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SERRI Report 70015-008

GUIDANCE FOR USING CEMENTITIOUSLY STABILIZED EMERGENCY CONSTRUCTION MATERIALS

OAK RIDGE
National Laboratory

SERRI Project: *Increasing Community Disaster Resilience Through Targeted Strengthening of Critical Infrastructure*

Mississippi State University
CMRC
Construction Materials
Research Center
"An Industry, Agency & University Partnership"

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SERRI Project: Increasing Community Disaster Resilience
Through Targeted Strengthening of Critical Infrastructure

Performing Organization Report No. CMRC-10-05

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SYMBOLS

CBR	California Bearing Ratio
CS	column stabilization
DCP	dynamic cone penetrometer
Dial	Pocket Geotester
E	elastic modulus
E_d	elastic modulus (design) corresponding to s_{ud}
F	friction factor
$\mathrm{G_s}$	apparent specific gravity
H	height
L	length
Lpm	liters per minute
LL	liquid limit
MS	mass stabilization
MPa	Mega Pascal’s
PFM	pneumatic flow mixing
PL	plastic limit
PI	plasticity index
Q	flow rate
SF	safety factor
SGM	super-geo material
Shear	Pocket Vane Shear Set
spl	pump model identifier
W	width
SO_3	sulfur trioxide
$TS_{\%}$	total solids (solid mass divided by total mass) as a percentage
$TS_{\%\text{-}IN}$	entering total solids (solid mass divided by total mass) as a percentage
$TS_{\%\text{-}OUT}$	exiting total solids (solid mass divided by total mass) as a percentage
q_{ult}	ultimate bearing capacity
c	soil cohesion
s_{ud}	laboratory mix design shear strength
V:H	vertical to horizontal slope
w	soil moisture content

ACRONYMNS

ASTM	American Society for Testing and Materials
CEE	Civil and Environmental Engineering
DHS	Department of Homeland Security
ERDC	Engineer Research and Development Center
HBI	Hayward Baker Incorporated
IDNR	Illinois Department of Natural Resources
IHNC	Inner Harbor Navigation Channel
ISTC	Illinois Sustainable Technology Center
JRAC	Joint Rapid Airfield Construction
MSU	Mississippi State University
NRF	National Response Framework
ORNL	Oak Ridge National Laboratory
SERRI	Southeast Region Research Initiative
USACE	United States Army Corps of Engineers
USCS	Unified Soil Classification System
WES	Waterways Experiment Station

EXECUTIVE SUMMARY

This report guides responders in effective use of the cementitiously stabilized high moisture content fine grained soils presented in *SERRI Report 70015-006* for emergency construction applications. Detailed information is presented on key construction equipment: positive displacement pumps, dredges, pugmill mixers, and concrete ready mix trucks. Thereafter, construction guidance and candidate applications are presented. Information obtained in *SERRI Report 70015-003*, *70015-004*, and *70015-007* are also incorporated into this report as appropriate. Construction guidance is given in flowcharts where key equipment is included alongside the appropriate order of activities. A specific example is provided to design a staging platform to support military helicopters in terms of bearing capacity.

The document is somewhat of a compilation report in the sense that it takes information from four other SERRI reports conducted under the same task order and uses them in an overall plan for disaster recovery. This document, however, has information unique to this report as discussed in the previous paragraph. Overall, the recommendation is to incorporate the emergency construction material into disaster recovery and to use positive displacement pumps, dredges, pugmill mixers, and concrete ready mix trucks as key construction equipment.

CHAPTER 1 - INTRODUCTION

1.1 General and Background Information

The work presented in this report was developed in partial fulfillment of the requirements of Task Order 4000064719 sponsored by the *Department of Homeland Security (DHS)* through its *Southeast Region Research Initiative (SERRI)* program administered by *UT-Battelle* at the *Oak Ridge National Laboratory (ORNL)* in Oak Ridge, Tennessee. The research was proposed by members of the *Department of Civil and Environmental Engineering (CEE)* at *Mississippi State University (MSU)* to *SERRI* in a document dated 1 June 2007. The proposed research was authorized by *UT-Battelle* in its task order dated 10 December 2007. This task order included a scope of work defined through joint discussions between *MSU* and *SERRI*. Work on the project was initiated on 1 January 2008. A modification of Task Order 4000064719 was proposed on 9 September 2008 and agreed upon on 29 September 2008. A second Task Order modification dated 22 June 2010 was also performed, which is the Task Order used to generate this report.

The scope of work associated with Task Order 4000064719 included several related components. The general objectives of the project were to investigate means for rapidly using on-site materials and methods in ways that would most effectively enable local communities to rebuild in the wake of a flooding disaster. Within this general framework, several key work components were associated with Task Order 4000064719. Specifically, the scope of work dated 22 June 2010 includes research efforts in the following six task groups:

Task 1: Erosion Control-Erosion Protection for Earthen Levees.

Task 2: Bridge Stability-Lateral & Uplift Stability of Gravity-Supported Bridge Decks.

Task 3: Levee Breach Repair-Closure of Breaches in Flood Protection Systems.

Task 4: Pavement Characterization and Repair.

Task 5: Emergency Construction Material Development-Staging Platform Construction.

Task 6: Fresh Water Reservoir-Restoration of Fresh Water Supplies.

The division of the research effort allowed the work to be broken into manageable portions so that key components could be reported in separate volumes to allow readers to obtain only the work related to their needs. The work contained herein was associated with Task 5. The report of this work was the 8th deliverable of the research project, hence the designation of the report as *SERRI Report 70015-008* of Task Order 4000064719. Work related to Task 5 was also submitted in *SERRI Report 70015-003, SERRI Report 70015-006,* and *SERRI Report 70015-007;* these four reports represent full completion of Task 5.

1.2 Objectives

The general objective of Task Order 4000064719 was to investigate several specific means by which local communities may best use available resources in an effort to rapidly recover from a flooding disaster. In the wake of a flooding disaster, this broad objective would include rebuilding a community with the efforts of a variety of professionals practicing within the physical and social sciences. The research conducted was much more narrowly focused upon certain recovery efforts typically associated with Civil Engineering.

A key component of this research was to develop solutions which may be rapidly deployed to achieve maximum benefit to the community, typically through the use of on-site materials, pre-engineered components, and innovative construction materials and techniques. This research aimed to develop solutions for protecting and/or expeditiously reconstituting critical civil infrastructure components. The research emphasized rapid constructability where existing on-site materials are used to strengthen selected infrastructure components. In this context, the specific objective of the total effort of Task Order 4000064719 was to develop specialty materials and design and construction procedures which may be rapidly deployed to protect and restore selected key civil infrastructure components. Combinations of dredging equipment, small barges, excavating equipment, positive displacement pumps, and soil mixing devices were investigated in terms of their ability to assist in construction of essential temporary infrastructure out of controlled low strength materials.

When areas are inundated with flood waters up to a few meters deep over an area covering many square kilometers, construction materials will be scarce during early recovery stages and any material of reasonable quality will have many uses and the supply will almost certainly not meet the demand. Construction approaches will also be limited in this environment. The objective of this report centers around design and construction guidance for using high moisture content cementitiously stabilized fine grained soils for disaster recovery. The report focuses on equipment and design guidance tailored to disaster environments.

1.3 Scope

For the specific research component described in this report (Task 5), the revised scope of work dated 22 June 2010 includes the nine items summarized below. These nine items are the full deliverable of Task 5; this report fully addresses item g). *SERRI Report 70015-007* fully addresses item d), *SERRI Report 70015-003* fully addresses item i), *SERRI Report 70015-006* fully addresses the remaining six items.

a) Acquire representative material for testing from locations that would be candidates for flooding (e.g. New Orleans and Mobile). The origin of the material will vary from dredging operations to native soils in these types of areas, and will be used throughout testing. Where applicable in-situ moisture contents will be obtained to provide a baseline of properties. Large quantities of three soils will be obtained with varying plasticity and organic content.

b) Characterize basic properties of materials. Testing will be performed to measure: 1) Activity (ASTM D 422), 2) Organic Content (ASTM D 2974 or equivalent), 3) Atterberg Limits (ASTM D 4318), 4) Specific Gravity (ASTM D 854), 5) USCS Classification (ASTM D 2487), 6) Particle Size Distribution (ASTM D 422), 7) XRF, and 8) pH.

c) Develop a comprehensive suite of load response properties with time for the soils described in a) using bench scale testing. The testing protocol will consist of shear strength testing of prepared stabilized slurry slabs and unconfined compression testing as appropriate. Very thin membranes will also be tested in conjunction with the materials. Both types of testing will be intended to simulate shear strength of the stabilized slurries with time over a period of seven days. The aforementioned test protocol was selected for two reasons. The slab testing method will be developed in a manner that will be applicable to on site responders, which makes it highly desirable. The stabilization materials to be blended with the candidate soils include: 1) *Type I* portland cement from both the major types of cement plants, 2) *Type III* portland cement from both major types of cement plants, 3) commercially available rapid set cement, 4) six specialty cements produced specifically from this research (four by interrupting normal production at both major types of portland cement plants and two blended calcium sulfoaluminate cements), 5) ground granulated blast furnace slag, and 6) two types of polymer fibers. This materials protocol includes 14 different stabilization additives encompassing a wide variety of properties. Development of the specialty cements will be performed using laboratory testing including semi-adiabatic calorimetry.

d) Investigate dewatering equipment and materials for applicability in disaster environments, in particular to assist in development of emergency construction materials with secondary emphasis in handling contaminated sediments. The investigation will focus on the use of polymers for dewatering a soil mass and also investigate geotextile tubes. A test environment will be developed where a series of potentially applicable polymers will be tested (in conjunction with scaled geotextile tubes in some instances as appropriate) to determine if the technology can produce sufficient material at an acceptable moisture content for large scale emergency construction material needs. Moisture content variability conditions will also be investigated in the context of dewatering. The effect of dewatering polymers on shear strength in the presence of multiple cements will also be investigated via slab and unconfined compression techniques.

e) Select cementitious materials investigated in the bench scale study c) will be further investigated in a mixing (or blending) study to evaluate effect of key parameters. Examples of key parameters would be cementitious sulfate content and its effect on shear strength and the effect of blending ground granulated blast furnace slag with portland cement in high moisture content fine grained soils.

f) Test the behavior of multiple cement blends (selected from the 14 original blends previously mentioned) in the presence of brackish water and seawater. Testing will be performed via slab and unconfined compression techniques. The bench and mixing studies only incorporate fresh (tap) water. A final blend will be selected for each soil type and set of conditions at the conclusion of this subtask considering all knowledge gained from subtasks a) to f).

g) Develop design and construction guidance (e.g. identifying suitable applications and providing placement and mixing approach) for using the emergency construction material blends developed at the conclusion of subtask f). Use of the material for the purpose of developing a staging platform will be highlighted. Strength and stiffness of the materials developed will be incorporated into the staging platform guidance (e.g. ability of staging platform to support helicopter loads and/or support freight lowered onto platform from a helicopter).

h) Design and construction procedures using the emergency material will be highly dependent upon the stabilized soil blend achieving a given set of properties with time.

For this reason, hand held field shear strength measurement devices will be evaluated statistically for the purpose of assessing risk associated with strength gain measurement over time (precision, accuracy, and repeatability are envisioned to be the focus of the assessment). The results of the hand held gage assessment could be used on site to quantify the impacts of equipment malfunctions, lack of personnel, or other events on the stability of the constructed platform or other structure.

i) Test material obtained from construction site visits in unconfined compression to provide a comparison of the properties of the stabilized blends made from materials obtained in subtask a). It is anticipated that test results will be obtained from three to five sites.

This document (*SERRI Report 70015-008*) is the last of the Task 5 reports. This report provides guidance in using the materials developed in previous reports. *SERRI Report 70015-006* provided discussion pertaining to Task 5 as a whole in the context of the *National Response Framework* (*NRF*).

1.4 Overview of Report

The report focuses on three types of equipment that are key to the disaster recovery process when using fine grained cementitious stabilized slurry: positive displacement pumps, dredges, and large scale mixers. Barges and floats are additional equipment that would likely have value, but their use will be highly application specific and be in a manner in accordance with current practice. Since barges and floats were not studied in depth and since current practice routinely performs the needed items, their use is summarized in the following paragraph and they are not given further attention.

Flexi float barges that are 3 by 6 m and 3 by 12 m could be useful. They can be transferred by truck and assembled at the site. Using anchor winches at the corners of the float would allow relatively precise positioning. Barges that carry salvage style cranes would have dimensions ranging from 36 to 61 m by 13 to 18 m depending on the crane capacity (100 to 450 tons is the typical range). A 0.9 m draft would be typical for any of these barges, which could be problematic in shallow water (e.g. Bay St. Louis). Barges with detachable pontoons are useful for some shallow water applications.

Stability of the materials used in terms of shear strength is a primary consideration. Limiting deflection is a secondary concern. Conceptual aspects of building temporary use structures with cementitiously stabilized fine grained soil built using positive displacement pumps, dredges, and large scale mixers is also addressed. Design shear strength and modulus values are also provided based on laboratory strength data presented in *SERRI Report 70015-006*.

CHAPTER 2 - PUMPING FINE GRAINED MATERIAL

2.1 Overview of Pumping Fine Grained Material

A major construction challenge for using the stabilized slurries developed in this research is their placement within a disaster area. In many applications, the ability to pump material into place would be of major advantage and could be the difference between effective use and an impractical technology for the application. The remainder of this chapter provides the current state of research and practice where pumps are being used in the context of fine grained slurries.

2.2 Pumping Literature and Practice Review

2.2.1 Discussion of Pumping Fine Grained Materials

Putzmeister has pumped fine grained sediments with their products for over two decades. The company does not have a standard analysis protocol, nor a standard experimental procedure based on fundamental properties (e.g. rotational viscosity) to evaluate whether a given material is pumpable. Particle sizes and liquid content are considered alongside experience and judgment. Company representatives indicated they had been searching for an equation based on fundamental properties that would describe the pumpability of sludge and similar materials for decades. At present, their perception was it was not possible to fully quantify pumpability with only analytical means. Deviation of a material with respect to concrete is also a criteria used on a frequent basis. In terms of testing, a pump test is used for some applications and if the hydraulic pressures are low enough the material is deemed pumpable and if not more fluid or other consistency changes are required to make the material pumpable. *Putzmeister* recommended screening the material (often a vibrating screen), mixing it, and pumping it.

The material being pumped must be a plastically deformable saturated mass. Three keys to conveyance of a material in pipes are consistency, viscosity, and fluidity. Excessive bleeding leading to a thicker medium that could block the pipe should be avoided. Material smaller than 0.5 mm is indicated by *Putzmeister* company literature to be important to the pumping process. Pipes must be designed according to applicable standards. High molecular polymers can be injected into the pipes to reduce pipe friction losses. With the right combination of parameters, conveying high density material distances in excess of 1000 m is achieveable. In June of 2009 *Putzmeister* representatives estimated that 1 to 5 km would be considered an average horizontal distance to pump routine (i.e. often not high density) fine grained materials, and that they have pumped fine grained materials up to 11 km (slurry was pumped into a coal mine). Vertical pumping of 300 to 500 m was said to be a daily business and that materials have been pumped vertically up to 600 m.

Discussion with an independent pumping consultant revealed settling (segregating) of sediment during pumping can pose difficulties. Also, it was indicated that a simple method of looking at a given material and telling how well it would pump was not readily available. A rule of thumb provided was the more fines (finer than 0.075 mm) the better and that rarely will a material with no fines pump efficiently. A material with fine grained particles of similar size was stated to be a significant factor in the ease of pumping sediment.

2.2.2 Testing Related to Pumping Fine Grained Material

Laboratory testing indicated that high pressure positive displacement pumps were capable of pumping low moisture content dredged sediments up to a threshold value (Parchure and Sturdivant 1997). The testing was performed on the *Waterways Experiment Station (WES)* campus and was essentially at full scale. Testing during development of the *DRYDredge^{TM}* used a concrete ready mix truck to mix the sediment and water. The chute was able to discharge material directly into the pump hopper. Parameters of the materials pumped can be seen in Table 2.1.

Table 2.1. Positive Displacement Pump Testing of Parchure and Sturdivant (1997)

Test	Clay (Type)	Clay (%)	Sand (%)	TS (%)	Bulk Density (g/cm^3)
1	Kaolinite	100	0	25	1.18
2	Kaolinite	100	0	29	1.23
3	Kaolinite	100	0	50	1.45
4	Kaolinite	50	50	50	1.53
5	Kaolinite	33	67	60	1.56
6	Kaolinite	---	---	74	1.75
7[A]	Kaolinite	---	---	>74	1.95
8	Bentonite	100	0	11	1.11
9	Bentonite, Kaolinite (50%)	100	0	18	1.11
10	Bentonite, Kaolinite (75%)	90	10	25	---
11	Bentonite, Kaolinite (64%)	85	15	25	---
12	Bentonite, Kaolinite (40%)	80	20	25	---

A: Too thick and dry to pump; 10% additional water was required to allow pumping

The results demonstrate that high percent solids can be pumped using positive displacement techniques. All Table 2.1 sediments (note the water added to Test 7) could be pumped through a 125 mm steel pipe 275 m long. Pipe pressures were 34.5 to 44.8 bar and were generally inversely proportional to moisture content. Pumping rates for these experiments were 23 to 30 m^3 per hour. Clays acted as a lubricant, made pumping of sand easier, and reduced head loss in the pipe during pumping. No specific indices or criteria were believed to exist at the time of the report for a formal characterization of high sediment low moisture samples to describe the ease of pumping through pipes.

2.2.3 Applications of Pumping Fine Grained Material

The *Putzmeister KOS 2100* (80 m^3 per hr, 130 bar, 300 kW diesel engine) pump has successfully been used to remove sediment build up. Information was obtained from *Putzmeister* regarding work at the Schlichem Dam in West Germany. The dam contains a large reservoir where 20,000 m^3 of mud and silt were removed. The material was pumped 1,200 m with a height difference of 50 m. The 125 mm pipeline was 1,540 m long to allow the material to be transported the necessary distances. The sediment transported contained everything from gravel to peat along with foreign matter larger than 50 mm. In-situ the dry solids varied between 55 to 86%.

The sludge was removed from the drained lake by loading shovels and emptied onto a vibrating screen to remove foreign matter in excess of 50 mm. The material fell through the screen into a mixing trough where the material was homogenized by two mixing augers rotating in opposite directions before being fed into the hopper of the pump. To obtain pumpable consistency small amounts of water were added to the trough as needed, and water was also added through a connection approximately 50 m after the pump to reduce friction at delivery pressures above 100 bar.

According to Putzmeister (2001) *PM Solids Pumps* from the *KOS* series have fed fuel in the form of a coal-limestone-water mixture at solids contents over 85%. Sludge removal has also been successfully performed with *PM Solids Pumps*. The sludge can be removed by means of bucket-wheel excavators or directly using immersion type *PM Solids Pumps*. Upper end properties of the pumps are: 1) output of 550 m^3/hr; 2) delivery pressures of 130 bar; and 3) conveying distances exceeding 2,000 m. Solids contents up to 68% have been successfully pumped (Putzmeister 2001). An example was provided of *KOS 25200* piston pumps pumping silt out of the sea in front of the Japanese coastline. The *KOS* piston pump was also used for removal of sludge from an Egyptian reservoir. *HSP* series pumps have been used successfully in mining applications where material needed to be pumped vertically up to 1,250 m. Finally, *PM Solid Pumps* (e.g. *KOS 1030*) have successfully conveyed cellulose and paper pulp with dry solids contents in excess of 20%.

A trailer mounted pump (BSA 14000-*KOS* design) was used during 2008 and 2009 (at a minimum) in Redwood City, CA to relocate material from an abandoned salt marsh. The material in the marsh was often larger than that of interest herein, but at times similar fine grained soils were moved. The materials being pumped were on the order of 900 m at a rate of 27.3 metric tons per hour. This level of pumping was maintained by controlling the water content and consistency of the material.

Research conducted within the same task order as this report revealed positive displacement pumps being used to fill geotextile tubes with fine grained sediment. A *Putzmeister 14000 HPD* pump was used to move material at solids contents in excess of 50%. Specific details of the project are provided in the corresponding research document *SERRI Report 70015-003*.

2.2.4 Sedimentation Research on the Illinois River

Research related to sedimentation in the Illinois River has been ongoing for over a decade. The *Illinois Sustainable Technology Center (ISTC)* has been performing research related to use of mud for several years. The goals of their research are long term in context and differ substantially from that of this project, but many of the tools being investigated have dual applicability. *ISTC* has graciously provided references to information published by their research group, as well as supplementary information that has not been published.

Marlin (1999) discusses some of the earlier efforts within *ISTC*. Sediments in the Peoria, IL area generally consist of fine grained silt and clay particles with very little sand, on the order of 50% moisture, and cookie dough consistency. Marlin (1999) provides conceptual information including conveyor belts believed to be able to move material for kilometers, as well as discussion of the *DryDredge™*.

The *Illinois Department of Natural Resources (IDNR)* and its collaborators have been investigating methods of sediment removal in ≈ 0.6 m of water for several years (e.g. Marlin 2002). Clamshells, positive displacement pumps, conveyors, slurry pumps, and mechanical dewatering were listed and discussed in Marlin (2002). Therein, floating conveyors over 60 m long that are commercially available were tested with river sediment. Testing arranged by *IDNR* showed the sediment maintaining a reasonably solid consistency; it did not liquefy. Marlin (2002) also notes high solids slurry pumps (e.g. *Eddy Pump™*) are commercially available and can be useful in transporting sediment with higher solids contents than traditional hydraulic dredges. Mechanical dewatering systems also exist (e.g. system developed by *J.F. Brennan Co, Inc*), that according to the company can discharge total solids of 40%. Marlin (2002) stated a need to bridge the gap between conventional crane mounted clamshells and hydraulic dredges.

The *DryDredge™* was used to construct a pilot scale island in 0.6 m of standing water (Marlin 2002). Sediment at in situ moisture was first pumped into geotextile tubes to form a perimeter and then the same sediment was pumped into the interior (with standing water). Soil data from 19 samples taken in-situ and prior to pumping resulted in the following mean properties: 6% sand, 40% silt, 54% clay, bulk density of 1.4 to 1.7, and moisture contents of 37 to 61% with an average value of 50%. The *IDNR* arranged a demonstration in *Upper Peoria Lake* in the spring of 2001.

The *DryDredge™* was delivered on a lowboy trailer, placed in the river with a crane, pushed to the site with jon boats, and once on site the dredge maneuvered with the help of walking spuds and its excavator arm. Water levels were variable and occasionally were slightly less than 0.6 m. The material exiting the pipe connected to the *DryDredge™* at the final location was said to be “quite stiff” and did not have free water. Sixteen samples were taken, tested for moisture, and showed the placed material had essentially the same moisture content as the in situ sediment.

Prior to constructing the pilot scale island, testing was performed inside a 2.44 m square box 0.46 m high to evaluate flowability of the material. Figure 2.1 is a photo not contained in Marlin (2002) but was provided by *ISTC*. From a stationary exit location the pumped sediment would not flow to fill the 2.44 m square box, rather built up to a height that caused the lightly braced back of the wooden frame to fail. The slope of the pile was on the order of 9:1.

To construct the pilot island discussed in Marlin (2002), the *DryDredge™* was first used to fill 4.57 m circumference geotextile tubes by pumping the aforementioned sediment directly into them to form a perimeter in the shape of a trapezoid. The area of the interior of the trapezoid was just over 200 m^2. The depth of the interior was on the order of 0.9 m. To fill the interior of the trapezoid perimeter, the discharge pipe of the dredge was placed over one of the tubes and the sediment was pumped directly into the standing water within the perimeter (water was up to 0.6 m deep). Construction was performed in one day, and the pilot island was monitored for the next several months. The only difficulty encountered during construction was getting the sediment to flow into the areas of the perimeter a considerable distance from the location of the discharge pipe. Additional water was added to the sediment to increase flowability to remedy this problem. Figures 2.2 and 2.3 are photos of the construction process not included in Marlin (2002) and provided by *ISTC*.

Figure 2.1. Wooden Box Testing of Dredged Material of Martin (2002) Provided by ISTC

Figure 2.2. Beginning of Pumping Sediment for Pilot Scale Island Provided by ISTC

Figure 2.3. Nearing Completion of Pumping Sediment for Pilot Island Provided by ISTC

Marlin (2003) noted the value of transporting and placing dredged material at or near in situ conditions, especially when it is intended for beneficial re-use. To this end, a detailed a demonstration of handling sediment was performed using a commercially available concrete pump truck and a commercially available telescoping conveyor (both products were manufactured by *Putzmeister*). The purpose of the demonstration was for proof of concept, not to determine specific capacities.

The sediment used for the demonstration was taken from the *Illinois River*; approximately 150 m^3 of sediment was obtained for the demonstration using a clamshell bucket and the material slumped only slightly when placed on the barge deck. The in situ sediment had a moisture content of 49 to 94%, with all but one of the samples being above 80%. The material was placed in a stockpile the day before the demonstration. Moisture in the stockpile at the beginning of the demonstration was 57 to 61%, and moisture in the post pumped material was 54 to 61%. Table 2.2 provides additional properties from two samples taken during the demonstration and two additional samples taken from a related project 35 km downstream.

Table 2.2. Test Results for Pumping Demonstration of Marlin (2003)

Sample	**w (%)**	**LL (%)**	**PL (%)**	**PI (%)**	**G_s (--)**	**Sand (%)**	**Silt (%)**	**Clay (%)**
Demonstration	49	41	30	11	2.59	26	46	28
Demonstration	94	89	40	49	2.55	9	53	38
Downstream	91	94	32	62	2.63	9	67	24
Downstream	93	96	37	59	2.62	6	64	30

The concrete pump truck used was a *BSF32-16* (also referred to as a *32Z* in some cases) with a 32 m articulated boom with a 125 mm line and a pump with a capacity on the order of 150 m^3/hr. The pump handled the material with ease. Note that on the order of 15 m^3 was pumped per hour due to inability to continuously load the pump with the equipment used during the demonstration. The hopper on the truck was also narrower than the bucket on the loader feeding it, which contributed to the slow feed of material to the pump. The purpose was to test the pump and it worked very well; an improved feeding system could be developed relatively easily.

Putzmeister representatives were on hand for the demonstration; the following quote is included in Marlin (2003) and was made by said representatives.

> "*Our observation was there is on problem whatsoever in pumping this material. The pressure readings were very low indicating little resistance or power required to move this material. We estimate no problem in moving this material over distances up to 2 miles horizontally with pumps based on appearance and flowability of the material, and pressure generated by the equipment.*"

Putzmeister employees also noted that they manufacture many types of pumps that are capable of moving this material. The take away from the demonstration was that the concrete pump truck (and similar styles of pumping systems) were very capable of handling debris-free material. A better hopper system is needed, and a vibrating screen could be needed to remove large foreign matter to prevent entry into the pumps.

A *TB105 Telebelt* conveyor was also successfully demonstrated with the same sediment. The sediment did not liquefy or slide on the belt. Note these behaviors could occur with higher moisture content sediment transported over long distances.

Marlin and Darmody (2005) present a dredging application referred to as *The Mud to Parks Project*. The motivation was to remove deposited sediment in the Illinois River that had accumulated and resulted in areas much too shallow for adequate performance and use the material as topsoil. Silt sized particles are the most common and the sediment organic content is similar to Illinois agricultural topsoils. A clamshell bucket of 4.2 m^3 capacity was used to fill barges to 1,360 metric ton capacity and the material was subsequently transported long distances for beneficial use as topsoil (two barges filled per typical day). *The Mud to Parks Project* was successful largely because it considered the sediment a valuable, though out of place, resource and the project demonstrated feasibility of transporting sediment long distances.

Marlin (2004) discussed the same application and provided additional detail. In-situ samples were taken using a vibracore over a 3 m depth; the moisture content results of on the order of 20 samples ranged from 72 to 101%. Additional moisture content samples (twenty five samples) were taken just after final placement; the results ranged from 80 to 121% indicating excessive moisture was not being incorporated during handling. According to Marlin and Darmody (2005), several groups are working together to develop equipment that will effectively operate in approximately 0.6 m of water while removing sediment with minimal added water. The *DryDredge™* of Parchure and Sturdivant (1997) was noted in the discussion, as well as the demonstrations performed in Marlin (2003).

2.3 Applicable Equipment for Pumping Fine Grained Material

In terms of the industrial pumps available, the *KOS* series is best suited according to correspondence with company representatives. *KOV* and *HSP* series would be the other potential product lines. *KOS* pumps use an *S-Tube* design thus providing a more positive means of charging and sealing the material cylinders. In contrast, *KOV* and *HSP* series use either a ball (*KOV*) or disc (*HSP*) approach. Technical personnel associated with *Putzmeister* expressed concern that with fine grained sediment there could be sealing problems when charging and sealing the material cylinders (in particular ball or disc designs), especially in a disaster environment. The *KOS* design is used on most *Putzmeister* truck and trailer mounted pumps. This is noteworthy since they are routinely sold in the US.

Tables 2.3 through 2.7 provide typical properties of a series of pumping options from *Putzmeister* that are intended to encompass the commercially available positive displacement pumps applicable to this research. The properties listed are the typical theoretical maximum values for the average material they are designed to pump (i.e. concrete) and are expected to vary within reasonable ranges during service. Tables 2.3 through 2.7 are not intended to represent all commercially available options (e.g. *Schwing* also manufactures similar products).

The data provided by Parchure and Sturdivant (1997) was used alongside internal calculation methods of *Putzmeister* to estimate the friction factor (*F*) based on the data provided. A friction factor on the order of 2 was calculated which equates to the equivalent consistency of concrete with a 6.4 cm slump. A concrete slump of this level would be considered stiff.

Table 2.3. *City Pump* Truck and Pump Specifications (Typical)

Model	**1409 H**	**2112 L**	**2116 H**
Max Output-Rod (m^3/hr)	90	109	160
Max Output-Piston (m^3/hr)	60	65	112
Max Pressure-Rod (bar)	70	70	85
Max Pressure-Piston (bar)	106	112	130
Horiz. Pump Dist-Rod (m)[2]	510	510	620
Horiz. Pump Dist-Piston (m) [2,3]	675	675	675
Vert. Pump Dist-Rod (m) [2]	175	175	210
Vert. Pump Dist-Piston (m) [2,3]	230	230	230
Hopper Capacity (m^3)	0.55	0.55	0.55
Engine Type	Diesel	Diesel	Diesel
Engine Power (kW)[1]	186	186	186
Length (m)	8.71	8.71	8.71
Width (m)	2.50	2.50	2.50
Height (m)	2.78	2.78	2.78
Weight (kg)	9,460	9,460	9,460

Note: GMC TT 7500 Used as Standard.
1: Power at 2,200 rpm.
2: 125mm pipe, 50 m³/hr output, 15cm slump (no admixtures), two elbows
3: Limited by power source in these conditions

Table 2.4. *KOS* Series Industrial Pump Specifications (Typical)

Model	**1050**	**1080**	**2180**	**25100**	**25200**
Max Output (m^3/hr)	36	80	115	200	500
Max Pressure (bar)	100	80	80	35	30
Length (m)	3.90	4.30	6.80	7.50	7.50
Width (m)	0.90	1.00	1.10	1.70	1.70
Height (m)	0.80	1.10	1.10	1.50	1.50
Weight (kg)	2,500	3,000	5,000	---	---

1: Separate power pack supplied per customer application

The *Putzmeister* internal calculation method has inputs of: pumping output, pipe diameter, pipe length (horizontal and/or vertical), number of elbows, and friction factor. Outputs of interest herein include horizontal pressure, vertical pressure, and required engine power. Any of these parameters could be the limiting condition for this application. Calculations were performed using this method for use in this research as seen in the following paragraph.

The horizontal and vertical pumping distances shown in Tables 2.3 through 2.7 were performed under the conditions shown in the footnotes. The slumps provided are for concrete; correlation of a given slurry would be for equivalent properties of a concrete slump which would very likely be a different slump if performed on the slurry itself. The equivalency of a variety of slurries to concrete is not available and is needed. The pumping demonstration discussed in Section 2.2.4 was used alongside the calculations from Parchure and Sturdivant (1997) to provide a reference point for pumping distance calculations (the reference was a balance of the two conditions).

The pipe used must be able to handle the pumping pressures (smaller pipe results in significantly higher pressures). A small pipe was coupled with a reasonably flowing concrete for the distance calculations. Standard and readily available pipe can be obtained with 85 and 130 bar pressure ratings. An output of 50 m^3 per hour was used in the calculations based on material feeding concerns in a disaster rather than pump capacity.

Table 2.5. *BSA* Series Trailer Pump Specifications (Typical)

Model	1409 D (spl 25)	2109 H-D (spl 48)	2110 HP-D (spl 50)	14000 HP-D (spl 56)	14000 HP-D (spl 58)
Max Output-Rod (m^3/hr)	91	95	102	102	200
Max Output-Piston (m^3/hr)	61	57	76	70	139
Max Pressure-Rod (bar) [2]	71	91	150	150	79
Max Pressure-Piston (bar) [2]	106	152	220	220	115
Horiz. Pump Dist-Rod (m) [1]	510	660	1090	1090	575
Horiz. Pump Dist-Piston (m) [1]	510	725	1200	1600	835
Vert. Pump Dist-Rod (m) [1]	175	225	375	375	195
Vert. Pump Dist-Piston (m) [1]	175	250	410	550	285
Hopper Capacity (m^3)	0.60	0.60	0.60	0.60	0.60
Engine Type	Diesel	Diesel	Diesel	Diesel	Diesel
Engine Power (kW)	140	200	330	470	470
Length (m)	5.93	6.59	6.81	6.71	6.71
Width (m)	1.58	1.98	1.98	1.95	1.95
Height (m)	2.31	2.64	2.50	2.97	2.97
Weight (kg)	4,872	6,174	8,165	10,145	10,544

1: 125mm pipe, 50 m^3/hr output, 15cm slump (no admixtures), two elbows

2: Pipeline rating must match pressure created

Table 2.6. *Thom-Katt®* Trailer Mounted Pump Specifications (Typical)

Model	TK 30[1]	TK 40[2]	TK 50[2]	TK 70[3]	TK 60 HP[2]
Rated Max Output (m^3/hr)	24	30	41	57	46
Max Pressure (bar)	79	79	79	78	100
Horiz. Pump Dist (m)	300	620	480	260	520
Vert. Pump Dist (m)	90	135	135	90	155
Hopper Capacity (m^3)	0.18	0.27	0.27	0.27	0.27
Engine Type	Diesel	Diesel	Diesel	Diesel	Diesel
Engine Power (kW)	30	50	72	72	98
Length (m)	4.45	4.85	4.85	4.85	4.85
Width (m)	1.78	1.78	1.78	1.78	1.78
Height (m)	1.73	1.80	1.80	1.80	1.80
Weight (kg)	2,220	2,540	2,720	2,900	2,900

1: 100mm pipe, rated output, 15cm slump (no admixtures), two elbows

2: 125mm pipe, rated output, 15cm slump (no admixtures), two elbows

3: 125mm pipe, 50 m^3/hr output, 15cm slump (no admixtures), two elbows

Of the options provided in Tables 2.3 through 2.7, the *KOS Industrial* series requires the most set up time and should be a last resort with respect to the other pump styles provided. The trailer pumps would be the most logical option in that they are very common and are easily transportable. The truck mounted concrete boom pumps (Table 2.7) would likely find their optimal use as placement devices at the final location and not as conveyors for long distance pumping (a task more suitable for trailer mounted pumps).

Table 2.7. Truck-Mounted Concrete Boom Pump Specifications (Typical)

Model	20Z-Meter[1] (20Z.09)	20Z-Meter[1] (20Z.12L)	61-Meter[2] (61.16H)	61-Meter[2] (61.20H)	70Z-Meter[3] (70Z.16H)
Max Output-Rod (m^3/hr)	90	109	160	---	160
Max Output-Piston (m^3/hr)	60	65	112	260	112
Max Pressure-Rod (bar)	70	70	85	---	85
Max Pressure-Piston (bar) [5]	106	112	130	85	130
Horiz. Pump Dist-Rod (m)	510	510	615	---	615
Horiz. Pump Dist-Piston (m)	770	810	945	615	945
Vert. Pump Dist-Rod (m)	175	175	210	---	210
Vert. Pump Dist-Piston (m)	265	275	325	210	325
Hopper Capacity (m^3)	0.55	0.55	0.55	0.55	0.55
Engine Type	Diesel	Diesel	Diesel	Diesel	Diesel
Engine Power (kW)	224	224	362	362	373
Length (m)	9.41	9.41	16.38	16.38	21.45
Width (m)	3.40	3.40	10.03	10.03	13.40
Height (m)	3.35	3.35	3.89	3.89	3.97
Weight (kg)	16,211	16,211	50,866	50,866	79,802
Vertical Reach (m)	19.46	19.46	60.10	60.10	69.3
Net Horizontal Reach (m)[4]	13.51	13.51	52.04	52.04	58.6

1: GMC TT8500 Used as Standard and 0.09 Pump Cell Used in Weight Determination
2: MACK MRU 613 Used as Standard and 0.16H Pump Cell Used in Weight Determination
3: Kenworth C500B Used as Standard
4: Net reach values reflect pumping over chassis cab
5: Pipeline rating must match pressure created

2.4 Use of Positive Displacement Pumps in Emergency Construction

A meeting was held in August of 2009 at *Putzmeister America, Inc* in Wisconsin to discuss pumping in general as well as evaluate pumpability of soils 1, 2, and 3 of *SERRI Report 70015-006* at 100% and 233% moisture. Samples of each soil and moisture content were presented and the conversation focused on movement of the material prior to cement addition. At 233% moisture all soils were said to be easily pumpable. At 100% moisture the following general statements were made: *Soil 1* was pumpable very long distances; 2) *Soil 2* was pumpable but distance quantification would require a pump test to be performed; and 3) *Soil 3* was pumpable with an estimated distance up to 4 km with steel pipe, minimal bends/elbows, a relatively large pipe, and a constant pipe diameter.

No assessment of the pumpability of soil containing fibers was made. Soils containing fibers would very likely be more difficult to pump. Fibers generally have a negative effect on pumpability of concrete.

Concrete does not tumble through and remix in straight constant diameter pipe. This is noted since the mixing of stabilization additives should not be expected to occur in the pipe without externally applied agitation. The study described in the following paragraph, however, demonstrates that mixing can be achieved in the pipe.

Oota et al. (2009) reported achieving turbulent mixing of the "plug flow" within a pipe using compressed air. The authors stated that conveyance of dredged soil over 1,500 m was possible. The method was referred to as pneumatic flow mixing (PFM) method. The

PFM method mixes dredged soil and cementitious material in the discharge pipeline via the plugs created using pneumatic pressure. The three phase flow (binder, soil, water) was reported to have less losses than only dredged material.

Pumping soil slurry (either stabilized or unstabilized) into place appears to be a viable and efficient option for many scenarios. Positive displacement pumps are required since the material being placed has a yield stress significantly in excess of threshold values of typical centrifugal pumps (see complimentary report *SERRI 70015-007*). Properties provided in Section 2.3 can be used for estimation of key construction parameters. Physical properties (e.g. mass) can be used for estimation of barge requirements, while performance properties can be used for estimation of construction options. A pumping rate of 50 m^3 per hour with 125 mm pipe is recommended for estimation calculations with pumping distances of 500 m or 1,000 m until further information becomes available.

Insufficient data is present to accurately quantify the distance a given material applicable to this research could be pumped. A series of experiments where pipe and pump characteristics are coupled with various slurries is needed where pipe pressures, pipe lengths, and pumping outputs are measured. A series of F values could then be calculated and used for more accurate assessments. It is likely that the parameters used for estimation within this research would be shown conservative, but with the current database no conclusive statements can be made.

CHAPTER 3 - DREDGES

3.1 Review of Dredging

The science of dredging has expanded over the past decades and now serves markets other than those commonly associated with dredging. Many associate dredging solely with navigation and flood control of waterways. A second category of uses is gaining favor that consists of material reclamation from beneath the water for use in construction. Beach nourishment and island construction are the two most prevalent users of the relatively recent adaptations of existing technology. For the current project, all categories of dredges could have applicability in certain conditions. Of particular interest to this project are small dredges that are maneuverable in relatively shallow water. Clamshell or similar dredging operations are also of interest as they can be used to directly feed positive displacement pumps. Clamshell dredges are established technologies and are thus not expanded upon in detail. *SERRI Report 70015-003* provides an ideal application of a clamshell dredge at *Peoria Island* feeding a positive displacement pump.

One of the most innovative public projects related to dredging is the *Dubai Waterfront Development*, which is the largest waterfront development in the world. The development is 100 million square meters. According to Dredging (2007), the project will ultimately require 325 million cubic meters of sand and 14.5 million cubic meters of varying sized stone. The offshore portion of the project was awarded in July of 2006. The construction is high paced and many just in time designs are being utilized. Cutter-head/suction dredges are actively acquiring caprock, sandstone, and coarse sand.

Most unbound materials can be dredged with the correct equipment. The materials can range from peats and organic materials to gravels and cobbles. Hummer (1997) provided a summary of dredging equipment available just over a decade ago. Broadly speaking, three dredging options were identified: 1) *Mechanical Dredges:* clamshell, backhoe, dipper, and bucket-ladder systems; 2) *Hydraulic Dredges:* suction, dustpan, and water injection systems; and 3) *Combination Mechanical/Hydraulic Dredges:* trailing suction hopper systems, cutter-head/suction, and bucket-wheel/suction systems. Table 3.1 summarizes the worldwide availability of these systems as of December 1993 as provided by Hummer (1997).

Table 3.1. Uses of Dredge Types From Hummer (1997)

Dredge Category	Dredge Type	Worldwide Distribution
Mechanical	Clamshell	497
	Backhoe	115
	Dipper	25
	Bucket-Ladder	25
Hydraulic	Suction	142
	Dustpan	7
	Water Injection	-*
Combination	Cutter-Head/Suction	1,001
	Trailing Suction/Hopper	318
	Bucket-Wheel/Suction	196

** Specialty device used almost exclusively for waterway maintenance.*

Parchure and Sturdivant (1997) performed surveys of dredges available in the US market in the early 1980's and 1990's. Dredging depths ranged from 3.1 to 18.3 m while production rates ranged from 15 to 1,375 m^3 (+) per hour. A more recent presentation obtained from the US Army Corps of Engineers (*USACE*) indicated mechanical dredge capacities, in general, are up to on the order of 1,150 m^3 per hour, and combination dredges can average capacities up to on the order of 2,300 m^3 per hour albeit with low percent solids contents compared to mechanical dredges.

3.2 Properties of Conventional Dredge

To provide a conventional dredge as a reference, plans and specifications for the dredging system used by the Port of New Orleans were graciously supplied by representatives of the Board of Commissioners as shown in Table 3.2. Note that many parameters can affect the moisture content of dredged material; operator skill is a major factor. Slurry densities exiting a pipeline are difficult to predict.

Table 3.2. Port of New Orleans Dredging System

Property Requirements/Parameters	Value
Solids Output Required	765 m^3/hr
Actual Solids Output*	800 m^3/hr
Total Discharge Quantity	70.25 m^3/min
Pumping Distance	305 m
Discharge Diameter	51 cm
Depth of Digging**	16.8 m
Velocity***	6.4 m/s
Total Dynamic Head	39 m
Slurry Density****	1,311 kg/m^3
Power Required	979 kW
Power Supplied	1,268 kW
Power Source	Marine Diesel Engines
Percent Solids by Volume	10 to 19%
G_s (silt and light sand)	2.61 to 2.71

**This value calculated with conservative velocity and 77% power utilization. Under disaster conditions this value would likely increase.*

*** Depth with 45 degree ladder inclination.*

**** Conservative value likely to be exceeded during operation.*

***** Dredge equipped with density measurement equipment for the outflow slurry.*

3.3 *DRYDredge™*

The focus of Parchure and Sturdivant (1997) was development of the *DRYDredge™*, which is a newly developed dredge category. As of March 2009 there was only one unit that had been manufactured and was currently in service; the unit resides in Peoria, IL. A key component of the research of Parchure and Sturdivant (1997) was to demonstrate that a high pressure positive displacement pump was capable of pumping dredged sediment at near in situ moisture content. Previously this concept had not been successfully demonstrated (specific positive displacement pump details are provided in Section 2.3).

The *DRYDredge*^{TM} contains a sealed clamshell (0.25 m^3 capacity) mounted on a rigid telescopic boom. The clamshell deposits material into the hopper of the positive displacement pump. Extensive training is not required and according to Parchure and Sturdivant (1997) setup requires a crane and 16 person hours.

Field testing was performed on the *DRYDredge*^{TM}. The first test was performed in a shallow lake, 0.3 to 1.2 m deep, with mainly silt and clay sediments. The dredged material was deposited approximately 457 m from and 6.1 m above the lake. The 457 m pipeline was made of 125 mm diameter steel (flexible hoses were replaced by steel pipes). The discharge stream contained approximately 70% solids (resembled toothpaste), a density of 1.7 g/cm^3, and less than 5 % free water. A channel had to be cut with a backhoe to launch the *DRYDredge*^{TM} into the lake. Pumping rates were 15 to 23 m^3 per hr during the field testing.

A second test was conducted after making key modifications to the dredge. Performance during the test was acceptable and contained pumping rates of 19 to 31 m^3 per hr. Based on all work performed by Parchure and Sturdivant (1997) the study concluded that the dredge was useful for the following operating conditions: 1) Shallow water depth (less than 4.5 m); 2) Small quantity of dredging; 3) Low output rate (less than 31 m^3/hr); 4) High fines low sand sediment; 5) Short pumping distance; and 6) No wave or current action.

3.4 *DINO Six*

The *DINO Six* dredge made by *Geofoam International Inc* weighs 1,200 kg when filled with fuel. The dredge uses a cutterhead system with an output capacity up to 6,800 Lpm and a maximum operating depth of 3 m. The dredge is 5.5 m long, 1.8 m wide, and 1.6 m tall. It can be pulled with a standard pick up truck.

3.5 *Nessie Model 8DX*

Dredging was conducted in the Bahamas during the 2004 hurricane season for beach restoration that totaled approximately 57,300 m^3 of sand and coral. The contractor utilized the *Nessie Model 8DX Dredge* developed by *Keene Engineering* of California. The device was said by the contractors performing the restoration to dredge 153 m^3 per hour with up to 80% solids and an overall average of 50% solids (Miller 2007).

Personal contact with *Keene Engineering* in May of 2008 revealed they are a relatively small company that builds on the order of 4 of the *Nessie Model 8DX Dredges* per year, and they have a single unit they rent out (primarily on the west coast). Representatives of the company cautioned the use of the average output of 50% solids, indicating it is possible for periods but that very low solids contents can also occur. An average solids content on the order of 20% seemed more reasonable to the manufacturers for general conditions and materials such as sand. The maximum capacity over a period of time should not be planned to be in excess of 152 m^3 per hour, even under ideal conditions.

The device contains a bucket wheel cutter head, is portable (trailer mounted), has its own propulsion, is controlled by electro-hydraulics, and is one of the only products available with this level of portability. See Figure 3.1a for a photo of the dredge on its transport trailer. It is designed to be operated by one person and is free of guiding cables (they require additional personnel). The *Nessie Model 8DX* can be transported on US highways with a two-ton rated truck. Additionally, typical dredges require cranes for deployment, while this particular dredge has hydraulics on the trailer that allow deployment.

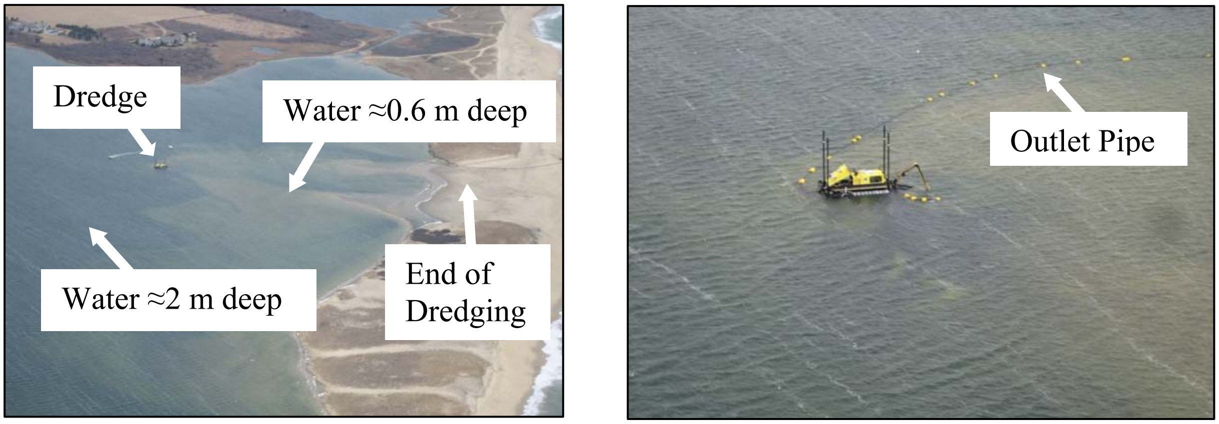
The portability and maneuverability of the device provide many conceptual advantages to rapid reconstitution of infrastructure after a water based disaster. It has a moderate fuel consumption of approximately 42 L/hr, a digging depth up to 6.1 m, the swing arm on the dredge can rotate up to 120 degrees, and the footprint in the water is only around 4.6 by 7.6 m. The total weight of the dredge is approximately 8,600 kg, and the cost as of May 2008 was on the order of $400,000.

To highlight the potential of such a device, the following case study is presented. The study is not published and details were obtained from *Keene Engineering* and assembled by the research team. *Edgartown Great Pond* in Massachusetts is a beautiful location, yet poses many challenges to maintain its beauty. Figure 3.1b is an aerial view of the site. Occasionally the pond is opened to the ocean during low tide for cleaning, and when the tide rises the pond is replenished and the opening is closed again. Opening of the pond is made more challenging due to sand that is blown into the pond during the year.

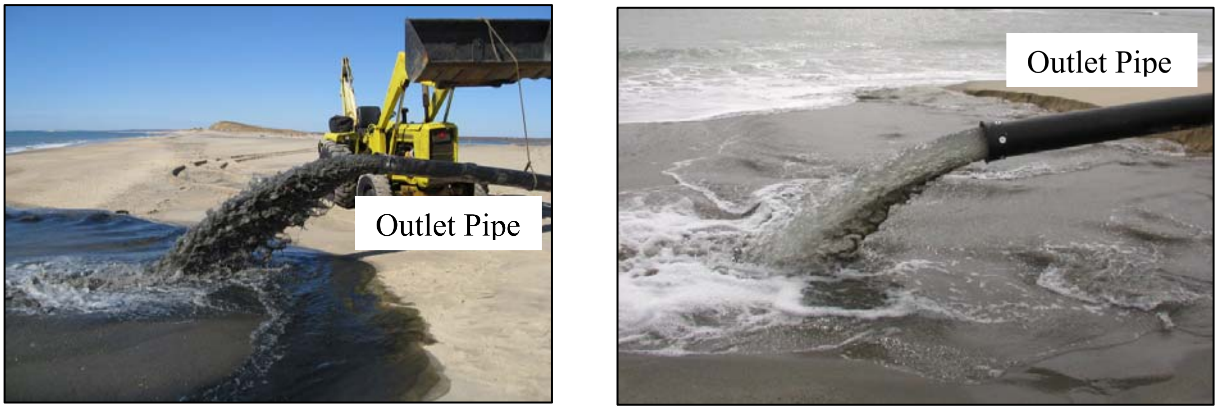
Keene Engineering used the *Nessie Model 8DX Dredge* to remove approximately 15,300 m^3 of sand over a three week period in near freezing temperatures coupled with high winds. This rate of production translates into an upper end solids production rate of 76.5 m^3 per hour (note a more reasonable estimate over several projects was noted by *Keene Engineering* to be 75 to 80% of this value). Once on site the device took approximately 4 hours to set up and deploy. The depth dredged varied between 0.6 to 4.6 m, and the width varied between 9 to 18 m.

Figure 3.1c shows the layout of dredging, and Figure 3.1d shows a close up view of the dredge in Figure 3.1c. Dredging commenced at the location seen and proceeded a short distance into the levee as shown. Figures 3.1e and 3.1f are photos of representative high solids and low solids outflows, respectively. The outflow of a dredge is very inconsistent with time, as seen in the figures.

(a) Nessie Model 8DX Dredge
(b) Aerial View of Great Pond



(c) Zoomed Out View of Dredging
(d) Zoomed in View of Dredging



(e) Output of High Percent Solids
(f) Output of Low Percent Solids

Figure 3.1. Dredging of Edgartown Great Pond

CHAPTER 4 - SOIL MIXING AND HANDLING EQUIPMENT

4.1 Overview of Mixing and Handling Equipment

This chapter is devoted to soil mixing and handling equipment. In place, single batch, and continuous mixers are presented. Handling equipment focuses on cementitious material as its handling poses challenges in disaster environments. This chapter does not cover all mixing and handling options available. The chapter presents a cursory review and provides one or more examples of equipment that could be deployed during a disaster to improve response.

There are few, if any, absolute statements that can be made regarding soil mixing that translate from one project to another. Generally speaking, if the material will enter a fluid like state, mixing efficiency increases. For most of the materials of interest in this research, they will be fairly fluid and should be good candidates for high mixing efficiency.

4.2 Cementitious Material Storage and Handling

All cementitious materials considered herein are delivered pre-blended to the disaster area in trucks capable of pneumatic offload. Three examples of cementitious material storage and handling systems are shown in Figure 4.1. Many different storage sizes are available. Pneumatic offload transfers material into the silo or shuttle in a loose state and the exhaust air is discharged through the filter house on the units. A variable speed auger is used to discharge the dense cementitious material from the silo. *Silo 1* holds two truck loads of cementitious material weighing 22.7 metric tons each and has a shipping weight of 4.5 metric tons. Shipping dimensions are 2.6 m wide by 11.3 m long by 4.1 m high. *Silo 2* holds just over one truck load of cementitious material weighing 22.7 metric tons and has a shipping weight of 3.6 metric tons. Shipping dimensions are 2.6 m wide by 7.9 m long by 4.1 m high.


(a) Silo 1 *(b) Silo 2* *(c) Cement Shuttle*

Figure 4.1. Portable Cementitious Material Storage and Handling

Cement is often handled in soil mixing applications with a cement shuttle. The application under investigation could be limited by the cement shuttle. Typical cement shuttles can provide 2.0 to 4.5 kg of cementitious material per second (3.0 kg per second is a reasonable estimate for maximum production calculations for sustained periods according to *Hayward Baker Inc* (*HBI*) representatives). When using cement shuttles for Mass Stabilization (*MS*) and dry soil mixing, 600 to 700 m^3 per 8 hour shift is a reasonable maximum production estimate in absence of specific inputs. Current *HBI* capabilities would allow three equipment systems, or 1,800 to 2,100 m^3 of stabilized soil per 8 hours. In current construction practices, the introduction of cement limits the quantity of soil stabilized. Multiple versions of cement shuttles have been used in practice. The model in operation by *HBI* as of May 2009 has two 6.36 metric ton capacity vessels that are each 7 m^3.

As an example, typical operation on the *Inner Harbor Navigation Channel* (*IHNC*) project visited by the author was injecting cementitious material at 1.8 to 1.9 kg per second with a cement shuttle to meet the project dosage rate of ≈250 kg/m^3. The cement shuttle had a 100 mm line that offloaded cementitious material. The line was reduced to 50 mm to feed cementitious material to the mixing tool. The time to complete a given project can increase when the dosage rate exceeds ≈275 kg/m^3.

Cement placement could be a logistical problem on site. *HBI* representatives indicated 60 to 115 m was the upper end range cement could be pneumatically pumped from a delivery truck to the cement shuttle. The high end of this range was used on the 17th Street Canal in New Orleans after *Hurricane Katrina* by placing the delivery hose over barrels to introduce turbulence and keep cement particles in suspension. Without somewhat elaborate measures 60 m is the upper end distance recommended for planning to pneumatically deliver cement from the delivery truck to the cement shuttle. On the order of 25 m or less is the maximum distance the cement shuttle can be from the mixing equipment. Environmental concerns are often a major consideration in handling cementitious materials. Cement placement in disaster environments using unconventional means would increase production but would potentially introduce environmental problems if the materials became airborne.

4.3 Pugmill Mixers

Pugmill mixing has been used in construction for some time, though portable pugmill mixers are becoming more popular in construction activities. An advantage of using pugmill mixing in a disaster environment is continuous material feed. Diesel generators are a common power source for the pugmill systems shown in this section. Pugmill mixers were identified that are capable of mixing 90 to 1,350 metric tons per hour of certain materials; all mixers were not designed for high portability. Conversation with a pugmill manufacturer indicated capacities in conjunction with dredged material (or similar materials) often reduce mixing capacity. In absence of additional data, an estimate of 180 to 270 metric tons per hour was stated to be a good range of values per pugmill in a disaster environment. A typical density for the materials of interest is 1.5 g/cm^3, resulting in a capacity of 120 to 180 m^3/hr per pugmill, which is a reasonable planning range for a disaster environment.

Figure 4.2 contains photographs of a candidate pugmill that is often used for mixing aggregates. For a 19 mm aggregate mixture the capacity is on the order of 680 metric tons per hour. The manufacturer estimated 270 metric tons per hour capacity for the materials of interest in this research, though this could fluctuate depending on material consistency. Approximate equipment dimensions are 3.5 m by 1.5 m by 1.5 m tall, the shipping weight is 4,600 kg, and the operational weight is 7,000 to 8,600 kg.

(a) Front View *(b) Back View*

Figure 4.2. Pugmill Systems Inc 750B Pugmill

Pugmill availability varies with time. They are often manufactured as ordered, though they are likely stocked by some manufactures in some cases. A lead time of six weeks would be considered typical to build and deliver a pugmill system once ordered. Availability from contractors for temporary purposes would be a likely source of pugmills for disaster response. Commercially available pugmill units are available from *Kolberg*®, *Mixer Systems Inc*, *McLanahan,* and *Pugmill Systems Inc* (other sources are likely). Table 4.1 summarizes key properties of several pugmills.

Table 4.1. Properties of Commercially Available Pugmill Mixers

Manufacturer	**Model**	**Capacity (T_mPH)**	**Shipping Wt (kg)**	**Operating Wt (kg)**	***L, W, H*** **(m)**
Mixer Systems	50-P	23	2,300	5,500	3.8, 1.5, 1.2
	125-P	58	3,000	8,500	4.7, 1.6, 1.4
	250-P	116	3,600	10,750	5.1, 1.8, 1.5
	400-P	185	4,500	14,000	5.5, 2.0, 1.5
McLanahan	72	65	4,550	6,250	4.6, 1.0, 0.6
	160	145	8,850	12,500	5.2, 1.4, 0.8
	300	272	14,200	21,200	6.1, 1.7, 0.9
	465	423	15,800	27,750	7.0, 2.0, 1.1
	610	555	23,300	42,750	7.6, 2.4, 1.3
	850	773	28,400	63,250	8.8, 2.9, 1.5
	1450	1318	34,000	94,250	10.1, 3.5, 1.8

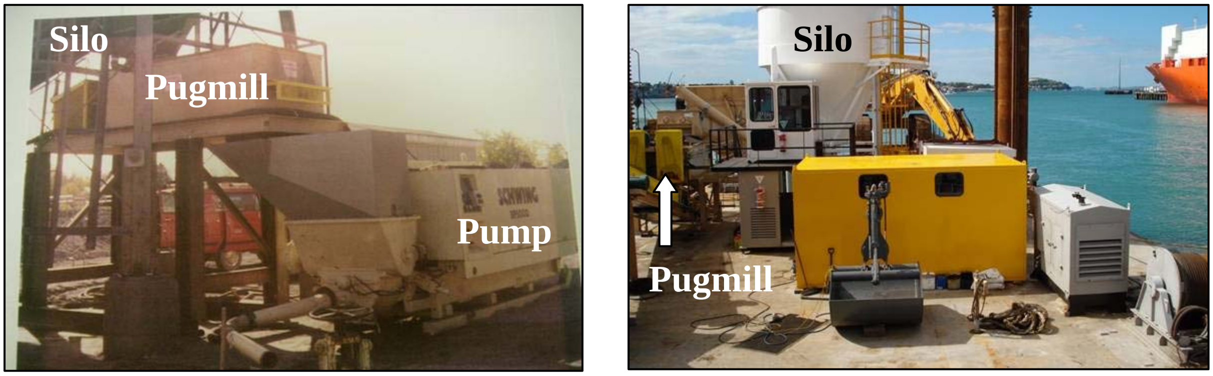
Note: Capacity is listed as metric tons per hour of 1.6 g/cm^3 material-capacity decreases with density reduction. Operating weights were estimated based on mixer volumes.

Numerous pugmill layouts can be fabricated; many systems are custom built for the needs of the application which requires a few weeks from order to delivery. Figure 4.3 shows a portable *Pugmill Systems Inc* stabilization plant that can be shipped in a 12.2 m container. This plant contains a 4.6 m^3 hopper system for feeding material to the pump. Hopper capacities of 3.8 to 9.2 m^3 are available on pugmill systems, with the upper end capacities more common on stationary systems.

(a) Overall View *(b) Loading into Truck*

Figure 4.3. Example Portable Stabilization Plant Incorporating a Pugmill

Example applications of pugmill systems are shown in Figure 4.4. Figure 4.4a shows a pugmill between a silo and a positive displacement pump being used to backfill a quarry in New York with flyash. Figure 4.4b shows a barge mounted pugmill in New Zealand being used to stabilize dredged material.



(a) Pugmill and Positive Displacement Pump *(b) Barge Mounted Pugmill*

Figure 4.4. Example Applications of Pugmill Systems

4.4 Concrete Ready Mix Trucks

For most of the slurries investigated in this research, a concrete ready mix truck would be a practical mixing solution. For stiff or low moisture content materials, clumps of wet soil would likely be coated by cementitious material and produce a relatively weak and highly variable product. *Soil 2* at 100% moisture might not be a good candidate for mixing in a ready mix truck, but all other soils and moisture conditions evaluated should be well suited for this approach. A standard ready mix truck can mix 6.9 m^3 at a time and provide on the order of 10 loads per hour. For planning purposes, a three axle ready mix truck with a length, width, and height of 9.5 m, 2.5 m, and 3.8 m, respectively, weighing 12,500 kg with no material in the drum is reasonable. The chute reach is typically 5 to 5.5 m.

Emery (1980) fed excavated sludge into a ready mix truck using a chute while a small conveyor belt fed cementitious material. The approach was reported to be very efficient. Other options were used with less success during the early stages of the project.

4.5 In Place Mass Stabilization Mixers

Dry soil mixing and stabilization relies on three primary pieces of equipment: 1) mixer arm; 2) carrier for mixer arm (e.g. trackhoe); and 3) cement shuttle (discussed previously). The mixer arm fits standard trackhoes and is compatible with pneumatic cement offload. For marine construction, an amphibious mounted trackhoe would allow access to the construction site, and the equipment can be barge mounted (Figure 4.5). The mixer arm varies between Mass Stabilization (*MS*) and Column Stabilization (*CS*) applications; Figure 4.6 shows one *MS* and one *CS* mixing tool. For *CS* mixer arms, the shear strength in situ prior to treatment cannot exceed ≈0.5 kg/cm^2. For *MS* mixers, shear strength in situ prior to treatment cannot exceed ≈0.1 kg/cm^2 and the depth of treatment cannot exceed 5 to 6 m.

Figure 4.5. Barge Mounted Soil Mixing Equipment

Wet soil mixing begins to be considered when in situ untreated shear strengths exceed approximately 0.3 kg/cm^2, and it is the only feasible option when the shear strength prior to treatment is noticeably in excess of 0.5 kg/cm^2. Wet soil mixing is selected when additional moisture could facilitate mixing, while the cementitious dosage rates don't necessarily change between techniques. The capacities and all other pertinent information do not change between wet and dry soil mixing with respect to trackhoe compatibility and cementitious material capacity. Wet soil mixing is not a likely candidate for the current research since shear strength prior to treatment should be less than 0.1 kg/cm^2.

Figure 4.6. Mass Stabilization (MS) and Column Stabilization (CS) Mixing Tools

CHAPTER 5 – GUIDANCE FOR EMERGENCY CONSTRUCTION MATERIAL USE

5.1 Overview of Construction Material Use Guidance

This chapter provides general guidance for using the emergency construction material developed in *SERRI Report 70015-006* alongside the construction equipment discussed in the previous chapters of this report. This chapter does not discuss standard equipment (e.g. trucks, generators), personnel, or commodity (e.g. fuel, lumber) needs as they will be specific to any one event and are well understood. This chapter focuses on more specialized equipment and processes specific to the concepts investigated in this research. This chapter also provides example applications where the material could be the most useful.

The *USACE* through its *Engineer Research and Development Center (ERDC)* conducted a sustained research effort referred to as the *Joint Rapid Airfield Construction (JRAC)* program beginning in the year 2002. Anderton et al. (2008) performed a *JRAC* demonstration where a helipad test area was constructed using cement and fiber stabilized compacted soils. The program reduced construction time of military airfields in a contingency setting, with the construction activities reducing the durations by intervals measured in days while still requiring times measured in days. The timelines of the *JRAC* demonstration may have applicability to the current research taking a minimum amount of time measured in days.

5.2 Guidance From Recent Construction Projects

Recent work in Japan incorporated several construction components of value to this report. Tanaka et al. (2009) describes a general construction sequencing layout using what is referred to as super-geo material (SGM). SGM was reported to have enough flowability to be cast in water. A cement silo and clay slurry agitator fed a screw mixer that introduced the mixed material into a concrete pump truck (not specifically stated but likely a positive displacement pump) that moved the material through the discharge line and to the track mounted crane that placed the material. A water borne vessel housed the needed equipment with a 360 m^3/hr capacity with average daily production volume of 2,000 m^3/day. The vessel contained an excavator, vibrating screen, hopper, clay slurry agitator, cement silo, and concrete pump, while the pipe and track mounted placement crane were resting on floats.

Nakai et al. (2009) reported 400,000 m^3 of SGM has been used in Japanese airports and port regions. Nakai et al. (2009) passed soil over a vibrating screen into a slurry tank and then combined it with cement in an agitator before pumping into a continuous mixer feeding the tracked crane placing the material. The continuous mixer utilized rotating mixer blades within sealed pipes without release of pressure to minimize anti-foaming.

5.3 Mobilization

One major concern regarding the construction process in a disaster area is mobilization. Mobilization is project specific and as a result guidance has been provided in general terms. For typical conditions mobilization takes a few days. A reasonable estimate provided by *HBI* in August of 2009 was $2 per km per truckload of standard weight equipment in a non-disaster environment.

The next two paragraphs propose a general mobilization plan using high moisture content cementitiously stabilized fine grained material. Once it is determined the material will be used, construction goals are established, and the general construction location is selected (i.e. within a few kilometers) mobilization can begin. Three items should occur simultaneously: 1) a senior level engineer or engineers should be deployed to the site; 2) key equipment should be located (e.g. positive displacement pumps and pugmill mixers) and mobilization commenced for these items; and 3) neighboring cement plants should be contacted so they can begin arrangements to produce cement with lowered SO_3 content as per the recommendations of *SERRI Report 70015-006*.

The senior level engineer or engineers should focus on selecting the best construction site within the general location. While that occurs, another person or persons should deliver a pail of cement from the plant(s) of interest with the SO_3 content typically produced. Specimens should be made on site and crushed one day later for use as a control in establishing the best SO_3 content for the project. If calcium sulfoaluminate cement is to be used instead of portland cement, three blends should be sent and one selected as opposed to SO_3 adjustments that are recommended for portland cement.

Calibration of hand held gages should occur during the same time period as activities in the previous paragraph. By this time the site should be selected and stabilization material quantities should be estimated based on test data provided in *SERRI Report 70015-006* coupled with project strength requirements, soil type, and moisture content at the site. The engineer or engineers should then plan routes to allow equipment to efficiently enter the site; *SERRI Report 70015-004* should be used as a guide. By the time all on site decisions have been made, key equipment and the first tanker or tankers of cement should arrive at the site and construction can begin. Daily strength tests can then be used to adjust the SO_3 content (or blend for calcium sulfoaluminate cement) to maximize strength for the application.

5.4 Emergency Construction Material Applications

The emergency construction material developed is best suited for use in fairly large masses up to moderate thicknesses (e.g. 1.5 m or less). The material is essentially fluid once mixed and can be used as a controlled strength material. The material can be removed with an excavator at the conclusion of the disaster. Example applications include, but are in no way limited to, fill for washouts, temporary anchor trenches (e.g. burial of pipe supporting geotextile for *SERRI Report 70015-010*), fill for temporary housing, temporary pavement subgrades, containing contaminated sediments, and platforms used to support any number of objects. The approach can also be used to remove mud that is impeding progress for disaster recovery and re-use it at another location in a beneficial way by pumping it to another location and mixing with cementitious material. Emergency material could be used to dispose of waste generated by cutting a channel for waterway access into the disaster area. Many other similar applications exist for the material, typically having the same general approach. Filling geotextile tubes to create temporary walls is another example use highlighted in *SERRI Report 70015-003*.

For any application where a fairly large mass of the material is used, the heat generated within the interior of the soil mass is expected to be more than adequate to offset disaster response in cooler temperatures (within reason) with respect to bench scale temperatures. It is unlikely that response to a hurricane (or similar event) would be performed at temperatures too cool for this assumption to be reasonable. Disaster response at near freezing temperatures is not considered. It is not uncommon for field projects to measure strength in excess of bench scale results, due at least in part to hydration heat generated within the mass.

5.5 Example Construction Scenarios

This section examines scenarios at a disaster location where high moisture content cementitiously stabilized fine grained soils could be used in conjunction with the equipment described previously. Three cases are considered as they could be useful in some situations. The cases focus on the method to obtain soil (hydraulic or mechanical dredge) and the location of the soil (on site or from remote location). Use of a hydraulic dredge on site is not considered as any advantages seem isolated and minimal. Remote locations are not explicitly defined, but generally speaking are 100 to 1,500 m from the site where they would be used.

Figure 5.1 is a flowchart summarizing use of the emergency construction material in conjunction with a hydraulic dredge at a remote location. The anticipated percent solids entering and exiting dewatering ($TS_{\%\text{-}IN}$ and $TS_{\%\text{-}OUT}$, respectively) are on the order of 10 and 30%. A typically expected flow rate (Q) would be 7,500 liters per minute (Lpm). This approach could prove useful to move mud that has accumulated due to hurricane surge and re-deposit after stabilization at a location washed out during the storm for temporary use. The approach is also useful for contaminated sediments. The Figure 5.1 approach could also be advantageous provided the location of interest was a bound surface (e.g. concrete) that needed to be elevated a given distance (e.g. 1 m) to support a pump station, for example. Urban flooded areas could have bound surfaces for considerable distances.

Figure 5.2 is a flowchart summarizing use of the emergency construction material in conjunction with a mechanical dredge. Two options are provided depending on whether the material to be used is on site or at a remote location. This scenario uses soil at a percent solids ($TS_{\%}$) level of 30 to 50% and is highly preferred for most applications. Less cement is needed and higher strength per unit cost can be obtained. Production rates in Figure 5.2 are based on positive displacement pump and pugmill capacities obtained from equipment manufacturers presented in earlier chapters. The approach shown in Figure 5.2 could be used for essentially any application discussed previously provided soil at 30% solids or higher is available, and in most cases it should be available.

Hand held gages calibrated on site are the preferred quality control tool and can be used with Figure 5.1 or Figure 5.2 scenarios. The *Dial* gage is recommended until it peaks for stronger blends, and for stronger blends the *Shear* gage is recommended. An alternative approach that could be useful in isolated instances is coring/drive sleeve extraction of specimens (e.g. 6 by 12 cm) for unconfined compression testing. For cooler weather, temperature probes inserted into the curing soil mass should be considered. The probes can be attached to hand held data loggers for efficient temperature measurements in real time.

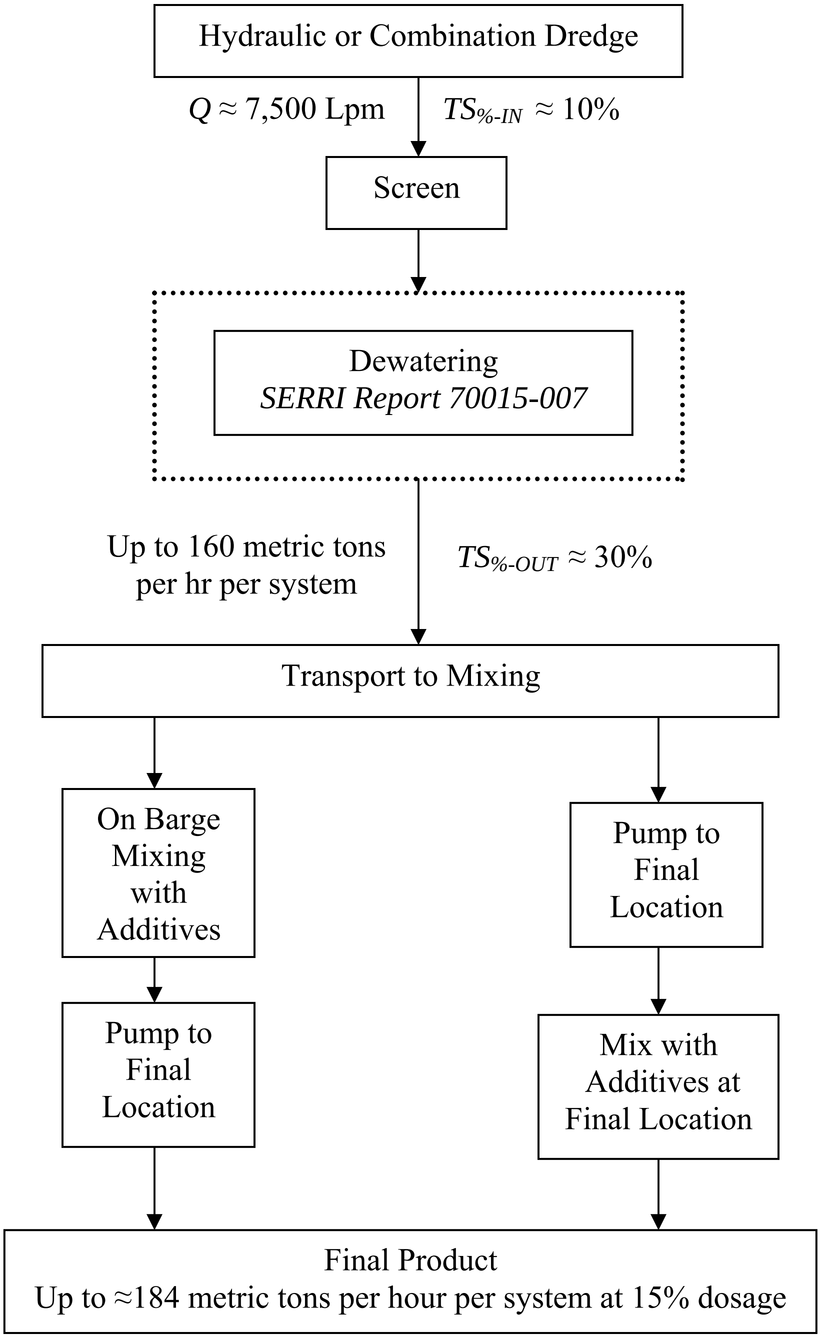


Figure 5.1. Construction Case 1: Hydraulic or Combination Dredge at Remote Location

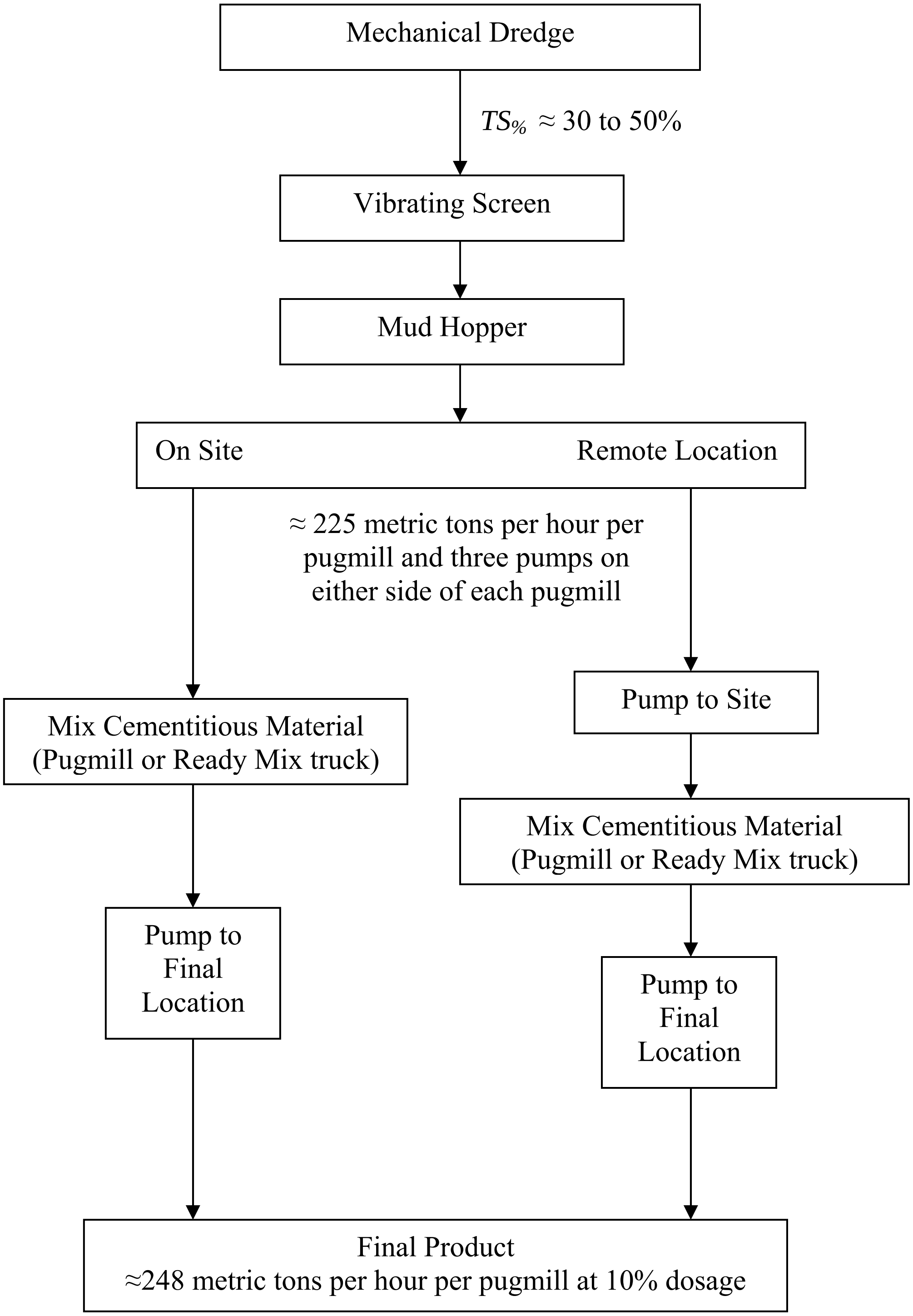


Figure 5.2. Construction Cases 2 and 3: Mechanical Dredge

CHAPTER 6 – STAGING PLATFORM

6.1 Staging Platform Overview

This chapter highlights use of the emergency construction material developed from cementitiously stabilized fine grained slurry for the purpose of building a staging platform. The construction cases presented in Figures 5.1 and 5.2 are applicable and one of them would be used; site specific conditions would determine if Figure 5.1 or Figure 5.2 was used. No further construction details are pertinent, so this chapter presents preliminary design concepts, selects a final design, provides example design loads (helicopters), and determines needed strength requirements. This chapter could serve as an example of how to select uses for the emergency construction material immediately after a disaster.

6.2 Preliminary Design Concepts

Four preliminary designs were considered for the platform perimeter. Thin steel tubing and geotextiles was the first preliminary design (Figure 6.1). To design the perimeter tubing would require lateral force analysis (e.g. laterally loaded piles embedded into the soil) and the geotextile would require analysis (finite element analysis would likely be needed) to ensure it could transfer lateral forces to the tubing via mobilization of tensile forces. Potential construction difficulties led to this design option being abandoned.

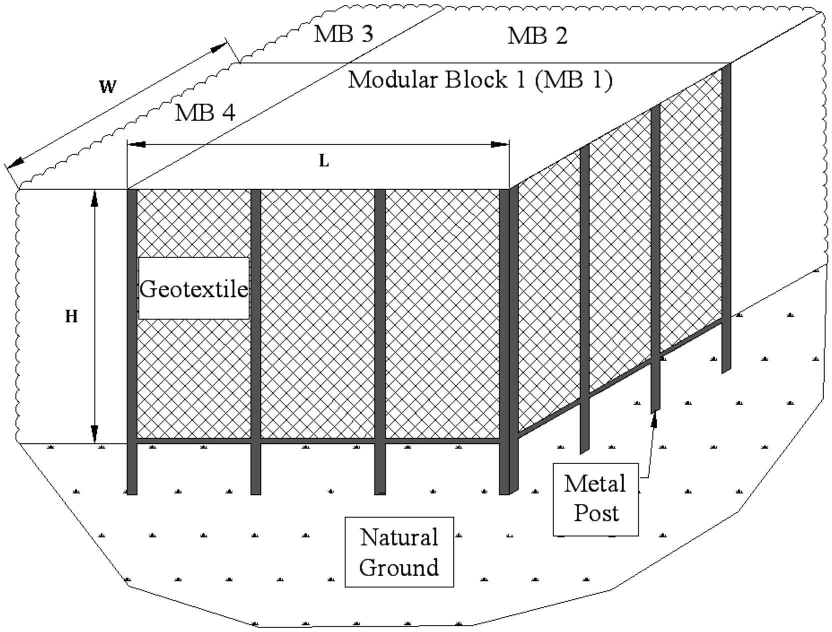


Figure 6.1. Modular Block Preliminary Design Option

Design option 2 had an impermeable perimeter and a geocell at the bottom of the platform. The geocell would be filled with treated soil while the water in the interior of the area was pumped out. Stabilized slurry would be filled over the geocell prior to the interior water level being reduced to the height of the geocell. A cursory evaluation of this approach in conjunction with achieveable stabilized soil slurries rendered this option impractical.

Design option 3 used cementitiously filled geotextile tubes, pumped the water from the interior of the area, and used the interior as the staging area. Design option 3 requires a parking lot (or similar) to be present and places the staging surface beneath the water. As a result, the stability of the geotextile tubes would need to be greater than if the working surface were at or above the water level to protect the safety of personnel working in the area. Sealing the area would also require effort. All factors considered, this approach was not deemed optimal.

Design option 4 used geotextile tubes to form the perimeter of the staging platform. Construction would be more simplistic than the other design options and the perimeter would provide notable structural support. *SERRI Report 70015-003* analyzed stacked geotextile tube walls filled with the emergency construction material and concluded the approach was promising.

The raw materials used were comparable in all four designs. Design option 4 was selected due to ease of construction as pumping geotextile tubes with emergency construction material can be performed with the same equipment as needed to place the remainder of the emergency construction material. Once design option 4 was selected, the usefulness of the approach was evaluated in the next section.

6.3 Project Parameters

A rigid surface (e.g. parking lot) should be located and used for the site if possible. If this is not possible, a surface with a shear strength of greater than 0.5 kg/cm^2 should be located or created. Stabilizing the site with *CS* (Figure 4.6) is an option if a surface with suitable shear strength cannot be located. For purposes of discussion, a parking lot is used as the staging platform site.

Investigation during the research revealed that a shallow platform (e.g. 1 m) would probably be more applicable than a deep platform (e.g. 3 m) since flexible floats could likely perform the function of a staging platform in 3 m of water, thus removing need for the platform. As a result, a shallow platform is considered in the remainder of this chapter. The key issue to designing a shallow platform with geotextile tubes serving as a perimeter is bearing capacity. Slope stability analysis in *SERRI Report 70015-003* found 0.3 kg/cm^2 to be required for slope stability of stacked geotextile tubes. Higher strength will be required for bearing capacity than slope stability in this application since only one small geotextile tube would be required for the perimeter (a 4.6 m circumference tube is recommended if available and if not available a 9.14 m circumference tube should be used). Lateral stability is not a concern for the shallow perimeter.

6.4 Design Loads

Properties of select aircraft are shown in Table 6.1 for typical conditions; properties vary reasonable amounts depending on the specific features of the aircraft. The CH-46 provides the most severe loading condition as it has the highest tire pressure and a maximum takeoff weight that is nearly as high as the CH-47. The CH-46 is equipped to handle standard military pallets or wire baskets and has cargo and personnel hoist system. Key dimensions of the CH-46 are shown below.

- Wheel track (transverse direction): 3.9 m
- Wheel base (longitudinal direction): 7.5 m
- Rotor diameter: 16 m
- Length with rotors: 26 m
- Fuselage (i.e. length without rotors): 14 m
- Width without rotors: 5 m

Table 6.1. Pertinent Properties of Selected Helicopters

Helicopter	Tire Pressure (kPa : kg/cm^2)	Wheel Configuration	Min Takeoff Weight (kg)	Max Takeoff Weight (kg)
UH-60[1]	655 to 965 : 6.7 to 9.9	Two Wheels	5,100	7,700
CH-47	605 : 6.2	Six Wheels[2]	12,200	24,500
CH-46	1,035 : 10.6	Six Wheels[3]	14,800	24,300

1: Tail wheel tire pressure is 655 kPa and main wheel tire pressure is 965 kPa.
2: Quadricycle contact pattern with twin wheels in front and single wheels in rear.
3: Tricycle contact pattern with two wheels at each contact point.

6.5 Design Strength and Elastic Modulus

The design shear strength (s_{ud}) of the emergency construction material is 1/4th of the laboratory measured shear strength based on testing and evaluation presented in *SERRI Report 70015-006*. The design elastic modulus (E_d) is taken from plots relating shear strength to elastic modulus by entering the plot at s_{ud}.

Bearing capacity for cohesion only materials when loaded at the ground surface is represented by Eq. 6.1 when the failure mode is punching into the ground surface and by Eq. 6.2 when the failure mode is rotation (Bowles 1996). These equations are not traditionally used for design. The Terzaghi (1943) bearing capacity equation reduces to that shown in Eq. 6.3 for a material with no internal friction, a round footing (tire loads would resemble round footings), and loads at the ground surface. Eq. 6.3 was used for calculations. For typical shear failure bearing capacity analysis, q_{ult} is reduced by a safety factor (SF) of 1.2 to 2.5, but this was not performed in this case since s_{ud} has already been reduced by a factor of 4.

$$q_{ult} = 4(c) \tag{6.1}$$

$$q_{ult} = 2(\pi)c \tag{6.2}$$

$$q_{ult} = 7.41(c) \tag{6.3}$$

Where,

q_{ult} = ultimate bearing capacity
c = soil cohesion, taken as s_{ud} in this analysis

This application requires high early strength, so for purposes of the example it is assumed a soil with a liquid limit and organic content on the order of 50 and 5, respectively is available. With a similar study, calcium sulfoaluminate cement was able to produce a laboratory shear strength of 3 kg/cm^2 at one day with a 15% dosage (see Table 16.4 and Chapter 10 of *SERRI Report 70015-006*), which results in s_{ud} of 0.75 kg/cm^2. Converting this value to q_{ult} results in an ultimate bearing capacity of 5.6 kg/cm^2.

When compared to the helicopter loads presented in Table 6.1, the material is not able to support any of the aircraft after one day when the laboratory strength is reduced by a factor of four. The q_{ult} value of 5.6 kg/cm^2 is 90% of that required to safely support the CH-47; laboratory strength of 3.4 kg/cm^2 would be required for the CH-47 tire pressure. A slight increase in cement dosage, or longer curing would allow direct landing onto the material. As a reference, 20% dosage would allow any of the helicopters to land safely directly onto the emergency material after one day of curing (see Figure 10.11 of *SERRI Report 70015-006*).

The elastic modulus for the soil and cement type is best represented by *Soil 1* in Figure 10.13 of *SERRI Report 70015-006*, which has an elastic modulus in units of MPa 12.2 times s_{ud} in units of kg/cm^2. To support the CH-46, s_{ud} would be 1.43 kg/cm^2, making the design elastic modulus (E_d) 17.5 MPa. The actual modulus for this condition could be as high as 70 MPa considering the shear strength was reduced by a factor of 4.

As a reference, Rushing et al. (2006) landed CH-46 rotary wing military aircraft on SP-SM soil with dynamic cone penetrometer (DCP) correlated California Bearing Ratio (*CBR*) values of 5 to 11. Heukelom and Foster (1960) proposed a widely used equation relating *CBR* to elastic modulus (E) in units of MPa, which is shown in Eq. 6.4. The 10.34 constant is the typically used value, though in the original work the outer bounds of the data were 4.7 to 18.8.

$$E = 10.34(CBR) \tag{6.4}$$

A 5 *CBR* equates to an E value of 51.7 MPa. Considering the design elastic modulus of 17.5 MPa was based on a shear stress reduced by a factor of four, the work by Rushing et al. (2006) seems to indicate the design values for the emergency construction material are reasonable and would safely support the design aircraft.

The previous paragraphs serve as an example of how to meet project requirements with the emergency construction material. During the mobilization stage, on site personnel can produce specimens with a variety of cement contents and test the specimens one day later. The resulting data can be used as a guide for cement dosage requirements using on site soil at on site moisture, which will produce reliable results.

6.6 Platform Configuration

If the platform is used in absence of a wearing surface, fibers should be considered near the surface of the mass (e.g. top 0.2 m) where heavy repeated loads and environmental changes could result in cracking of non-fiber reinforced material. Additionally, loads should be placed no closer than a 1V:1.5H slope from the edge of the platform. For a 1 m tall platform, no loads should be within 1.5 m of the edges. Shapiro and Shapiro (2011) recommend this configuration for crane loading. One effective method of accomplishing this objective is to fill the geotextile tubes in the perimeter to a height slightly above the interior (e.g. 1.2 m) so the tubes serve as a slightly raised outer perimeter.

An alternative approach to meeting design requirements by increasing the cement content near the surface of the perimeter is do use a matting system and make small helicopter landing pads (5 m by 10 m based on wheel track and wheel base of CH-46) at discrete locations on the staging platform. The staging platform could thus be built with less cement as bearing capacity of crates and the like would be less than helicopter tires. Numerous matting systems are available to meet disaster application needs. For example, Anderton and Gartrell (2005) performed a helipad exercise using CH-47 and UH-60 aircraft. Evaluation criteria for matting systems included: a) lightweight and easily transported; b) potentially able to sustain direct helicopter loads; c) ability to be installed manually; and d) commercially available. Two mats met the exercise requirements (Mobi-Mat® and MP Fiberglass Matting). Mobi-Mat® can be installed quickly (47 m^2 per person hour) but is porous and did not provide considerable bearing capacity improvement. MP Fiberglass Matting was reported to be better for bridging over soft soil and had minor observed deflections, making it suitable for use on the staging platform.

6.7 Staging Platform Summary

This chapter served as a fairly detailed example of using the emergency construction material made by blending high moisture content fine grained soil with cementitious material. The example presented in this chapter is unlikely to be needed exactly as presented in a disaster due to the variables involved, but it does show the versatility of the approach. To effectively implement the material, only a few pieces of information are needed, and the cementitious material can be delivered in a just in time approach, which is ideal for disaster recovery.

CHAPTER 7 - CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

- The construction procedures discussed in this report appear capable of improving disaster recovery operations.

- Positive displacement pumps are capable of filling geotextile tubes. The *DRYDredge™* uses a positive displacement pump and successfully filled geotextile tubes with fine grained material in one study reviewed for this report. Percent solids of 11 to 74% were pumped through a 275 m long pipe at 23 to 30 m^3/hr.

- Positive displacement pumps appear capable of moving high moisture content fine grained soil slurry long distances. Pump distances of 500 to 1,000 m appear reasonable for planning purposes, though much longer distances appear feasible in some conditions. Longer pump distances were documented in Chapter 2.

- *KOS* series positive displacement pumps are the most suitable for a disaster environment. The pumps are readily available and come in truck and trailer mounted versions.

- Pump capacity of 50 m^3 per hour per positive displacement pump appears to be a reasonable planning estimate. The capacity appears to be driven more by ability to feed material to the pump than to the pump itself.

- Small dredges used in conjunction with positive displacement pumps could be useful in dealing with contaminated sediments in a disaster area.

- Pugmill mixers and concrete ready mix trucks appear capable of effectively mixing high moisture content cementitiously stabilized fine grained materials.

7.2 Recommendations

- Implement the construction procedures into disaster recovery in applicable situations as described in this report.

- Observe additional construction sites where pugmill mixers and positive displacement pumps are used with soil slurries, especially if projects can be located using cementitiously stabilized soil slurries as they appear to be rare. A nationwide search for applicable projects should be conducted.

- Search for additional emergency construction material applications. Review previous disasters and see what impact the material could have had in those situations.

- Contact construction companies alongside equipment manufacturers when trying to locate suitable equipment for a disaster recovery project. Many manufacturers do not keep large equipment inventories so it is possible that more equipment can be located at construction companies than from manufacturers on short notice.

- Perform pilot testing and establish production rates for pugmill mixers and ready mix trucks for different soil types, moisture contents, and cement dosage rates. The investigation should be performed to determine conditions that would maximize strength and minimize variability.

- Perform pilot testing and establish pumping distances for different soil types, moisture contents, and cement dosage rates. Upper end positive displacement pump distances are not fully understood for these materials. Some information is available in this regard, but more needs to be learned.

CHAPTER 8 - REFERENCES

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