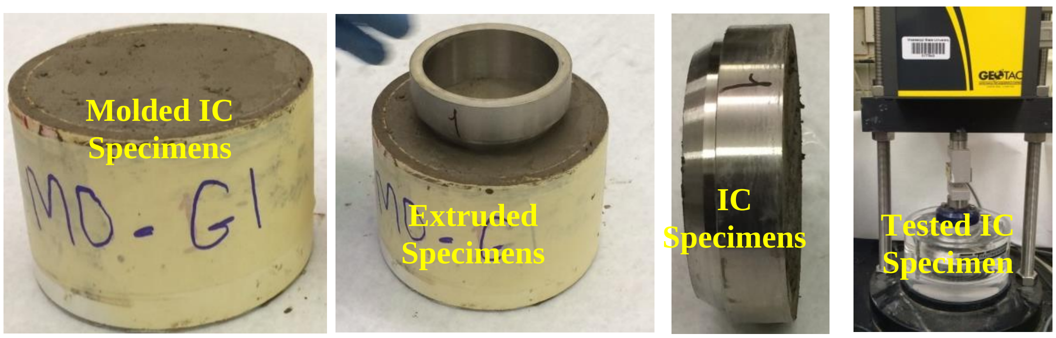


Figure 6.5. IC Specimen Testing.

6.3 Results and Discussion

6.3.1 VHMS Property Modifications

Moisture content, dry density, void ratio, and Atterberg Limits were evaluated for UC specimens that were produced and cured for 90 days. The resulting properties are presented herein. Unconfined compression, unconsolidated undrained triaxial, and incremental consolidation test results are presented in Sections 6.3.2, 6.3.3, and 6.3.4, respectively.

A decrease in initial water content could be noticed immediately following the addition of cement. Water contents following 90 days of near sealed curing in a room at 100% relative humidity are presented in Figure 6.6. As shown in Figure 6.6a, water contents for Memphis soils were reduced from 90% by 2 to 8% and from 100% by 7 to 17%. Figure 6.6b presents data for Mobile soils, which were reduced from initial water 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 contents are not linear. These results were relatively expected as others have reported similar results of decreasing water content rapidly by mixing dry OPC with clay slurry at high initial water contents (e.g. Kamon et al., 1991; Chew et al., 2004).

It is worth noting that PLC seems to have produced marginally more water content reduction for Memphis soils. When comparing the 12 combinations of soil source, initial water content, and cement content, PLC generated more moisture reduction for 8 of the 12 combinations presented in Figure 6.6. 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 and should be investigated further.

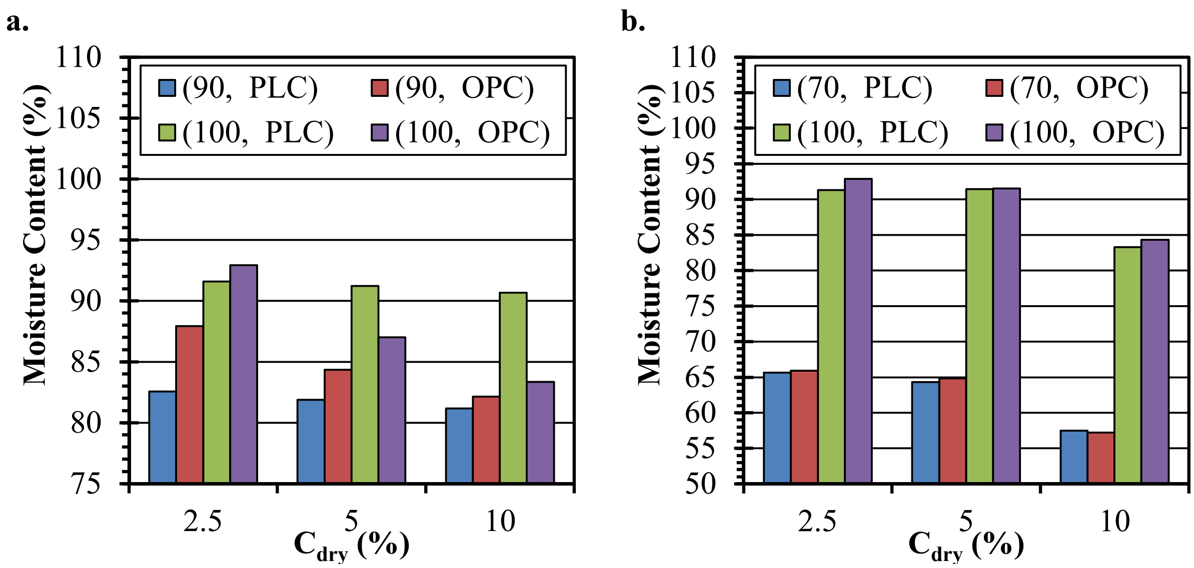


Figure 6.6. 90 Day W_c vs. C_{dry}: a.) Memphis b.) Mobile

Dry densities were evaluated for each UC specimen presented herein. Average values for dry density of specimens tested in UC at 90 days are provided in Figure 6.7. As shown in Figure 6.7a, Memphis specimens ranged from 0.74 g/cm^3 to 0.82 g/cm^3 in dry density. Figure 6.6b presents dry densities recorded for Mobile specimens, which ranged from 0.70 g/cm^3 to 1.00 g/cm^3. For both soils, the dry density resulting 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.

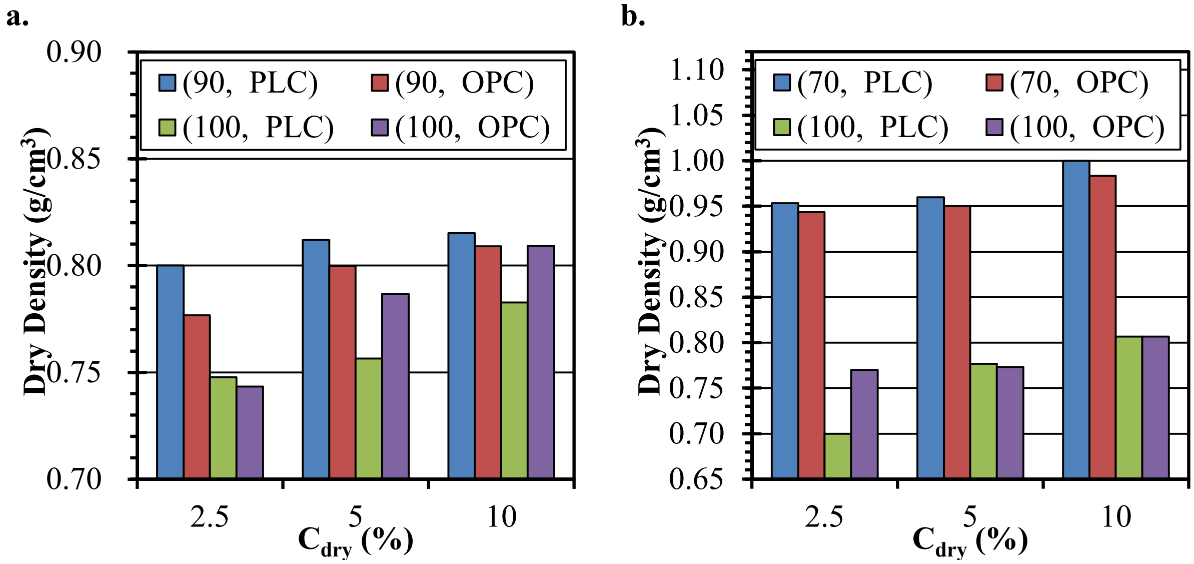


Figure 6.7. Dry Density vs C_{dry}: a.) Memphis b.) Mobile

Void ratios were determined using wet unit weight and dry unit weight. According to the results shown in Figure 6.8, void ratios ranged from 0.57 for Mobile soil treated with 10% OPC by dry mass of soil at an initial water content of 70% to 0.93 for Memphis and Mobile soils treated with 2.5% OPC at initial water contents of 100%. Based on the results shown in Figure 6.8, void ratios for Memphis (Figure 6.8a) and Mobile (6.8b) soils tend to consistently decrease as cement content is increased for PLC and OPC. This is expected as 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 water content with 10% and 15% cement.

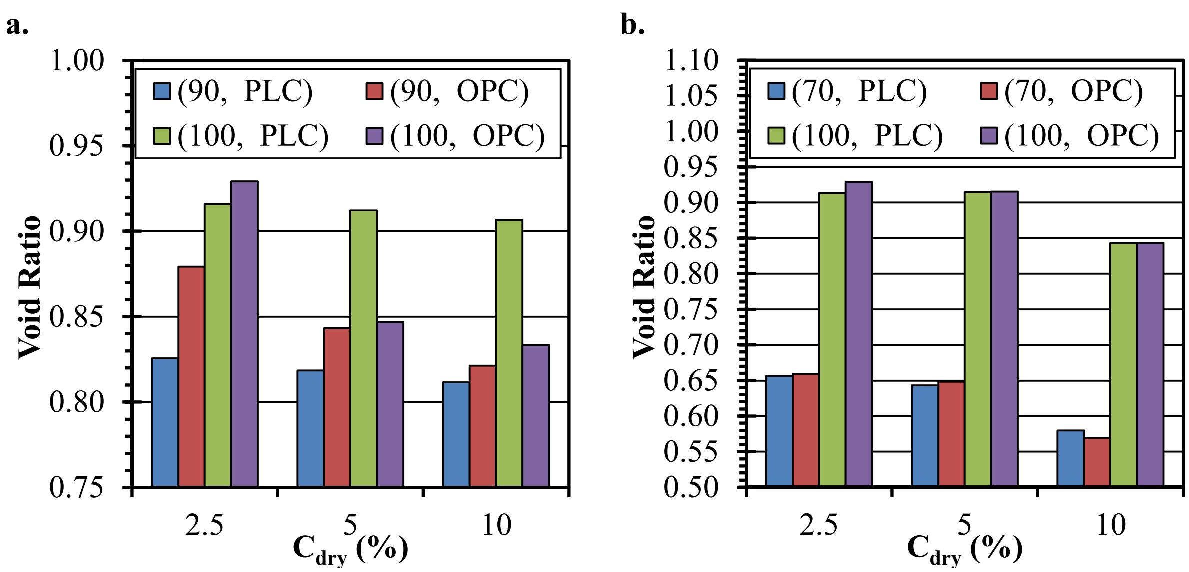


Figure 6.8. Void Ratio vs C_{dry}: a.) Memphis b.) Mobile

Results of Atterberg limit testing for stabilized Memphis and Mobile soils are shown in Figures 6.9 and 6.10, respectively. As shown, LL decreased significantly and PL increased marginally to cause a decrease in PI for each initial water content, soil source, and cement type combination when dosed with 2.5% cement by dry mass of soil. 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 constant for additional increases in cement content 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.

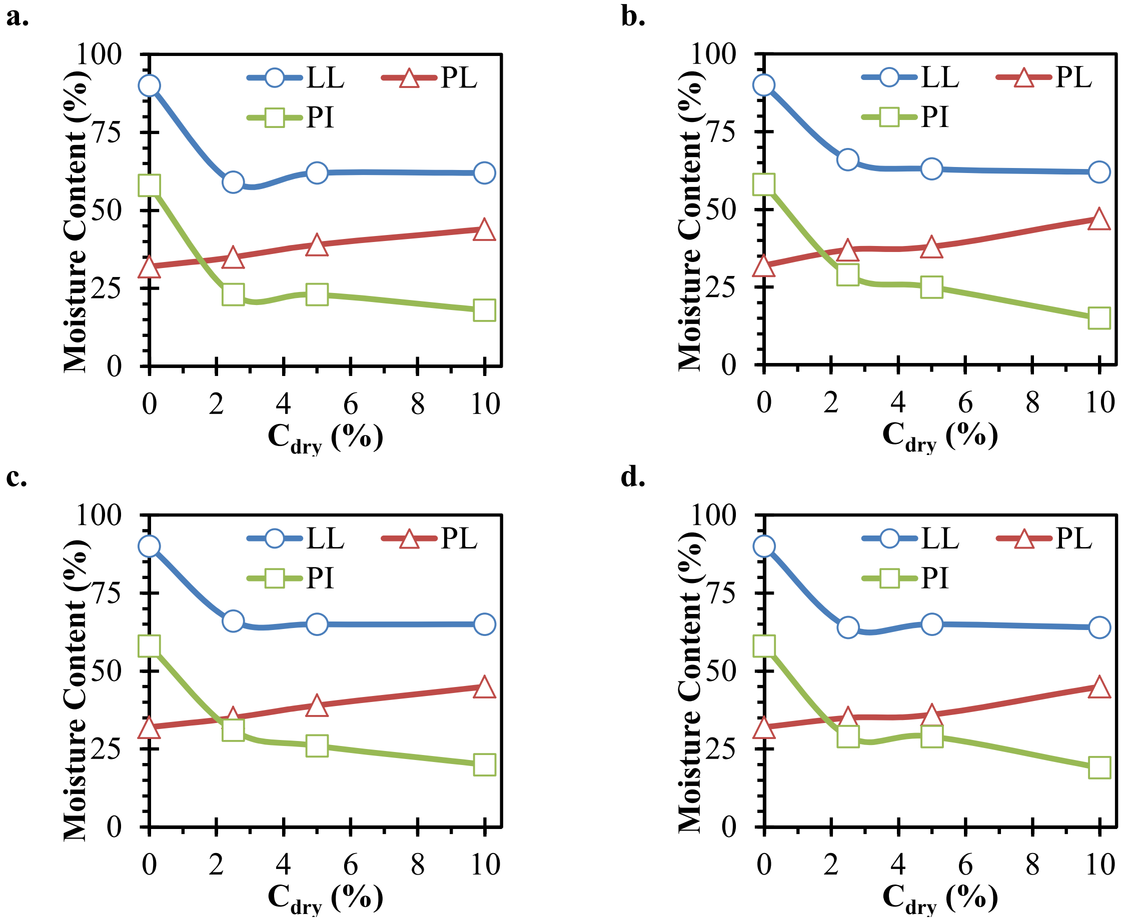


Figure 6.9. Atterberg Limits for Memphis Soils vs Cement Content:
a.) 90% w_c and PLC b.) 90% w_c and OPC c.) 100% w_c and PLC d.) 100% w_c and OPC

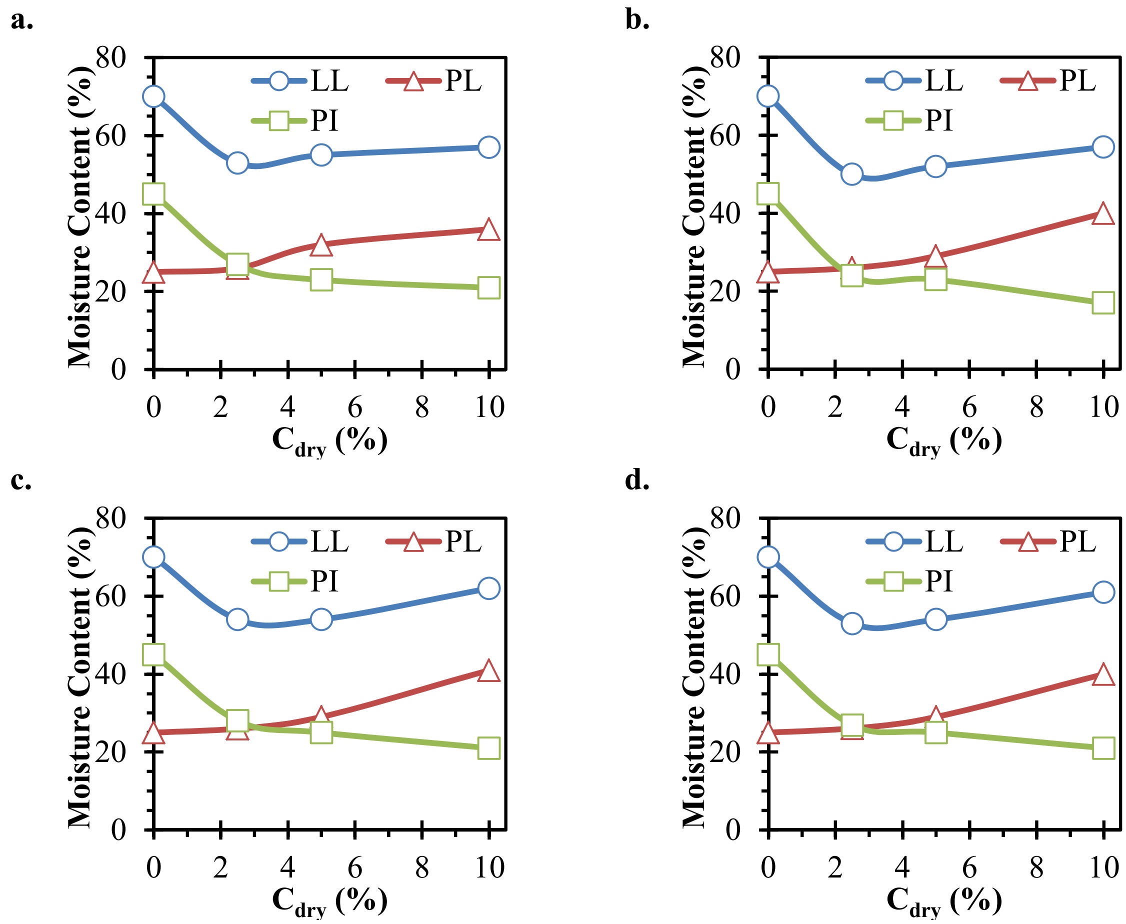


Figure 6.10. Atterberg Limits for Mobile Soils vs. Cement Content: a.) 70% w_c PLC b.) 70% w_c OPC c.) 100% w_c PLC d.) 100% w_c OPC

6.3.2 Unconfined Compressive Strength Test Results

Relationships between q_u of stabilized VHMS, cement type, cement content, initial moisture content, and soil type are presented in Figures 6.11 and 6.12 for Memphis and Mobile soils, respectively. UC Test results are average values of maximum applied stress from consistent test samples following the test matrix shown in Table 6.1. When evaluated after the same cure time, q_u increased with cement content and decreased with initial water content increases.

As shown in Figure 6.11, modest strengths were obtained by Memphis specimens when treated with 2.5% and 5% cement, regardless of cement type. However, reasonable strength gains were observed for Memphis specimens treated with 10% cement for both cement types and initial water contents evaluated. It is worth noting that PLC specimens cured for 90 days seem to consistently have higher q_u than OPC for both initial water contents considered for Memphis soils.

Data from Howard and Carruth (2015) was used to benchmark Figures 6.11 and 6.12. Soil 3 tested by Howard and Carruth (2015) was from Mobile and had similar properties to the Mobile soil tested in this report. 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 6.12.

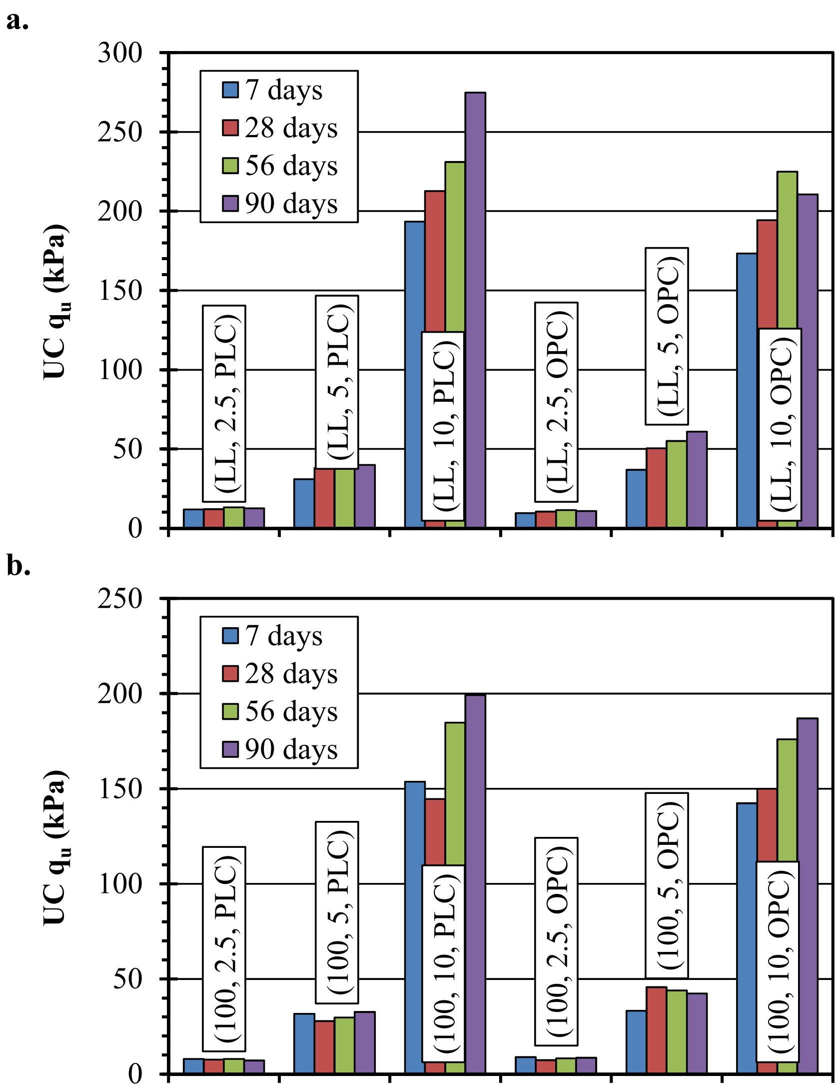


Figure 6.11. Unconfined Compressive Strengths for Memphis Specimens a.) Initially at LL b.) Initially at 100%

As shown in Figure 6.12, there was no strength gain for Mobile specimens treated with 2.5% cement and 100% initial water content and very little strength gain with 5% cement. However, reasonable strength gain was observed for Mobile soils treated with 10% OPC at 70% initial water content while noticeably higher q_u was observed for Mobile soils treated with 10% PLC at 70% initial water contents. Mobile specimens seemed to have higher compressive strengths for PLC specimens than for OPC specimens for both initial water contents evaluated.

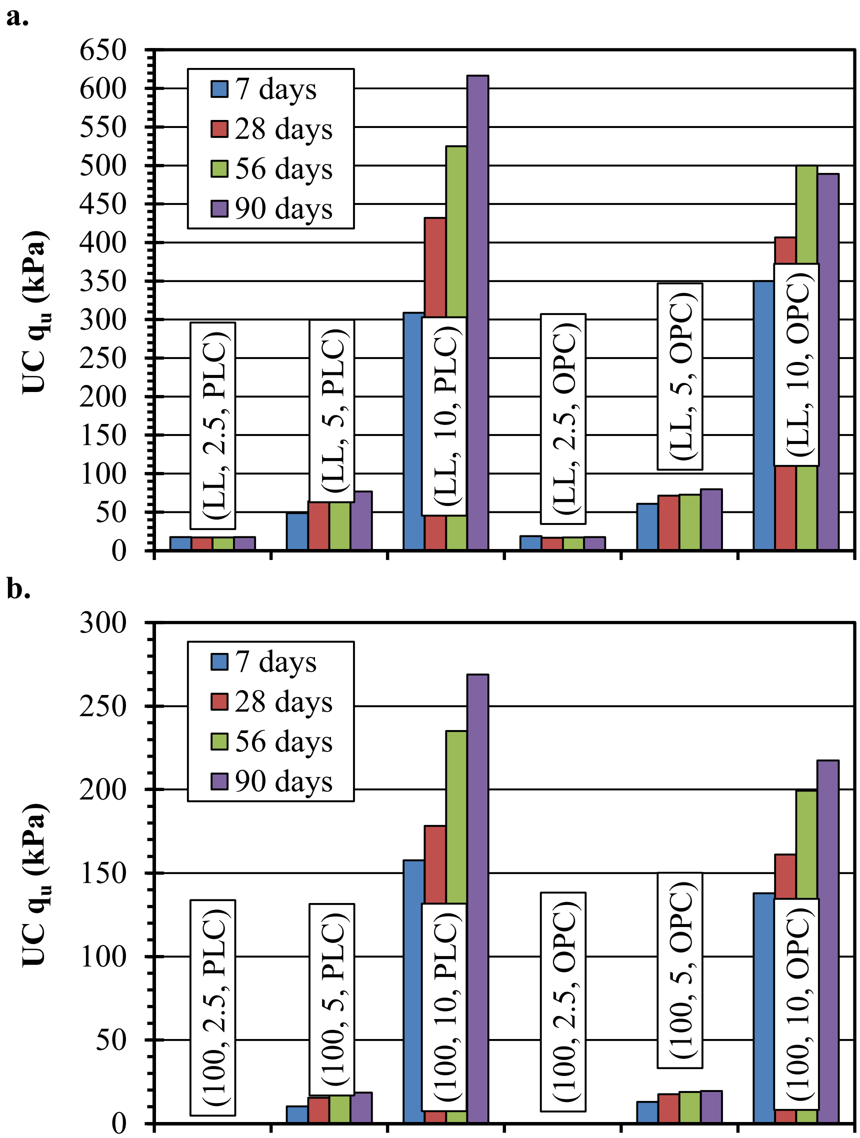


Figure 6.12. Unconfined Compressive Strengths for Mobile Specimens a.) Initially at LL b.) Initially at 100%

The statistical approach used herein was based on analysis of variance (ANOVA) evaluations with factorial arrangements of treatments and a response variable q_u. The majority of statistical 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 water content were considered as treatments. Results of ANOVA analysis are shown in Table 6.4. Before investigating the impact of factors involved, investigation into interaction between factors was first evaluated. For cases where interaction is shown to be present, analysis of single factor impacts is 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.

Table 6.4. 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. x Cement Type x Water Cont.	2	0.1501	No	2	0.8855	No
Cement Cont. x Cement Type	2	<0.0001	Yes	2	0.0224	Yes
Cement Cont. x Water Cont.	2	<0.0001	Yes	2	<0.0001	Yes
Cement Type x 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		

Based on Table 6.4, differing cure times produced statistically different q_u for specimens exposed to the same treatment combinations (an expected result). Also, two factor interaction was significant for cement content and cement type as well as cement content and water 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. Results of multiple comparison procedures are shown in Table 6.5.

Table 6.5. 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	A	PLC	10%	70%	479.8	A
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	F	OPC	5%	100%	17.2	E
OPC	2.5%	90%	10.5	F	PLC	5%	100%	15.3	E
OPC	2.5%	100%	8.2	F	OPC	2.5%	100%	0.0	E[1]
PLC	2.5%	100%	7.6	F	PLC	2.5%	100%	0.0	E[1]

1: With such a large range of values these cases were not statistically different, but they are practically different.

As shown in Table 6.5, LC-VHMS specimens treated with 10% cement of dry soil mass 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 for 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 vs. 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 6.6 and 6.7 provide ANOVA summaries for statistical evaluations for these four additional evaluations. Tables 6.8 and 6.9 provide results of multiple comparison procedures where cure time and initial moisture content combinations are ranked based on q_u.

Table 6.6. 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 x 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		

As shown in Table 6.6, there is no significant two way interaction between cure time and water content for Memphis or Mobile specimens stabilized using PLC. Also, cure time and water 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.

Table 6.7. 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 x 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		

As shown in Table 6.7, there is no significant two way interaction between cure time and water content for Memphis specimens stabilized using OPC, and cure time and water 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 water 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 water content must be considered when ranking treatment combinations for Mobile specimens stabilized with OPC.

Table 6.8. 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 6.9. 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 Tables 6.8 and 6.9, 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. There were circumstances where q_u after 90 days of curing was less than q_u at 56 days of curing. However, these decreases in q_u were not statistically significant and were practically meaningless. 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 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.

6.3.3 Unconsolidated Undrained (UU) Triaxial Test Results

Shear strengths (τ_u) for UU test results are presented in Figures 6.13 and 6.14 for Memphis and Mobile soils, respectively. Mohr's circles for each of the 192 previously described UU triaxial tests are presented in Figures 6.15 through 6.22. Mohr-Coulomb (M-C) failure envelopes are plotted for each set of specimens tested at differing confining pressures. M-C envelopes were plotted using stress path methods. Shear strengths were calculated using:

$$\tau_u = c_u + \sigma \tan(\phi_u) \tag{6.2}$$

where c_u is the undrained cohesion, and ϕ_u is the undrained friction angle, and σ is the normal stress applied to the specimen. The shear strengths shown in Figures 6.13 and 6.14

are calculated using σ = 150 kPa, a normal stress suitable for low ground pressure construction equipment.

For cases where M-C envelopes produced through the stress path method resulted in negative ϕ_u, ϕ_u was assumed to be zero and c_u was assumed to be equal to the average maximum shear stress observed for the specimen group. This same assumption was used for cases where ϕ_u calculated from the stress path method was greater than 15°. Results of UU triaxial tests are summarized in Table 6.10. Due to logistical factors, UU tests originally planned for 90 days were conducted after 115 days of curing.

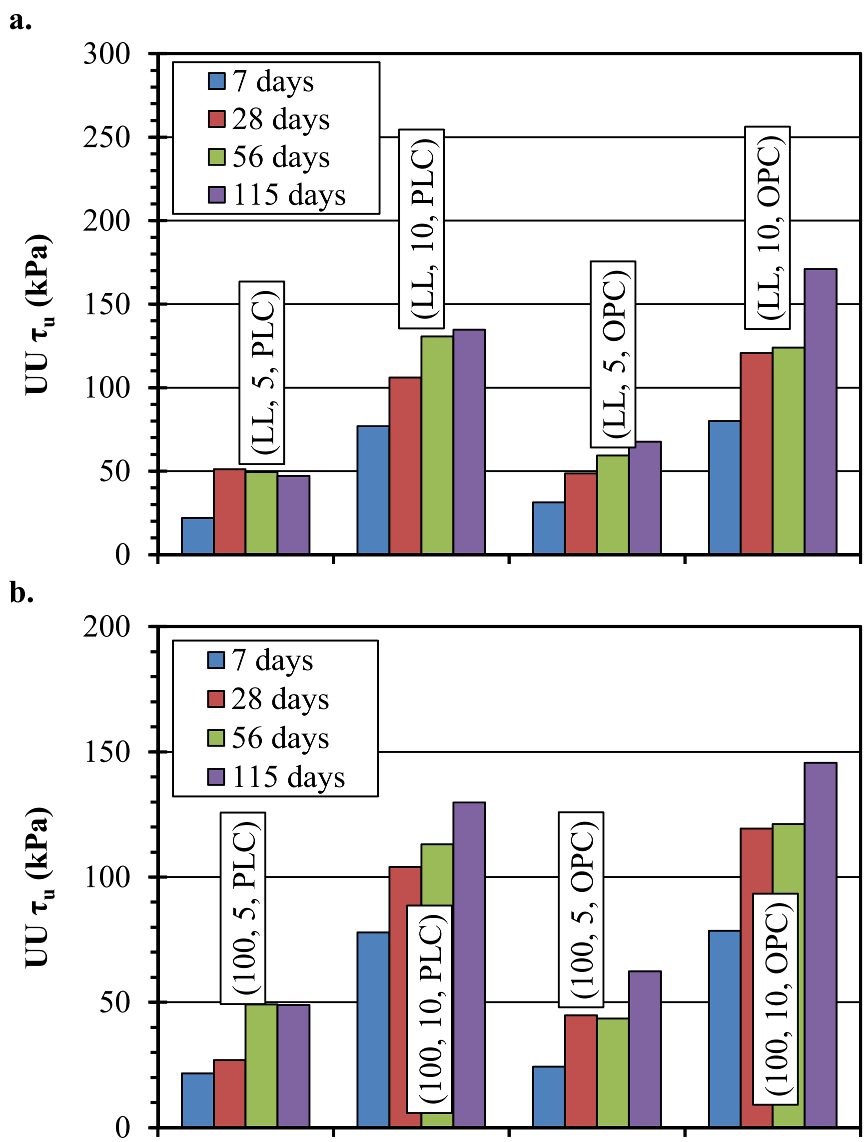


Figure 6.13. Shear Strengths for Memphis Specimens with σ=150 kPa a.) Initially at LL b.) Initially at 100%

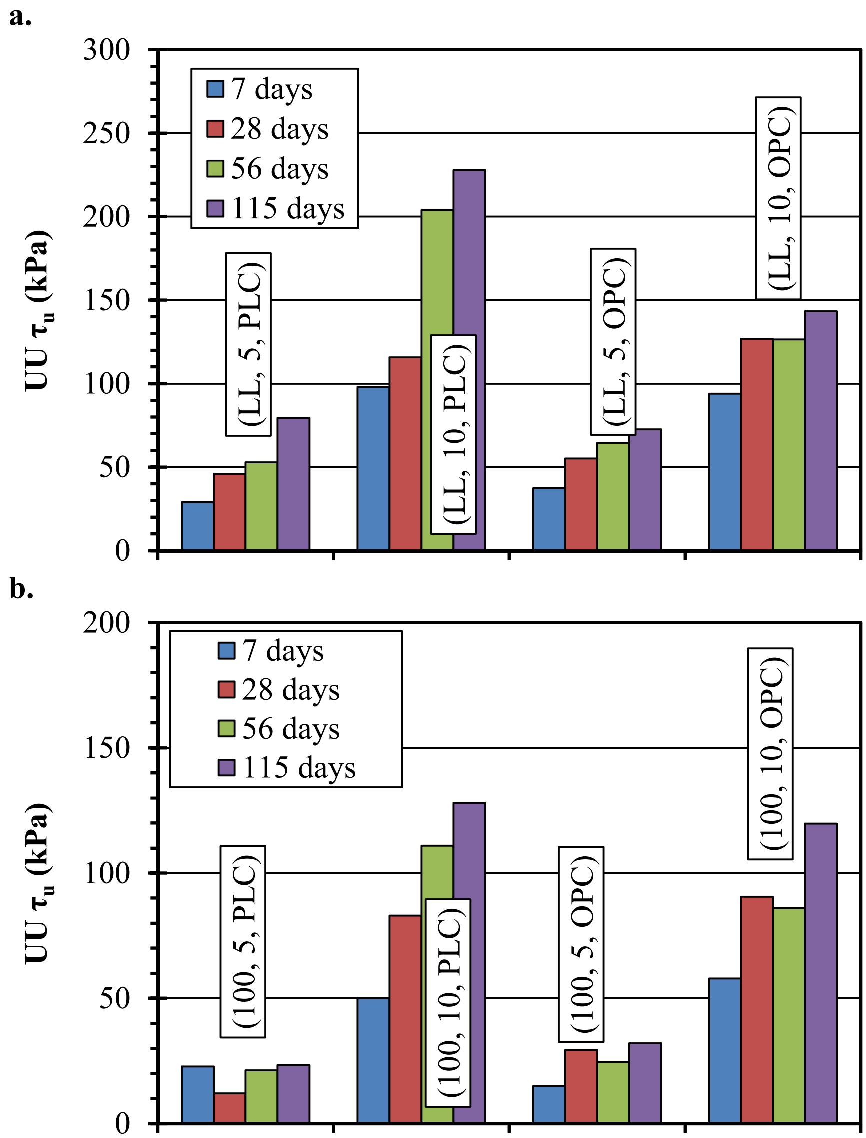


Figure 6.14. Shear Strengths for Mobile Specimens with σ=150 kPa a.) Initially at LL b.) Initially at 100%

Table 6.10. Summary of UU Triaxial Test Results

Site	Initial w_c (%)	Cement Type	Group No.	C_{dry} (%)	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	90	PLC	UUG1	5	22	0	30	8	39	4	42	2
			UUG2	10	77	0	93	5	107	9	132	1
		OPC	UUG3	5	26	2	46	1	41	7	33	13
			UUG4	10	80	0	97	9	124	0	158	5
	100	PLC	UUG5	5	19	1	27	0	36	5	41	3
			UUG6	10	78	0	91	5	100	5	114	6
		OPC	UUG7	5	19	2	29	6	33	4	36	10
			UUG8	10	76	1	82	14	108	5	143	1
MO	70	PLC	UUG1	5	29	0	46	0	45	3	42	14
			UUG2	10	77	8	92	9	204	0	196	12
		OPC	UUG3	5	19	7	42	5	54	4	70	1
			UUG4	10	94	0	95	12	116	4	138	2
	100	PLC	UUG5	5	7	6	12	0	16	2	18	2
			UUG6	10	50	0	83	0	111	0	107	8
		OPC	UUG7	5	15	0	11	7	14	4	19	5
			UUG8	10	58	0	88	1	86	0	96	9

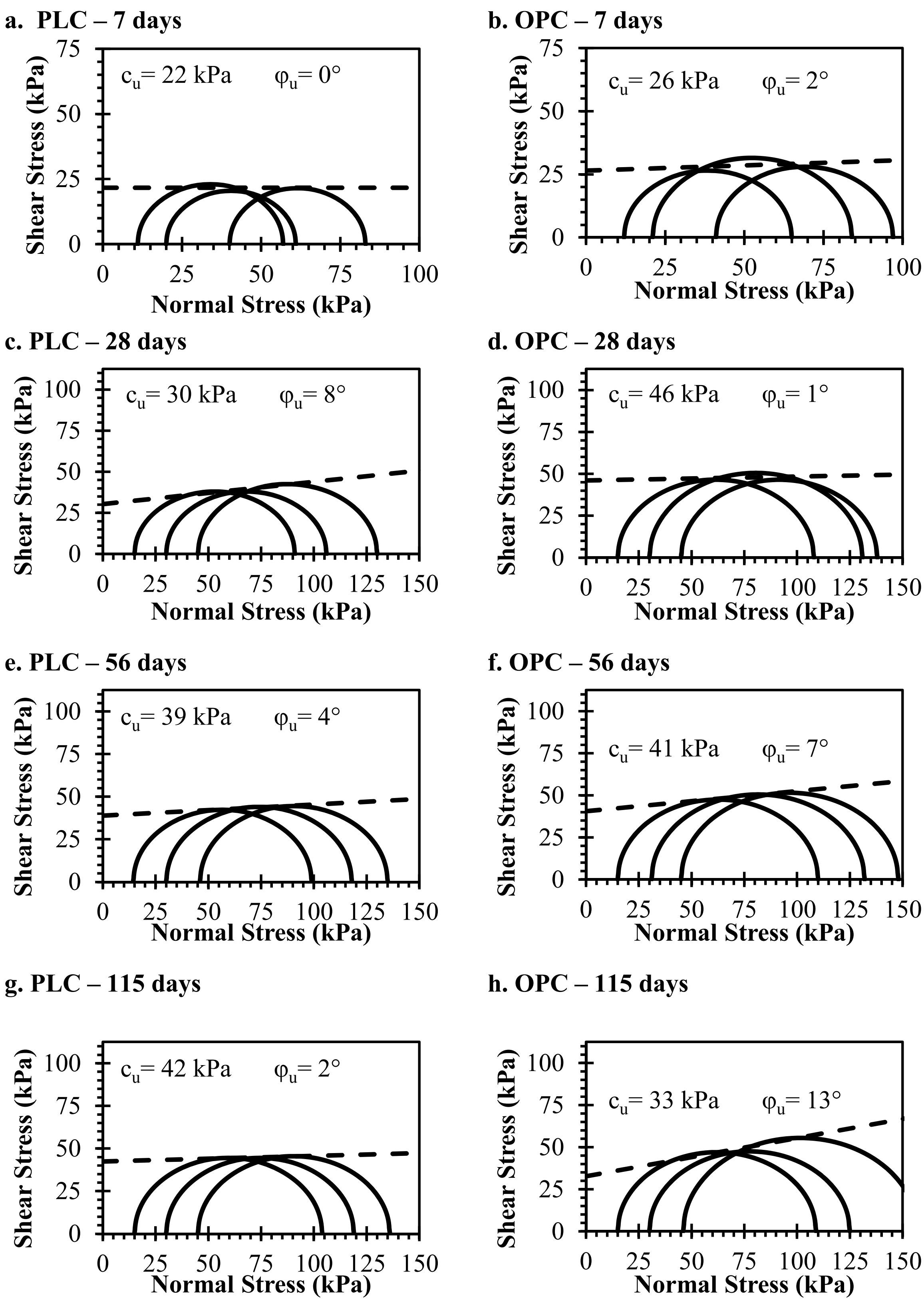


Figure 6.15. UU Triaxial Results: Memphis 5% C_{dry} LL% Initial w_c

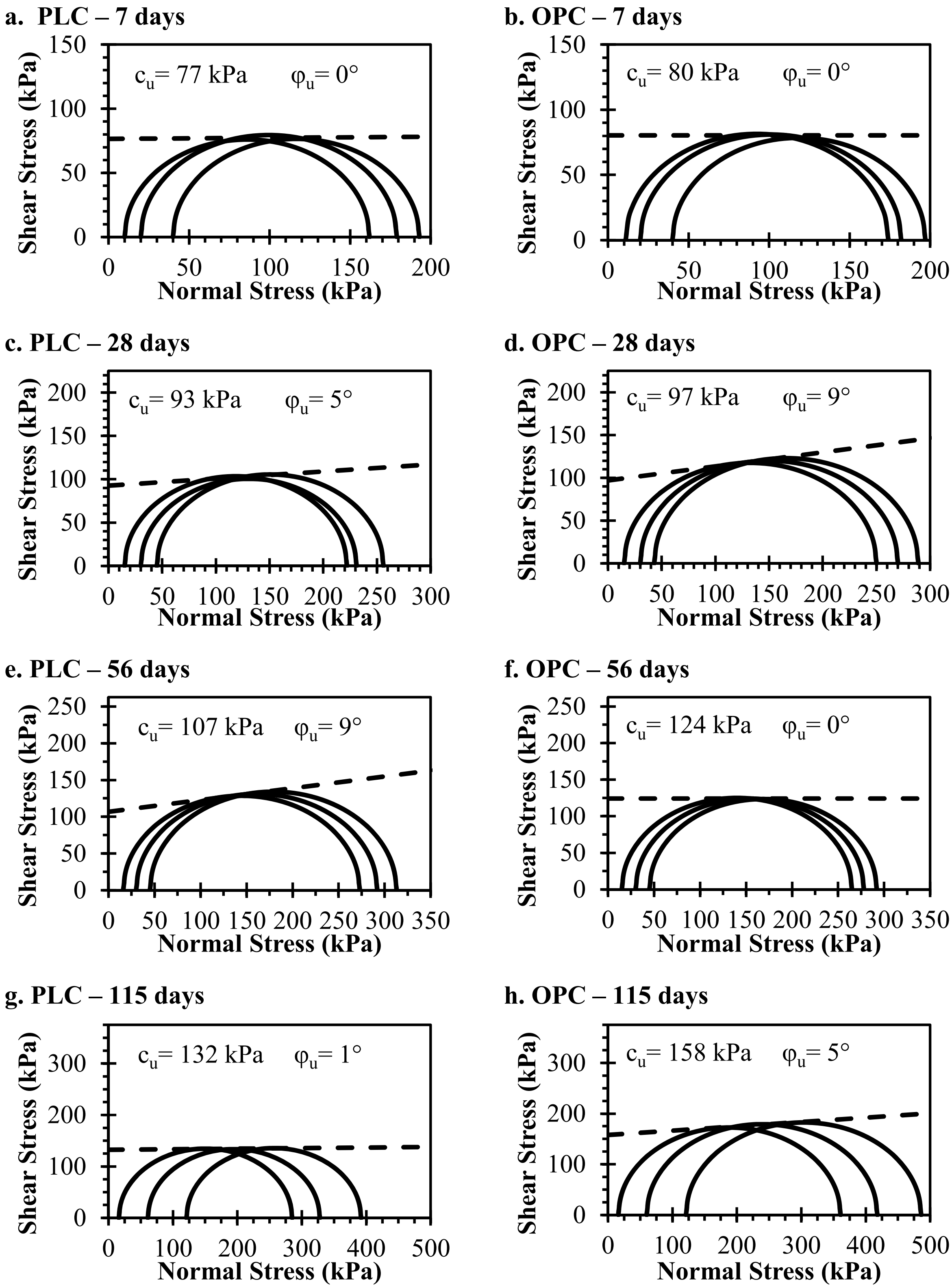


Figure 6.16. UU Triaxial Results: Memphis 10% C_{dry} LL% Initial w_c

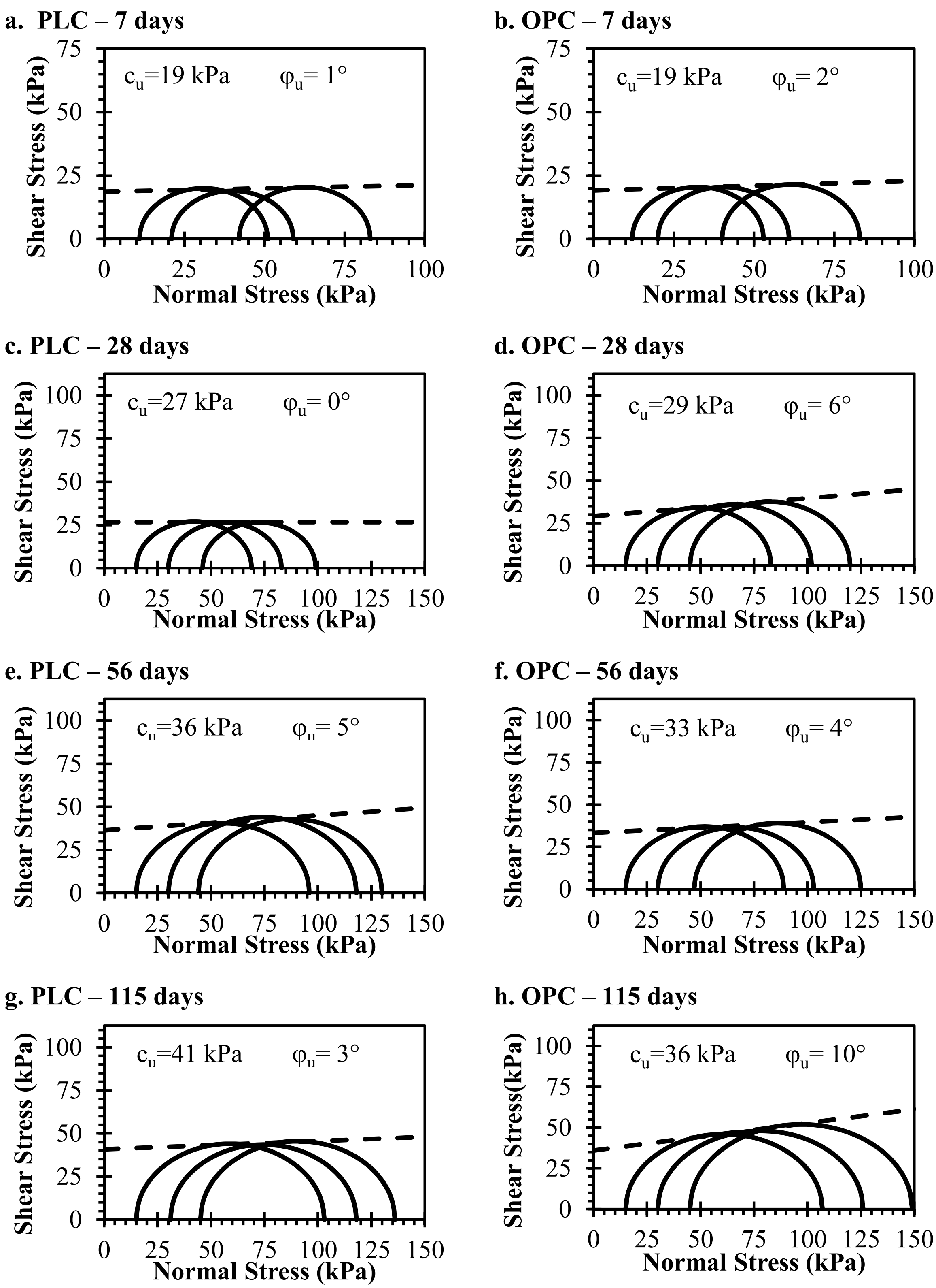


Figure 6.17. UU Triaxial Results: Memphis 5% C_{dry} 100% Initial w_c

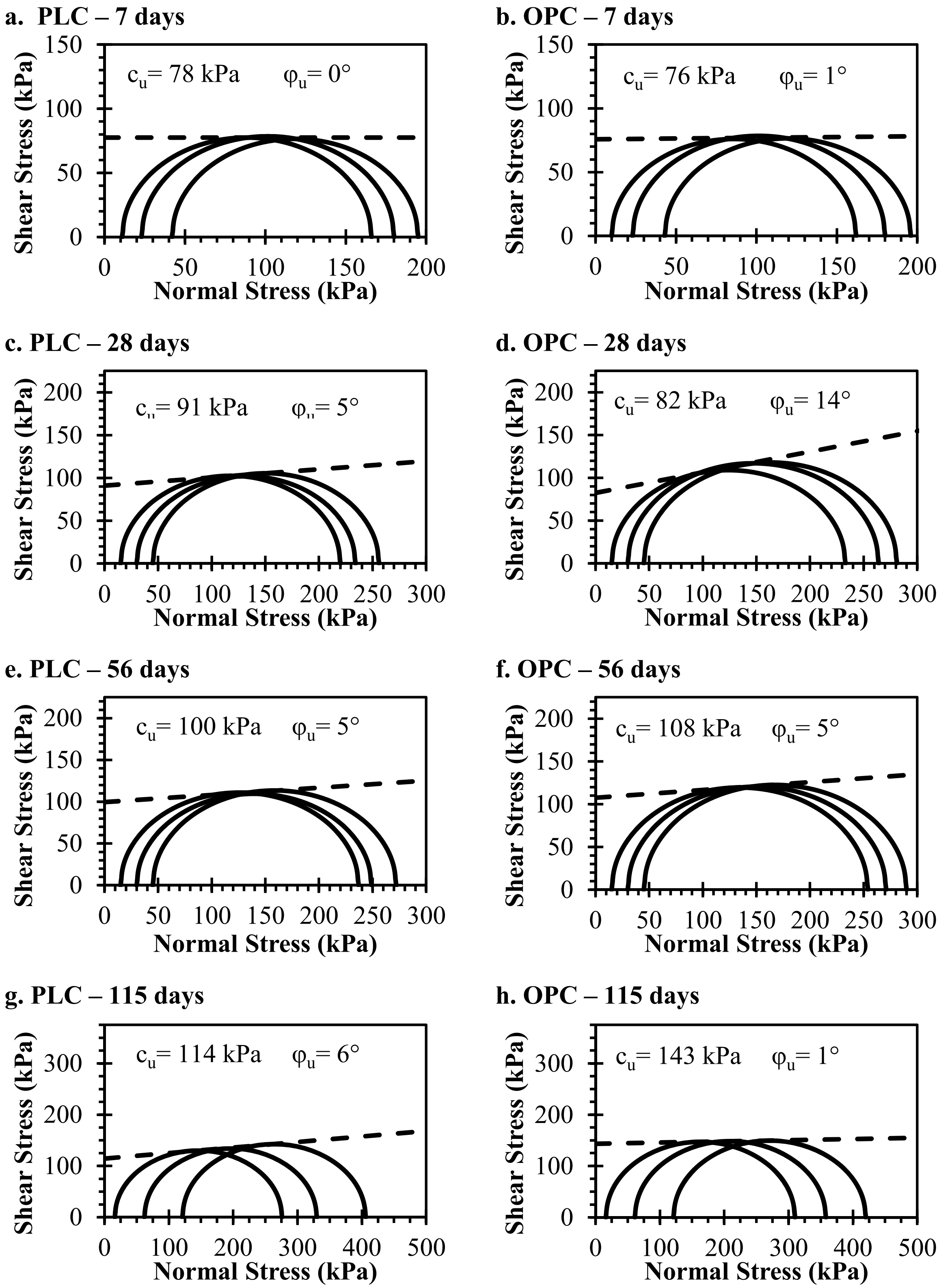


Figure 6.18. UU Triaxial Results: Memphis 10% C_{dry} 100% Initial w_c

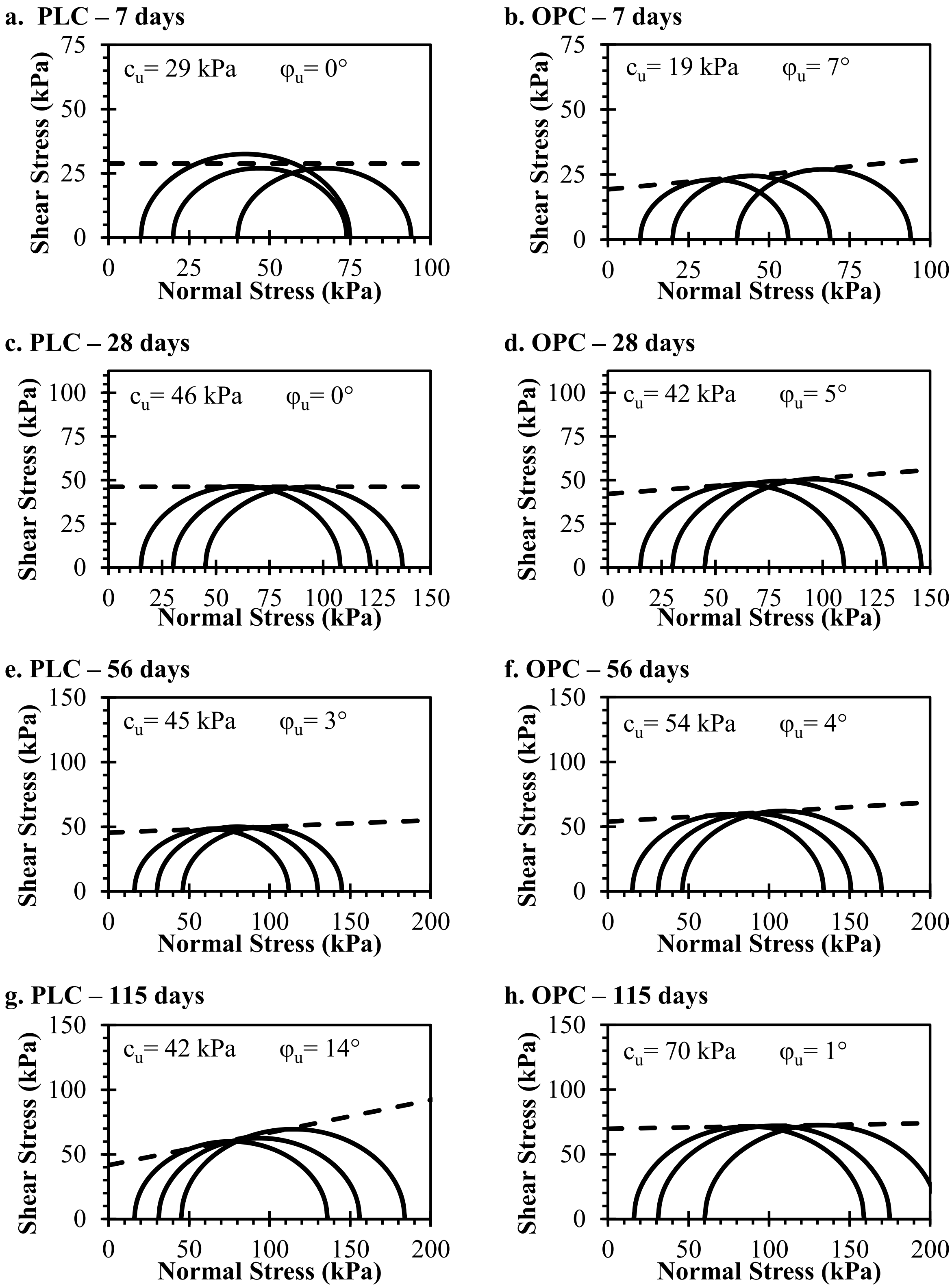


Figure 6.19. UU Triaxial Results: Mobile 5% C_{dry} LL% Initial w_c

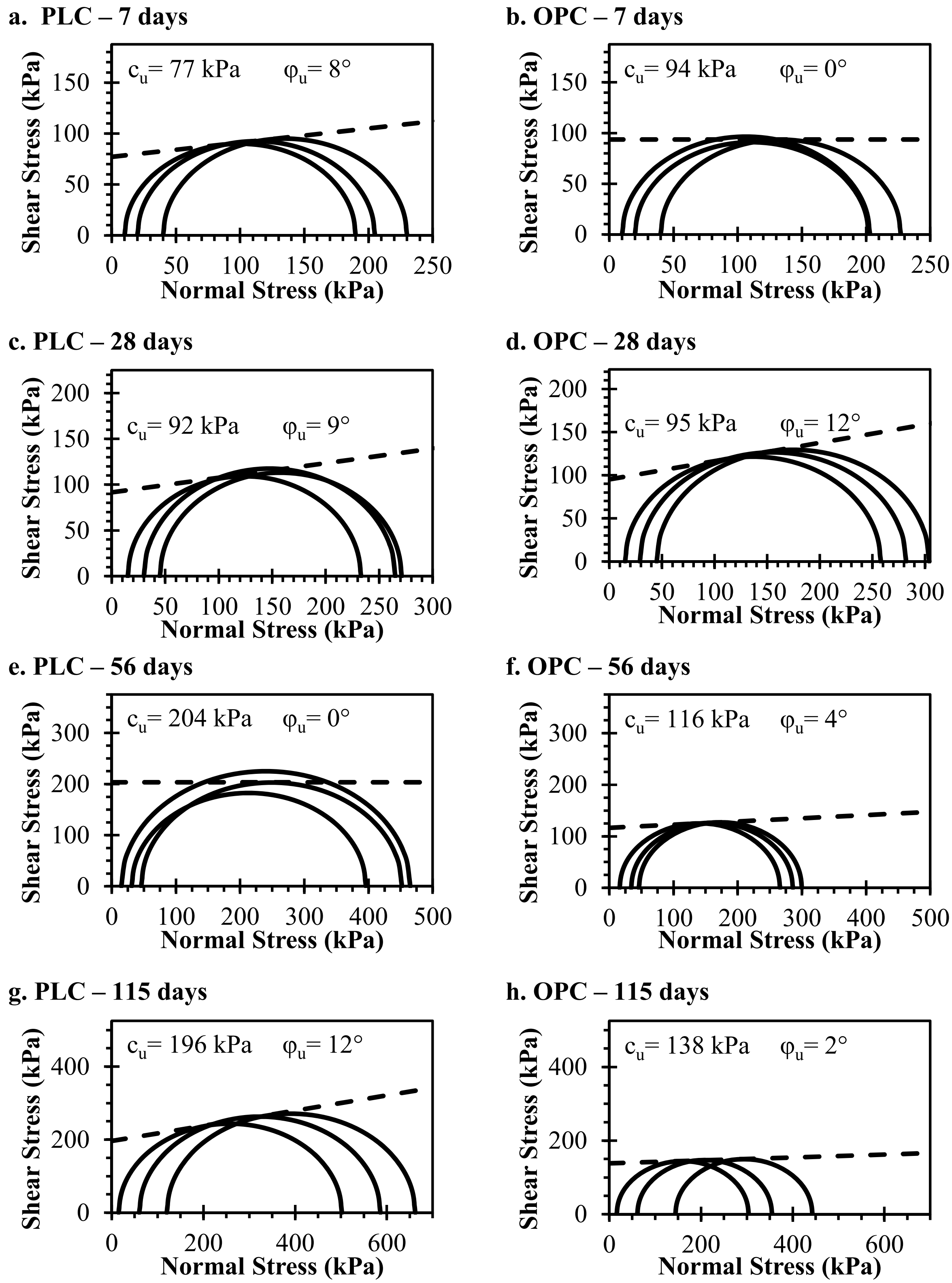


Figure 6.20. UU Triaxial Results: Mobile 10% C_{dry} LL% Initial w_c

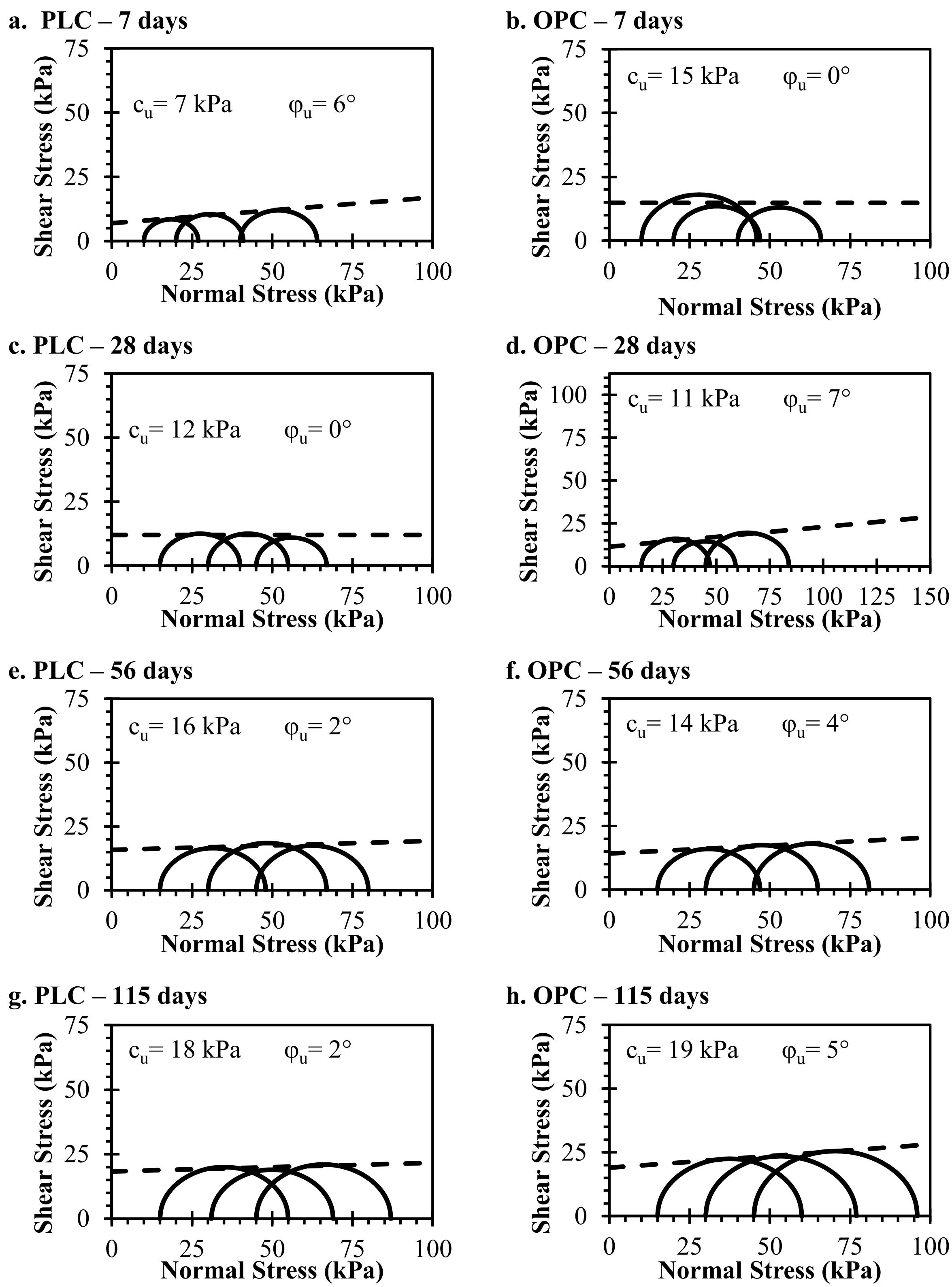


Figure 6.21. UU Triaxial Results: Mobile 5% C_{dry} 100% Initial w_c

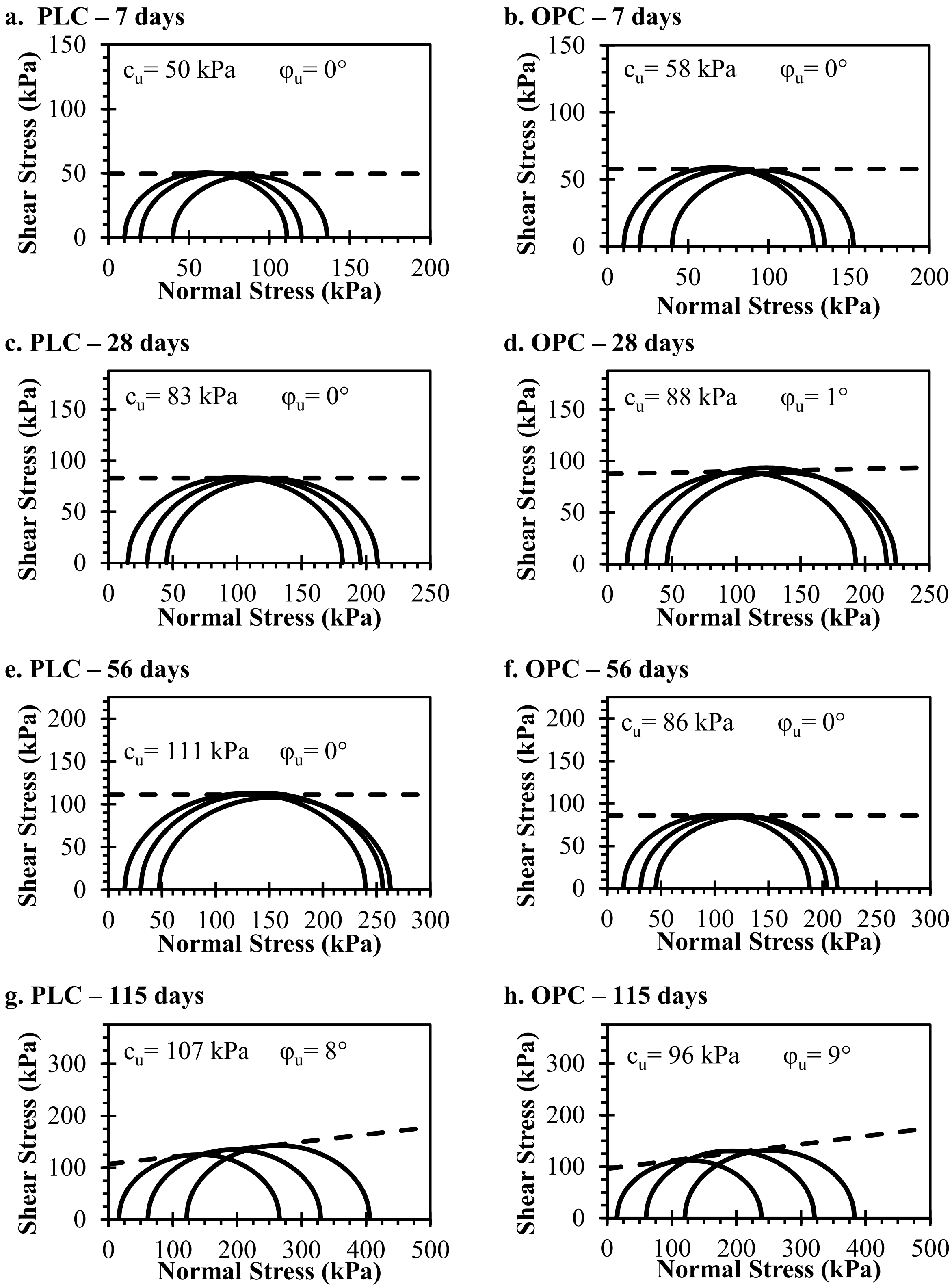


Figure 6.22. UU Triaxial Results: Mobile 10% C_{dry} 100% Initial w_c

6.3.4 Incremental Consolidation Test Results

The results of consolidation testing for Mobile soils are presented in Table 6.11 and Figure 6.23. The results confirmed compressibility improvement after stabilizing. The results show that the preconsolidation pressure, σ'_{pc}, increases by increasing the cement percent. The increase in σ'_{pc} can be attributed to increase in dry density and initial strength due to hydration. Further, Table 6.11 shows a decrease in swell pressure by increasing the cement content. The coefficient of consolidation, C_v, was determined for each test following Casagrande's graphical method. Furthermore, compression index, C_c, and rebound index, C_r, show improvement by increasing the cement percent.

Table 6.11. Summary of Consolidation Test Results

Cement type	Group	C_{dry} (%)	σ'_{pc} (kPa)	C_r	C_c	C_v (mm^2/sec)	Swell pressure (kPa)
PLC	G1	5	30	0.0022	0.099	0.09-0.7798	4.72
	G2	10	50	0.0063	0.104	0.12-0.88	3.16
OPC	G3	5	50	0.0116	0.1443	0.098-1.775	2.95
	G4	10	80	0.0076	0.1725	0.0.119-1.655	1.05

Notes:
σ'_{pc} preconsolidation pressure, C_v coefficient of consolidation, C_r rebound index, C_c compression index

a. PLC, 7 days **b. OPC, 7 days**

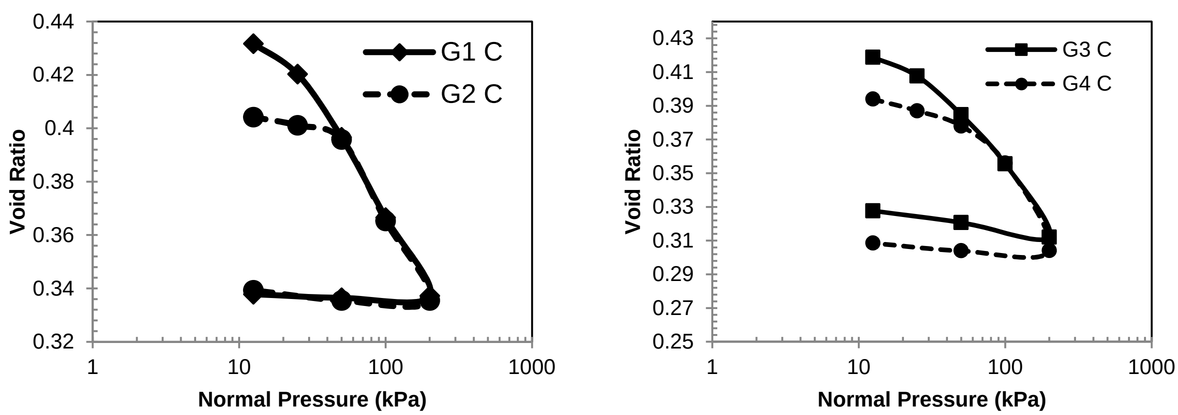


Figure 6.23. Consolidation Result Void Ratio Verses Normal Pressure

6.4. Summary of Detailed LC-VHMS Property Evaluation

Based on the results presented, 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 at to above their liquid limit. A key finding from this chapter 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. Applications are discussed in Chapter 9 of this report.

Unconfined compression tests 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, reduces plasticity, void ratio and moisture content, while increasing dry density. As expected, results indicated that strength increases as cement content increases. 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 affected at lower cement content levels. 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. Relative behaviors between OPC and PLC are an area where further study would be worthwhile.

Incremental consolidation test results indicated improvement per consolidation pressure, compression index, rebound index, and coefficient of consolidation by mixing VHMS with varying percentages of cement. The improvement increased by increasing the cement percentage. The results also showed a decrease in swell pressure by increasing the amount of cement added to VHMS.

CHAPTER 7 – Re-Use of Multiple On Site Materials

7.1 Overview of Re-Use of Multiple On Site Materials

The Memphis site provided an interesting opportunity to consider re-use of multiple on site materials in a beneficial manner. Memphis soil and the bottom ash adjacent to the Memphis dredged disposal facility were combined in varying proportions (0, 20, and 40% ash by dry soil mass) and treated with varying cement dosages (2.5 and 5% PLC, and 5% OPC). Cement contents in this chapter are reported on a slurry mass basis. Mixtures of VHMS and ash were first proportioned for equal flow, treated with cement, cured, and subsequently tested for unconfined compressive (UC) strength (q_u) after varying cure times (7, 28, and 56 days). Memphis dredged materials are described in Section 4.4.1. Cement properties are described in Section 4.4.2, and bottom ash properties are described in Section 4.4.3.

7.2 Flow Modification of Test Specimens

The Memphis disposal facility is located above the Mississippi River. Thus, materials were proportioned to a consistency that would allow them to be pumped from the disposal area to a barge on the river for subsequent transport to the beneficial reuse site where cementitious material could be added.

The National Ready Mixed Concrete Association recommends ASTM D 6103 to test for flow of low strength materials and describes flow between 15.2 cm and 20.3 cm as normal flow. Initially, soil mixtures were prepared to varying moisture content (w_c) and measured for flow according to ASTM D 6103 as shown in Figure 7.1. Regression analysis was performed on flow results to determine the relationship between flow and moisture content (w_c) of the Memphis soil as shown in Figure 7.2.

Figure 7.1. ASTM D 6103 Testing

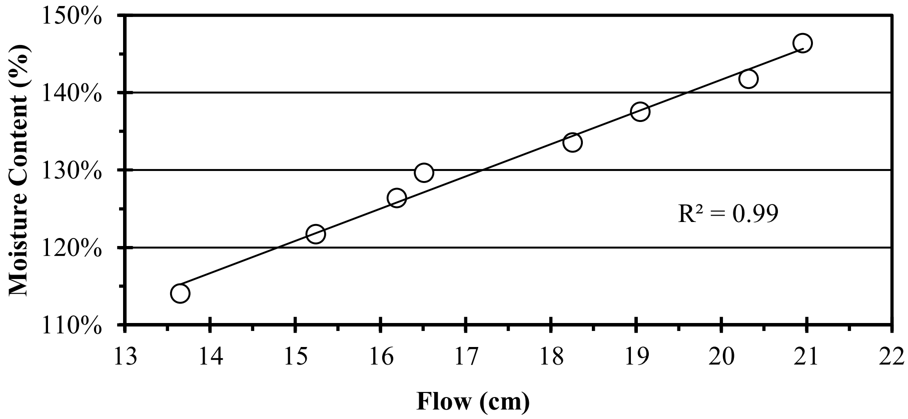


Figure 7.2. Flow vs. Moisture Content (0% Bottom Ash and 0% Cement)

Moisture contents of soil and bottom ash mixtures were modified to achieve 17.8 cm of flow. Flow of 17.8 cm was chosen herein as the midpoint between high and low flow. This was to maximize the amount of variation allowed between specimen groups while still maintaining normal flow. The process shown in Figure 7.2 was also used for specimen groups containing 20 and 40% bottom ash. Flows of 17.8 cm were achieved at 135, 110, and 100% w_c for mixtures containing 0, 20, and 40% bottom ash, respectively. These moisture contents were used when developing the experimental program as discussed in Section 7.3.

7.3 Experimental Program

Nine groups of specimens were fabricated following the test matrix shown in Table 7.1. A group is defined herein as a collection of specimens having identical stabilization treatment. All 9 specimens from a single group had the same initial moisture content, bottom ash content, cement content, cement type, and soil source. A primary focus herein was to evaluate changes in material properties as a result of varying bottom ash contents. However, variations of cement content (2.5 and 5%) and cement type (PLC and OPC) were also considered. A total of 81 specimens were tested in unconfined compression; 3 replicates at 7, 28, and 56 days per specimen group.

Table 7.1. Specimen Group Proportions

Specimen Group	Cement Type	Cement (%)[1]	Bottom Ash (%)[2]	w_c[3] (%)
G1	PLC	2.5%	0%	135%
G2			20%	110%
G3			40%	100%
G4		5%	0%	135%
G5			20%	110%
G6			40%	100%
G7	OPC	5%	0%	135%
G8			20%	110%
G9			40%	100%

[1]Based on percent of slurry mass.
[2]Based on dry soil mass.
[3]w_c is mass of water divided by mass of dry soil plus mass of dry bottom ash.

Soil and bottom ash mixtures were first mixed to uniform consistency using a hand drill mixer and moisture contents were taken prior to cement addition. Then, cement was gradually mixed into the soil, water, and bottom ash mixture (see Figure 7.3a). Following cement introduction the mixture was mixed until uniform and moisture contents were taken immediately following mixing (see Figure 7.3b). Specimens were then prepared using plastic molds (76 mm diameter and 152 mm tall) which were fitted with a 2 mm thick aluminum plate at the bottom of the mold to help facilitate extrusion. Specimen molds were filled using two lifts while rodding specimens 20 times after each lift and consolidating specimens by tapping the bases of the mold against a solid surface 20 times prior to leveling the tops (see Figure 7.3c). Following fabrication, specimens were stored in a curing room maintained at 100% relative humidity and between 21.4 and 22.9°C based on directly measured values. Curing room temperatures were 22.0°C on average with a standard deviation of 0.3°C.

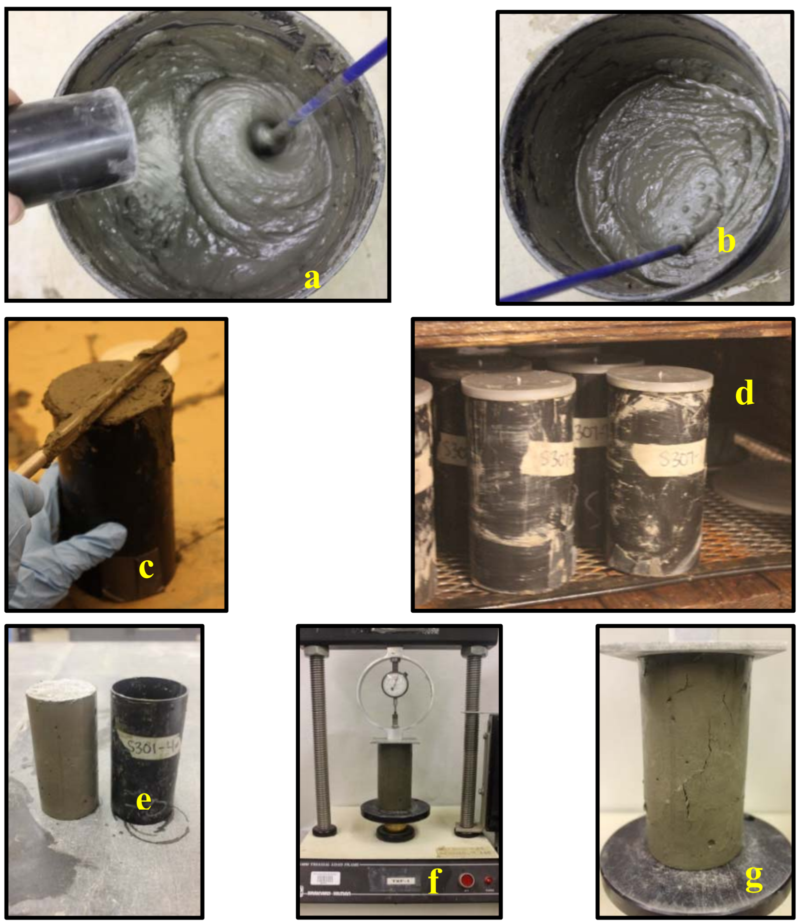


Figure 7.3. Specimen Fabrication, Curing, and Testing

After curing, specimens were UC tested. Specimens were first extruded from molds (Figure 7.3e) and weighed. Specimens were then tested at 0.23 cm/min with failure defined as the maximum applied load (Figure 7.3f). A typical specimen failure is shown in Figure 7.3g. After testing, the top half of the second specimen tested in a group of specimens for a given day was retained and tested for moisture content.

7.4 Results and Discussion

7.4.1 UC Test Results

Compressive strengths resulting from UC testing are shown in Figure 7.4. It should be noted that each bar in Figure 7.4 is an average of three specimens cured for the same amount of time and from the same specimen group. Compressive strengths of 20 kPa to 118kPa were obtained when stabilizing bottom ash and dredged materials simultaneously, and these results are discussed further in the following paragraphs.

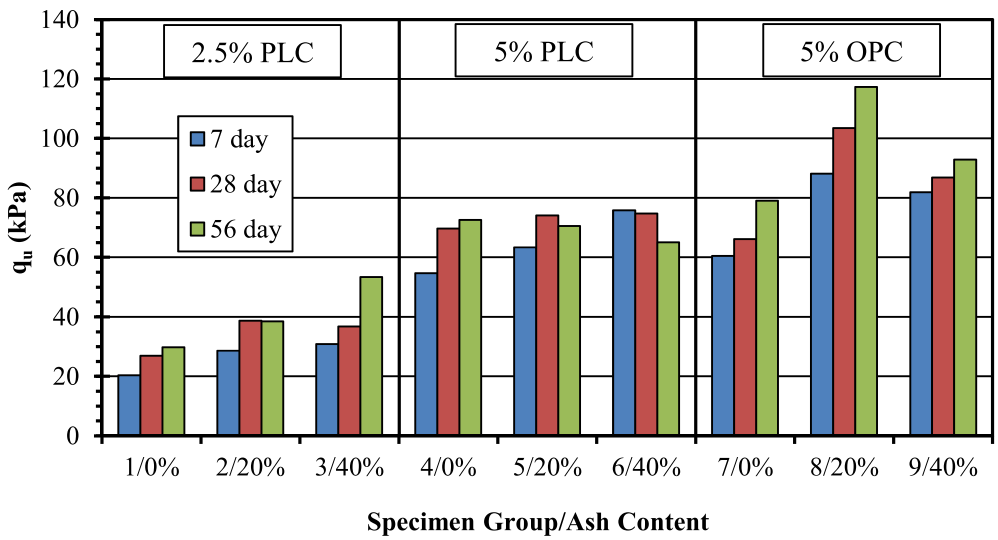


Figure 7.4. UC Test Results

As expected, q_u tends to increase with additional cement content and additional cure time. Note that q_u for specimens fabricated using 5% PLC and 40% bottom ash was meaningfully less after 56 days of curing than for identical specimens which were cured for 7 days or 28 days. The authors have reason to believe this is a result of testing error and that true values exceeded 65 kPa. Compressive strengths obtained by these specimens are likely higher than the numbers measured.

A randomized block design considering cure times as blocks was used to evaluate the effects of bottom ash content and cement type. Differences between q_u obtained after curing were compared against OPC and PLC specimens when stabilized with 0, 20, and 40% bottom ash and 5% cement. Results are provided in Table 7.2.

Table 7.2. Cement Type ANOVA

Source	d.f.	p-value	Significant?
Total (Corrected)	53		
Cure Time (Block)	2	<0.0001	Yes
Cement Type x Ash Content	2	<0.0001	Yes
Cement Type	1	<0.0001	Yes
Ash Content	2	<0.0001	Yes
Error	46		

As shown in Table 7.2, cure time produces a statistical difference, as expected. Cement type and bottom ash contents also produced significant effects with respect to q_u. However, there is significant two factor interaction between cement type and bottom ash content. It is inappropriate to consider effects of individual treatment levels when two factor interaction is present, because the effect of one treatment factor can be altered as the level of another treatment changes when interaction is apparent. Rather, multiple comparison procedures can be used to rank combinations of treatments when interaction is present.

Multiple comparison procedures were used to rank cement type and bottom ash content combinations, and results are shown in Table 7.3. It is also worth noting that while additional bottom ash may have improved strength properties, initial moisture contents were also reduced when additional bottom ash was used. Thus, higher strengths resulting from higher bottom ash contents could also be the result of VHMS having lower initial moisture content when cement was introduced. However, this is realistic for an application, as minimal moisture to achieve the desired flow would be added.

Table 7.3. Ranking of Cement Type and Bottom Ash Content Combinations

Cement Type	Bottom Ash Content (%)	Cement Content (%)	Mean q_u (kPa)	t-group
OPC	20	5	103.0	A
OPC	40	5	87.2	B
PLC	40	5	71.9[1]	C
PLC	20	5	69.4	C
OPC	0	5	68.6	C
PLC	0	5	65.7	C

[1]Testing error believe to reduce this value somewhat.

As shown in Table 7.3, specimens stabilized with bottom ash and 5% OPC had statistically higher q_u than specimens stabilized with 5% PLC or 5% OPC with no bottom ash. Further, specimens containing 5% PLC had statistically similar q_u regardless of bottom ash content. It is worth noting that in Chapter 6 of this report, LC-VHMS from Memphis produced higher q_u when stabilized with PLC and no bottom ash than when stabilized with OPC and no bottom ash. This behavior is discussed in the following paragraph.

Two primary differences in this chapter which could contribute to changes in cement behaviors when no bottom ash is involved are higher initial moisture contents and not allowing specimens to cure for up to 90 days. PLC performed significantly better than OPC when comparing q_u after 90 days of curing in Chapter 6. However, when comparing q_u after 56 days of curing, q_u was marginally (less than 10 kPa) higher for specimens treated with PLC in chapter 6. Alternatively, q_u is marginally (less than 10 kPa) higher for specimens treated with OPC in this chapter. Thus, q_u values observed for mixtures containing no bottom ash seem reasonably similar after 56 days of curing. It is possible that q_u may have continued to increase after 56 days of curing. However, this behavior was not investigated in this chapter.

It is worth noting that q_u was statistically higher for specimens containing 20 and 40% bottom ash when stabilized with 5% OPC. As stated earlier, testing error in 5% PLC specimens treated with 40% bottom ash should be considered when viewing these results. To this end, it is reasonable to infer that mixtures containing bottom ash performed better than LC-VHMS containing no bottom ash. It also appears that OPC out performed PLC up to 56 days of curing.

7.4.2 Moisture Content Test Results

As described in Section 7.3, w_c of each group of specimens were measured prior to cement addition, immediately following cement addition, and after curing. Moisture content results are shown in Figure 7.5. Moisture contents were reduced immediately as a result of introducing additional solid material (cement) and over time as a result of cementitious reactions producing more solids.

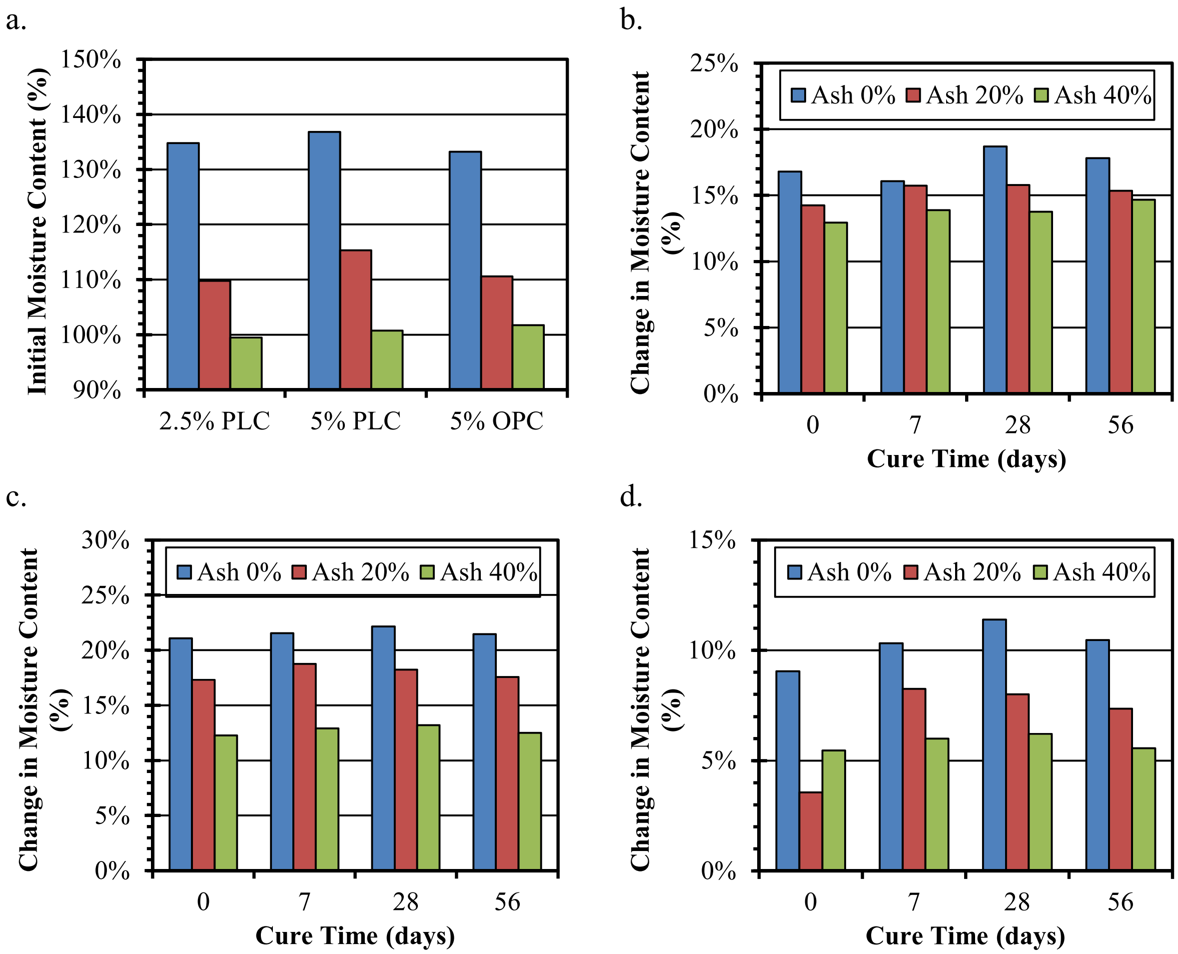


Figure 7.5. Moisture Content vs. Cure Time: a.)Initial Moisture Contents b.) 5% OPC c.) 5% PLC d.) 2.5% PLC

As shown in Figure 7.5, w_c for some groups seemed to decrease for up to 7 days after cement stabilization. However, after 7 days, w_c seemed to reach equilibrium. There is also an obvious relationship between w_c reduction and bottom ash content. This is likely to be the result of mixtures containing less bottom ash having higher w_c at the time of cement addition. For this combination of materials, w_c reduction is more exaggerated in mixtures containing 5% PLC than in mixtures containing 5% OPC. Differences between OPC and PLC moisture content modifications are shown in Figure 7.6 and discussed in the following paragraph.

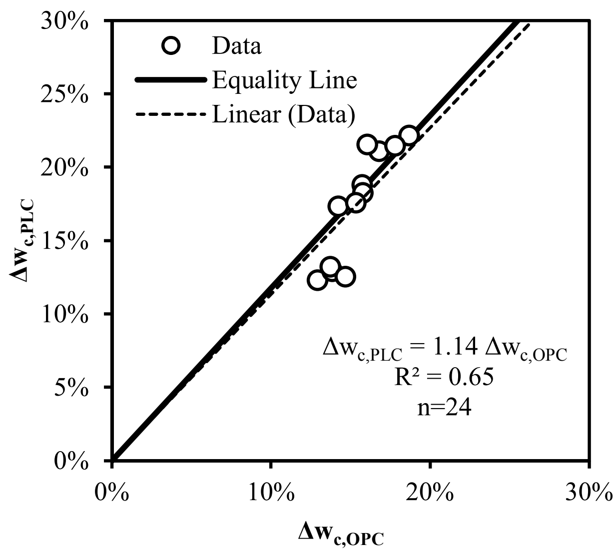


Figure 7.6. Comparison of Moisture Content Reduction of VHMS using 5% PLC vs 5% OPC

Figure 7.6 is an equality plot relating reduction of initial moisture contents for VHMS treated with 5% PLC and 5% OPC. As shown in Figure 7.6, PLC was 14% more effective than OPC at reducing moisture content on average. The difference between OPC and PLC mixtures can also be seen in Figure 7.5b and 7.5c where moisture contents of specimens treated with 5% PLC were further reduced than specimens treated with 5% OPC. It is possible that moisture contents could be reduced further after longer cure times as a result of pozzolanic reactions, and pozzolanic tendencies of OPC relative to PLC cements are largely unexplored as discussed in Chapter 6. After longer cure times, it would be possible for moisture contents to be reduced further as a result of pozzolanic reactions. However, it was not expected for there to be an immediate difference between moisture reduction of OPC and PLC cement mixtures. This could be the result of many factors and should be investigated further.

7.4.3 Specimen Densities

Specimens were fabricated using molds of uniform volume (nominally speaking and neglecting manufacturing tolerances) as described in Section 7.3 and were weighed prior to testing. Summary statistics of resulting densities are shown in Table 7.4. Readers should note that volumes for resulting densities shown in Table 7.4 are based on specimen mold volume and not on volumes measured for individual specimens.

Table 7.4. Specimen Moist Density by Group

Group	Avg. Moist Density (g/cm^3)	Range (g/cm^3)	St. Dev. (g/cm^3)
1	1.37	0.020	0.006
2	1.42	0.022	0.009
3	1.46	0.037	0.012
4	1.40	0.037	0.012
5	1.44	0.026	0.008
6	1.48	0.028	0.010
7	1.39	0.017	0.006
8	1.45	0.032	0.009
9	1.48	0.022	0.007

7.5 Summary of Re-use of Multiple on Site Materials

Based on results presented herein, LC-VHMS containing bottom ash can be produced with cement contents on the order of 5% of slurry mass. This finding is not especially surprising, but there were apparent differences between drying-tendencies of OPC and PLC cements that were not necessarily expected. For mixtures stabilized herein, 5% PLC seemed to be around 14% more efficient at reducing initial moisture contents than 5% OPC. Tendencies of OPC and PLC cements to reduce moisture content of VHMS should be investigated further to evaluate differences therein.

Unconfined compression tests were performed, and results indicate that cement contents of up to 5% cement based on slurry mass can considerably improve shear strength and decrease moisture contents. Use of dredged soil combined with bottom ash seems to be an option worth considering for a marginal geotextile tube fill after lightly cementing.

CHAPTER 8 – VEGETATION EXPERIMENTS

8.1 Overview of Vegetation Experiments

A series of vegetation experiments were performed to examine possibilities of incorporating portland cement into VHMS for shorter term purposes, while not prohibiting vegetation establishment for long term purposes. These experiments were performed with and without geotextile tubes. ME and MO soils were used alongside Bermuda and Fescue grass, OPC and PLC cement, and three types of geotextile pillows (see Chapter 4). Soil used for vegetation experiments could have been used previously for tests such as proctor compaction, but no cement had been added to the soils prior to use in vegetation experiments. The majority of the soil used for vegetation experiments had not been previously used for other laboratory tests.

8.2 Grass Seed Application Rates

Information was taken from (http://www.bermudagrass.com/info/seeding-lawns.html, Accessed 7/12/2014) regarding Bermuda grass and corresponding vegetation establishment. Likewise, (http://www.fescue.com/ and http://www.grassing.com/, Accessed 7/12/2014) were referenced for fescue grass. A summary of the most pertinent information obtained that was used to develop the experimental program presented in this document is contained in the remainder of this paragraph. Bermuda grass is best planted in spring to early summer in a soil with a pH of 6 or more having proper drainage. Planting depths should not exceed 0.6 cm to facilitate germination. A mid-range Bermuda seeding rate was given as 0.00122 g/cm^2 (2.5 lb per 1000 ft^2). In ideal conditions, full coverage was stated to take 6 to 10 weeks. Fescue is a cool season grass that is best planted in the fall or spring, fall being the best time. Soil pH of 5.5 to 8.0 was generally observed to be a reasonable range for fescue.

To determine the Bermuda seeding rate, the volume in the top 0.6 cm of the plastic buckets used as controls was estimated to be 440 cm^3, and the as mixed soil slurry density was taken as 1.4 g/cm^3 (densities could vary $\pm$ 0.1 g/cm^3 to slightly more). For these approximate, yet reasonable, conditions, the total mass is 616 g. If the moisture content is taken as 100%, 308 g of dry soil is present in the total volume. Some of the cases were mixed at above 100% moisture, but it should be noted that soon after experiment initiation moisture contents would drop below 100%. The surface area of the plastic buckets used for controls was estimated to be 730 cm^2, which requires 0.89 g of grass seed to cover the area based on the mid-range seeding rate presented in the previous paragraph. Taking the ratio of 0.89 g of grass seed divided by 308 g of dry soil leads to needing approximately 2.9 g of grass seed per kg of dry soil. To account for shrinkage soon after beginning the experiments, the Bermuda grass seed application rate in experiments was taken as 2.5 $\pm$ 0.15 g per kg of dry soil. Based on the same logic, but adjusting the base application rate for grass seed type, the fescue grass seed application rate in experiments was taken as 5.0 $\pm$ 0.15 g per kg of dry soil.

8.3 Vegetation Specimen Preparation

A total of 29 vegetation experiments were performed that are summarized in Table 8.1. Initially, water was added to moist soil and mixed to uniformity to produce VHMS

(Figure 8.1a); mixing time was not monitored. Pre-weighed grass was then introduced uniformly into the VHMS while being mixed over a period of one minute (Figure 8.1b), and thereafter the VHMS and grass seed were mixed for one additional minute (two minutes from beginning of seed introduction to the end of mixing). When PLC was incorporated, it was simultaneously introduced with grass seed during the same time frames (Figure 8.1c). No fertilize was used upon initial mixing, or throughout the monitoring period.

Table 8.1. Vegetation Experiment Test Plan

Phase	ID	Soil	Grass	Cement	Initiated	Ended	Type	$w_{\%}$
I	1	MO	Bermuda	---	7/14/2014	7/17/2015	Bucket	100
	2	MO	Bermuda	PLC	7/14/2014	7/17/2015	Bucket	100
1 yr	3	ME	Bermuda	---	7/14/2014	7/17/2015	Bucket	100
	4	ME	Bermuda	PLC	7/14/2014	7/17/2015	Bucket	100
	5	MO	Bermuda	---	7/15/2014	7/17/2015	GT 500	120
	6	MO	Bermuda	PLC	7/17/2014	7/17/2015	GT 500	150
	7	ME	Bermuda	---	7/17/2014	7/17/2015	GT 500	150
	8	ME	Bermuda	PLC	7/17/2014	7/17/2015	GT 500	168
II	9	MO	Fescue	---	10/16/2014	10/6/2015	Bucket	100
	10	MO	Fescue	PLC	10/16/2014	10/6/2015	Bucket	100
1 yr	11	ME	Fescue	---	10/18/2014	10/6/2015	Bucket	114
	12	ME	Fescue	PLC	10/18/2014	10/6/2015	Bucket	114
	13	MO	Fescue	---	10/17/2014	10/6/2015	GT 500	150
	14	MO	Fescue	PLC	10/17/2014	10/6/2015	GT 500	150
	15	ME	Fescue	---	10/16/2014	10/6/2015	GT 500	150
	16	ME	Fescue	PLC	10/16/2014	10/6/2015	GT 500	150
III	17	MO	Fescue	PLC	4/10/2015	10/6/2015	Bucket	150
	18	MO	Bermuda	PLC	4/10/2015	10/6/2015	Bucket	150
0.5 yr	19	MO	Bermuda	PLC	4/10/2015	10/6/2015	GT 500	150
	20	MO	Bermuda	PLC	4/10/2015	10/6/2015	GT 1000M	150
	21	MO	Bermuda	PLC	4/10/2015	10/6/2015	GC 1200MB	150
	22	ME	Fescue	PLC	4/10/2015	10/6/2015	Bucket	150
	23	ME	Bermuda	PLC	4/10/2015	10/6/2015	Bucket	150
	24	ME	Fescue	PLC	4/10/2015	10/6/2015	GT 500	150
	25	ME	Bermuda	PLC	4/10/2015	10/6/2015	GT 500	150
	26	ME	Fescue	PLC	4/10/2015	10/6/2015	GT 1000M	150
	27	ME	Bermuda	PLC	4/10/2015	10/6/2015	GT 1000M	150
	28	ME	Fescue	PLC	4/10/2015	10/6/2015	GC 1200MB	150
	29	ME	Bermuda	PLC	4/10/2015	10/6/2015	GC 1200MB	150

--PLC, when applied, was 5% of dry soil mass.

Once fully mixed, VHMS with grass seed (and PLC where appropriate) was placed into either 19 liter (5-gallon) plastic buckets or small scale geotextile tubes (often referred to as *pillows*). Five evenly spaced holes (1.3 cm diameter) were drilled into the bottom of each bucket (Figure 8.1d), and two layers of TenCate Mirafi HP270 geotextile were placed in the bottom of the bucket. Coarse sand was then placed around 10 cm deep and lightly tamped (Figure 8.1e) before placing two more layers of HP270 above the sand for separation and containment. VHMS was then placed into the bucket and the surface was leveled (Figures 8.1f, 8.1g, and 8.1h). Small holes were also drilled into the sides of the buckets.

Geotextile tube experiments consisted of filling a *pillow* by attaching a funnel to the threaded top port, while the geotextile *pillow* was resting on a stand with a mesh bottom that had a pan underneath to capture drainage (Figure 1j). Seeded and if applicable cemented VHMS was poured into the *pillow* (Figure 1k) until filled (Figure 1i). pH data was collected on water escaping geotextile tubes. Water that collected in the pan underneath the geotextile tube *pillows* was collected for the first 30 minutes after the tube was filled, and thereafter, the first pan was quickly traded for a second clean pan where water was collected for 30 additional minutes. This provided water pH for the first 30 minutes of drainage and the second 30 minutes of drainage after the tube would be closer to a steady state drainage condition. pH data was collected in this manner for the first four geotextile experiments. Water was visibly cleaner in the second 30 minute pan. Figure 8.1l shows the contents captured in the pan being collected for pH testing.

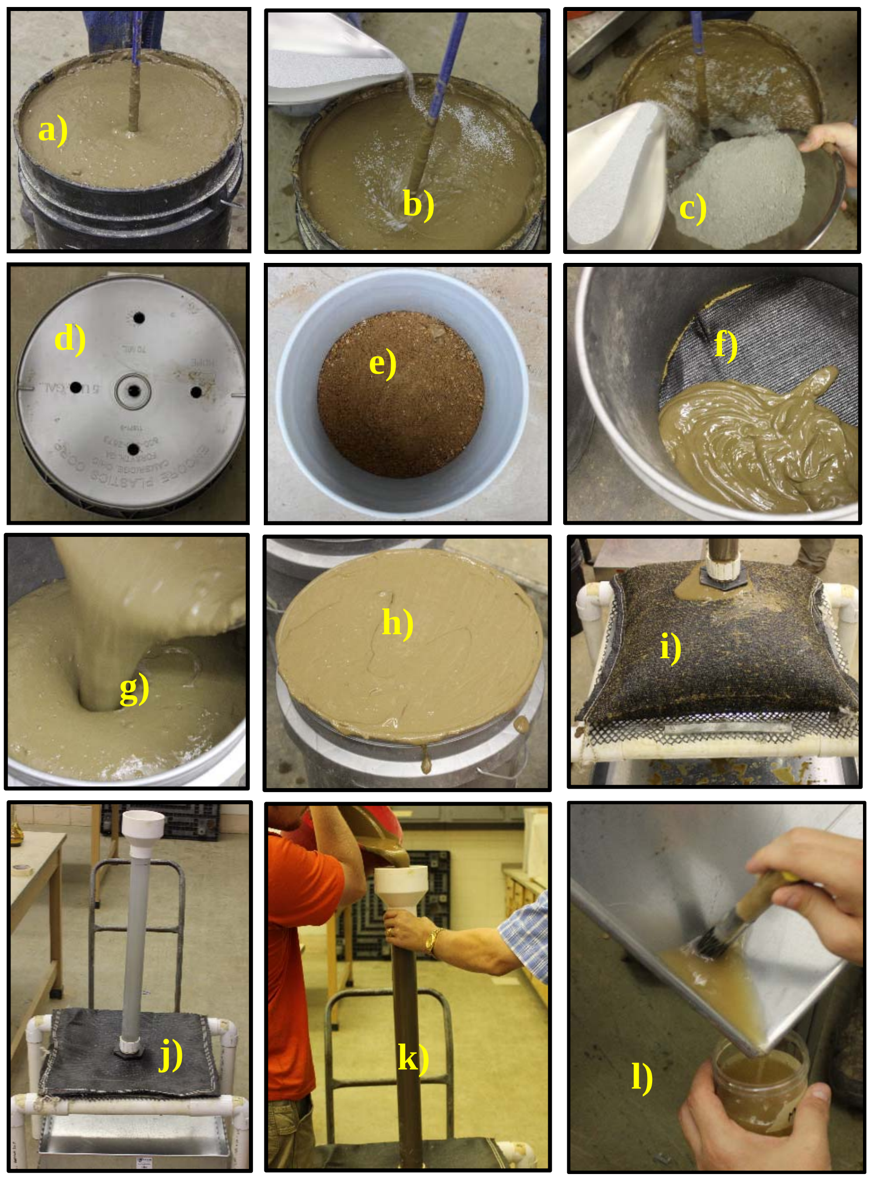


Figure 8.1. Vegetation Experiment Specimen Preparation: Buckets & Geotextile Pillows

Vegetation experimental units were produced in three phases that occurred at different times (Table 8.1). All experimental units within a phase began within at most 4 days of each other and ended on the same day. Vegetation experimental units were placed outside on a relatively impermeable surface in Starkville, MS on the same day they were mixed (Figure 8.2). Thereafter, these materials were monitored and photographed periodically over time to document the successfulness of the grass growing experiments. Moisture conditions within these experiments were probably lower, overall, than they would be in an application because these specimens were drained and sitting on a relatively impermeable surface.

a) Phase I-July 17, 2014 *b) Phases I, II, and III-May 8, 2015*

Figure 8.2. Outdoor Monitoring of Vegetation Experiments

8.4 Vegetation Test Methods

Vegetation test methods were simplistic as this was an exploratory, proof of concept, effort. Testing intended to answer two questions: 1) can vegegation be established in conjunction with cement; and 2) are pH levels within water exiting geotextile tubes suitable for typical conditions where one might consider cemented and seeded VHMS? Question 1 was answered by monitoring the Table 8.1 outdoor experiments and photographing them periodically. Question 2 was answered as described in the following paragraph.

Soil, water, and cement pH of samples prior to mixing were measured, as was pH of the water exiting geotextile tube experiments 5 to 8. MS U's Environmental Laboratory SOP #12, which is based off McLean (1982), was used to measure pH. Measurements of pH below 7 are acidic, measurements above 7 are alkaline, and measurements of 7 are neutral. The scale is logarithmic; for example, 6.0 is 10 times more acidic than 7.0. Figure 8.3a. shows an example pH measurement photo of one of the water samples, while Figure 8.3b shows the ten water samples to show how they varied visually at the time of testing. These water samples were held for several weeks prior to testing.

Figure 8.3. pH Testing

8.5 Vegetation Experiment Results

8.5.1 Vegetation Establishment Results

To quantify vegetation establishment numerically, Table 8.2 was developed. Photographs were taken on the order of every month and these photographs were scaled as per Table 8.2. Figure 8.4 provides summary photographs of geotextile tube and bucket experiments at a range of Table 8.2 scores. Each photograph in Figure 8.4 has a caption that shows the experimental unit, date photo was taken, and the Table 8.2 score assigned. For example ID1-Jul 28-1.0 is experimental unit 1, the photo was taken July 28, 2014, and there was very low (i.e. score of 1.0) vegetation establishment. Figure 8.5 plots Table 8.2 numerical values versus time for all 29 experimental units.

Table 8.2. Vegetation Establishment Scale

Scale	Vegetation Description	Numerical Value
N	None	0.0
VL	Very Low	1.0
L	Low	2.5
M	Modest	4.0
R	Reasonable	5.5
G	Good	7.0
VG	Very Good	8.5
FC	Full Coverage	10.0

Note: scale refers to live (or green) grass. Brown grass was neglected.

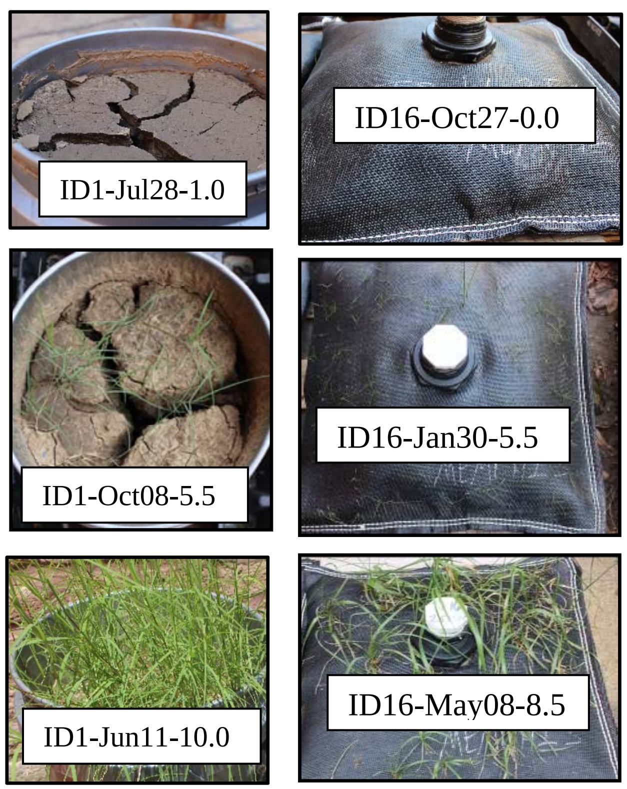


Figure 8.4. Representative Photos of Vegetation Experiments

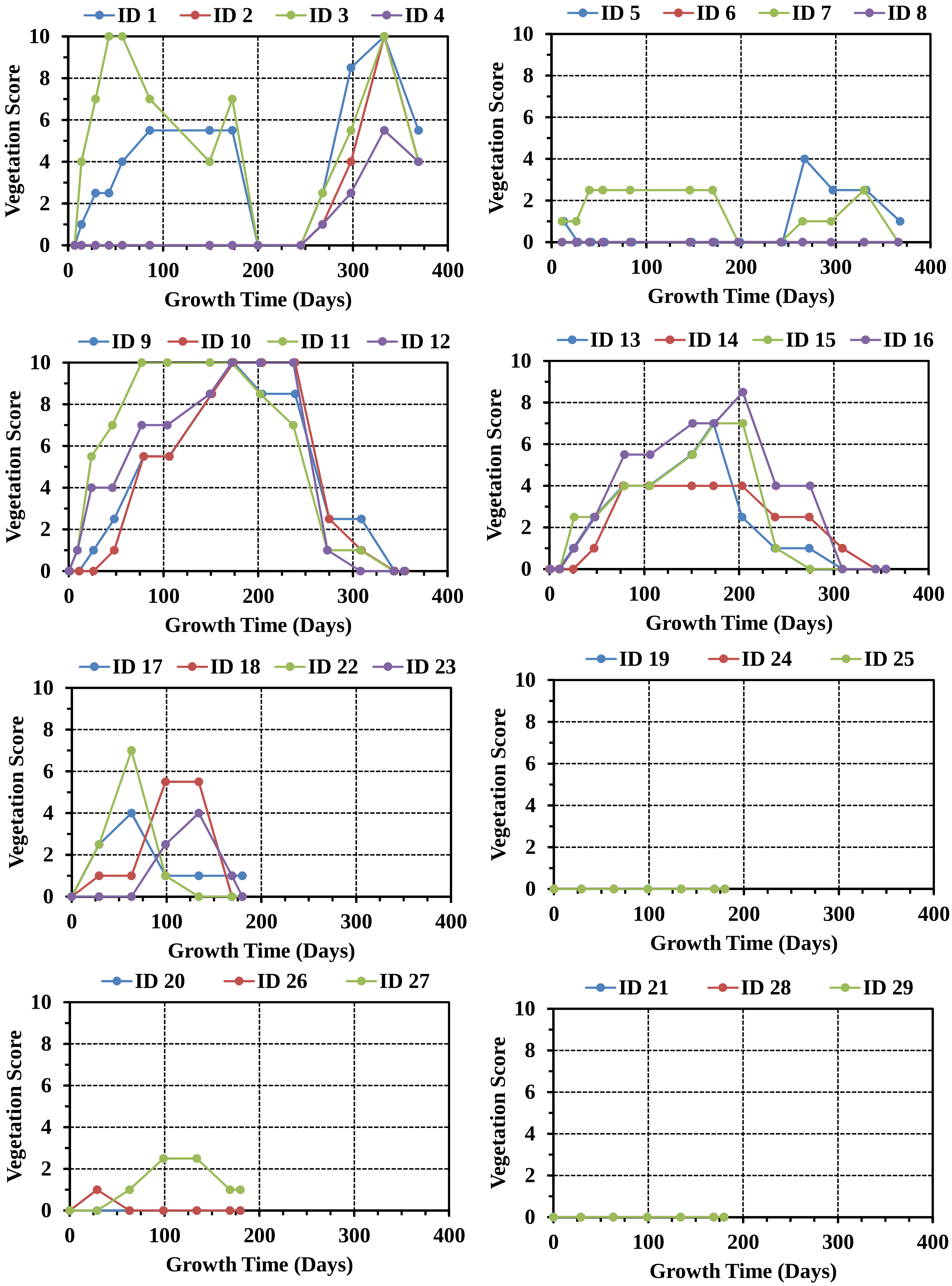


Figure 8.5. Numerical Vegetation Test Results Plotted Versus Growth Time

8.5.2 pH Results

8.3 provides pH test results. Mobile soil had medium acidity, and tap water had medium alkalinity. When mixed without PLC, the result was between these two cases and was fairly stable over time; i.e. pH was 6.5 to 6.7. When PLC was added, there was a sharp drop in pH between water collected in the first 30 minutes and that collected in the second 30 minutes. pH in the first 30 minutes was quite high with PLC, but dropped below that of tap water relatively quickly. Some PLC probably escaped the geotextile tube prior to the fabric being blinded and steady state being achieved. With the ME soil, pH values were fairly stable. The raw soil had the lowest pH at 7.7, with the highest pH being only slightly higher than the tap water used at 8.4. There were no other noticeable trends with the ME soil other than pH levels were not problematic.

Table 8.3. pH Test Results

Description	pH	pH Description
PLC	12.8	Strongly Alkaline
Tap Water	8.3	Medium Alkaline
MO Soil	5.8	Medium Acid
MO Soil, 0% PLC, 1st 30 minutes of drainage	6.7	Very Slightly Acid
MO Soil, 0% PLC, 2nd 30 minutes of drainage	6.5	Very Slightly Acid
MO Soil, 2.5% PLC, 1st 30 minutes of drainage	10.4	Strongly Alkaline
MO Soil, 2.5% PLC, 2nd 30 minutes of drainage	8.0	Slightly Alkaline
ME Soil	7.7	Slightly Alkaline
ME Soil, 0% PLC, 1st 30 minutes of drainage	8.2	Medium Alkaline
ME Soil, 0% PLC, 2nd 30 minutes of drainage	8.4	Medium Alkaline
ME Soil, 2.5% PLC, 1st 30 minutes of drainage	7.8	Slightly Alkaline
ME Soil, 2.5% PLC, 2nd 30 minutes of drainage	8.3	Medium Alkaline

Note: Bermuda was used in all soil, cement, and/or grass seed combinations.

8.6 Discussion of Vegetation Results

Phase I experiments were with Bermuda grass. Examining ID's 1 to 4 (Figure 8.5), it can be seen that full Bermuda vegetation was established without PLC for both soils in bucket experiments. ME soil without PLC established Bermuda vegetation the earliest, but growth was inhibited in ME soil by PLC as only reasonable vegetation establishment occurred with PLC (versus full vegetation establishment). MO soil had fully established Bermuda vegetation for a brief period with PLC as it did without PLC. Geotextile tubes noticeably inhibited Bermuda establishment (i.e. comparing ID's 5 to 8 with ID's 1 to 4). Some Bermuda grass was able to grow through the synthetic fabric, but to a much lesser scale than in the bucket experiments. It is noteworthy, that all Bermuda experiments initiated in mid-July, which is later in the growing season that is optimal for Bermuda grass. At a minimum, the Bermuda experiment showed PLC does not fully inhibit vegetation establishment.

The Phase II experiment with fescue (ID's 9 to 16) was initiated in mid-October, which is more suitable for this grass. Fescue vegetation was readily established in all buckets irrespective of whether or not PLC was included. Interestingly, ID 9 was the lowest overall growth, and it did not contain PLC. As with Bermuda grass, the synthetic geotextile inhibited vegetation growth, but not nearly to the extent of the Bermuda experiment. Considering the dry conditions of this experiment, fescue grass was reasonably established in conjunction with GT 500 geotextile fabric. At a minimum, the fescue experiment showed PLC does not inhibit vegetation establishment and that vegetation can be established (at least to some extent) through a synthetic fabric in a lightly cemented medium.

The Phase III experiments contained Bermuda and fescue grass and were intended to compliment findings of Phase I and Phase II. Unfortunately, weather conditions did not lend themselves well to complimentary comparison. NOAA data reported on October 1, 2015 suggested short term (typically less than 6 months) abnormally dry conditions around the test site (http://www1.ncdc.noaa.gov/pub/data/cmb/sotc/drought/2015/09/20150929_usdm.png). This lack of typical rainfall coupled with the already free draining conditions of the test site resulted in extremely harsh growing conditions. Rainfall was not monitored around the experiments, but rainfall was modest to non-existent for a considerable portion of the Phase III growing duration.

Phase III contained four bucket experiments that were, for practical purposes, matched pairs of other experiments contained in Phase I or Phase II. The pairs are as follows with the Phase I or II pair listed first: 10 and 17; 2 and 18; 12 and 22; and 4 and 23. In all four cases, vegetation was more readily established in Phase I or II than Phase III. Experiments 2, 10, and 12 all achieved full vegetation, while their counterparts in Phase III achieved maximum scores of 4 to 7. Experiment 4 (Phase I) did not achieve full vegetation, but its score of 5.5 still exceeded its Phase III counterpart of 4.0. The findings of these four bucket experiments should be taken into consideration when comparing types of geotextile tube fabric.

Three Phase III experiments (19, 24, and 25) utilized GT 500 fabric, and no vegetation was documented in any of these experiments throughout the 0.5 yr growing duration. This agrees with the findings with PLC and Bermuda soil from Phase I (i.e. that grass did grow through GT 500 fabric), but not with PLC and fescue soil from Phase II (i.e. experiment 16 experienced noticeable growth whereas experiment 24 did not). GT 1000M saw modest vegetation success in experiment 27 with PLC, but overall vegetation was not established with this fabric. GC 1000MB had no evidence of vegetation growth with PLC. Overall, vegetation was not established through geotextile tubes filled with LC-VHMS in more cases than when it was established.

In addition to the primary experimental results presented thus far, there were additional findings of potential relevance moving forward. As expected, there was considerable shrinkage that occurred in the seeded LC-VHMS materials. Sophisticated shrinkage measurements were not taken, but they can be seen visually when comparing Figure 8.1h as cast conditions to the progression over time shown in Figure 8.4. The geotextile tube experiments presented in this chapter provided evidence that manageable cement dosage rates should be achievable that allow soil to be kept inside the geotextile tubes when made from traditional materials. Considerable experience is available in the field of geotextiles and polymer dosing for dewatering applications that can also be drawn from to suggest that keeping soil inside the geotextile tubes for LC-VHMS applications with conventional fabrics is feasible. The water quality from the experiments in this chapter is also subjective evidence supporting the ability adequately separate water from LC-VHMS materials. Biodegradable tubes, however, could pose more difficulty in this area. Future investigations should consider biodegradable fabrics.

This chapter aimed to make a contribution at the boundary of the natural and built environments and progress ASCE's sustainability triple bottom line of environment, economics, and social well-being. The primary objective of this chapter was to investigate the concept of establishing vegetation in lightly cemented VHMS with or without geotextile tubes. This objective was met as test results showed established vegetation, thus demonstrating viability of combining vegetation and portland-limestone cement. Vegetated LC-VHMS would have an intended purpose of, for example, using dredged material to produce land adjacent to a port that can blend into the natural environment.

Literature review identified several recent references where vegetation establishment and engineering with nature were investigated. With regard to other applications, re-establishment of salt marshes is an area of possible interest. This evaluation only considered fresh water systems, but the data presented in this chapter coupled with possible applications in higher salinity environments and the recent interest in projects of this nature make this an area of interesting future study. Also, the only case considered in this chapter was grass seed introduced into the soil at the same time as the cement. Future work should investigate stockpiling LC-VHMS to reduce plasticity, then seeing the material at a later date. Another potentially appealing idea for future study would be to evaluate seeded LC-VHMS in a more realistic (i.e. less harsh) moisture condition (e.g. partially submerged) that would occur frequently in a riverine, port, or shoreline application.

CHAPTER 9 – PORT APPLICATONS, SUSTAINABILITY, AND ECONOMIC COMPETIVENESS

9.1 Overview

This chapter aims to take the information from chapters 1 to 8 to provide guidance and in some cases concepts to consider for ports in the southeastern US. The chapter is divided into three major focus areas: applications, sustainability, and economic competiveness, each of which is contained in a separate section of this chapter. There are some parts of this chapter where several simplifying assumptions were made so as to highlight key points absent what would typically be project specific details.

9.2 Potentially Relevant Applications for Southeastern US Ports

9.2.1 Relevant Applications

As documented in earlier chapters, geotextile tubes provide a vehicle for beneficial reuse of soils dredged adjacent to the construction site. Ports could make use of this vehicle for applications where material of modest quality is needed in high volumes. For example, ports could make use of this vehicle when adjacent land areas are being developed in such a way that large volumes of fill material are required.

Chapter 2 documents many applications where dredged sediments (some contaminated and some non-contaminated) were handled. Table 9.1 presents a summary of applications for dredged sediments found in literature. There are large variations between projects where dredged sediments are handled, but many projects can be grouped into applications as presented in Table 9.1. Applications shown in Table 9.1 could potentially be combined for specific situations around ports (e.g. constructing a wall of geotextile tubes filled with LC-VHMS and subsequently using stabilized dredged sediments as lightweight backfill). Use of LC-VHMS as fill for geotextile tube walls is the primary focus of discussion for the remainder of this chapter.

Table 9.1. Dredged Material Applications Found in Literature

Dredged Sediment Project Description	References or Locations
Geotextile Tubes Used in Stabilization Prior to Removal or Landfilling	Zhu and Beech (2015); Connor Creek, MI[1]; Lake Sorte So in Denmark[1]
Geotextile Tube Fill for Temporary or Permanent Dike Construction	Lake Dianchi, China[1]; Drakes Creek, TN[2]
Geotextile Tube Fill for Permanent Construction (e.g. for large area fills adjacent to dredge locations)	Tianjin Eco-City, China[1]; Svartsjon Lakes, Sweden[1]; Grubers Grove Bay[1]; Canal de Fundao, Brazil[1]; Embraport Terminal Expansion, Brazil[1]
Stabilization Prior to Removal – No Geotextile Tubes	Austin and Wilk (2004)
Permanent Construction with No Geotextile Tubes (e.g. lightweight backfill, dike construction, land creation, pavement subbase and base layers)	Tsuchida et al. (2001); Zele et al. (2014); Matthews and Wilk (2004); Arora et al. (2006)
Beach Erosion Control or Riverbank Refurbishment	Shin and Oh (2007); De Mars on Ijssel River, Netherlands[1]

[1]Project Described in TenCate™ (2013)
[2]Project Described in Howard et al. (2009)

9.2.2 Construction Sequencing of Relevant Applications

Use of LC-VHMS, in particular as geotextile tube fill, would be more appealing for longer term port needs than for shorter term needs. Optimum use of LC-VHMS is likely to make use of longer periods of drying/dewatering and hydration than many US construction endeavors are accustomed to. There is a major inertia in a considerable number of US construction projects to rely on construction materials that gain adequate strength quickly so that projects can be built as fast as possible. Projects desiring rapid construction schedules are not likely to be well suited for LC-VHMS, unless the strength of LC-VHMS is to largely be neglected in design.

Portland cement is a key aspect of the built environment, and properties of portland cement in a given construction market provide a perspective of the items that are important to that market. As discussed in the previous paragraph, construction speed is important in the US construction market. To support this point, PCA (1996) provides data comparing cements of the 1950's to those of the 1990's and shows a generally increased amount of tricalcium silicate (C_3S) and a decreased amount of dicalcium silicate (C_2S). Note that C_3S is related to early strength gain. Data also showed modern cements (i.e. 1990's cements) generally gained strength more rapidly in the first 7 days to meet needs of modern construction practices.

If a port desired to, for example, develop a portion of their property over a 5 year period while reducing the amount of dredged material stored in confined disposal areas, LC-VHMS could be a very appealing option. In this scenario, the rate of strength gain and settlement with time of LC-VHMS fill inside geotextile tubes could be used to establish construction sequencing. The opposite approach could also be used where construction sequencing could govern the LC-VHMS cementitious dosage rate. An example application is described in the following paragraph.

An example where ports could make use of LC-VHMS is filling lower rows of geotextile tubes with LC-VHMS in the first construction season (e.g. beginning late summer to early fall), that are left for a considerable amount of time (e.g. from early winter to spring, say November 15 to March 15). Thereafter, these tubes could be re-filled, and a second row of tubes stacked since sufficient strength would have been mobilized in the lower row of tubes. This process could continue until the desired height has been achieved, and thereafter, backfill could be placed behind the tubes (also produced from C or LC-VHMS). This backfill could also be placed coinciding with each row of geotextile tubes if desired. It is envisioned that the geotextile tubes would be filled with flowable materials tested in Chapter 6 and 7 (e.g. Mobile at 100% initial moisture content from Chapter 6 and all blends from Chapter 7) and that backfill would not be as flowable (e.g. Memphis at 90 to 100% initial moisture content and Mobile at 70% initial moisture content). Whatever the actual construction sequencing, the key would be to make use of a considerable amount of time, but also to do so while greatly reducing the amount of dredged material stored in confined disposal facilities, and based on the information presented in Chapter 2 and Section 9.4, reducing costs in at least some cases.

Three cases of retaining walls constructed from LC-VHMS are used as examples and discussed in this chapter. The cases discussed in the following paragraphs are Case I, Case II, and Case III, which have heights of 2.5, 3.5, and 5.0 m, respectively. A primary construction sequencing issue is insuring that materials contained within lower geotextile tubes obtain adequate strength to support additional loads prior to increasing layers of geotextile tubes or prior to applying lateral forces. Case I could be constructed from a single geotextile tube filled with LC-VHMS, which is unlikely to have stability issues if foundation soil is suitable (foundation soils are beyond this project's scope). Thus, construction sequencing becomes much simpler and slope stability calculations for such an application are not included herein. However, slope stability calculations should be considered when planning construction sequencing for applications containing multiple layers of geotextile tubes.

For Case II and Case III, a pyramid configuration is considered. Walls constructed with heights around 3.5 m (i.e. Case II) could likely be constructed using three geotextile tubes with a row of two geotextile tubes first and an additional geotextile tube on top. Walls with heights around 5 m (i.e. Case III) could likely be constructed using six geotextile tubes using three rows with three geotextile tube on the bottom row, two geotextile tubes on the second row, and one geotextile tube on the top row. This is expounded upon more later in this chapter. To simplify calculations and comparisons between walls constructed using differing geotextile tube materials, wall crests for slope stability considerations were maintained at 2 m. Case II considers an assumed wall base width of 7 m and wall height of 3.5 m. Case III considers a wall base width of 10 m and a wall height of 5 m.

Two-dimensional limit equilibrium slope stability analyses were performed using SLIDE. Spencer's method was employed in these analyses, which explicitly satisfies all three equilibrium conditions (i.e. horizontal and vertical force as well as moment equilibrium conditions). Undrained analysis was performed since undrained shear strength and short-term conditions are likely to be limiting factors when constructing slopes using VHMS.

For Case II and Case III, which are described in the two previous paragraphs, slope materials were considered homogenous with a conservative unit weight of 1.83 g/cm^3 and the foundation was assumed to be competent, preventing deep-seated failures. Case II is a 54.5° slope and Case III is a 51.3° slope. Because both cases considered are assumed to be symmetric, only half of the slope geometry was modeled.

Parametric studies were performed to illustrate the effect of undrained shear strength (s_u) on factor of safety (Fs) of stabilized VHMS slopes. Figure 9.1 demonstrates the increasing trend of Fs versus s_u for Case II and Case III. As expected, the Fs for case II increases more rapidly than Fs for case III. For Case II and Case III, the minimum s_u to obtain a Fs of 1.5 was 9 kPa and 12 kPa, respectively, which is 18 to 24 kPa unconfined compressive strength.

a. **b.**

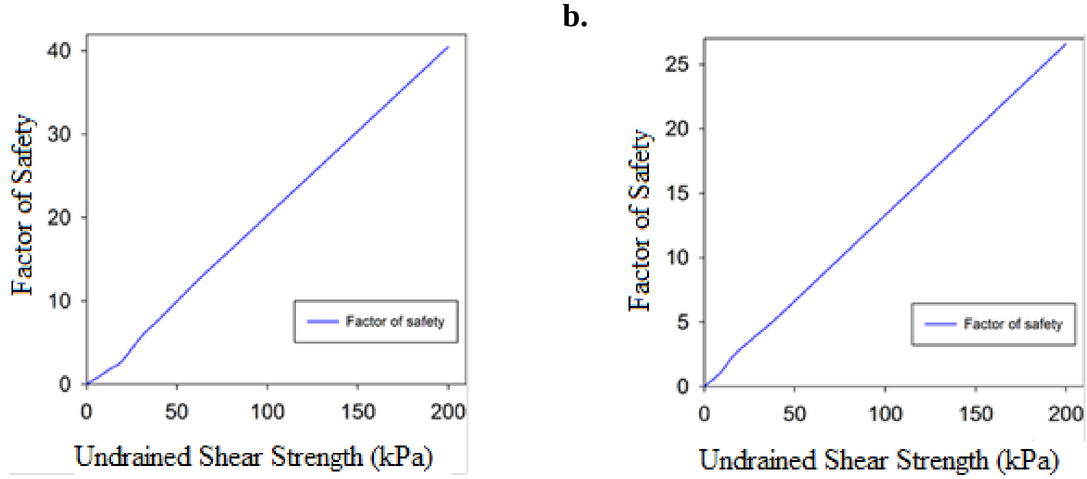


Figure 9.1. Factor of Safety vs. Undrained Shear Strength: a.) Case II b.) Case III

Table 9.2 presents ranges of s_u for flowable materials tested in Chapter 6 (Mobile at 100% initial moisture content) and Chapter 7 (Memphis at 135% initial moisture content). Note that s_u values presented in this chapter were determined using unconfined compressive strengths (q_u). Some mixtures produced in Chapter 6 (Memphis at 90% and 100% initial moisture content and Mobile at 70% initial moisture content) were at conditions which did not flow when evaluated using ASTM D6103, and are thus not included in this discussion. The relationship between s_u and q_u is provided in Equation 9.1.

$$s_u = q_u/2 \tag{9.1}$$

Table 9.2. Undrained Shear Strengths of Flowable Materials

Site	Flow (cm)	LL Ratio[1]	Cement (%)[2]	Range of s_u from UC (kPa)		
				7 days	28 days	56 days
Memphis	17.8	1.5	2.5	10-11	14	15
			5.0	27-32	30-36	34-41
Mobile	25.4	1.4	2.5	5-7	8-9	9-10
			5.0	69-79	81-89	100-118

[1]LL Ratio is initial w_c (%) divided by LL (%).
[2]Cement contents reported on slurry mass.

Using undrained shear strengths from Table 9.2 and plots presented in Figure 9.1, Fs for Case II and Case III can be determined for various cement and initial water content configurations. As previously mentioned, a Fs of 1.5 was satisfied for Case II and Case III with s_u of 9 kPa and 12 kPa. Thus, adequate strengths for a 3.5 m tall wall built from geotextile tubes could likely be obtained after 56 days if 2.5% cement by slurry mass were used for geotextile tube fill (note that Table 9.2 values likely under-represent s_u at later days in service due to consolidation and drying that is likely to occur). This could affect construction sequencing in such a way that initial geotextile tubes were filled, allowed to hydrate, de-water, and consolidate for a minimum of 2 months before the third geotextile tube was added. For cases where construction speed is of high enough concern where construction sequencing can't allow for 2 months of hydration, de-watering, and consolidation, lower tubes could be constructed from higher cement contents in such a way that necessary s_u to provide required Fs.

In cases where a geotextile tube wall having a height of 10 m were to be considered, cement contents would likely need to be higher than 2.5%. However, cement contents lower than 5% could be a reasonable choice as Fs for mixtures containing 5% cement herein would likely be on the order of 5 to 10. Readers should note that these values are not provided as design considerations. Rather, these values are provided to support that cement contents between 2.5 and 5% of slurry mass could be reasonable for producing LC-VHMS as fill for geotextile tube walls that can be manageable for some construction purposes, as considered herein.

At least one study has performed analysis for stability of geotextile tube slopes which considers effects of geotextile tubes rather than homogenous slopes. Zhu et al. (2014) presented a parametric study which considered geotextile mattresses (much more shallow and wide than geotextile tubes considered herein) and provided a series of slope stability charts for cases using geotextile mattresses. External failure modes (i.e. failure between geotextile materials and not of individual tubes) considered in Zhu et al. (2014) were, sliding of geotextile tubes past each other, global slope failure between geotextile tubes not including foundation soil, global slope failure between geotextile tubes and through foundation soil, failure of foundation bearing capacity, and failure of foundation through settlement. While external failure modes of stacked geotextile tubes were not considered herein, literature review shows it is a feasible concept to stack geotextile tubes under proper conditions.

9.2.3 Quantities of Material for Relevant Applications

As seen in Chapter 2, there are many applications where geotextile tubes can be utilized in and around ports and harbors. Two applications that seem promising are: 1) use of geotextile tubes to form a wall or barrier around an area of land where the port desires to raise the elevation using dredged material that is not contaminated (possibly LC-VHMS) over time; and 2) use of geotextile tubes to contain a considerable amount of contaminated sediment that likely has been lightly cemented and left in place to create functional land. Of these two applications, a wall lends itself better to calculations absent a specific project scenario at a port. The Embraport terminal project described in Chapter 2 made it clear that it is feasible to stack geotextile tubes filled with dredged material and subsequently build a structure over the tubes.

A review of literature shows that there is a substantial amount of dredged material recovered within the US annually. However, further review of literature indicated that re-use applications within the US have historically utilized less dredged soil than projects in other countries. Quantities of dredged soil recovered in the US from individual projects and nationwide for the USACE are provided in Table 9.3. Similarly, quantities of stabilized dredged soil from differing projects from the US and around the world are shown in Table 9.4. As shown in Table 9.4, projects utilizing dredged soils within the US typically utilize less than 100,000 m^3 of dredged materials while the majority of projects studied outside the US use well over 100,000 m^3. As discussed earlier, re-use of dredged materials are likely better suited in applications where large quantities of material are needed.

Table 9.3. Dredged Material Production Found in Chapter 2 Literature Review

Reference	Location	Quantity	Project Type
Lovelace (2014)	Mobile, AL	4.59 million m^3	Single Site Annual Maintenance
Landers (2015b)	Charleston, SC	30.58 million m^3	Single Site Channel Deepening
Landers (2015c)	New York, NY	451,000 m^3	Gowanus Canal Cleanup
Malasavage and Doak (2015)	Oakland, CA	9.79 million m^3	Single Site Channel Deepening
EPA/USACE (2007)	Entire US	>200 million m^3	Total USACE Annual Handling

Table 9.4. Dredged Material Utilization Found in Literature

References	Location	Quantity	Project Type
Howard et al. (2009)	Tennessee	16,800 m^3	Geotextile Tube Fill – Dike Construction
Karnati et al. (2012)	Illinois	38,000 m^3	Geotextile Tube Fill – Island Construction
Austin and Wilk (2004)	California	12,600 m^3	Stabilization of Contaminants - Landfilled
Matthews and Wilk (2004)	Massachusetts	9,000 m^3	Cement Stabilized Land Creation
TenCate™ (2013)	China	2.4 million m^3	Land Elevation
TenCate™ (2013)	Sweden	300,000 m^3	Geotextile Tube Fill – Land Creation
TenCate™ (2013)	Brazil	600,000 m^3	Geotextile Tube Fill – Landscape Shaping
Tencate™ (2013)	Brazil	600,000 m^3	Geotextile Tube Fill – Terminal Expansion
Zele et al. (2014)	Belgium	60,000 m^3	Cement Stabilized Dike Construction

9.3 Sustainability Implications for Southeastern US Ports

9.3.1 Carbon Footprint of Raw Materials

As previously discussed, constructing shorter retaining walls of geotextile tubes filled with LC-VHMS could be a more sustainable option in some situations than constructing walls of concrete. This section provides sustainability comparisons between using concrete and LC-VHMS for retaining walls. The calculations performed are approximate and rely on many assumptions, which are described in the following paragraphs. The purpose of these calculations is to highlight points to consider, and they are not intended to fully represent any given project. Calculations in this section are reported on materials considered in these approaches (i.e. concrete mixture materials, cement for LC-VHMS, and geotextile tube materials). The amount of energy in finishing concrete, constructing forms, pumping material into geotextile tubes, and other non-material production energies are not considered.

According to Struble et al. (2004) a concrete mixture containing 15% cement by mass embodies approximately 2.07 GJ/m^3 or 0.89 MJ/kg with the majority of the embodied energy coming from portland cement at 4.9 MJ/kg. Because the majority of raw materials (i.e. dredged material and water) would likely be contained on site for a port application, this section assumes that all embodied energy per unit of LC-VHMS is contributed through cement and geotextile materials. Embodied energy per unit of LC-VHMS is discussed in the following paragraph.

Cement contents determined to contribute strength gain to LC-VHMS of possible interest in this report generally ranged from 2.5 to 5% cement by slurry mass (i.e. soil and water). Therefore, the assumption can be made that LC-VHMS used to construct retaining walls could be 2.4 to 4.8% cement by total mass (i.e. cement, soil and water). Assuming an embodied energy for cement of 4.9 MJ/kg (note PLC embodies less energy than OPC, but that is not directly considered in these calculations) and the previously stated cement contents, a corresponding LC-VHMS could embody 0.12 to 0.24 MJ/kg. Using dry density and moisture contents reported in Chapter 6, moist specimen densities ranged from 1.4 to 1.6 g/cm^3 with an average moist density of 1.46 g/cm^3. Thus, a prepared mixture of LC-VHMS could embody approximately 0.18 to 0.35 GJ/m^3. For comparison, all embodied energy calculations in the following paragraphs were also converted to carbon footprints. Carbon footprint is measured in metric tons of carbon dioxide equivalent (tCO2e), and is discussed later in this section. According a unit convertor published by the EPA (http://www3.epa.gov/cmop/resources/converter.html), 2647 MJ of embodied energy is comparable to 1.00 tCO_2e.

Embodied energies for retaining walls of 3 heights are considered herein (2.5, 3.5, and 5.0 m). Many concrete retaining wall designs could be considered, but for the purpose of sustainability calculations, the assumption to construct a gravity retaining wall of concrete was used herein. Approximate dimensions to begin design for a gravity retaining wall are provided in Figure 9.2 as shown in Das (2011). For these assessments, a minimum stem thickness of 0.3 m and overall heights of 2.5, 3.5, and 5.0 m were assumed. Resulting concrete volumes and embodied energies per linear meter of retaining wall are shown in Table 9.5. Volumes per linear meter of wall are based on minimum and maximum values to begin analysis provided in Das (2011).

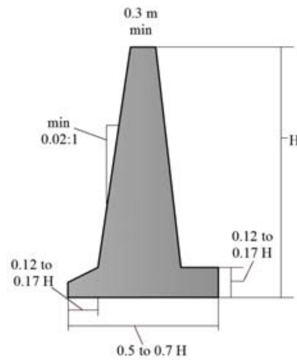


Figure 9.2. Initial Dimensions for Gravity Retaining Wall (Das 2011)

Table 9.5. Concrete Retaining Walls Volume, Embodied Energy, and Carbon Footprint

Retaining Wall Height (m)	Volume per Length of Wall (m^3/m)	Embodied Energy per Length of Wall (GJ/m)	Carbon Footprint (tCO_2e)
2.5	1.13 to 5.31	2.34 to 10.99	0.88 to 4.15
3.5	1.85 to 10.41	3.83 to 21.55	1.45 to 8.14
5.0	3.21 to 21.25	6.64 to 43.99	2.50 to 16.62

In Howard and Trainer (2011) geometries of filled geotextile tubes were calculated. As shown in Figure 9.3, additional layers of geotextile tubes could experience an estimated 67% of the elevation change experienced if the geotextile tubes were sitting on a flat surface (note this estimation is based on stacking and not the effects of consolidation). This approach was used to estimate the amount of LC-VHMS needed to construct walls of comparable height to those shown in Table 9.5. While Howard and Trainer (2011) focused on flooding applications, most applications discussed herein can ignore the effects of water shown in Figure 9.3 though they might have some lateral forces due to hydraulic placement of VHMS depending on construction sequencing. Geotextile tube retaining wall designs studied herein are described in Tables 9.6 to 9.8. For cases where more than one geotextile tube was considered herein, a multi-layer pattern where additional layers contained one geotextile tube fewer than the layer immediately below it was used.

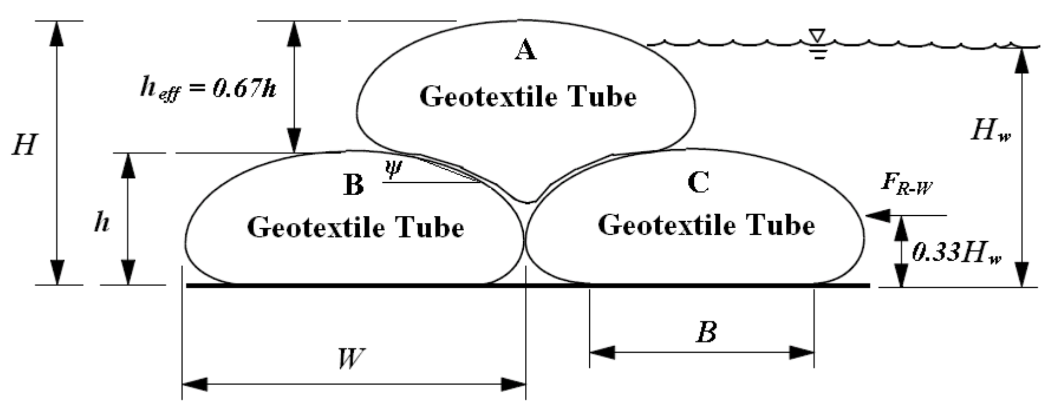


Figure 9.3. Dimensions for tubes filled with LC-VHMS (Howard et al., 2011)

Table 9.6. LC-VHMS Volumes and Embodied Energies for Geotextile Tube Walls

Potential Wall Height (m)	No. of Tubes	Tube Material	Tube Circumference (m)	h (m)	B (m)	W (m)	V (m^3/m)	Embodied Energy (GJ/m)	
								2.5% Cement	*5% Cement*
2.65	1	GT 1000M	13.72	2.65	3.83	5.49	12.22	2.15	4.31
3.64	3	GT 1000M	9.14	2.18	1.80	3.39	18.27	3.22	6.45
3.46	3	GT 500	9.14	2.07	2.01	3.46	17.82	3.14	6.29
5.10	6	GT 1000M	9.14	2.18	1.80	3.39	36.54	6.43	12.90
4.84	6	GT 500	9.14	2.07	2.01	3.46	35.64	6.27	12.58

Note: h, B, and W are defined in Figure 9.3, and V is tube volume per unit length.
Note: SG of internal material was assumed to be 1.2.
Note: Tube heights are based on Table 5.4 in Howard and Trainer (2011).

Table 9.7. Carbon Footprint Contributed by Cement in Geotextile Tube Walls

No. of Tubes	Tube Material	Tube Circumference (m)	Carbon Footprint (tCO_2e/m)	
			2.5% Cement	*5% Cement*
1	GT 1000M	13.72	0.81	1.63
3	GT 1000M	9.14	1.22	2.44
3	GT 500	9.14	1.19	2.38
6	GT 1000M	9.14	2.43	4.87
6	GT 500	9.14	2.37	4.75

-- Cement by slurry (soil plus water) mass

According to information provided by TenCate™, the carbon footprint of representative geotextile tubes (values can vary with materials and manufacturing) can be estimated to contain 4.5 to 5.0 kg of CO_2 equivalents per kg of final geotextile tube. The weight (kg) of geotextile tube can be determined by use of the length, circumference and Table 4.6 mass per unit of area. Carbon footprint is measured in metric tons of carbon dioxide equivalent (tCO_2e). The carbon dioxide equivalent (CO_2e) allows different greenhouse gases to be compared on a like-for-like basis relative to one unit of CO_2. CO_2e is calculated by multiplying the emissions of each of the six greenhouse gases by its 100 year global warming potential (GWP). This range of CO_2e values for geotextile tubes is comprised of production of raw materials, transportation of materials, and manufacture of geotextile products. These ranges were used when determining final ranges of carbon footprints for LC-VHMS retaining walls. Total carbon footprints for geotextile tube walls considered herein are provided in Table 9.8.

Table 9.8. Total Carbon Footprint of Geotextile Tube Walls

Potential Wall Height (m)	No. of Tubes	Tube Material	Tube Circumference (m)	Carbon Footprint (tCO_2e/m)		
				of Cement	*of Geotextile*	*of Total*
2.65	1	GT 1000M	13.72	0.81 to 1.63	0.069 to 0.077	0.88 to 1.71
3.64	3	GT 1000M	9.14	1.22 to 2.44	0.138 to 0.153	1.36 to 2.59
3.46	3	GT 500	9.14	1.19 to 2.38	0.072 to 0.080	1.26 to 2.46
5.10	6	GT 1000M	9.14	2.43 to 4.87	0.276 to 0.307	2.71 to 5.18
4.84	6	GT 500	9.14	2.37 to 4.75	0.144 to 0.160	2.51 to 4.91

When comparing carbon footprints of various construction options described in this section, it seems that there is potential for a savings of carbon emissions in choosing geotextile tube walls over concrete retaining walls. However, these savings can be modest and there are also potential scenarios where geotextile tube walls are not the more sustainable solution. Energy and resource savings from utilizing dredged materials are most likely formed by utilizing a material that has potential to be very costly to manage if on-site capacities are exceeded. This decision depends heavily on the dredged soil management options available, which are port specific and were not directly considered in these calculations. The intention of these calculations was to show ports that there could be value in the approaches presented from a sustainability perspective, and to provide some data for ports that they can couple with their own dredged material data.

9.3.2 Use of Multiple Material Streams

As previously discussed, it is common for a high level of industrial activity to occur in and around ports. In the overwhelming majority of industrial activities, there is at least one byproduct stream associated with production. In circumstances where one or more byproduct streams may be incorporated into beneficial use projects, two benefits are found. First, a material that was once an item to manage is now being used as a resource. Secondly, re-use of byproduct stream materials as raw materials can prove to be cost effective.

As has been previously stated in Chapter 2, VHMS are commonly seen as a material that must be managed as a burden (one exception is the port of New York/New Jersey where state agencies have mandated that these materials must be looked at as resources and re-use applications must be considered before disposal). As previously discussed re-use of VHMS as a raw material in construction applications where high volumes of low strength material are needed could prove to be sustainable, economically viable, and environmentally conscious while suiting the needs of society. Incorporation of byproduct streams, such as ashes from industrial activity, into construction applications could further benefit the environment and be economical without causing detriment to performance if all engineering and environmental aspects are handled properly. As shown in Chapter 7, LC-VHMS mixtures containing 20 to 40% industrial ash and Memphis soil performed better than mixtures containing no ash from an unconfined compressive strength perspective.

9.3.3 Ability to Integrate with Natural Landscape

Traditional alternatives such as concrete or masonry walls are valuable infrastructure elements that serve most applications very well. There are, however, some applications in and around ports and harbors that might benefit from alternative walls where relatively shallow depths are present and there is a desire for integration into the natural landscape. Better integration into the natural landscape improves harmony between the natural and built environments.

In cases where harmony with natural surroundings is desired, it is possible to construct walls out of LC-VHMS in such a way that vegetation can grow in the soils or to construct walls using biodegradable tubes. Some studies presented in Chapter 2 discuss cases where walls constructed using geotextile tubes were later vegetated (Marlin, 2013; Marlin and Darmody, 2005; Coulet et al., 2014). Other studies presented in Chapter 2 provided examples where tubes could potentially be produced using biodegradable materials, thus decreasing the amount of synthetic fibers remaining following construction (Saride et al., 2014; Lovelace, 2014). While tubes used in construction of walls discussed in this report are typically synthetic in nature, use of natural fibers in construction is a concept that could be worth considering for future research.

9.4 Economic Implications for Southeastern US Ports

A key objective of this chapter is to make an assessment of economic implications of utilizing LC-VHMS in construction. In the ports survey provided in Chapter 3, participants were asked "On a scale of 1 to 10, do you feel beneficial reuse of dredged soil might improve your facilities economic competitiveness?". Participants responded with an average score of 3.6 out of 10 and seven open ended comments were received. Of the seven comments provided, only three respondents seemed to believe that re-use of dredged material would be economically beneficial. A fourth respondent remained neutral in their response, but stated that the concept is worth further examination.

While the general assessment of survey respondents was that of uncertainty or doubt, other factors from Chapters 2 and 3 provided evidence that use of geotextile tubes for marine and shoreline applications can have positive economic advantages. Use of more conventional construction techniques making use of, for example, concrete, rip rap, soil from borrow pits, and so forth works and works well for most applications. Economically, however, use of materials near the project site that have to otherwise be stored in confined facilities, can lead to economic advantage if the properties of these materials can be improved and used instead of more traditional techniques. The remainder of this section presents a summary of information previously presented and discusses economic benefits of beneficial reuse of dredged materials.

A few projects that experienced meaningful cost savings through using geotextile tubes filled with dredged materials are summarized in Table 9.9 and the following paragraph. Some of the projects presented in Table 9.9 occurred outside the US, making direct economic comparisons invalid, though the trends are still useful. More specific details on re-use of dredged materials in the southeastern US are provided in later portions of this section.

Table 9.9. Project Cost Savings and Material Re-use

Reference	Location	Amount of Re-used Material	Cost Savings
Zhu and Beech (2015)	Mississippi	Dewatering – Likely No Re-use	$3 million
Embraport	Brazil	600,000 m^3	$50 million
Tencate (2013)[1]	Netherlands	Unknown	30%

[1]Some unpublished information for this project was also provided.

Circumstances surrounding the three projects summarized in Table 9.8 varied greatly. For the project in Mississippi, geotextile tubes were used in a dewatering application, and geotextile tube fill materials were likely not re-used. However, a cost savings of approximately $3 million was reported. For the project in Brazil, a port expansion costing $1.15 billion saved a reported $50 million through using geotextile tubes filled with dredged materials. The project in the Netherlands utilized an unreported amount of dredged material in a harbor and riverbank refurbishment project to produce an estimated cost savings of 30%. While the economic savings described in Table 9.8 do not apply to ports in the southeastern US, unit costs presented in the next few paragraphs can be used to describe the potential for cost savings for ports in the southeastern US.

Many unit costs in Chapter 2 and Chapter 3 were associated with re-use of dredged materials, disposal of dredged materials, and applications where conventional construction materials (which could potentially be replaced by LC-VHMS) were used. These unit costs are summarized in Table 9.9. Many of the unit costs presented in Table 9.10 were found in survey responses presented in Chapter 3 and are site specific. Thus, these unit costs are likely to have large variations depending on location.

Table 9.10. Unit Costs Related to Re-Use of Dredged Materials

Reference	Description	Unit Cost	
		($/m^3)	**($/yd^3)**
Grubb et al. (2010b)	Total Cost of Matl.Re-used for Structural Fill	13-16	17-21
Chapter 3 (AL-Mobile)	Upland Disposal (On-Site)	6	8
Chapter 3 (AL-Mobile)	Upland Disposal (Off-Site)	18	23
Chapter 3 (FL-Manatee)	Upland Disposal	9	12
Chapter 3 (FL-Manatee)	Imported New Containment Construction Matl.	4-12	5-15
Chapter 3 (TX-Houston Authority)	Maintenance Dredging	4-6	5-8
Chapter 3 (TX-Houston Authority)	Off-Site Disposal (In addition to Dredging)	Up to 7	Up to 9

As shown in Table 9.10, the total cost of beneficially re-using dredged materials for structural fill applications in Virginia was estimated to cost $13 to $16 per m^3 in 2010. This estimated cost was for a location not in the southeastern US, but is used for discussion purposes herein. In comparison to applications where off-site upland disposal is required, beneficial use applications costing $13 to $16 per m^3 could be more cost effective (e.g. Mobile, AL at $18/m^3), equally cost effective (e.g. Houston, TX at up to $13/m^3), or possibly less cost effective (though no unit costs presented in Chapter 3 provided such a case). However, when coupled with reduction in costs of imported raw materials (e.g. $4 to $12/m^3 for a Florida Project), it is possible that construction projects beneficially re-using dredged materials could save significant amounts when considering savings of disposal costs and reduced quantities of imported materials. Similarly to calculations presented in section 9.3.1, potential costs or savings associated with beneficially re-using dredged materials could vary greatly from one location to another. The intention of presenting these values was to show ports that there could be economic value in beneficially re-using dredged materials, and to provide some examples for ports that they can couple with their own dredged material data and future construction needs.

CHAPTER 10 – TECHNOLOGY TRANSFER

10.1 Overview of Technology Transfer

This project provided opportunities for technology transfer to a variety of individuals and groups. These opportunities covered a broad spectrum of experiences ranging from pre-college grades all the way to adults practicing in civil engineering and related fields. Activities are separated in the remainder of this chapter according to pre-college (i.e. K-12) grades, college students, and practitioners.

10.2 K-12 Technology Transfer

K-12 is a term sometimes used in the United States (and possibly elsewhere) to describe school grades prior to college that are publically-suppoerted. The method of K-12 transfer in this project was the Mississippi Summer Transportation Institute (MSTI) held in the summer of 2014. Another K-12 program (QUEST) was explored, but an opportunity for technology transfer did not materialize relative to the scope of this project.

MSTI is a summer camp lasting approximately two weeks that is sponsored by the Mississippi Department of Transportation (MDOT), mostly for rising high school sophomores and juniors (other grades participate occasionally). The portion of MSTI related to this project occurred on parts of two days and included a classroom presentation (Figure 10.1) and hands on activities with soil, cement, and geotextile tubes (Figure 10.2). Twelve campers (three groups of four) participated in the activities shown in Figures 10.1 and 10.2. The main purpose of these activities was to give campers a general understanding of: beneficual reuse, the importance of sustainability, and how to work with geotextile tubes, cement, and very high moisture content soils in a hands on exercise.

The morning's activities began with the presentation represented by Figure 10.1 where campers were taught about beneficial reuse and told their hands on activities would consist of mixing soil, water, and cement with the intention of making three 7.6 cm diameter by 15.2 cm tall unconfined compression test specimen and to filling one geotextile pillow per group. Each of the three groups were given a data sheet to encourage campers to properly document their work. On each data sheet was a few sentences about VHMS. Each group was initially provided moist clay of high plasticity, portland-limestone cement, a geotextile pillow, and water. At convient times, cement paste cylinders that had been made previously were tested in unconfined compression (the cement paste cementitious blends contained sustainable materials) as a demonstration for the campers.

Students had difficulty mixing the materials, which led to adjustments to the original plan to allow all points to be made but stay within time allotments. Hand drills were used alongside coarse sand to facilitate mixing, and only one geotextile pillow ended up being fully filled while all campers watched. This tube was examined afew days later. Also, the highly plastic clay did not drain enough water for campers to catch as originally envisioned. Overall, the exercises provided exposure to the key points of interest for campers and gave them exposure to handling and mixing materials. When testing their mixed unconfined compression cylinders a few days after preparation, campers used manual proving rings and calculated applied stresses manually. Compressive strengths between groups varied by up to a factor of 3, which was used to emphasize the importance of quality control and consistency.

Figure 10.1. Summary of Twelve Slide MSTI Presentation Titled: GeoMaterials (Emphasis on Beneficial Reuse and Sustainability)

Figure 10.2. Summary of MSTI Presentation Titled: GeoMaterials (Emphasis on Beneficial Reuse and Sustainability)

10.3 College Student Technology Transfer

MSU-CEE students were engaged in benefical reuse or other relevant port activities by way of financial support, coursework, and/or research activities. The three student authors and the five students listed in the acknowledgements were able to further their education due to the experiences and/or financial support provided by this project. As such, technology was transferred to these students through their engagement in this project.

Three graduate courses incorporated content relevant to this project during the time frame of this project. CE 7000-Directed Individual Study was offered once in the spring of 2014 and once in the summer of 2014, both related to the Panama Canal in some way. CE 8303: Material Characterization included a project in the spring of 2015 where students could pick to do out of class work on one of four topics. One of the topics was titled: use of hydraulic cements for beneficial reuse and/or management of contaminated sediments. The class project was worth 30% of the class grade, and three students elected to do their project on the aforementioned topic. CE 8443: Soil Behavior included a project in the spring of 2015 where students could pick to do out of class work on one of three topics. One of the topics was titled: engineering properties of stabilized contaminated sediments and dredged soils for beneficial reuse and/or management. The class project was worth 15% of the class grade, and three students elected to do their project on the aforementioned topic.

10.4 Practitioner Technology Transfer

Practitioner technology transfer occurred in two manners during the course of this project. Both of the activities that have occurred were in association with the American Society of Civil Engineers (ASCE). These activities are described in the following paragraphs. At some point in the future, it is anticipated the work performed in this project will be submitted for peer review to a journal, and there may be other future technology transfer activities related to practitioners.

The first completed practitioner technology transfer activity occurred in September of 2014 as part of the Mississippi (MS) state section meeting of ASCE in Vicksburg, MS. A 32 slide presentation was given titled “Beneficial Reuse of Very High Moisture Soils by way of Geotextile Tubes and Low Cementitious Dosage Rates”. The presentation discussed motivations for beneficial reuse of VHMS, material properties of potential applicability, and applications of potential interest. Industrial partners TenCate™ and Holcim (US), Inc. assisted with the presentation assembly and had representatives in attendance at the event.

The second practitioner technology transfer activity occurred in March of 2015 at the annual meeting of the ASCE Geo-Institute, which was named the International Foundations Congress and Equipment Expo (IFCEE). A thirteen slide presentation was given titled “Beneficial Reuse of Fine Grained Soils for Port, River, and Shoreline Applications”. This presentation covered all content in Chapter 5 of this report, and Bazne et al. (2015) is the resulting publication.

CHAPTER 11 – SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

11.1 Summary

The primary objective of this report was to study use of geotextile tubes filled with cementitiously stabilized very high moisture content fine grained dredged soils for beneficial reuse. The purpose of doing so would be to sustainably enhance intermodal freight operation of ports. This objective was met as the study uncovered several interesting applications that made use of geotextile tubes, potential economic advantages were seen in other projects reviewed, and a detailed set of engineering properties were provided to allow more informed decisions regarding when to consider lightly cemented very high moisture soils (LC-VHMS) and/or geotextile tubes.

At the beginning of this effort, the largest potential benefit was envisioned to be assisting ports in transitioning their operations to the larger ships and freight quantities from the Panama Canal expansion. This did not end up being as much of a focus as originally envisioned, largely due to the ports survey conducted, though it was still part of the work. A theme that has recently gained momentum, especially during the time frame of this project, is Engineering With Nature (EWN), which ended up being a large factor in the direction taken within this effort. Use of, for example, dredged material to create land adjacent to a port (i.e. the built environment) that can blend into the natural environment through vegetation establishment would be an example of EWN.

A relatively unique component of this study was incorporation of portland-limestone cement (PLC), which is fairly new to the southeastern US construction market and has not been studied within lightly cemented soil systems in a comprehensive manner to the knowledge of the authors. In that several applications could utilize materials with only modest unconfined compressive strength, dredged soil stabilized with LC-VHMS containing PLC (ASTM C595 or C1157) is a very sustainable option since PLC has less embodied energy than the commonly used ordinary portland cement (OPC) specified by ASTM C150. Tendencies of US construction projects to be fast paced has likely been one of the considerable factors that has led to cement contents used to stabilize fine grained soils to be above those considered in this work. Characterization of LC-VHMS is not well established as most past efforts have focused on C-VHMS (i.e. higher cementitious dosage rates).

11.2 Conclusions

The overall conclusion of this report is that LC-VHMS should be considered as geotextile tube fill for some applications and LC-VHMS could have some value absent geotextile tubes in other applications in and around ports and harbors. EWN applications could make use of lightly cemented materials as they have the potential to improve properties to levels suitable for low strength applications. LC-VHMS is most suitable for projects where relatively long time periods are available before useable properties are needed. Specific conclusions are provided in the following list.

- Testing a soil with a liquid limit of 55 at 100% moisture (i.e. at 1.8 times the soil's liquid limit) and a portland cement dosage of 2.5% of slurry mass produced an unconfined compressive strength of around 100 kPa at later ages (97 to 115 kPa at 56 to 180 days of curing), which is useable for lower strength applications.

- LC-VHMS was not effectively produced with slag cement replacement of portland cement.
- LC-VHMS can produced unconfined compression strengths of 150 kPa or more after 7 days of room temperature curing, and 200 kPa or more after 90 days of room temperature curing when the moisture content is up to 1.4 times the soil's liquid limit.
- Portland-limestone cement (PLC) is promising as a sustainable stabilization agent for fine grained dredged soil, in particular for the potential to enhance pozzolanic (or late age) strength gain.
- Multiple on site materials can be combined, such as dredged soil and ash, to produce LC-VHMS with useable strength properties that is flowable enough to be pumped. After curing for 28 to 56 days, unconfined compressive strengths of around 60 to 120 kPa were produced with Memphis soil with 5% cement by slurry mass for a range of bottom ash contents.
- Full vegetation was established with portland-limestone cement (PLC) incorporated at 5% of dry soil mass in some experiments.
- Some level of vegetation establishment occurred with LC-VHMS inside small scale geotextile tubes, but the tube noticeably inhibited growth in several instances. Fescue grass was reasonably established in conjunction with GT 500 fabric.
- There are applications of potential interest to southeastern US ports where geotextile tubes could be filled with marginal materials, but geotextile tubes filled with marginal materials do not seem to be employed as mush in the US as in other countries.
- Stacked geotextile tube walls filled with LC-VHMS can be competitive from a sustainability perspective with respect to more conventional techniques.
- There are notable potential economic advantages for use of LC-VHMS as geotextile tube full, or as a standalone low strength construction material.

11.3 Recommendations

The overall recommendation from this project is for decision makers at ports and harbors to consider geotextile tubes and/or LC-VHMS for applications at their facilities. It is expected that some ports would not find any applications, but it is also expected that some ports are likely to find value from the techniques described in this report in some way. Specific recommendations are provided in the following list.

- Perform a relatively small full scale demonstration at a port that includes filling a geotextile tube or tubes with LC-VHMS by way of positive displacement pumps. If a larger experiment is desired, multiple types of tubes should be filled including conventional woven geotextiles, marine composite fabrics, and biodegradable materials. The test plan could include use sampling and probing vehicles (e.g. Geoprobe equipment) to obtain undisturbed specimens throughout the depth of the tubes, as well as to measure in situ penetration resistance and moisture content gradients. These properties could then be compared to specimens produced on site that are cured, consolidated, and tested in a variety of different manners. The tubes should be monitored over time after being filled. This type of a demonstration should provide design and full scale construction and performance guidance that compliments the data collected for this project very well.

- Producing LC-VHMS via in situ grouting of soil once inside geotextile tubes might also be worth exploring (as opposed to mixing cement and soil prior to introduction into the geotextile tube). Conventional systems inject grout into the soil system, they do not have mixing capabilities at the point of injection. Improved understanding of grout injection into fine grained soil after dewatering could be useful to help determine if adequate pressure can be applied to distribute the grout, but not rupture the tube.
- While not directly considered in this study, the work performed could improve a variety of river operations including restoration (Holm et al. 2012), long-term sustainability of coastal ecosystems and communities (Landers 2013), and managing contaminated dredged river sediments (Landers 2011 and 2012). It is recommended to consider expanding the scope of potential applications for the activities studied in this report to rivers.
- While not directly considered in this study, mixing LC-VHMS, stockpiling, and reusing at a later date as a compacted material off site has potential and should be studied. It is anticipated that LC-VHMS will behave quite differently depending on consolidation, compaction, and drying potential.
- Portland-limestone cement (PLC) should be studied further for its ability to sustainably stabilize dredged soils.
- Additional technology transfer opportunities should be made available for the content in this report to reach a wider audience about the potential advantages geotextile tubes and/or LC-VHMS could bring to beneficial use of dredged material and other marginal materials.

CHAPTER 12 – REFERENCES

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