Lightly cementing marginal materials to improve sustainability and economic competitiveness near ports and harbors

By

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competitiveness near ports and harbors

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Large amounts of dredged sediment are removed from ports and river channels annually to maintain necessary depths in the maritime industry. The most common management approach for dredged soils throughout the southeast US is disposal in confined facilities. This may be the most feasible approach for ports with modest amounts of dredged soil and ample capacity for disposal. However, there is likely a more feasible option for some ports desiring to increase dredged soil containment capacity.

This thesis evaluates the beneficial reuse of dredged soils after lightly cementing with 5.0% or less cement by slurry mass. A previously conducted survey was interpreted prior to performing a literature review, testing, and performing sustainability calculations for reuse of dredged soil when lightly cemented. There were 239 experiments performed as part of this thesis to evaluate the feasibility of utilizing dredged soils after lightly cementing for beneficial reuse projects near ports.
DEDICATION

This thesis is dedicated to my family for their continued support as I have worked on this degree. Thank you to my parents who inspired me to succeed and to my wife, Paige, who has joined in pushing me to keep going. I owe you all a great deal for your encouragement and support through this process.
ACKNOWLEDGEMENTS

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Thanks are also due to many MSU students who assisted in specimen fabrication, testing, and slope stability calculations. Alyssa Barksdale, Patrick Kuykendall, Drew Moore, Matt Roddy, Shariar Shahrokhabadi, and Mohammed Bazne each assisted this thesis in some way.
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<th>Description</th>
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<tbody>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>B</td>
<td>Base Width of a Geotextile Tube</td>
</tr>
<tr>
<td>BCD</td>
<td>Burns Cooley Dennis</td>
</tr>
<tr>
<td>C</td>
<td>Cemented</td>
</tr>
<tr>
<td>C_{fp}</td>
<td>Carbon Footprint</td>
</tr>
<tr>
<td>CLSM</td>
<td>Controlled Low Strength Material</td>
</tr>
<tr>
<td>CO_{2e}</td>
<td>Carbon Dioxide Equivalents</td>
</tr>
<tr>
<td>C-VHMS</td>
<td>Cemented Very High Moisture Soil</td>
</tr>
<tr>
<td>f_{t}</td>
<td>Flow as Determined in ASTM D 6103</td>
</tr>
<tr>
<td>f_{pre-cement}</td>
<td>Flow Prior to Mixing with Cement</td>
</tr>
<tr>
<td>f_{post-cement}</td>
<td>Flow Immediately after Mixing with Cement</td>
</tr>
<tr>
<td>f_{30min}</td>
<td>Flow 30 minutes after mixing with Cement</td>
</tr>
<tr>
<td>h</td>
<td>Achievable Height of a Geotextile Tube</td>
</tr>
<tr>
<td>ha</td>
<td>Hectare</td>
</tr>
<tr>
<td>HDPE</td>
<td>High Density Poly Ethylene</td>
</tr>
<tr>
<td>h_{eff}</td>
<td>Effective Height of Geotextile Tubes</td>
</tr>
<tr>
<td>LC</td>
<td>Lightly Cemented</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>---------------------------------------------------</td>
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<tr>
<td>LC-VHMS</td>
<td>Lightly Cemented Very High Moisture Soil</td>
</tr>
<tr>
<td>LL</td>
<td>Liquid Limit</td>
</tr>
<tr>
<td>LNG</td>
<td>Liquid Natural Gas</td>
</tr>
<tr>
<td>MSU</td>
<td>Mississippi State University</td>
</tr>
<tr>
<td>NCFRP</td>
<td>National Cooperative Freight Research Program</td>
</tr>
<tr>
<td>NCITEC</td>
<td>National Center for Intermodal Trans. for Economic Competitiveness</td>
</tr>
<tr>
<td>NRMCA</td>
<td>National Ready Mixed Concrete Association</td>
</tr>
<tr>
<td>OPC</td>
<td>Ordinary Portland Cement</td>
</tr>
<tr>
<td>PFM</td>
<td>Pneumatic Flow Mixing</td>
</tr>
<tr>
<td>PI</td>
<td>Plasticity Index</td>
</tr>
<tr>
<td>PL</td>
<td>Plastic Limit</td>
</tr>
<tr>
<td>PLC</td>
<td>Portland Limestone Cement</td>
</tr>
<tr>
<td>ppm</td>
<td>Parts Per Million</td>
</tr>
<tr>
<td>PRISMA</td>
<td>Promoting Integrated Sediment Management</td>
</tr>
<tr>
<td>$q_u$</td>
<td>Unconfined Compressive Strength</td>
</tr>
<tr>
<td>$q_{u-i}$</td>
<td>Unconfined Compressive Strength of Immediately Molded Specimens</td>
</tr>
<tr>
<td>$q_{u-30min}$</td>
<td>Unconfined Compressive Strength of Specimens Held Before Molding</td>
</tr>
<tr>
<td>RSDM</td>
<td>Remolded Solidified Dredged Material</td>
</tr>
<tr>
<td>SDM</td>
<td>Solidified Dredged Material</td>
</tr>
<tr>
<td>SERRI</td>
<td>Southeast Region Research Initiative</td>
</tr>
<tr>
<td>SGM</td>
<td>Super Geo-Material</td>
</tr>
<tr>
<td>S/S</td>
<td>Stabilization and Solidification</td>
</tr>
<tr>
<td>SSF</td>
<td>Steel Slag Fines</td>
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x
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$s_u$</td>
<td>Shear Strength</td>
</tr>
<tr>
<td>t</td>
<td>cure time</td>
</tr>
<tr>
<td>TEU</td>
<td>Twenty Foot Equivalent Unit</td>
</tr>
<tr>
<td>tonne</td>
<td>Metric Ton</td>
</tr>
<tr>
<td>tCO$_2$</td>
<td>Metric Ton of Carbon Dioxide</td>
</tr>
<tr>
<td>TRB</td>
<td>Transportation Research Board</td>
</tr>
<tr>
<td>UC</td>
<td>Unconfined Compression</td>
</tr>
<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>USACE</td>
<td>US Army Corps of Engineers</td>
</tr>
<tr>
<td>VHMS</td>
<td>Very High Moisture Soil</td>
</tr>
<tr>
<td>W</td>
<td>Total Width of a Geotextile Tube</td>
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CHAPTER I
INTRODUCTION

1.1 Introduction

Efficient operation of ports is critical to successful outcomes of any intermodal freight system. In some cases, ports define the true nature of intermodal activities as they are the transfer point that connects ships or barges to rail lines or trucks. As stated by one department of transportation director discussing the Fix America’s Surface Transportation (FAST) Act, “Freight moves from one mode to another… Ultimately, the more we improve the connectivity of the overall system, improve the performance of each individual mode, {the more likely it is that} we’re removing bottlenecks and points of constraint for businesses that are moving products.” (Landers, 2016).

Efficient port operation is imperative to maintain freight movement and subsequent economic competitiveness. However, maintaining efficient port and river operations is challenging. A key challenge associated with maintaining port and river operations is dredging. Maintaining and improving operation of ports along the Gulf Coast and along the Mississippi River up to Memphis, TN requires almost continuous dredging, which produces large volumes of dredged materials. For example, the port of Mobile, Alabama requires 4.59 million m³ of dredged material to be removed annually for maintenance (Lovelace, 2014).
Dredged material properties vary greatly and can 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 the key item of emphasis in this thesis.

Two approaches that are potentially useful for utilization of very high moisture content fine grained soils are stabilization in conjunction with geotextile tubes and stabilization/solidification (S/S) via cement. Geotextile tubes are versatile products that have found their way into many applications including sediment containment, shoreline protection, and breakwaters. While pairing the aforementioned concepts for soil stabilization and beneficial reuse is promising, the primary focus of this thesis is to evaluate the use of marginal materials (such as dredged sediments) for beneficial reuse in and around ports using lower than traditional cement dosages.

A few terms are important with regard to this thesis and are used multiple times. The first is VHMS, which is an abbreviation for Very High Moisture Soils. VHMS, as defined in this thesis and in several other documents from the Construction Materials Research Center (CMRC), is a 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 slurry 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 at present is largely associated with research performed at Mississippi State University (MSU), is lightly cemented (LC). LC is a term meaning a soil has been dosed with 5% or less cementitious material by slurry mass. For example, LC-VHMS would be appropriate to
describe a soil with a 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 and Scope

This thesis coincides in some areas with a larger study conducted for the US Department of Transportation through the National Center for Intermodal Transportation for Economic Competitiveness (NCITEC) on the beneficial reuse of fine grained soil for river and port applications. The sponsor report, which the author of this thesis contributed to, is publically available in Vahedifard et al. (2015). The primary objective of this thesis is to evaluate the feasibility of using lightly cemented soil (e.g. dredged sediments) in LC-VHMS applications in and around ports (e.g. as fill for geotextile tubes in wall construction). The following tasks were performed to fulfill the previously described objective.

- Conduct a literature review.
- Analyze results of a survey in Chapter 3 of (Vahedifard et al., 2015).
- Evaluate LC-VHMS mixtures produced using dredged material sampled from a site adjacent to the Port of Memphis, Tennessee based on:
  - Flow ($f_i$) According to ASTM D 6103
  - Atterberg Limits According to ASTM D 4318
  - Unconfined Compressive Strength ($q_u$)
- Compare the carbon footprint of traditional construction materials and potential applications where geotextile tubes filled with LC-VHMS may be used.

- Use slope stability calculations from Vahedifard et al. (2015) to discuss the feasibility of utilizing LC-VHMS in construction applications.

Chapter 2 provides a practice review by summarizing survey responses from a ports survey conducted in Vahedifard et al. (2015) and a literature review where key points of discussion are applications for beneficial reuse of dredged materials and feasibility of utilizing LC-VHMS in construction. The experimental program, including material descriptions, specimen fabrication, test methods, and test matrices are provided in Chapter 3. Chapter 4 contains results and discussion of laboratory tests including flow, unconfined compression (UC), and Atterberg limits. Chapter 5 provides discussion of sustainability and overall usefulness for implementing LC-VHMS. Conclusions and recommendations pertaining to LC-VHMS in and around ports are provided in Chapter 6.
CHAPTER II
LITERATURE AND PRACTICE REVIEW

2.1 Overview

This chapter is divided into two primary categories: practice review and literature review. The practice review was conducted and documented in Vahedifard et al. (2015), and the literature review is primarily divided into dredged material reuse approaches, factors related to feasibility of using LC-VHMS, and engineering properties of C-VHMS. The practice review is presented in section 2.2 while literature review is presented in sections 2.3 through 2.5.

2.2 Practice Review

The 10 question survey in Vahedifard et al. (2015) was conducted between July and October of 2014 and it was explained to participants that research was being conducted to explore possibilities of utilizing lightly cemented stabilized dredged material as geotextile tube fill for applications in and around ports. Survey participants were told that geotextile tube use and cement stabilization were mature approaches in geotechnical applications, but that the two technologies were not commonly used together. The survey further explained that the utilization of LC-VHMS as geotextile tube fill was even less common. A total of 38 ports were identified as ports of interest to the study, and 12 ports ultimately responded to the survey. The ports which provided responses to the survey are described in Table 2.1.
Questions from the survey which were identified as relevant to this thesis are provided in the following six sections with questions provided in italics and summaries of responses following each question. Some questions from the original survey are omitted from this section, but the questions provided herein were used to form an understanding of dredged material practices in the southeast US from the viewpoint of port and harbor decision makers.

1.1.1 Question 3

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

Responses to question 3 describe variations of dredged material practices from one port to another throughout the southeast US. Of the twelve written responses to
question 3, all ports described at least some amount of disposal for dredged materials. However, four ports (33%) identified efforts for beneficial reuse of dredged material with specific approaches provided for beach replenishment and aquatic habitat preservation projects. One of the four ports making efforts to beneficially reuse dredged material no longer allows private terminals to place dredged material into their disposal areas without removing “… an amount equal to two times the volume placed into our site…”

With 67% of ports responding to question 3 making no mention of dredged material reuse, it seems that there are many circumstances where ports believe that dredged material disposal is currently the most feasible approach. However, there are a some ports that have found viable methods for beneficially reusing dredged materials.

2.2.2 Question 4

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

In responses to question 4, eight survey participants (67%) stated that beneficial re-use applications have been considered in the past while four participants (33%) stated that beneficial re-use strategies have not been considered. Of the eight participants that have evaluated reuse applications, reuse approaches varied considerably. Some re-use approaches of dredged material considered were: beach replenishment, marsh habitat replenishment/creation, low quality fill in abandoned borrow pits, and as a component in asphalt mixtures. However, there were two ports which made mention to reuse approaches considered to not being cost effective.
While 33% of respondents seem to be seeking alternative uses for dredged materials, 67% of ports responding to question 4 have evaluated reuse of dredged materials. This lends to the notion that ports are seeking feasible methods for utilizing dredged materials, but have not been successful in identifying such an application.

2.2.3 Question 6

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

Ten respondents provided numerical responses to question 6 which resulted in an average score of 3.6 out of 10 for general impression of benefits to economic competitiveness. Seven comments were also provided, and one comment showed great interest in re-use of dredged materials stating that “… would eliminate the enormous costs associated with excavation and offsite transport of material placed in our upland dredged material management sites.” Some comments seeming neutral on the issue ranged from “Circumstance dependent.” to “Need to learn more about the benefits and risks, but it does appear to be something worth further examination.” However, there were responses which showed doubt in the ability to economically re-use dredged material including “PHA periodically considers various options for other uses, but none have proven to be viable economically.” and “Don’t believe it would improve our economic competitiveness.”

The impression from port decision makers towards the economic benefit of being able to beneficially use dredged materials in construction seems highly variable. There were two ports (Mobile, AL and Miami, FL) which responded with 10 out of 10 for
economic competitiveness being economically beneficial. Both of the previously mentioned ports showed a specific factor influencing interest in economic competitiveness. The port of Miami was in the process of reusing 459,000 m$^3$ and the port of Mobile was seeking additional upland disposal capacity at the time of the survey. However, the average response indicates that many ports would not be able to economically benefit from beneficial reuse of dredged sediment.

2.2.4 Question 7

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

Of the twelve responses to question 7, there were two ports which provided examples of potential applications for dredged material reuse in and around their ports. Five of the responses (42%) indicated that ports could see potential applications for reusing dredged materials at their facility. Three responses (25%) indicated uncertainty of there being reasonable applications for reuse of dredged materials at their facility, and four (33%) of the responses indicated that ports didn’t feel that there were any applications at their facilities that would benefit from beneficial reuse of dredged materials. Reasons for hesitancy to consider dredged materials were limited land access to store dredged materials on-site prior to reuse and concerns of durability in high energy environments containing riprapped levees and bulk headed shorelines.
2.2.5 Question 8

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

From twelve responses to question 8, there were five (42%) responses which indicated that ports would potentially consider using geotextile tubes if proven durable and cost effective. One (8%) port indicated that geotextile tubes have already been successfully used in practice. Three (25%) ports indicated that consideration of geotextile tubes or LC-VHMS was unlikely, and two (17%) ports stated that use of geotextile tubes and LC-VHMS have not or would not be considered. Finally, one (8%) port indicated that beneficial use of dredged materials in geotextile tubes had been attempted with poor results.

2.2.6 Question 9

*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.*

Many unit costs were provided in response to question 9 which are 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 2.2.
Table 2.2  Unit Costs of Dredging Operations

<table>
<thead>
<tr>
<th>Port Location</th>
<th>Cost Description</th>
<th>Unit Cost</th>
<th>($/m³)</th>
<th>($/yd³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile, AL</td>
<td>Upland Disposal (On-Site)</td>
<td></td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Mobile, AL</td>
<td>Upland Disposal (Off-Site)</td>
<td></td>
<td>18</td>
<td>23</td>
</tr>
<tr>
<td>Manatee, FL</td>
<td>Upland Disposal</td>
<td></td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Manatee, FL</td>
<td>Imported New Containment Construction Matl.</td>
<td></td>
<td>4-12</td>
<td>5-15</td>
</tr>
<tr>
<td>Houston, TX</td>
<td>Maintenance Dredging</td>
<td></td>
<td>4-6</td>
<td>5-8</td>
</tr>
<tr>
<td>Houston, TX</td>
<td>Off-Site Disposal (In addition to Dredging)</td>
<td></td>
<td>Up to 7</td>
<td>Up to 9</td>
</tr>
</tbody>
</table>

Based on responses to the survey in Vahedifard et al. (2015), practices for dredged material management seem to vary widely for ports throughout the southeast US. A common theme throughout port responses is to dispose of dredged sediments in confined disposal facilities when allowable. However, some responses to the survey (e.g. Mobile, Alabama and Manatee, Florida) indicate that costs for disposal of dredged materials can become substantial once convenient disposal locations reach capacity.

2.3  Potential Approaches for Beneficial Reuse of Dredged Materials

In attempts to mitigate dredged material disposal costs, some have utilized dredged materials for beneficial reuse in construction applications. Many cases which evaluate approaches to beneficially reuse dredged material are provided in literature. These approaches range from utilization of raw dredged materials within geotextile tubes to utilization of un-encased stabilized dredged materials for embankment construction. Section 2.3.1 section provides a literature review of approaches for beneficial reuse of
dredged materials when encased (e.g. in geotextile tubes), and approaches where dredged materials are beneficially reused without the use of a container are presented in section 2.3.2.

2.3.1 Reuse of Encased Dredged Materials

Geotextile tubes have been used for many applications such as erosion protection for shorelines, flood control, environmental applications, dike construction, underwater berms, and island creation. Any of these applications for geotextile tubes may be performed without beneficially reusing dredged materials. However, some cases in literature make use of geotextile tubes filled with dredged materials to accomplish some of the aforementioned applications, and this section describes many of these projects.

2.3.1.1 Drakes Creek Dike

A dike was constructed in a permanent application for Drakes Creek in Tennessee. The project was presented during the 2008 Geotextile Tubes Workshop documented in Howard et al. (2009). Approximately 640 m of geotextile tube with a 13.7 m circumference were filled with dredged material containing organics, silty sand, and stone for the US Army Corps of Engineers (USACE). Note the dredged materials used were not stabilized. When the dike was constructed in 2000, a total of 16,800 m$^3$ was dredged, and the dike was still in service eight years later.

2.3.1.2 Lower Peoria Lake Island Creation

A project documented in (Howard et al. 2012; Karnati et al. 2012) utilized geotextile tubes filled with native unstabilized fine grained sediment. Three rows of geotextile tubes were placed adjacent to one another to form a perimeter of an island
created at lower Peoria Lake. A patented environmental clamshell bucket was used during high solids dredging, sediments were passed over a vibrating screen, and sediment having liquid limit (LL) ranging from 56 to 72 was pumped into the geotextile tubes at approximately 70% moisture using a positive displacement pump. There were around 38,000 m$^3$ of fine grained dredged materials pumped into the geotextile tubes during the project, and large stone was placed to protect against erosion in some areas. A secondary construction phase was intended to involve addition of a geotextile tube above the lower layer of three geotextile tubes while using dredged material to fill the center of the island to a maximum elevation of about 1 m above the fourth geotextile tube (Karnati et al., 2012).

2.3.1.3 Embraport Container Terminal

Embraport is a large container terminal that was recently constructed in Brazil, and has been a well-documented project (e.g. TenCate$^{TM}$ 2013; TenCate$^{TM}$ 2014; Stephens and Melo 2014). The following four paragraphs summarize portions of this project obtained from multiple sources. The total project, which was constructed at the Port of Santos in Brazil, cost an estimated $1.15 billion.

Construction of the new container terminal required dredging 600,000 m$^3$ of contaminated sediments to accommodate larger container ships, and upland disposal was originally included in the project’s construction agreement. The terminal construction required 1.5 million m$^3$ of fill, but beneficial re-use of the 600,000 m$^3$ of contaminated sediments in geotextile tubes allowed for a 400,000 m$^3$ reduction of needed imported fill. The geotextile tubes used during construction were 65 m long and had a 36.5 m circumference. The beneficial re-use of these contaminated sediments prevented the
necessity to purchase more land or decrease the terminal footprint, and both of the aforementioned options were reported to threaten the project’s economic competitiveness.

The re-use approach involved dewatering sediments under the planned container platform, leaving the dewatered geotextile tubes as fill, placing fill over the tubes, and ultimately building a pavement structure over the tubes. Three challenging factors considered during design which are most relevant to this thesis were: 1.) is it possible for geotextile tubes to securely encase and dewater dredged sediments; 2.) can effluent water from dewatered sediments be processed and returned to the natural surroundings; 3.) can a stable platform capable of storing stacked ocean containers and heavy port traffic loads be developed.

During construction, 4.5 m tall containment dykes were constructed around the project’s perimeter, while 2.5 m tall internal berms were installed to produce several dewatering cells. Dredging was preformed hydraulically at 1,400 m$^3$/hr, mixed with an organic polymer, and pumped into geotextile tubes in multiple cycles to maximize the amount of material in each tube. The geotextile tubes captured 99.9% of all suspended solids during dewatering, and dewatered tubes were ultimately 1.8 m tall containing about 2,145 m$^3$ of material. Thus, the total dewatered tube fill volume was about 446,160 m$^3$.

Dewatering was performed until mixtures reached 55% solids or more. Then 8 tonne/m$^2$ of fill was placed over the geotextile tubes to induce consolidation. Once consolidation was complete, excess fill was removed with a minimum thickness for fill of 20 cm remaining above the filled, dewatered, and consolidated tubes. Finally, a pavement
surface containing two layers of geotextile reinforcement to control differential settlement, 70 cm of well graded gravel, and concrete pavers for a surface was placed. Other projects in TenCate™ (2013) with relevance to this thesis are discussed in section 2.3.1.4 to section 2.3.1.7.

2.3.1.4 Tianjin Eco-City Lake Remediation

A total of 2.4 million m³ of contaminated sediments were dredged from a lake, dewatered, and used to form a landscaped mound at Tianjin Eco-City in China. During the project, a wastewater impoundment was restored to form a wetland and recreational lake. The landscaped mound was approximately 9 m tall with an area of approximately 12 ha. Geotextile tubes were filled with dredging materials and were allowed to dewater before being filled again, which is a fairly common approach for filling geotextile tubes. This process was repeated a total of 6 or 7 cycles per tube. After the target height was achieved for each layer, additional tubes were placed on top of lower layers until tubes were stacked four layers high. HDPE geomembranes were used to surround the top and bottom of the geotextile tubes, and the mound was capped with 1.5 m of enriched topsoil following construction.

2.3.1.5 Svartsjon Lakes Remediation

Activity in the mid 1900s led to a fair amount of mercury contamination of the two Svartsjon lakes in Sweden. A remediation project involved the removal of 300,000 m³ of contaminated sediments to decrease the mercury contamination level, which was estimated to be between 0.5 and 4 ppm (parts per million). The project involved dewatering sediments using geotextile tubes that were left in place, which prevented the
need to remove de-watered sediments in an area with narrow roads. The geotextile tubes, which were contained in a landfill-based barrier system, had a circumference of 16 m and were 50 m long. After dewatering and consolidation, the total volume of sediments remaining was approximately one third of the insitu sediment volume.

2.3.1.6 Grubers Grove Bay

A total of 42 Geotube® dewatering containers were used to dewater sediments dredged from Grubers Grove Bay in Wisconsin, which contained excessive nutrients, mercury, copper, and lead. During dredging operations, sediment slurry was pumped into Geotube® units with solids concentrations between 7 and 10%. Dredging and dewatering operations were carried out over a six month period, resulting in solids concentrations ranging from 30 to 40% over a 40,000 m² area. After dewatering, geotextiles tubes were capped with a 0.9 m thick soil layer that was later vegetated.

2.3.1.7 Canal do Fundao

The Canal do Fundao, which was constructed in the early 1950’s, experienced a level of sediment buildup preventing the canal from properly discharging sewage, domestic waste, and industrial waste. During a canal revitalization project, 2 million m³ of sediments were dredged from the canal. Most of the dredged sediments removed (i.e. 1.4 million m³) were considered uncontaminated and were disposed of offshore, but the remaining 600,000 m³ of contaminated sediment was dewatered with GT 500 geotextile tubes at Fundao Island. Geotextile tubes were filled and dewatered until a final dewatered height of 2.1 m was achieved, and tubes were stacked three layers tall during the project. The effluent water quality was determined to be adequate for discharge in the canal. After
dewatering, topsoil was placed over the tubes and vegetated to integrate with the surrounding landscape at Fundao Island.

2.3.2 Non-Encased Reuse of Dredged Materials

Several cases are provided in literature where dredged materials were utilized for beneficial use absent geotextile tubes. Some projects where dredged materials were used without geotextile tubes are discussed in the following six sections.

2.3.2.1 Lightweight Backfill from Tokyo Bay

Tsuchida et al. (2001) presented a study where dredged materials from Tokyo bay were stabilized with portland cement and lightweight materials (i.e. air foam or expandable polystyrol beads). The authors noted increased demands on quality construction materials in coastal areas and the high availability of materials dredged from ports and channels. The two primary objectives of the study were to produce a quality soil for construction while reducing the disposal of dredged materials. While producing lightweight backfill, mud was successfully collected from the seabed with a floating barge and bucket dredge, mixed with cementitious materials, and pumped into place. The materials tested therein were pumped into 1.8 m cubical molds for evaluation. The lightweight materials tested therein had mean unconfined compressive strengths ranging from 559 to 1,601 kPa after 28 days of curing and cement contents on the order of 10 to 20%.

2.3.2.2 Super Geo-Material

C-VHMS has been used as a backfill material outside the US, known in those works as Super Geo-Material (SGM) which is prepared using the pneumatic flow mixing
(PFM) method (Tanaka et al. 2009; Oota et al. 2009; Nakai et al. 2009). The PFM consists of combining dredged soils and binders (e.g. portland cement) in a pipeline and allowing turbulent flow produced by inducing compressed air pockets to adequately mix the materials. The three aforementioned references document projects where 6.8 \times 10^4 to 8.6 \times 10^6 \text{ m}^3 of SGM or PFM was placed in thickness ranging from 2.5 to 13.8 m for tunnel backfill and land reclamation. These projects range from tunnel backfill at Tokyo International Airport to backfill material in the Osaka Bay area.

Engineering properties of SGM mixtures produced for projects described in the previous paragraph varied with raw sediment properties and material application. Raw soils had liquid limits between 58 and 91%. Water contents during stabilization ranged from 85 to 250%, and cement contents ranged from 3.3 to 14.8% by slurry mass with the majority of mixtures containing at least 8.7% cement. Unconfined compression strengths for 28 day laboratory mix designs ranged from 157 to 294 kPa. While the cement contents were higher in the previously described SGM mixtures than for the mixtures evaluated in this thesis, the concept of producing modest strengths for large volume fill materials is of interest for the materials evaluated.

2.3.2.3 Belgium Dike Construction

The construction process of an 800 m long dike with a volume of 100,000 \text{ m}^3 is described in Zele et al. (2014). The project was completed to protect the Flemish part of the Scheldt estuary in Flanders, Belgium. Construction factors of the aforementioned reference are discussed in the following paragraph, and applications of stabilized dredged material are described in this paragraph. The dike was constructed with a minimum threshold of 60% of the volume being dredged material. Dredged materials were
stabilized using portland cement and fly ash in a mixing plant prior to loading into dump trucks that placed the materials directly into a berm at the dike construction location.

The construction process involved mechanically dredging sediments, loading them onto barges for transportation to the re-use site, vibrating the sediments over a sieve, capturing them in a buffer, and piston pumping sediments to the stabilization plant. The stabilization plant contained two independent mixers which contained an additive dosing system. After mixing, stabilized sediments were loaded into dump trucks which offloaded materials directly into the berm at the dike construction site. After five days of curing, a low-impact excavator leveled the stabilized sediments.

Two disadvantages of geotextile tubes discussed in Zele et al. (2014) were: high demands for transport water and difficulties in settlement assessment. However, one example is provided in another portion of this chapter (e.g. Howard et al. 2012; Karnati et al. 2012; Marlin 2003) where materials of relatively low moisture content (i.e. near LL) are pumped long distances. There are also cases presented where trends of settlement are either observed or adequately used to predict final settlement (e.g. Bazne et al. 2015; Coulet et al. 2014; Howard and Trainer 2011; Kim et al. 2015).

2.3.2.4 East Coast Land Creation

Stabilization/solidification (S/S) technology was used to create two acres of usable land at the New Bedford Harbor Superfund site (Matthews and Wilk, 2004). Dredged sediments containing PCBs were used following mixing with 13% portland cement by mass. After pugmill mixing materials, the stabilized mixture was stockpiled for a period between 24 hours and 3 months to achieve a workable consistency. After sufficient properties were achieved, the material was compacted in multiple lifts behind a
bulkhead at the site. The beneficial reuse of 9,000 m$^3$ of dredged sediments as structural fill produced meaningful cost savings.

### 2.3.2.5 Pavement Base Construction

A project documented in Arora et al. (2006) included the treatment of dioxin polluted sediments in Gulfport, MS. Some contaminated soils were incinerated prior to producing mixtures, and mixtures included combinations of soil, soil ash, and portland cement while some mixtures contained no soil ash. Cement quantities were between 4.7 and 14% for pavement subbase and pavement base layer applications which covered approximately 13 acres. Dioxin leachability tests performed during the study showed that cement stabilization of the sediments was an effective treatment. Unconfined compressive strengths ($q_u$) for pavement subbase locations ranged from 550 to 760 kPa following 11 days of curing. However, the pavement base section achieved 4,600 kPa after 7 days of curing.

### 2.3.2.6 Embankment Construction

Malasavage et al. (2012) performed an analysis of dredged material from Baltimore Harbor when combined with varying amounts of steel slag fines (SSF). The authors performed a laboratory evaluation with blends of 100/0, 80/20, 60/40, 50/50, 40/60, 20/80, and 0/100 on a percent of dry mass basis when considering dredged material to SSF. The authors additionally evaluated field performance of five embankments constructed from blends of 100/0, 80/20, 50/50, 20/80, and 0/100 on a percent of dry mass basis of dredged material to SSF. Mixtures were pugmill mixed and stockpiled prior to embankment construction.
Embankments compacted in Malasavage et al. (2012) were constructed on top of the natural ground surface near the mixing location. The embankment cores were approximately 3.6 m tall, 3.6 m wide, 15.2 m long, and had 3:1 end slopes and 2:1 side slopes. The embankment constructed from 100% SSF material was compacted to 95% of modified Proctor compaction while the 20/80 and 50/50 blends of dredged material to SSF were compacted to 92% and 90% of modified Proctor density, respectively. Finally, embankments of 80/20 dredged material to SSF and 100% dredged material were compacted to 85% of modified Proctor density. Following construction, embankments were tested according to ASTM D 5778-95 for cone penetrometer resistance. The authors concluded that the dredged material and SSF mixtures achieved strengths comparable or superior to traditional materials used for embankments.

2.3.2.7 Great Lakes Region Activity

Pebbles (2002) discussed several categories of locations where stabilized dredged materials have been beneficially reused in the Great Lakes region. One project was a specifically constructed confined disposal facility with an approximately 14 million m³ capacity which also provided protection of marshlands and provided wildlife habitat. Other categories of beneficial reuse were beach nourishment, topsoil production, landfill capping, mine land reclamation, and road construction. Each of these alternative use categories provide a method to offset confined disposal facility demand of dredged materials when dredged materials can meet project requirements.

Clark et al. (2015) shows evidence of the practicality of transforming dredged material confined disposal facilities to processing and reuse facilities. The Erie Pier
confined disposal facility which was built in the late 1970s is provided as an example site where a confined dredged material disposal facility has been modified to perform as a processing and reuse facility. The transformation, which has consisted of constructing an elevated dredged material off-load platform and haul roads around the exterior of the facility, was reported to have cost over $2 million and been a gradual process over the past ten years.

2.4 Feasibility Factors of LC-VHMS

This section presents a review of literature relevant to the feasibility of using LC-VHMS in and around ports. Section 2.4.1 presents a review of literature on shipping industry factors relevant to this thesis while sections 2.4.2 through 2.4.3 present factors relevant to construction, sustainability, and economics, respectively.

2.4.1 Economic Factors of Landside Development

This section focuses on economic factors surrounding ports and harbors with specific emphasis on the beneficial re-use of marginal materials in and around ports.

2.4.1.1 Dependency on the Shipping Industry

A common topic of discussion in many venues is development and maintenance of the multi-modal shipping industry that the US and other countries rely so heavily on for the transport of goods and services. The US transportation system moved 17.6 billion tons of freight with a value of $16.8 trillion in 2011 (Landers, 2013). European ports processed 3.7 billion tons of freight in 2012 and 48% of new container ship orders are 10,000 twenty foot equivalent unit (TEU) or larger (EC, 2014).
Bomba (2015) reported on factors relevant to the shipping of energy supply materials, and a fair amount of discussion was focused on shipment of petroleum products and liquefied natural gas (LNG). It was reported therein that US gulf coast ports handle approximately half of all foreign waterborne commerce, and that more LNG export terminals were approved for construction along the gulf coast. A key opportunity for constructing LNG export terminals along the gulf coast is the expanded Panama Canal. Prior to the Panama Canal expansion, more than 90% of the global fleet of LNG tanker vessels could not pass the locks. However, approximately 90% of the global fleet of LNG tanker vessels can pass the canal now that the expansion has been completed.

TRB (2013) prepared a list of critical transportation issues for 2013. The document stated that ports and waterways lead to more than $1 trillion in annual commerce and that the 12 largest ocean ports with over 9,000 vessels and 30,000 barges moving 157 billion ton-miles annually on the 25,000 miles of navigable channels of the Inland Waterway System. Many ocean ports are seeking deeper ports and harbors as a result of the Panama Canal expansion.

2.4.1.2 Port and Harbor Landside Development Needs

A common problem experienced by ports and harbors is the limited amount of usable land adjacent to water. The efficiency of ports and harbors is vital to the overall efficiency of an intermodal freight system as it is the transition point between freight modes (i.e. ship, truck, and rail). There have been multiple investigations to the overall health of deep water ports in the US over the past decade (e.g. Ashar and Swigart, 2007; Harrison and Trevino, 2013).
In Ashar and Swigart (2007), the authors surveyed intermodal efficiency between maritime and railroad shipping for Louisiana’s deep water ports (i.e. New Orleans) in comparison with ports at Mobile, Alabama, Jacksonville, Florida, Savannah, Georgia, and Charleston, South Carolina. Each of the ports included in the study had plans at the time to increase berthing space and the limited amount of waterfront land was discussed as a potential reason that none of the ports were considering on-dock ship to rail intermodal facilities. Rather, ports were considering nearby locations for intermodal transitions to rail.

Harrison and Trevino (2013) performed an evaluation of anticipated impacts of the Panama Canal expansion for Texas ports to the Gulf of Mexico. While the authors stated that the effects of the Panama Canal expansion cannot be fully understood until the effects take place, the authors anticipated that there would be short and long term benefits through an expedited trade route. However, the authors made mention on multiple occasions of the need to improve multi-modal inefficiencies, specifically in the area of ship to rail transition points and deepening of port channels where possible. One example provided was the Port of Houston Authority was estimated to exceed terminal capacity within a 5 to 7 year period calling for a series of port investments such as channel maintenance, terminal productivity, and potentially landside access improvements for truck and rail.

As stated in Meitzen (2013), there were 11,000 ton-miles of freight moved per capita in the US in 2007. Though not the primary focus of the document, this amount of freight movement per capita lends to the dependency on the multimodal freight system. It
was stated in the document that several economic growth aspects have led to increased competition for land and resources around freight corridors and facilities.

2.4.1.3 Benefit of Alternatives to Disposal Methods

Transitioning from disposal practices for managing dredged materials is unlikely to become a reality on a broad scale without having first demonstrated an economic benefit to changes in practices. The following three paragraphs present literature on economic benefits of having alternatives to disposing of dredged sediments.

According to NCFRP 16, two primary maintenance factors for the maritime shipping transportation network are dredging and lock maintenance. Therein, a figure prepared from data collected by the U.S. Army Corps of Engineers is provided to demonstrate an increase in the average cost of dredging since the 1960s from approximately $1.50/yd³ in the 1960s to more than $3.00/yd³ in 2010. These figures were reported in constant dollar terms. The authors further discussed that disposal of dredged materials can be challenging through either finding a suitable location nearby or highly increased costs incurred through remote disposal. This concept is supported in unit costs relevant to dredging unit costs provided in Table 2.2, and the following two paragraphs present literature on economic factors related to beneficial reuse of dredged materials.

A cost estimate based on 2007 unit costs was performed in Grubb et al. (2010b). Cost factors included were dredging source costs, bulkhead offloading, cementitious materials, processing, and final placement of stabilized dredged materials. Region specific cost estimates resulted in an overall reuse cost estimate between $13 and $16 per m³ (approximately $9 to $12 per yd³), which was reported to be low for the New York
City metropolitan region and similar to costs of structural fill materials in many east coast areas.

One example where beneficial reuse of dredged materials could be beneficial is in the Mobile Harbor navigation project where approximately 4.6 million m$^3$ are removed annually costing $25$ million (Lovelace, 2014). An example project which has already been completed is the Embraport terminal expansion discussed in section 2.3.1.3 where the project owner was reported to experience a cost savings of $50$ million by reducing site development costs by 20 to 30% through the beneficial reuse of dredged materials in geotextile tubes.

A primary conclusion from Grubb et al. (2010b) was that expansion of port facilities is an outstanding opportunity to utilize beneficial reuse on a record scale. The authors make mention that high costs for importing large quantities of selected materials are frequently encountered by ports and that ports could further benefit by utilizing large volumes of dredged soils and other marginal pozzolanic materials produced by power plants and available at bulk terminals used by cement and power industries.

2.4.2 Construction Considerations

There are multiple factors to consider during construction when using LC-VHMS. These factors range from consistency, placement method, sediment handling, re-use technology, mixing water, and settlement prediction.

2.4.2.1 Beneficial Re-Use Technologies

While the majority of this chapter focuses primarily on beneficial re-use of dredged sediments through encasement, solidification and stabilization (S/S), or a
combination thereof, there are several approaches to modifying properties of dredged material for beneficial reuse. Estes and McGrath (2014) provides an in-depth review of literature where varying technologies related to beneficial reuse of dredged materials were evaluated, including: biological treatment, chemical oxidation, chemical extraction, electrokinetic, soil washing, solidification/stabilization, thermal, capping, and water treatment. While technologies for beneficial reuse of contaminated dredged materials varied greatly, S/S was a predominately discussed treatment method. Therein S/S, which is commonly performed through the introduction of cementitious materials, is identified as the most readily implementable technology and one of the most promising treatment methods for beneficial reuse of dredged materials. However, two key disadvantages of S/S provided were that contaminants in dredged sediments are not removed and that sediments contaminated with oils may have poor performance due to interaction between oils and cement hydration.

2.4.2.2 Sediment Handling

While there are multiple methods for handling dredged materials discussed in literature, the mixtures evaluated in this thesis would likely be used in conjunction with some level of pumping to transport sediment mixtures. The next two paragraphs discuss pumping of dredged sediments.

Field trials included in a project focusing on Promoting Integrated Sediment Management (PRISMA) attempted to pump sediment using submersible pumps in an undiluted state (PRISMA, 2012). After submersible pump performance was deemed unsuccessful, submersible pumps were replaced with concrete pumps and sediments were successfully transported through pipelines to reach further than cranes or excavators.
could. Although the use of a vibrating screen and large hopper was necessary to provide a steady stream of sediments to the concrete pump while avoiding spillage, sediments were evaluated for transport of distances from 12 to 120 km. It was stated in the report that the group performing the field trials sought to ultimately fill geotextile tubes with undiluted sediments using concrete pumps.

A large amount of work relevant to the conveying of dredged materials over long distances and at high moisture contents is presented in Oota et al. (2009) and Marlin (1999, 2002, 2003). Marlin (1999, 2002, 2003) performed pilot tests show that pumping of fine grained sediments is possible. In fact, some of the soils in Marlin (2003) used dredged sediments within 10% of the respective LL for the soil.

It has also been shown feasible to load excavated sludge in to concrete ready-mix trucks (Emery, 1980). Field trials used a chute to load sludge into concrete ready-mix trucks and incorporate stabilizing agents thereafter. In the study reported, it was determined that ready-mix truck stabilization was efficient enough to avoid the construction of a bigger stabilization plant.

2.4.2.3 Consistency Testing

The National Ready Mixed Concrete Association (NRMCA, n.d.), recommends use of ASTM D 6103 for testing flow consistency of controlled low strength materials (CLSM). Therein, CLSM is defined as materials with an upper limit compressive strength of 8,273 kPa or less with typical CLSM applications requiring compressive strengths less than 2,068 kPa. Three categories of flowability are defined in NRMCA (n.d.): low, normal, and high. These flow categories correspond to flows of less than 15 cm, 15 to 20 cm, and greater than 20 cm, respectively. According to ASTM D 6103-04, flowable
CLSM used to fill spaces without the use of vibration typically have a flow between 20 and 30 cm. Further, flow cylinders with an inner diameter of 76 ± 3 mm are required for use in ASTM D 6103, making the minimum flow of any mixture 7.6 cm.

2.4.2.4 Placement Method

There are two construction approaches which have been presented in earlier sections of this chapter: 1.) using dredged materials (stabilized or not) which flow into place and are not compacted and 2.) using stabilized dredged materials which are allowed to mellow for a period of time prior to re-mixing and compacting in place. The majority of studies presented in this chapter evaluated properties of mixtures which would be placed shortly after stabilization and left, but the following two paragraphs present studies which evaluate factors relative to differences in material properties through immediate placement or placement after an extended period of time.

Huang et al. (2011) evaluated engineering properties of solidified dredged material (SDM) and remolded solidified dredged material (RSDM). Therein, differing amounts of cementitious material were introduced to slurries of dredged material prior to curing in an environment at ambient temperature and high humidity. SDM specimens were produced in cylindrical molds of 39.1 mm diameter that were 80 mm tall for unconfined compression (UC) tests and isotropically consolidated undrained triaxial compression tests. SDM specimens were also produced with 61.8 mm diameters and 20 mm heights for oedometer tests. RSDM specimens were mixed in the same way as SDM specimens. However, RSDM specimens were crumbled to particles finer than 2 mm after curing and subsequently prepared with standard Proctor compaction in a 102 mm diameter mold prior to being trimmed to similar size as SDM specimens. Strengths of
RSDM specimens tested in UC were approximately 20 to 40% of that for SDM specimens. However, failure of RSDM materials were found to be at strains more than four times that of SDM materials.

Grubb et al. (2010b) utilized SDM which had been mellowed for a period of time (e.g. 3 days) that was compacted after mellowing (i.e. it was not VHMS). It was reported that for SDM fill to be trafficable and constructible with low ground pressure equipment, a 28 day \( q_0 \) of 138 kPa is needed. Each of the compacted SDM blends considered therein achieved the preliminary 138 kPa minimum \( q_0 \).

### 2.4.2.5 Mixing Water

The effect of mixing water type was evaluated in Carruth et al. (2014), which tested soils with LL between 50 to 100 and cement contents ranging from 10 to 15%. The water types had varying salinity concentrations, which could be of particular interest to ports along the gulf coast. The primary evaluations were tap water (i.e. no salinity), brackish water (i.e. 5 parts per thousand salinity), and salt water (i.e. 40 parts per thousand salinity), and brackish water and salt water levels chosen are like those of Lake Pontchartrain and the Gulf of Mexico water, respectively. While water salinity was found to have an effect on strength gain, the use of C-VHMS was deemed to be feasible as the effect on strength gain was dependent on soil and water type.

### 2.4.2.6 Settlement Prediction

As discussed in section 2.3.2.3, adequately determining or predicting settlement of geotextile tubes filled with fine grained sediments is a concern for some situations.
The following three paragraphs describe efforts to predict volume change of geotextile tubes filled with fine grained dredged soil.

Coulet et al. (2014) documented a study in the United Kingdom where predictive calculations estimated settlements of 0.5 m and secondary settlement of 0.6 to 0.9 m for a geotextile tube filled with fine grained dredged materials. After construction, the predictive calculations showed to be accurate.

Howard and Trainer (2011) and Bazne et al. (2015) documented simplistic volume change (or settlement). Volume change associated with filling a geotextile tube with C-VHMS was investigated by monitoring height change in a laboratory scale geotextile container of irregular shape since volume change has an effect on the final height of a geotextile tube. Height change was recorded with respect to time for 1 to 3 days in laboratory tests of submerged and emerged tests. Although height changes of the containers would not correlate with geotextile tubes of a different shape, documented height changes were between 10 and 24% with most of the height change occurring within hours of filling the container.

Kim et al. (2015) performed large scale model tests using geotextile tubes and transparent geobags to evaluate settlement behaviors and final geometries of tubes filled with un-stabilized dredged materials. Dredged material slurries were prepared with approximately 300% moisture content prior to filling permeable tubes (geotextile tubes) and impermeable tubes (geobags). Tube heights and widths were monitored over time, and tubes were filled and dewatered on multiple occasions (both tubes were 4 m long and had 0.7 m and 1.0 m diameters for geobag and geotextile tubes, respectively). Consistent
trends relating final tube width, theoretical tube diameter, and filled tube height were found for both drained and undrained conditions.

2.4.3 Port Sustainability

Sustainability has been a growing topic of discussion in recent years. 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…” This section presents literature relevant to sustainability and factors related to the sustainability of using dredged materials.

Puppala and Chittori (2014) state that projects achieve higher sustainability with more agreement between social, environmental, and economic impacts. One specific opportunity to increase sustainability used by the authors is geotechnical engineering which has the ability to interface the built and natural environments with a key portion of sustainability research centered around the reuse of marginal materials. The expansion or improvement of landside areas at ports provides enough overlap of social, environmental, and economic impacts to be an excellent opportunity to make advancements in port sustainability.

Vellinga et al. (2014) presents the argument that ports which strive to be green or sustainable tend to benefit economically whereas ports which strive for minimum compliance to federal regulations can tend to struggle economically. Therein, a definition of a sustainable port is quoted as, “A sustainable port is one in which the port authority together with port users, proactively and responsibly develops and operates, based on an
economic green growth strategy, on the working with nature philosophy and on stakeholder participation, starting from a long term vision on the area in which it is located and from its privileged position within the logistic chain, thus assuring development that anticipates the needs of future generations, for their own benefit and the prosperity of the region that it serves” (Vellinga et al. 2014).

The utilization of dredged materials can also lead to a decreased carbon footprint in applications where large areas are filled with dredged materials rather than virgin materials from more distant locations. Utilization of dredged materials in geotextile tubes as fill material in the Embraport terminal expansion discussed in section 2.3.1.3 ultimately reduced the project carbon footprint by approximately 7,900 tCO₂e (TenCate™, 2014).

2.5 C-VHMS Engineering Properties

This section provides engineering properties of stabilized dredged materials found in literature. It should be noted that many of the engineering properties presented in this section pertain to C-VHMS mixtures and not LC-VHMS mixtures, which are expected to be of lower strength than C-VHMS.

SGM as documented in (Tanaka et al. 2009; Oota et al. 2009; Nakai et al. 2009) used sediments with liquid limits of 58 to 91 and moisture contents of 85 to 250%. Cement dosages therein were 3.3 to 14.8% by slurry mass (contents greater than 8.7% were most common), which produced 28 day laboratory mix design q₀ of 313 to 588 kPa.

Four dike design requirements in Zele et al. (2014) included: 1.) permeability lower than 1e-7 m/s, 2.) minimum angle of internal friction of 25°, 3.) minimum
undrained shear strength of 35 kPa, 4.) minimum cohesion of 4 kPa. Mix designs considered use of portland cement, quicklime, fly ash, bottom ash, slag cement, and sodium silicate. Specimens were produced, sealed, and cured at room temperature until testing occurred with a motorized laboratory vane apparatus. Mixtures using 4 to 14% additive by slurry mass were able to produce $q_u$ of 70 kPa after 28 days with moisture contents between 50 and 150%.

Howard et al. (2012) sampled fine grained soil used to fill geotextile tubes at Peoria, IL as described in Karnati et al. (2012) and tested strength over time at the in situ moisture content of 70%. After 3 days of submerged room temperature curing, $q_u$ was 98, 510, and 1373 kPa for dosages of approximately 5%, 10%, and 15% cement by slurry mass which increased to 137, 706, and 1844 kPa after 7 days of submerged room temperature curing.

Approximately 1,200 UC tests on VHMS produced with three soils having liquid limits between 50 and 100, cement contents of 5 to 15%, and moisture contents of 100% or 233% (15% cement was only tested at 233% moisture) in Howard and Carruth (2015). Testing occurred after submerged curing at room temperature for 1 to 7 days, and unconfined compressive strengths ranged from 20 kPa to 745 kPa for the entire data set. The data set produced therein which is most related to this thesis was tested at 5% cement by slurry mass and 100% moisture. After 1, 3, and 7 days of curing, $q_u$ ranged from 57 – 147, 71 – 218, 73 – 245 kPa, respectively.

Grubb et al. (2010a), which is a companion to Grubb et al. (2010b) and one other paper focused on stabilized dredged material. Grubb et al. (2010a) provides the primary evaluation of twenty combinations of dredged sediments and cementitious materials.
ranging from cement kiln dust to fly ash. A Virginia confined disposal facility was the source utilized for the study with an insitu moisture content of 130%, average LL of 62, and USCS soil classification as CH/OH. Unconfined compression tests were performed after 7, 28, and 180 days on moisture contents ranging from 80 to 150%. The most relevant mixture which evaluated $q_u$ of dredged materials treated with 5% of lime on a total dredged material basis produced $q_u$ of 30 kPa after 28 days.
CHAPTER III
EXPERIMENTAL PROGRAM

3.1 Overview

Testing in this thesis was performed in three phases: 1.) unconfined compressive strength ($q_u$) and flow ($f_l$) variations with moisture content and cure time for a single mixture of stabilized dredged material, 2.) evaluation of cement type and molding speed on mixture properties, and 3.) evaluation of marginal material mixtures produced with dredged material and bottom ash. The primary test methods used herein are unconfined compression (UC) testing and flow ($f_l$) testing (ASTM D 6103). While liquid limit (LL) and plastic limit (PL) testing were performed as per ASTM D 4318. In total, there were 30 flow tests, 181 UC tests, 14 LL tests, and 14 PL tests. The following sections provide descriptions of the materials tested, testing matrices, specimen fabrication, and test methods used.

3.2 Materials Tested

Materials tested in this thesis consist of dredged material and coal bottom ash sampled from Memphis, Tennessee as well as portland-limestone cement (PLC) and ordinary portland cement (OPC) produced by Holcim in Theodore, Alabama. Properties for each of the aforementioned materials are provided in this section. Further description of sampling sites and materials tested are provided in (Vahedifard et al., 2015).
3.2.1 Soil Properties

The single dredged material utilized herein was sampled from a dredged disposal site maintained by the Port of Memphis, where the dredging is performed by the US Army Corps of Engineers (USACE). Dredged material was placed into the site between October 2013 and April 2014 as follows. Water achieved minimum depths of 0.6 m and up to 1.8 to 2.4 m in some locations. After settling, water was allowed to run out of a weir box, which took 1 to 2 weeks. Dredging was performed with cutter head hydraulic dredging at around 10% solids. Photos of the surrounding areas adjacent to the port of Memphis are provided in Figure 3.1a to 3.1c as well as the bulk sampling location prior to and after sampling in Figure 3.1d to 3.1e.

Figure 3.1 Dredged Disposal Facility and Surrounding Area
Table 3.1 provides soil properties as determined by MSU and as determined by Burns Cooley Dennis, Inc. (BCD). Properties shown are for bulk samples utilized for testing presented in later chapters of this thesis. Properties were in reasonable agreement between the two laboratories.

Table 3.1 Properties of Memphis Soil Tested

<table>
<thead>
<tr>
<th>Property</th>
<th>MSU</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>D698 $\gamma_d$ (g/cm$^3$)</td>
<td>1.32</td>
<td>1.31</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>D698 OMC (%)</td>
<td>30.0</td>
<td>33.1</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>D4318 LL (%)</td>
<td>90</td>
<td>82</td>
<td>86</td>
<td>103</td>
</tr>
<tr>
<td>D4318 PL (%)</td>
<td>32</td>
<td>25</td>
<td>29</td>
<td>35</td>
</tr>
<tr>
<td>D4318 PI (%)</td>
<td>58</td>
<td>57</td>
<td>57</td>
<td>68</td>
</tr>
<tr>
<td>D854 $G_s$</td>
<td>2.67</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>D1140 $P_{200}$ (%)</td>
<td>97.0</td>
<td>99.6</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>D2974 $P_o$ (%)</td>
<td>12.0</td>
<td>10.9</td>
<td>12.2</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Note: Maximum Dry Density ($\gamma_d$)
Note: Optimum Moisture Content (OMC)
Note: Soil Specific Gravity ($G_s$)
Note: Particles Finer than 0.075 mm ($P_{200}$)
Note: Percent Organic Material ($P_o$)

3.2.2 Cement Properties

Two cements produced in Theodore, Alabama were utilized in the experimental program for this thesis: PLC and OPC (Table 3.2). Portland-Limestone Cement (PLC) was chosen as the primary cement utilized due to its more sustainable properties when compared to ordinary portland cement (OPC). Properties in Table 3.2 were measured in one laboratory on samples provided.
Table 3.2  Cement Properties as Supplied by Holcim (US), Inc.

<table>
<thead>
<tr>
<th>Cement ID</th>
<th>PLC</th>
<th>OPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM Designation</td>
<td>C1157</td>
<td>C150</td>
</tr>
<tr>
<td>Cement Type</td>
<td>GU</td>
<td>I/II</td>
</tr>
<tr>
<td>Blaine Fineness (m²/kg)</td>
<td>538</td>
<td>405</td>
</tr>
<tr>
<td>Limestone Content (%)</td>
<td>12.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Percent Finer than 45 μm</td>
<td>99.5</td>
<td>96.9</td>
</tr>
<tr>
<td>Initial Vicat (min)</td>
<td>135</td>
<td>90</td>
</tr>
<tr>
<td>Final Vicat (min)</td>
<td>190</td>
<td>170</td>
</tr>
<tr>
<td>CaO (%)</td>
<td>64.3</td>
<td>64.1</td>
</tr>
<tr>
<td>AL₂O₃ (%)</td>
<td>4.2</td>
<td>4.8</td>
</tr>
<tr>
<td>SiO₂ (%)</td>
<td>18.2</td>
<td>19.9</td>
</tr>
<tr>
<td>1 Day Mortar Cube Strength (MPa)</td>
<td>20.4</td>
<td>16.6</td>
</tr>
<tr>
<td>3 Day Mortar Cube Strength (MPa)</td>
<td>31.0</td>
<td>28.6</td>
</tr>
<tr>
<td>7 Day Mortar Cube Strength (MPa)</td>
<td>39.2</td>
<td>35.2</td>
</tr>
<tr>
<td>28 Day Mortar Cube Strength (MPa)</td>
<td>45.6</td>
<td>44.7</td>
</tr>
</tbody>
</table>

Note: Target PLC limestone contents were generally 10%.
Note: Limestone (%) measured using cement carbon measurements with a LECO carbon/sulfur analyzer.

3.2.3  Ash Properties

There is a considerable amount of industrial activity, including coal burning power plants, adjacent to the Memphis dredge disposal site. A sample of bottom ash was collected from Memphis, Tennessee and was utilized for testing herein. The test site where ash samples were collected is shown in Figure 3.2. The sample was analyzed by Holcim (US), Inc. with an X-ray machine not calibrated for ash, which provided reasonable, but not especially precise results in all cases. X-ray evaluation resulted in 38% SiO₂, 14% Al₂O₃, 22% Fe₂O₃, 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). The gradation of the ash material used is provided in Figure 3.3.

![Figure 3.2 Photos of Ash Adjacent to Memphis Dredge Disposal Facility](image)

![Figure 3.3 Gradation of Ash Adjacent to Memphis Dredge Disposal Facility](image)

### 3.3 Specimen Preparation

Several soil slurry mixtures were produced in the preparation of this thesis. Generally speaking, soil and water mixtures were mixed for about two minutes prior to cement addition. Cement was then then gradually mixed into the soil slurry mixture and continually mixed for approximately two more minutes prior to filling molds.
Specimens herein were molded in plastic molds (76 mm diameter and 152 mm tall) which were fitted with a 2 mm thick aluminum plate at the bottom of each mold to help facilitate extrusion. Specimen molds were filled using two lifts while consolidating specimens following each lift by tapping the base of each mold against a solid surface 20 times. Following consolidation of the second lift, any remaining volume in the mold was filled with stabilized dredged material and the tops were leveled. Specimens were then cured in a room maintained at 100% relative humidity and temperatures between 20.4°C and 23.4°C until tested. Specimen fabrication and curing processes are shown in Figure 3.4.

![Figure 3.4 Specimen Fabrication and Curing](image)

3.4 Test Methods

Three test methods were chosen to evaluate engineering properties of marginal materials. ASTM D 6103 was chosen to evaluate the flow of slurry materials, UC testing was performed to determine engineering strength properties, and ASTM D4318 was utilized to evaluate consistency of stabilized materials.
3.4.1 Flow Testing (ASTM D 6103 – 04)

The National Ready Mixed Concrete Association recommends ASTM D 6103 to test for the flow of low strength materials and describes flow between 15.2 cm and 20.3 cm as normal flow. Flow testing was performed herein according to ASTM D 6103 using a plastic sleeve of 7.6 cm diameter and 15.2 cm height. Soil slurries tested for flow were mixed to a consistent state, used to fill a plastic sleeve, and resulting flows were measured across two diameters immediately after raising the sleeve. Images of a filled sleeve as well as an example of low and high flow are provided in Figure 3.5. Flow testing in this thesis was performed using single replicates.

Figure 3.5 Flow Testing (ASTM D 6103)

3.4.2 Unconfined Compression Testing

In most cases throughout this thesis, UC testing was performed on groups of three replicate specimens produced from one sub-sample (i.e. one bucket) of dredged material at one point in time. Unconfined compression testing in this thesis was performed at a rate of 2.3 mm/min. Specimens were first extruded from molds as shown in Figure 3.6a.

40
prior to being loaded until failure. The load frame used is shown in Figure 3.6b, and a representative failure is shown in Figure 3.6c.

![Image](image_url)

Figure 3.6 Unconfined Compression Testing

### 3.4.3 Atterberg Limit Testing (ASTM D4318 – 10)

After testing of UC specimens cured for 56 days as described in Section 3.4.2, specimens were air dried, pulverized using a mortar and pestle, materials finer than 0.425 mm were water washed to separate from coarser materials, materials were then dried back to moisture contents above the LL while at room temperature. Once dried to a reasonable moisture content (Figure 3.7a), samples were mixed (Figure 3.7b). Then, liquid limit testing was performed as shown in Figure 3.7c to 3.7e. Plastic limit testing was performed as shown in Figure 3.7f and 3.7g. Following testing, moisture content specimens were oven dried as shown in Figure 3.7h.
3.5 **Test Matrices**

This investigation was performed in a three part process where variations of a single mixture were evaluated first and properties of alternative mixtures were evaluated in phases two and three. The single mixture chosen for initial evaluations was dredged material stabilized with 5% PLC on a slurry mass (soil plus water) basis. Variations in phase one were moisture content and cure time. LC-VHMS mixtures in phase two considered multiple cements (PLC and OPC) at varying dosages (2.5% and 5.0%) and
moisture contents (135% and 155%). Phase three evaluated effects of incorporating bottom ash via UC testing.

3.5.1 Variations of Single Mixture Testing

Unconfined compression testing was performed after varying cure times in a humid room maintained at 20.4°C to 23.4°C for dredged materials initially at 135% moisture dosed with 5% PLC by slurry mass. Engineering properties at varying moisture contents of the same mixture were evaluated using flow testing at three points (i.e. prior to cement mixing, after mixing, and after holding for 30 minutes following cement mixing) and UC testing after 28 days of curing. The corresponding test matrix is shown in Table 3.3.
### Table 3.3 Variations of Single Mixture Test Matrix

<table>
<thead>
<tr>
<th>Initial Moisture (%)</th>
<th>Flow Evaluations</th>
<th>UC Test Time (days)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>Before Cementing</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>120%</td>
<td>Before Cementing,</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>After Mixing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>135%</td>
<td>Before Cementing,</td>
<td>1, 3, 7, 28, 56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>After Mixing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Held for 30 Minutes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>145%</td>
<td>Before Cementing,</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>After Mixing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Held for 30 Minutes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>155%</td>
<td>Before Cementing,</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>After Mixing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Held for 30 Minutes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Four UC tests were conducted after 7 days of curing, other cure times had three replicates.*

#### 3.5.2 LC-VHMS Testing

The second phase of this investigation was performed to evaluate the short and long term effects of modifying agents in stabilized dredged materials (i.e. amount and type of cement used), moisture content, and construction timing. Two moisture contents (135% and 155%) were used to produce flow behaviors in dredged materials from Memphis of normal flow (i.e. approximately 18 cm) and high flow (i.e. above 20 cm) as defined by (NRMCA, n.d.). Each mixture prepared in phase two of this investigation was
evaluated with UC testing after 28 and 56 days of curing to investigate changes to engineering properties. UC test specimens tested after 56 days of curing were dried for several days, washed over a No. 40 sieve and tested according to ASTM D 4318.

Table 3.4 LC-VHMS Test Matrix

<table>
<thead>
<tr>
<th>Initial Moisture (%)</th>
<th>Flow Testing</th>
<th>Cement Type</th>
<th>Cement Content (%)</th>
<th>Molded After (min)</th>
<th>UC Test Time (days)</th>
<th>LL &amp; PL Test Time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before OPC Cementing</td>
<td>2.5</td>
<td>0</td>
<td>28, 56</td>
<td>56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>135</td>
<td>5.0</td>
<td>30</td>
<td>28, 56</td>
<td>---</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After Mixing, Held for 30 Minutes PLC</td>
<td>2.5</td>
<td>0</td>
<td>28, 56</td>
<td>56</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>30</td>
<td>28, 56</td>
<td>---</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before OPC Cementing, After Mixing</td>
<td>2.5</td>
<td>0</td>
<td>28, 56</td>
<td>56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>155</td>
<td>5.0</td>
<td>30</td>
<td>28, 56</td>
<td>---</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note – Testing was performed using 3 replicates for UC, 1 replicate for LL, and 1 replicate for PL.
3.5.3 Multiple Marginal Materials Testing

The third phase of laboratory experiments in this thesis evaluated the effects of incorporating additional marginal materials into mixtures containing dredged materials. Incorporation of bottom ash has potential for the dredged material disposal facility in Memphis, Tennessee (see section 3.2.3). However, this phase of testing was performed to evaluate the possibility of incorporating marginal materials into dredged materials and not to promote any one individual marginal material for use.

Dredged material and bottom ash mixtures tested herein were all prepared to maintain consistent initial flows of 18 cm for bottom ash and/or soil slurries with initial moisture content as the controlled variable. Initial moisture contents were chosen to maintain slurry material flows prior to cement addition around 18 cm. The test matrix for phase three of testing in this thesis is provided in Table 3.5 where all mixtures were evaluated using UC testing after three cure times and using ASTM D 4318 after 56 days of curing.
Table 3.5 Multiple Marginal Materials Test Matrix

<table>
<thead>
<tr>
<th>Cement Type</th>
<th>Cement Content (%)</th>
<th>Bottom Ash1 (%)</th>
<th>Initial Moisture (%)</th>
<th>UC Test Time</th>
<th>LL &amp; PL Test Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLC</td>
<td>0%</td>
<td>135%</td>
<td>7, 28, 56</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5%</td>
<td>20%</td>
<td>110%</td>
<td>7, 28, 56</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>40%</td>
<td>100%</td>
<td>7, 28, 56</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>135%</td>
<td>7, 28, 56</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>20%</td>
<td>110%</td>
<td>7, 28, 56</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>40%</td>
<td>100%</td>
<td>7, 28, 56</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>135%</td>
<td>7, 28, 56</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>OPC</td>
<td>5%</td>
<td>20%</td>
<td>110%</td>
<td>7, 28, 56</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>40%</td>
<td>100%</td>
<td>7, 28, 56</td>
<td>56</td>
<td></td>
</tr>
</tbody>
</table>

1Percent of dry soil mass.

Note – Testing was performed using 3 replicates for UC, 1 replicate for LL, and 1 replicate for PL.
CHAPTER IV
TEST RESULTS

4.1 Overview

This chapter provides results of laboratory measured properties of lightly cemented mixtures of marginal materials. First, this chapter presents unconfined compression and flow results for the three phases of testing described in Chapter 3: 1.) variations of a single mixture produced using 5% PLC; 2.) evaluation of short term and long term engineering properties in LC-VHMS as a result of changes to molding time, moisture content and cementitious components; 3.) evaluation of engineering properties for LC mixtures containing multiple marginal materials. After presenting strength and flow data, results of ASTM D 4318 testing are presented.

4.2 Moisture Content and Cure Time Effects

Engineering properties as a function of moisture content for the primary mixture evaluated herein (i.e. dredged material from Memphis, TN with 5% PLC by slurry mass) were flow ($f_i$) and unconfined compressive strength ($q_u$) after 28 days of curing. Flow results at three points in time (i.e. $f_{pre-cement}, f_{post-cement}$, and $f_{30min}$) and $q_u$ after 28 days of curing are presented for varying moisture contents in Section 4.2.1 while results of $q_u$ after varying cure times are provided in Section 4.2.2.
4.2.1 Effect of Moisture Content

An understanding of engineering properties for varying moisture contents of a stabilized marginal mixture could be helpful when planning beneficial reuse construction (e.g., selecting reasonable moisture contents for a given re-use technique). Measured engineering properties for Memphis, TN dredged material mixtures produced with varying moisture contents and 5% PLC are provided in Figure 4.1. Along the same lines, an approach where \( f_l \) behaviors are understood at multiple points in time and for multiple moisture contents could be of potential use in the event that a port elected to beneficially re-use dredged materials.

\[
\begin{align*}
q_u (kPa) &= 218x^2 - 722x + 650 \\
R^2 &= 0.99
\end{align*}
\]

\[
\begin{align*}
f_{l_{\text{pre-cement}}} &= 39.3x - 32.3 \\
R^2 &= 0.98
\end{align*}
\]

Figure 4.1 Flow and Unconfined Compressive Strength vs. Moisture Content
Trends of engineering properties in Figure 4.1 suggest that $q_u$ after 28 days of curing can be reasonably predicted between 100 and 155% moisture with a second order polynomial for this single soil and cement combination, and $f_{\text{pre-cement}}$ can be reasonably predicted between 100 and 155% moisture using a linear regression. It should also be noted that $f_i$ of 7.6 cm is the minimum possible as per ASTM D 6103 (i.e. 7.6 cm is no flow). In many cases, mixtures gained enough viscosity to become non-flowing within 30 minutes of mixing with cement. For each moisture content tested, $f_i$ was measured for each of the three previously mentioned points in time. Once a non-flowing measurement was taken for a given mixture, $f_i$ measurements were discontinued. Table 4.1 presents a summary of flow characteristics for the five moisture contents evaluated in this section as described in NRMCA (n.d.).

<table>
<thead>
<tr>
<th>Moisture Content (%)</th>
<th>100</th>
<th>120</th>
<th>135</th>
<th>145</th>
<th>155</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{\text{pre-cement}}$</td>
<td>None</td>
<td>Low</td>
<td>Normal</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>$f_{\text{post-cement}}$</td>
<td>None</td>
<td>None</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>$f_i \text{30min}$</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

4.2.2 Effect of Cure Time on Unconfined Compressive Strength

Results of UC testing for a single LC-VHMS mixture (5% PLC at 135% moisture) are provided in Figure 4.2 with respect to cure time ($t$), where each point provided is representative of one specimen. Results shown in Figure 4.2 are of specimens produced on two different days. All specimens tested with less than 7 days of curing and
one specimen tested after 7 days of curing were produced on a single day and from one mixed batch, while three specimens tested after 7 days of curing and all specimens tested after more than 7 days of curing were produced from a second batch produced on one day a few weeks earlier.

\[
q_u (kPa) = 6.08 \ln(t) + 48.1 \\
R^2 = 0.82 \\
n = 16
\]

Figure 4.2  UC Strength vs. Cure Time (5% PLC at 135% Moisture)

A completely randomized statistical evaluation was utilized where cure time (t) was considered as the treatment to evaluate strength gain with time. As shown in Figure 4.2, t produced a statistically significant effect on \(q_u\), as expected. Knowing which values of t produce significantly different strength is potentially useful for construction phasing. Results of least squared difference comparisons are also provided in Figure 4.2, which provides a measure of significance on differences in \(q_u\) with respect to t.
An understanding of strength gain during early stages of curing is of particular interest to successful re-use of LC-VHMS, because early strength gain would play an important role on the approach used (e.g. choosing containment approach). As shown in Figure 4.2, the mean $q_{tu}$ for specimens cured over time produced a reasonable amount of strength, relatively speaking, after one day (64% of 56 day $q_{tu}$) and continued to gain strength. Also shown in Figure 4.2, $q_{tu}$ was not significantly different between 28 days and 56 days of curing, which implies that cementitious reactions were beginning to subside. While the observed $q_{tu}$ for 7 days was less than that for 3 days, these values were not significantly different. Variation in dredged materials likely caused this difference.

4.3 LC-VHMS Testing

4.3.1 Overview

This section presents results and discussion of early age (i.e. $f_i$) and late age (i.e. $q_{tu}$) engineering properties of multiple LC-VHMS mixtures. Flow results from ASTM D 6103 are shown in Figure 4.3 and discussed in section 4.3.2 while UC test results are presented in Figure 4.4 and discussed in Section 4.3.2 and Section 4.3.3. UC test results are reported as after a cure time of 28 or 56 days and as unconfined compressive strength of specimens molded immediately after mixing ($q_{tu,i}$) or unconfined compressive strength of specimens molded after 30 minutes ($q_{tu-30min}$).
Figure 4.3  Flow of LC-VHMS Mixtures

Figure 4.4  UC Results of Multiple LC-VHMS Mixtures
4.3.2 Effect of Holding Time

This section provides analysis to characterize the effect of construction timing (i.e. a 30 min holding time) on LC-VHMS mixtures. First, the effects of holding time on early age LC-VHMS properties as shown in Figure 4.3 are evaluated. Then, an equality plot relating average $q_u$ for specimens molded immediately after mixing cement and $q_u$ of similar specimens held for 30 minutes prior to molding is presented in Figure 4.5.

It should be noted that a total of eight LC-VHMS mixtures are represented in Figure 4.3. Mixtures were produced from separate buckets of dredged material sampled from Memphis, TN, and flow characteristics of some non-cemented mixtures were not as expected (e.g. Flow of VHMS at 135% moisture was used to produce a 2.5% PLC LC-VHMS was higher than expected). This is likely the result of variability of dredged materials and the absence of replication.

As expected, there was an immediate decrease in $f_i$ for all mixtures and a further loss in $f_i$ after an additional 30 minute hold time after cement addition. The average reduction in $f_i$ between $f_{pre-cement}$ and $f_{post-cement}$ was 13.3 cm and the average reduction in $f_i$ between $f_{post-cement}$ and $f_i\,30\text{min}$ was 1.7 cm. It is worth noting that only one mixture tested for $f_i$ after cementing produced normal $f_i$ (i.e. between 15 cm and 20 cm) while all other mixtures tested gained enough viscosity immediately after cementing to have low $f_i$.

Further, most (i.e. three of four) mixtures where an initial soil moisture content of 135% was evaluated produced enough viscosity to make $f_i$ measurements reach a minimum of 7.6 cm within 30 minutes of mixing. Practically speaking, it would be easiest to place a LC-VHMS mixture with 2.5% cement and initial moisture content of 155%.
As shown in Figure 4.5, there is a good correlation between average $q_{u-i}$ and $q_{u-30min}$. When initially considering results of specimens of comparable treatment in Figure 4.5a, it appears that there is little change in $q_u$ as a result of a 30 minute holding period prior to molding. However, when removing results of specimens made with comparable treatments but differing batches (Figure 4.5b), trends analysis supports that there could be a modest increase in $q_u$ as a result of a 30 minute holding time prior to molding. This is useful as it gives time between mixing cement into VHMS and placement of this material without causing a detrimental effect on strength properties.

When performing 95% confidence level matched pair $t$-tests of data presented in Figure 4.5, different results are reached with respect to considering data presented in Figure 4.5a and Figure 4.5b. A 95% confidence level matched pair $t$-test of data presented in Figure 4.5a supports that there is no significant effect of a 30 minute holding time on $q_u$. However, a 95% confidence level matched pair $t$-test of data presented in
Figure 4.5b supports that there is a significant effect of a 30 minute holding time with respect to $q_u$ with a $p$-value of 0.001 and an average increase in $q_u$ of 4.1 kPa for specimens which were held for 30 minutes prior to molding. Due to the nature of cementitious reactions, there is likely a maximum amount of time that LC-VHMS mixtures can be held without causing detrimental effects to late age properties. However, the data presented herein suggests that it would be reasonable for a LC-VHMS mixture to be mixed and not placed for up to 30 minutes without causing detrimental effects to compressive strength. For statistical considerations in Section 4.3.3, matched pair $t$-tests from Figure 4.5a are considered as Section 4.3.3 considers all data points shown in Figure 4.5a.

4.3.3 Non-Construction Timing Statistical Evaluations

This section provides analysis to characterize the effects of non-construction timing factors in LC-VHMS production. As presented in Section 4.3.2, there is not sufficient evidence of a significant effect of holding time on $q_u$ for the data set presented in this section (i.e. Figure 4.5a). Thus, a single randomized complete block design statistical evaluation with a $2^3$ factorial arrangement of treatments may be used to characterize the effects of varying treatments (i.e. cement content, cement type, and water content) while using cure time as a block factor. The ANOVA shown in Table 4.2 represents the results of the analyses for UC results following 28 days and 56 days of curing.
Table 4.2  Non-Construction Speed Effects ANOVA

<table>
<thead>
<tr>
<th>Source</th>
<th>d.f.</th>
<th>p-value</th>
<th>Sig?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (corrected)</td>
<td>95</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Cure Time</td>
<td>1</td>
<td>0.0010</td>
<td>Yes</td>
</tr>
<tr>
<td>Cement Cont.</td>
<td>1</td>
<td>&lt;0.0001</td>
<td>yes</td>
</tr>
<tr>
<td>Cement Type</td>
<td>1</td>
<td>&lt;0.0001</td>
<td>yes</td>
</tr>
<tr>
<td>Cement Cont. × Cement Type</td>
<td>1</td>
<td>0.5931</td>
<td>no</td>
</tr>
<tr>
<td>Water Cont.</td>
<td>1</td>
<td>&lt;0.0001</td>
<td>yes</td>
</tr>
<tr>
<td>Cement Cont. × Water Cont.</td>
<td>1</td>
<td>0.6719</td>
<td>no</td>
</tr>
<tr>
<td>Cement Type × Water Cont.</td>
<td>1</td>
<td>0.4173</td>
<td>no</td>
</tr>
<tr>
<td>Cement Cont. × Cement Type × Water Cont.</td>
<td>1</td>
<td>0.5835</td>
<td>no</td>
</tr>
<tr>
<td>Cont.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>87</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

As expected, the Table 4.2 ANOVA supports that there is a significant effect of cure time, cement content, cement type, and water content on $q_a$ after 28 days and 56 days of curing. Further, there is no significant interaction between the three treatments considered. Thus, the effect of each treatment may be considered independently of one another. Figure 4.6 presents mean response plots for $q_a$ with the average change and standard deviation of changes in $q_a$ for each of the LC-VHMS treatments considered.
Figure 4.6  Mean Response Plots of $q_u$ vs.: a.) Cement Content, b.) Cement Type, and c.) Moisture Content
Figure 4.6 (Continued)

According to the analysis of variance provided in Table 4.3, all three treatment factors produce significant effects on $q_u$ of LC-VHMS for the mixtures tested. Because there is not significant interaction present for the data set in question, it is reasonable to make conclusions for the effects of individual treatments considered in this section. From the data set in question, the following conclusions can be made for this combination of dredged material and cements:

- An increase in cement content from 2.5% to 5.0% produced an average increase in $q_u$ of 40.6 kPa irrespective of moisture content or cement type.
- On average, LC-VHMS mixtures produced using PLC had 8.5 kPa higher $q_u$ than mixtures produced using OPC.
- An increase in moisture content from 135% to 155% produced an average decrease in $q_u$ of 11.0 kPa irrespective of cement content or cement type.
4.4 Multiple Marginal Materials Testing

Lightly cemented mixtures containing multiple marginal materials were stabilized and tested in phase III of this thesis, and results are presented herein. Compressive strengths resulting from UC testing are shown in Figure 4.7. It should be noted that each bar in Figure 4.7 is an average of three specimens cured for the same amount of time and produced from one mixture of stabilized marginal materials. Compressive strengths of 20 kPa to 117 kPa were obtained when stabilizing bottom ash and dredged materials simultaneously, and these results are discussed in the following paragraphs.

As expected, $q_u$ tends to increase with additional cement and additional cure time. Note that $q_u$ was meaningfully less for specimens fabricated using 5.0% PLC and 40% bottom ash after 56 days of curing than for identical specimens which were cured for 7 days or 28 days. The author has reason to believe this is a result of testing error and that
true values exceeded 65 kPa. Compressive strengths of 5% PLC – 40% bottom ash mixtures at 56 days are likely higher than as measured. A randomized block statistical evaluation was used to evaluate the effects of bottom ash content and cement type in mixtures with 5.0% cement. Results are provided in Table 4.3, and evaluations in this section do not consider mixtures with 40% bottom ash due to the suspected testing error.

Table 4.3  Multiple Marginal Material Mixtures ANOVA

<table>
<thead>
<tr>
<th>Source</th>
<th>d.f.</th>
<th>p-value</th>
<th>Significant?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (Corrected)</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cure Time (Block)</td>
<td>2</td>
<td>&lt;0.0001</td>
<td>Yes</td>
</tr>
<tr>
<td>Cement Type x Ash Content</td>
<td>1</td>
<td>&lt;0.0001</td>
<td>Yes</td>
</tr>
<tr>
<td>Cement Type</td>
<td>1</td>
<td>&lt;0.0001</td>
<td>Yes</td>
</tr>
<tr>
<td>Ash Content</td>
<td>1</td>
<td>&lt;0.0001</td>
<td>Yes</td>
</tr>
<tr>
<td>Error</td>
<td>30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As shown in Table 4.3, cure time produces a statistical difference in $q_u$, 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, which makes it inappropriate to consider effects of individual treatments. It is inappropriate to individually consider treatments with interaction because the effects of one treatment factor can be altered as the level of another treatment changes when interaction is present. However, 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 4.4. It is 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 $f_i$ would likely be added, and all these combinations had the same $f_{\text{pre-cement}}$.

Table 4.4  Ranking of Cement Type and Bottom Ash Content Combinations

<table>
<thead>
<tr>
<th>Cement Type</th>
<th>Bottom Ash Content (%)</th>
<th>Cement Content (%)</th>
<th>Mean $q_u$ (kPa)</th>
<th>t-group</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC</td>
<td>20</td>
<td>5</td>
<td>103.0</td>
<td>A</td>
</tr>
<tr>
<td>PLC</td>
<td>20</td>
<td>5</td>
<td>69.4</td>
<td>B</td>
</tr>
<tr>
<td>OPC</td>
<td>0</td>
<td>5</td>
<td>68.6</td>
<td>B</td>
</tr>
<tr>
<td>PLC</td>
<td>0</td>
<td>5</td>
<td>65.7</td>
<td>B</td>
</tr>
</tbody>
</table>

4.5  ASTM D 4318 Results

Results of Atterberg limit testing are presented in this section. Strength properties of mixtures evaluated using ASTM D 4318 are described in Section 4.3 and Section 4.4.

4.5.1  ASTM D 4318 Results of LC-VHMS Mixtures

Figure 4.8 presents results of Atterberg Limits testing for LC-VHMS mixtures containing only cement and dredged sediments from Memphis, TN. These properties
include liquid limit (LL), plastic limit (PL), and plasticity index (PI), which were measured after 56 days of curing on specimens molded immediately after mixing.

Strength properties of mixtures presented in Figure 4.8 are discussed in Section 4.3, and properties of non-stabilized dredged materials are provided for comparison in each of the four cement stabilization portions in Figure 4.8.

![Graph showing ASTM D 4318 Results for LC-VHMS Mixtures After 56 Days of Curing](image)

Plasticity indices resulting from light cement stabilization ranged from 23 to 32 with an average PI of 28 being less than half of the PI for unstabilized dredged material from Memphis. As expected, there seems to be a meaningful decrease in plasticity index due to the incorporation of cement with dredged materials from Memphis. This change appears to be predominately caused by a large decrease in LL. This change is expected due to cationic exchange between Ca$^{++}$ from cement with Na$^{+}$ and K$^{+}$ from clay particle surfaces (Mitchell, 1976).
Though there was no replication in Figure 4.8, a randomized complete block statistical design can be used to evaluate changes in PI while considering moisture content and cement type as treatment factors and cement type as a block factor. Table 4.5 presents results of an ANOVA where PI is considered as the response. There was not sufficient evidence to determine significant differences between treatment factors considered based on the Table 4.5 ANOVA. However, there was a meaningful decrease in PI for all mixtures after stabilizing with cement.

Table 4.5  ANOVA of Plasticity Index for LC-VHMS Mixtures

<table>
<thead>
<tr>
<th>Source</th>
<th>d.f.</th>
<th>p-value</th>
<th>Sig?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (corr)</td>
<td>7</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Cement Type</td>
<td>1</td>
<td>1.0000</td>
<td>no</td>
</tr>
<tr>
<td>Cement Cont.</td>
<td>1</td>
<td>0.1635</td>
<td>no</td>
</tr>
<tr>
<td>Water Cont.</td>
<td>1</td>
<td>0.0917</td>
<td>no</td>
</tr>
<tr>
<td>Water Cont. x Cement Cont.</td>
<td>1</td>
<td>0.5836</td>
<td>no</td>
</tr>
<tr>
<td>Error</td>
<td>3</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

4.5.2  ASTM D 4318 Results of Multiple Marginal Materials

Figure 4.9 presents results of Atterberg limit testing for mixtures of multiple marginal materials. Properties of non-stabilized dredged materials are provided for comparison in each of the three cement stabilization portions of Figure 4.9, and strength properties of mixtures evaluated in Figure 4.9 are provided in Section 4.4.
As expected there seems to be a meaningful decrease in PI when dredged materials are stabilized using bottom ash and cement. Resulting plasticity indices for mixtures including bottom ash, dredged sediments, and cement ranged from 20 to 27 with an average of 23. The cause of PI reduction is expected to be the result of cation exchange between stabilization materials and clay particle surfaces. A randomized block statistical design considering cement type as a block factor and treatment factors of bottom ash content and cement content was used to investigate the potential for varying amounts of bottom ash to cause significant effects on PI. The ANOVA presented in Table 4.6 presents the results of that evaluation. However, there is not sufficient evidence to draw significant conclusions from Table 4.6.
Table 4.6  ANOVA of Plasticity Index for Multiple Marginal Material Mixtures

<table>
<thead>
<tr>
<th>Source</th>
<th>d.f.</th>
<th>p-value</th>
<th>Sig?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (corr)</td>
<td>8</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Cement Type</td>
<td>1</td>
<td>0.2697</td>
<td>no</td>
</tr>
<tr>
<td>Cement Cont.</td>
<td>1</td>
<td>0.2697</td>
<td>no</td>
</tr>
<tr>
<td>Ash Cont.</td>
<td>2</td>
<td>0.1094</td>
<td>no</td>
</tr>
<tr>
<td>Ash Cont. x Cement Cont.</td>
<td>2</td>
<td>0.1694</td>
<td>no</td>
</tr>
<tr>
<td>Error</td>
<td>2</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

4.6  Summary of Test Results

Based on results presented in earlier sections of this chapter, there are several recommendations that can be made for groups desiring to beneficially reuse dredged materials in a LC-VHMS application. First, for mixtures containing a single cement content and dredged material source, it is recommended to evaluate corresponding $q_u$ and $f_i$ for varying moisture contents to determine the most suitable moisture content (or $f_i$) to perform stabilization where the best combination of $q_u$ and $f_i$ is considered. Secondly, there is evidence that LC-VHMS mixtures can be produced in a slurry state and held for at least 30 minutes prior to being placed into the final location without causing detrimental effects to $q_u$ at later ages.

Of the stabilization methods utilized, there were a wide range of UC strengths observed for mixtures containing only dredged sediments and cement ranging from approximately 10 kPa to almost 80 kPa. It was further observed that the following changes resulted in an increase in UC strength: increase in cement content, changing
cement type from OPC to PLC, and reducing the initial water content. For mixtures utilizing multiple marginal materials (i.e. dredged sediments and bottom ash), $q_u$ ranged from approximately 25 to 117 kPa after 28 to 56 days of curing. It should be noted that mixtures containing multiple marginal materials were produced to have similar $f_i$ behaviors prior to cementing, and mixtures containing bottom ash required lower initial moisture contents to achieve desirable $f_i$ behaviors. There was also evidence that OPC mixtures containing bottom ash produced higher $q_u$ after curing than PLC mixtures containing bottom ash.

Results of a series of ASTM D 4318 tests show that there is a meaningful decrease in PI of dredged materials when lightly cemented, predominately through LL reduction. Due to low replication of ASTM D 4318 results, ANOVA provided few results for comparing PI of one stabilization method to another. However, plasticity indices for LC-VHMS mixtures ranged between 22 and 30 with an average reduction in PI of 27 while mixtures containing multiple marginal material mixtures achieved PI between 20 and 27 with an average reduction in PI of 23.
CHAPTER V
DISCUSSION OF SUSTAINABILITY AND FEASIBILITY

5.1 Overview

This chapter provides discussion of sustainability and overall feasibility of utilizing lightly cemented marginal materials (e.g. dredged soils and bottom ash) in and around ports. Section 5.2 provides discussion of sustainability factors relative to the beneficial reuse of dredged materials in and around ports, and Section 5.3 discusses factors making the beneficial reuse of lightly cemented marginal materials feasible.

Two approaches to beneficially reuse marginal materials that are documented in Chapter 2 are: 1.) use a lightly cemented marginal material mixture to act as backfill to produce elevation changes desired for landside development (e.g. Tsuchida et al. 2001; Tanaka et al. 2009; Oota et al. 2009; Nakai et al. 2009; Zele et al 2014) and 2.) construct a wall or dike using geotextile tubes in a pyramid formation (e.g. Howard et al. 2009; Howard et al. 2012; Karnati et al. 2012) that could be filled with lightly cemented marginal materials. These two approaches have the potential to be used independently or in conjunction to improve sustainability and economic competitiveness.

5.2 Sustainable Development

As presented in Chapter 2, the three factors of sustainability that stem from the definition presented at the 2005 world summit were: social development, economic development, and environmental protection. This section provides discussion of these
three factors from the viewpoint of a group considering to lightly cement marginal materials for beneficial reuse in and around ports, but the majority of discussion is aimed at the discussion of carbon emissions contributed by using traditional materials versus lightly cemented marginal materials.

5.2.1 Social Development

There is little question that society depends heavily on the shipping industry for the transfer of goods and services domestically and internationally. As discussed in Section 2.4.1.1, there is a staggering amount of freight moved per capita in the US on an annual basis. Further, the recently completed expansion of the Panama Canal discussed in Harrison and Trevino (2013) and Ashar and Swigart (2007) has been predicted to produce widespread changes to port practices throughout the southeast US.

A primary change anticipated in the US infrastructure is the overall improvement of the intermodal freight system that the US heavily depends on (Landers, 2016). According to Ashar and Swigart (2007), all five deep water ports of interest as competitors to the port of New Orleans were working on plans to make improvements to usable waterfront land areas at their respective facilities in 2007. Harrison and Trevino (2013) stated that the Port of Houston Authority anticipated reaching terminal capacity without the improvement of port inefficiencies, and landside access improvements for truck and rail were discussed as potential efficiency improvement options. However, obtaining adequate construction materials for land-side development can be difficult (Grubb et al. 2010b; Meitzen 2013; Tsuchida et al. 2001).

A secondary issue relative to the maintenance of ports and harbors which meet the needs of society is the effective management of dredged sediments. As shown in the
practice review provided in Chapter 2, a common theme of ports described in Section 2.2 of this thesis is to dispose of dredged sediments in confined disposal facilities while having considered beneficial reuse of dredged sediments in the past. However, at least two ports (Mobile, Alabama and Manatee, Florida) indicated that dredged material management costs can increase considerably once traditional dredged material placement areas reach capacity.

If feasible for construction use, the ability to beneficially reuse dredged sediments for landside development projects could be an opportunity to simultaneously meet two societal needs: providing usable materials near ports and providing often much needed dredged sediment management capacity.

5.2.2 Economic Development

The second sustainability factor discussed in this chapter is the ability of lightly cemented marginal materials to economically benefit ports utilizing lightly cemented materials. Rural ports with ample land available for disposal of dredged sediments or modest amounts of dredged sediment production are unlikely to economically benefit by reusing dredged sediments. However, there are some factors that could combine to make beneficial reuse economical for ports with land constraints or high volumes of dredged sediment.

There were three respondents to the survey in Section 2.2 that provided unit costs related to the dredging and disposal of sediments. The responses included a wide range of costs for dredging and up-land disposal costs ranging from $4/m³ for facilities with sufficient capacity to dispose of dredged sediments on site up to $18/m³ for ports having to excavate and transport dredged sediments off-site for disposal. One port provided a
cost estimate for materials which ranged from $4 to $12 per m³ for importing raw materials used to construct additional capacity for an on-site dredged material confinement area. The combination of savings incurred through minimizing off-site disposal and imported materials could prove beneficial for a port with a large volume of dredged sediments such as Mobile, Alabama (Lovelace, 2014). One example from literature that produced a reported $50 million in savings through the beneficial reuse of dredged materials was the Embraport container terminal discussed in Section 2.3.1.3.

5.2.3 Environmental Protection

This section makes comparisons between the carbon footprint of raw materials once delivered to construction sites based on the applications described in Section 5.1 (i.e. use as fill material or in wall construction). Section 5.2.3.1 presents a comparison of carbon footprints using traditional materials versus lightly cemented marginal materials for fill, and Section 5.2.3.2 presents a comparison of carbon footprints for constructing retaining walls out of traditional materials (i.e. concrete) or lightly cemented marginal materials encased in geotextile tubes. It is worth noting that the following two sections do not consider any specific project, but are provided to discuss potential implications for substituting LC-VHMS for more traditional materials.

5.2.3.1 Carbon Footprint of Fill Materials

This section presents a hypothetical comparison between the carbon footprint of 1 m³ of LC-VHMS and 1 m³ of more traditional materials (e.g. construction aggregates or bentonite clay). Some assumptions and boundaries were maintained to make this evaluation possible: 1.) final in place material densities were assumed to be 1,800 kg/m³;
2.) dredged materials were not considered to contribute to carbon footprint as materials would likely pre-exist on site; 3.) on-site construction practices were not considered as construction practices could be highly variable irrespective of the construction materials used.

Information from Shillaber et al. (2016), which presents an approach for determining the embodied energy and carbon contribution of ground improvement works, was used to determine an estimated carbon footprint contributed by transporting traditional materials to a construction site. From information provided, it can be estimated that 8.6 to 181.8 kgCO₂ would be embodied in each m³ of fill if the materials had final densities of 1800 kg/m³ and the embodied carbon was between that for aggregates (0.0048 kgCO₂/kg) and bentonite clay (0.101 kgCO₂/kg). Further, it was estimated that 0.08 to 3.18 kgCO₂/m³ of material with a final density of 1800 kg/m³ would be emitted by trucking materials between 0.4 km and 16.1 km using class 8 heavy duty trucks. This trucking emissions estimate includes the average fuel mileage (2.42km/L) and truck payload (240kN) of class 8 heavy duty trucks and the carbon emissions of diesel fuel (3.25 kgCO₂/L). Thus, a total carbon footprint of materials delivered to a project was estimated to be 8.7 to 185.0 kgCO₂/m³.

The carbon footprint contributed by utilizing lightly cemented marginal materials already existing at a construction project was determined based on the carbon embodied in cement and the carbon emitted through transporting cement to the project site. Using the approach for determining transportation emissions used in the previous paragraph, between 1.36 (10⁻⁵) and 1.77 (10⁻³) kg CO₂ could be emitted per 1 kg of cement trucked a distance of 0.4 km to 16.1 km using class 8 heavy duty trucks (Shillaber et al. 2016).
Further, the amount of carbon embodied per kg of cement was assumed to be between 0.85 kgCO₂ and 0.95 kgCO₂ (Shillaber et al. 2016; Bushi and Meil, 2014). Thus 1 m³ of material with a density of 1800 kg/m³ and a cementitious content ranging from 2.4% to 4.8% by total mass (note 2.4% and 4.8% cement by total mass corresponds to 2.5% and 5.0% cement by slurry mass, respectively) could embody between 38.3 and 85.6 kgCO₂/m³ if the carbon embodied in dredged sediments was disregarded.

Based on the estimations in this section, the carbon footprint of fill materials used for landside development could be similar between LC-VHMS and traditional fill materials if the proper materials were available within a 16 km radius. There are some combinations where the carbon footprint of traditional fill materials are much higher than that estimated for LC-VHMS. However, there are also some combinations where traditional materials could be a more environmentally sustainable option over LC-VHMS mixtures. Note this estimate does not necessarily consider all factors at any given project.

### 5.2.3.2 Carbon Footprint of Retaining Wall Materials

To compare the carbon footprint for retaining wall construction materials, three approximate heights of retaining wall were considered herein ranging from approximately 2.5 m to 5 m. Considerations for the carbon footprint of concrete retaining walls include the carbon footprint embodied in raw concrete materials while considerations for walls built using geotextile tubes and LC-VHMS mixtures consider the carbon footprint embodied in geotextile tube materials and that of lightly cemented marginal material mixtures calculated in Section 5.2.3.1.

Many concrete retaining wall designs could be considered, but the assumption to construct a gravity retaining wall of concrete is used for the purposes of carbon footprint
calculations. Approximate dimensions to begin the design for a gravity retaining wall are provided in Figure 5.1 as shown in Das (2011). A minimum wall thickness of 0.3 m and total elevation changes of 2.5 m, 3.5 m, and 5.0 m were used for calculations. Approximate ranges of concrete materials used per unit length of wall are provided in Table 5.1 (Note these volumes of concrete materials in a retaining wall are provided for comparison purposes only, and not for specific projects). Further, there are approximately 272 to 299 kgCO₂ embodied per m³ of concrete mixture (Bushi and Meil, 2014). This comparison considers a single concrete mixture with OPC or PLC replacement. Carbon footprints per linear meter of concrete retaining wall are provided for each height of retaining wall considered in Table 5.1.

Figure 5.1 Initial Ratios for Gravity Retaining Walls (Dimensions from Das, 2011)
Table 5.1  Concrete Wall Volume and Carbon Footprint

<table>
<thead>
<tr>
<th>Retaining Wall Height (m)</th>
<th>Volume per Length of Wall (m³/m)</th>
<th>Carbon Footprint (tCO₂e/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>1.13 to 5.31</td>
<td>0.31 to 1.59</td>
</tr>
<tr>
<td>3.5</td>
<td>1.85 to 10.41</td>
<td>0.50 to 3.11</td>
</tr>
<tr>
<td>5.0</td>
<td>3.21 to 21.25</td>
<td>0.87 to 6.35</td>
</tr>
</tbody>
</table>

Five preliminary configurations for geotextile tube walls filled with LC-VHMS are described in the Table 5.2 and Table 5.3, which are based on approximate calculations in Howard and Trainer (2011). For cases where more than one geotextile tube is considered, additional layers are all assumed to contain one less geotextile tube than the layer which it is supported by. As shown in Figure 5.2, additional layers of geotextile tubes could experience an estimated 67% of elevation change compared to that experienced if geotextile tubes were sitting on a flat surface (note this estimation is based on stacking and not on the effects of consolidation.) Further, the shortest wall considered herein (2.5 m) could potentially be constructed using a single geotextile tube, but taller walls considered would likely be constructed in a pyramid configuration using multiple layers of geotextile tubes.
Table 5.2  Volumes of Geotextile Tube Walls

<table>
<thead>
<tr>
<th>Potential Wall Height (m)</th>
<th>No. of Tubes</th>
<th>Tube Material</th>
<th>Tube Circumference (m)</th>
<th>h (m)</th>
<th>B (m)</th>
<th>W (m)</th>
<th>V (m$^3$/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.65</td>
<td>1</td>
<td>GT 1000M</td>
<td>13.72</td>
<td>2.65</td>
<td>3.83</td>
<td>5.49</td>
<td>12.22</td>
</tr>
<tr>
<td>3.64</td>
<td>3</td>
<td>GT 1000M</td>
<td>9.14</td>
<td>2.18</td>
<td>1.80</td>
<td>3.39</td>
<td>18.27</td>
</tr>
<tr>
<td>3.46</td>
<td>3</td>
<td>GT 500</td>
<td>9.14</td>
<td>2.07</td>
<td>2.01</td>
<td>3.46</td>
<td>17.82</td>
</tr>
<tr>
<td>5.10</td>
<td>6</td>
<td>GT 1000M</td>
<td>9.14</td>
<td>2.18</td>
<td>1.80</td>
<td>3.39</td>
<td>36.54</td>
</tr>
<tr>
<td>4.84</td>
<td>6</td>
<td>GT 500</td>
<td>9.14</td>
<td>2.07</td>
<td>2.01</td>
<td>3.46</td>
<td>35.64</td>
</tr>
</tbody>
</table>
The carbon footprints of raw materials to construct the five potential configurations described in Table 5.2 are presented in Table 5.3. The carbon footprint contributed by geotextile tubes was estimated based on tube circumference, specified geotextile tube material, geotextile tube densities provided in Vahedifard et al. (2015), and carbon footprint estimates provided by TenCate™ for geotextile materials. Geotextile tube materials used in Vahedifard et al. (2015) were 585 g/m² for GT 500 materials and 1119 g/m² for GT 1000M materials, and information provided by TenCate™ suggested that the carbon footprint embodied per kg of geotextile tube material could be on the order of 4.5 to 5.0 kgCO₂ depending on raw materials and manufacturing process.

Table 5.3  Carbon Footprint of Geotextile Tube Walls

<table>
<thead>
<tr>
<th>Potential Wall Height (m)</th>
<th>No. of Tubes</th>
<th>Tube Circumference (m)</th>
<th>Tube Material</th>
<th>Carbon Footprint</th>
<th>Geotextile Tube (tCO₂/m)</th>
<th>LC-VHMS (tCO₂/m)</th>
<th>Total (tCO₂/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.65</td>
<td>1</td>
<td>13.72</td>
<td>GT 1000M</td>
<td></td>
<td>0.07 to 0.08</td>
<td>0.47 to 1.05</td>
<td>0.54 to 1.13</td>
</tr>
<tr>
<td>3.64</td>
<td>3</td>
<td>9.14</td>
<td>GT 1000M</td>
<td></td>
<td>0.14 to 0.15</td>
<td>0.70 to 1.56</td>
<td>0.84 to 1.71</td>
</tr>
<tr>
<td>3.46</td>
<td>3</td>
<td>9.14</td>
<td>GT 500</td>
<td></td>
<td>0.07 to 0.08</td>
<td>0.68 to 1.53</td>
<td>0.75 to 1.61</td>
</tr>
<tr>
<td>5.10</td>
<td>6</td>
<td>9.14</td>
<td>GT 1000M</td>
<td></td>
<td>0.28 to 0.31</td>
<td>1.40 to 3.13</td>
<td>1.68 to 3.44</td>
</tr>
<tr>
<td>4.84</td>
<td>6</td>
<td>9.14</td>
<td>GT 500</td>
<td></td>
<td>0.14 to 0.16</td>
<td>1.36 to 3.05</td>
<td>1.50 to 3.21</td>
</tr>
</tbody>
</table>

As shown in Table 5.1 and Table 5.3, the total carbon footprint for raw materials used to construct retaining walls from 2.5 m to 5.0 m tall could be highly variable for walls of similar height. The carbon footprints of concrete walls with heights on the order of 2.5 m, 3.5 m, and 5.0 m were estimated to be 0.31-1.59 tCO₂, 0.50-3.11 tCO₂, and
0.87-6.35 tCO₂, respectively. The carbon footprints of geotextile tube walls on the order of 2.5 m, 3.5 m, and 5.0 m tall were estimated to be 0.54-1.13 tCO₂, 0.75-1.71 tCO₂, and 1.50-3.44 tCO₂, respectively. Much like the carbon footprint of fill materials evaluated in the previous section, carbon footprints of LC-VHMS walls have potential to be much lower than the carbon footprint of concrete walls with the same height. However, carbon footprints of LC-VHMS walls are likely to be at least comparable to carbon footprints of traditional walls. Note the estimates in this section do not necessarily consider all factors at any given project.

5.3 Feasibility

The feasibility of using lightly cemented marginal materials for applications in and around ports is largely determined by the engineering properties of the mixtures produced. This section discusses the implications of engineering properties measured in Chapter 4 with respect to the feasibility of utilizing the mixtures in construction applications. This section focuses on the engineering properties necessary to construct a geotextile tube wall using LC-VHMS as fill. Section 5.3.1 discusses results of early age properties (i.e. $f_i$) and Section 5.3.2 discusses results of late age properties (i.e. $q_u$ and Atterberg Limits).

5.3.1 Early Age Properties of Lightly Cemented Mixtures

According to NRMCA (n.d.), the recommended $f_i$ of a controlled low strength mixture that is placed without the use of compaction or consolidation is on the order of 20 cm. While mixtures with a higher $f_i$ are likely to be easier to place into geotextile tubes, it would be at best more difficult for mixtures exhibiting no $f_i$ to be placed into a
geotextile tube. Table 5.4 presents a summary of which mixtures exhibit more feasible $f_i$ behaviors immediately after and up to 30 minutes after mixing with cement. Moisture contents on the order of 135% or less (i.e. $f_{\text{pre-cement}}$ less than 20 cm) are unlikely to be adequate for applications such as this as there is minimal time after mixing that LC-VHMS mixtures could be pumped into geotextile tubes (this scenario is for a soil with a LL of 90%). Moisture contents of 155% (i.e. $f_{\text{pre-cement}}$ higher than 20 cm) decreased viscosity meaningfully enough to allow time for mixtures to be mixed and handled for up to 30 minutes while maintaining measurable $f_i$ prior to placement.
Table 5.4 Consistency Feasibility Summary

<table>
<thead>
<tr>
<th>Moisture Content (%)</th>
<th>Cement Content (%)</th>
<th>Cement Type</th>
<th>30min Feasible</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>135</td>
<td>5.0</td>
<td>PLC</td>
<td>No</td>
</tr>
<tr>
<td>145</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>155</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>135</td>
<td>2.5</td>
<td>OPC</td>
<td>No</td>
</tr>
<tr>
<td>135</td>
<td></td>
<td>PLC</td>
<td>Yes(^1)</td>
</tr>
<tr>
<td>155</td>
<td>5.0</td>
<td>OPC</td>
<td>No</td>
</tr>
<tr>
<td>155</td>
<td></td>
<td>PLC</td>
<td>No</td>
</tr>
<tr>
<td>135</td>
<td>2.5</td>
<td>OPC</td>
<td>Yes</td>
</tr>
<tr>
<td>155</td>
<td></td>
<td>PLC</td>
<td>Yes</td>
</tr>
<tr>
<td>155</td>
<td>5.0</td>
<td>OPC</td>
<td>Yes</td>
</tr>
<tr>
<td>155</td>
<td></td>
<td>PLC</td>
<td>Yes</td>
</tr>
</tbody>
</table>

\(^1\)fi, 30 min was measurable, but less than 8 cm.
\(^2\)fi, 30 min above 7.6 cm is considered feasible.

5.3.2 Late Age Properties of Lightly Cemented Mixtures

Late age properties of lightly cemented marginal mixtures measured in Chapter 4 were \(q_u\) and Atterberg Limits. This section presents a discussion of feasibility through adequate strength properties with respect to \(q_u\) results obtained in Chapter 4 and slope stability calculations performed in Vahedifard et al. (2015). Because there was no

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significant difference in plasticity index for stabilized mixtures in Chapter 4, this section does not consider Atterberg Limits as feasibility factors.

The following four paragraphs consider walls constructed using a pyramid configuration of geotextile tubes filled with LC-VHMS as described in Figure 5.2 and Table 5.2. Two-dimensional limit equilibrium slope stability analysis was utilized to determine what level of $q_a$ would be appropriate for wall construction using LC-VHMS. A 2.5 m tall wall such as the one considered in Section 5.2.3.2 could likely be constructed using a single geotextile tube, and would be unlikely to experience slope failure if an adequate foundation was used. (Note: foundation considerations are not within the scope of this thesis.) Thus, only two wall heights (3.5 m and 5.0 m) were considered in slope stability calculations which could be used for construction phasing and are used in this section to determine adequate material strengths for wall configurations. Wall heights of 3.5 m and 5.0 m were assumed to be constructed using 3 and 6 geotextile tubes, respectively.

Calculations maintained several simplifying assumptions as this section focuses primarily on the concept of using lightly cemented mixtures in wall construction and not on any one project. Walls were assumed to be of homogenous composition, which is likely conservative as geotextile tubes could provide some degree of resistance to shear stresses. Slopes were also assumed to be uniform with a unit weight of 1.8 g/cm$^3$, and foundations were assumed to be adequate to prevent deep-seated failures. Wall geometries maintained uniform crest widths of 2.0 m for both considerations, and base widths were assumed to be 7 m and 10 m for wall heights of 3.5 m and 5.0 m.
respectively (Note: these approximate wall base widths correspond to two or three times the width of filled geotextile tubes from Table 5.2).

SLIDE was used to perform a two-dimensional limit equilibrium slope stability analysis using Spencer’s method, which explicitly satisfies all three equilibrium conditions (i.e. horizontal forces, vertical forces, and moment equilibrium conditions). Undrained conditions were considered as undrained shear strength and short-term conditions would be of most concern when constructing a wall using LC-VHMS. Slope angles of the previously described wall geometries were 54.5° and 51.3° when measured from horizontal for wall heights of 3.5 m and 5.0 m, respectively. Further, evaluations for both wall heights considered only one slope as walls were assumed to be symmetric. Results of the analysis suggest that $q_u$ of 18 kPa and 24 kPa would provide a factor of safety (FS) of 1.5 for wall heights of 3.5 m and 5.0 m, respectively.

Table 5.5 presents a summary for combinations of moisture content, cement content, and cement type that could be adequate for utilization in geotextile tube walls based on $q_u$ results presented in Chapter 4. As shown, mixtures with 5.0% cement mobilized enough strength to support wall heights of up to 5.0 m after 28 days of curing for all cases considered (note that values measured in Chapter 4 are likely conservative as they do not permit dewatering or consolidation due to submerged curing). However, mixtures with 2.5% cement content and 155% moisture content prior to cementing did not mobilize enough strength to support 5.0 m tall walls (again note the conservative $q_u$ measurement methods).
<table>
<thead>
<tr>
<th>Moisture Content (%)</th>
<th>Cement Content (%)</th>
<th>Cement Type</th>
<th>Adequate 28 day $q_u$?</th>
<th>Adequate 56 day $q_u$?</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Yes</td>
<td>Yes</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>120</td>
<td>Yes</td>
<td>Yes</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>135 5.0 PLC</td>
<td>Yes</td>
<td>Yes</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>145</td>
<td>Yes</td>
<td>Yes</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>155</td>
<td>Yes</td>
<td>Yes</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>2.5 OPC</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>135 5.0 OPC PLC</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>2.5 OPC</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>155 5.0 OPC PLC</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Adequate $q_u$, defined as $q_u$ to produce FS ≥ 1.5 based on Chapter 4 $q_u$ results. Chapter 4 $q_u$ results were measured conservatively.

### 5.4 Discussion Summary

This section provides a summary of discussion provided in the previous two sections. Based on discussion provided for sustainability and feasibility, the concept presented in this thesis is a concept worthy of consideration for agencies with limited dredged sediment containment areas and the need for landside development.

For the sustainability discussion where comparison estimates were made between carbon footprint of raw materials in lightly cemented materials and traditional materials,
lightly cemented materials produce at least a comparable if not a lesser impact on the environment from carbon footprint (recall several generalities were made and project specific items were not considered). LC-VHMS as a concept becomes more sustainable when combined with factors which could make its utilization economically feasible while meeting the need for usable construction fill materials for some groups.

While all mixtures tested in this thesis may be useful for some applications, a select few mixtures tested seem best suited for utilization as fill for geotextile tube walls. The mixtures deemed feasible for construction of 3.5 m and 5.0 m tall geotextile tube walls are described in Table 5.6. Mixtures with $f_{\text{pre-cement}}$ above 20 cm seem best suited for applications where flow is required after cementing. However, some mixtures with 2.5% at 155% moisture did not mobilize adequate strength for a 5.0 m tall wall.

Table 5.6 LC-VHMS Mixtures Feasible for Filling Geotextile Tubes

<table>
<thead>
<tr>
<th>Moisture Content (%)</th>
<th>Cement Content (%)</th>
<th>Cement Type</th>
<th>Feasible for 3.5 m wall?</th>
<th>Feasible for 5.0 m wall?</th>
</tr>
</thead>
<tbody>
<tr>
<td>135</td>
<td>2.5</td>
<td>PLC</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>145</td>
<td>5.0</td>
<td>PLC</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>155</td>
<td>2.5</td>
<td>PLC</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>OPC</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Feasible defined as $q_{\text{u}}$ for $FS=1.5$ and measurable $f_{\tau_{30\text{min}}}$.

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CHAPTER VI
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This thesis, which has some overlap with a larger overall study for the National Center for Intermodal Transportation for Economic Competitiveness (NCITEC) and focused on factors relevant to lightly cementing marginal materials in and around ports to increase sustainability and economic competitiveness. Testing herein consisted of flow, unconfined compressive strength, liquid limit, and plastic limit for mixtures of dredged soils from Memphis, TN after stabilization with up to 5.0% cement. Some mixtures also included up to 40% bottom ash to investigate the option of incorporating a secondary marginal material in beneficial reuse.

6.1.1 Practice Review

The practice review showed that very high moisture soils from dredging operations in the southeast US are most commonly disposed of and not commonly treated as a beneficial resource. However, there was a commonality for ports seeking alternatives to off-site disposal if local dredged disposal facilities are nearing capacity.

6.1.2 Flow Testing

- Flow results presented in Section 4.2 show a linear trend for \( f_{pre} \) with respect to moisture content with \( f_{pre} \) ranging from 7.6 cm at 100%
moisture to approximately 30 cm at 155% moisture. Further, mixtures containing 5% PLC and 145% or 155% moisture before mixing produced measurable $f_{\text{post-cement}}$ and $f_{\text{30min}}$ whereas most other mixtures gained enough viscosity within 30 minutes of mixing to have $f_{\text{30min}}$ which was not measurable. Thus, a moisture content of 155% was best suited for mixtures containing no bottom ash.

- Results presented in Section 4.4 included mixtures of dredged soil and bottom ash which were mixed to equal $f_{\text{pre-cement}}$ of 18 cm prior to mixing with cement. It was noted that less moisture was required to achieve equal $f_{\text{pre-cement}}$ as additional bottom ash was incorporated with dredged soils. However, $f_i$ behaviors after mixing with cement were not monitored.

### 6.1.3 Unconfined Compressive Strength Testing

- Results presented in Section 4.2 indicate that additional moisture content was shown to produce a decrease in $q_u$, and a second order polynomial regression was able to produce a reasonable relationship between $q_u$ after 28 days of curing and moisture content between 100% and 155%.

- The effect of cure time had a significant effect on a mixture produced using 5.0% PLC at 135% moisture with strength increasing significantly with time for the first 28 days of curing. However, strength gain appeared to be subsiding after 56 days of curing.
• There was evidence to suggest that there was no detrimental effect to $q_u$ by producing LC-VHMS and delaying mold placement for up to 30 minutes. However, there is an unknown maximum amount of time that mixtures can be cemented prior to placement in final locations before causing detrimental effects to $q_u$.

• Statistical evaluations performed in Section 4.3 support that the following changes produce a statistically significant increase in $q_u$ strength after curing for 28 or 56 days for the dredged materials from Memphis, TN and cement combinations evaluated: increasing cement content from 2.5% to 5.0%; utilizing PLC rather than OPC; and decreasing initial moisture contents from 155% to 135%.

• Results provided in Section 4.4 indicate that mixtures containing bottom ash produced higher $q_u$ after curing than mixtures which did not contain bottom ash. This is likely the result of decreased initial moisture contents to produce equal $f_{\text{pre-cement}}$ of 18 cm. However, increasing bottom ash from 20% to 40% produced a significant decrease in the mixture stabilized with OPC and did not change $q_u$ significantly for the mixture stabilized with PLC.

6.1.4 Atterberg Limits Testing

• Results of Atterberg limit testing provided in Section 4.5 indicate that stabilization of the dredged soil from Memphis, TN produces a meaningful decrease in soil plasticity primarily through the decrease in
liquid limit. However, statistical evaluations of plasticity indices after stabilization indicated there to be no significant changes in plasticity from one stabilization treatment to another. The average decrease in plasticity index was 27 for mixtures containing no bottom ash and 23 for the matrix of mixtures containing 0% to 40% bottom ash.

6.1.5 Sustainability and Feasibility Evaluations

- The sustainability and feasibility discussion provided in Chapter 5 supports that LC-VHMS is a concept worth consideration. Resulting carbon footprints were at least comparable if not more sustainable for circumstances where more traditional construction materials could be replaced with LC-VHMS. Several generalities were involved in the Chapter 5 sustainability estimates and were not for any particular project.

- The most feasible mixtures for utilization in geotextile tube walls up to 5.0 m tall consist of mixtures utilizing moisture contents of 145% or higher and cement contents of 5.0% for the Memphis soil. However, the mixture produced using 2.5% PLC mobilized enough strength after 56 days of curing to be utilized in a 3.5 m tall wall. Recall strengths measured were a conservative case absent dewatering or consolidation.

- The feasibility of utilizing LC-VHMS in a non-encased approach for beneficial reuse was not evaluated as the majority of laboratory evaluations in this thesis were more relevant for approaches where materials would be encased.
6.2 Recommendations

Recommendations relevant to the beneficial reuse of marginal materials near ports and harbors based on the information presented in this thesis are:

- Dredged sediments should, in some cases, be considered as a resource and not as a waste material that must be managed. Port facilities which are facing strained capacities for dredged sediment placement areas should consider beneficial reuse applications such as those presented in this thesis.

- Further research endeavors could consider full scale demonstrations of modest size where lightly cemented dredged sediments are used in conjunction with encased (i.e. in geotextile tubes) and non-encased approaches. For sediments comparable to those tested in this thesis, initial moisture contents on the order of 155% with 5.0% cement content are recommended for encased approaches, and initial moisture contents on the order of 135% with 2.5% cement contents are recommended for non-encased approaches.

- The behaviors of flow and unconfined compressive strength should be evaluated for most projects where beneficial reuse of lightly cemented dredged sediment is considered to optimize the relative behaviors of flow and strength.

- Ports electing to utilize lightly cemented dredged sediments should consider other marginal materials which exist in large quantities around ports for utilization in lightly cemented mixtures. Some possible benefits
of incorporating marginal materials are an increased potential for cementitious reactions (e.g. fly ash) and an increased workability prior to placement (e.g. bottom ash). Any leachate or other environmental considerations should be evaluated.

- Although not considered in the experimental program of this thesis, the approach of producing LC-VHMS mixtures, allowing time for strength gain, dewatering, and later compacting mixtures in-place should be investigated. It is expected that LC-VHMS mixtures which have differing opportunities for dewatering and are handled differently could exhibit differing engineering properties in-place.
REFERENCES


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