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Effects of Light Cement Stabilization on Properties of Fine-Grained Dredged Soils

Reference

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ABSTRACT

Dredged soils often have very high moisture content and exhibit poor engineering properties. This article presents experimental results to assess index properties and strength development of lightly cemented soils with very high moisture content over time. A key objective was to show that very-high-moisture soils can be stabilized with low dosages of portland-limestone cement (PLC) or ordinary portland cement (OPC) and still achieve useful properties for some beneficial reuse applications. Key factors separating this effort from past efforts are the use of lower cement dosages and comparisons between traditionally used OPC and a more sustainable alternative (PLC). Dredged soils were collected from two disposal facilities near the ports of Memphis, Tennessee, and Mobile, Alabama. Mixtures were prepared at two levels of moisture content with two cement types and three levels of cement content. Results showed soils stabilized at 10 % cement meet the target unconfined compressive strength for low ground pressure construction applications (>140 kPa). Findings supported the position that lightly cemented soils with very high moisture, especially with PLC, are sustainable and can achieve suitable properties for some applications.

Keywords

sustainable development, dredged soil, stabilization, portland-limestone cement, beneficial reuse

Introduction and Background

In recent years, dredging and associated dredged materials have drawn more attention because of, at least in part, the Panama Canal expansion. This attention has led to studies including but not limited to exploring beneficial reuse opportunities, minimizing environmental impacts, remediating problematic materials, and enhancing river and sea transportation (e.g., Siham et al. 2008; Sheehan and Harrington 2012; Cappuyns, Deweirt, and Rousseau 2015; Wang 2009; Miraoui, Zentar, and Abriak 2012; Howard and Carruth 2015; Grubb et al. 2010a; Bazne, Vahedifard, and Howard 2015; Vahedifard et al. 2015; Fattah, Nareeman, and Salman, 2011; Rakshith and Singh 2016). Also, placing millions of cubic meters of fine-grained very-high-moisture content soil (VHMS) from harbors, oceans, and rivers into disposal facilities has resulted in capacity issues. VHMS has undesirable properties such as low strength, handling problems, and high compressibility. Stabilization or remediation of dredged soils has been widely studied, including the possibility of cement stabilization to mitigate undesirable properties of dredged soil (e.g., Rakshith and Singh 2016). However, there is limited information in the literature regarding the possibility of meeting the needs of some projects by way of lightly cemented VHMS (LC-VHMS) (defined as 5 % or less cement by slurry mass), especially by way of a more sustainable alternative to ordinary portland cement (OPC) described in ASTM C150, *Standard Specification for Portland Cement*.

Portland-limestone cement (PLC), as described in ASTM C595, *Standard Specification for Blended Hydraulic Cements*, and ASTM C1157, *Standard Performance Specification for Hydraulic Cement*, is a more sustainable alternative to OPC. As of 2012, Type IL PLC was adopted in ASTM C595 and AASHTO M240, *Standard Specification for Blended Cement*, which was an important step towards acceptance of PLC into the U.S. market. Cost, Howard, and Shannon (2013) and Cost et al. (2015) provide background information on various applications of PLC products worldwide and also describe how PLC products are rapidly making their way into the U.S. market. PLC is relatively new to concrete in the U.S. market, which makes applicability in soil stabilization even more novel. LC-VHMS produced with PLC has a particularly low carbon footprint because of the use of lower dosages of more sustainable cement. Recent studies show that PLC offers a sustainable soil stabilization alternative to OPC while leading to comparable engineering properties (e.g., Bazne, Howard, and Vahedifard 2017; Smith, Howard, and Vahedifard 2017).

The primary objective of this study is to evaluate engineering properties of LC-VHMS for low ground pressure construction applications while comparing the performance of PLC for soil stabilization purposes versus traditionally used OPC. Dredged soils were collected from two disposal facilities near the ports of Memphis, Tennessee, and Mobile, Alabama. For each site, twelve mixtures were prepared (two moisture contents, two cement types, and three cement contents). A series of index, unconfined compression (UC), and unconsolidated undrained (UU) triaxial tests were conducted. Prior to presenting the experimental plan and results, literature review is provided focusing on the applications and relevant properties of stabilized fine-grained soils.

Properties and Applications of Stabilized Fine-Grained Soils

Stabilized VHMS has been evaluated for construction fill applications (e.g., Chew, Kamruzzaman, and Lee 2004; Horpibulsuk, Miura, and Nagaraj 2005; Sariosseiri and Muhunthan, 2009; Bazne, Vahedifard, and Howard 2015). Others have studied the use of cement stabilization of soft dredged material that could not otherwise be used as fill material because of inadequate shear strength (e.g., Kim, Kim, and Lee 2008). Stabilized VHMS could be, or in some cases has been, used for applications including the following: filling geotextile tubes (Howard and Trainer 2011; Howard et al. 2012; Bazne, Vahedifard, and Howard 2015); backfill materials (Huang et al. 2011); and a variety of general purpose land improvement or land creation applications in and around ports, such as shoulder protection (Vervaeke et al. 2003).

Hydraulic (or hydration) and pozzolanic reactions are possible when cement is mixed into clay soils (Kim et al. 2010; Azhar, Chan, and AbdKarim 2014). Grubb et al. (2010a) studied properties of 20 stabilizing combinations mixed with dredged soils from Craney Island, Virginia, and showed the effects of pozzolanic reactions between combinations. Howard, Carruth, and Cost (2015) performed UC tests to study the chemical properties of VHMS stabilized with cement, and their results indicated 20–745 kPa unconfined compressive strength could be achieved after 1–7 days of room temperature curing for various combinations of moisture and cement content, ranging from 100 to 233 % and 5 to 15 % (of slurry mass), respectively. Grubb et al. (2010b) studied stabilized dredged material classified as CH or OH with in situ moisture of around 130 % with various combinations of cementitious materials. The primary finding was that stabilized dredged materials exhibit suitable strength, compressibility, and bulking characteristics to be favorable for large fill and subgrade improvement applications at costs equal to or less than conventional construction materials.

Experimental Program

MATERIALS TESTED

Fine-grained dredged soils were collected from two U.S. Army Corps of Engineers dredge disposal facilities (**Table 1**). The first soil was sampled from Memphis, Tennessee, and is labeled ME. The second soil was sampled from Mobile, Alabama, and is labeled MO. Both soils were classified as CH or OH. The dredged soils were evaluated in conjunction with two cement types produced at the same facility: (1) Type GU PLC specified under ASTM C1157 and (2) Type I/II OPC specified under ASTM C150. The PLC had approximately 13 % limestone, and the OPC had approximately 2 % limestone. Embodied energy decreases as limestone content increases because ground limestone replaces cement clinker.

SLURRY PREPARATION

Dredged soil at an initial moisture content (w_c) was mixed into VHMS slurry (soil plus water). The initial moisture content of soil slurry was selected to be the liquid limit (LL) and 100 % for MO and ME soils. As shown in **Table 1**, the LL values for MO and ME soils were measured to be 70 % and 90 %, respectively. LL is

TABLE 1. Average index properties of dredged soils collected from Memphis (ME) and Mobile (MO) dredge disposal facilities.

Property	Unit	Test Method	Soil Site	
			ME	MO
Specific Gravity (G_s)	–	ASTM D584	2.66	2.57
Initial Water Content (w_c)	%	ASTM D2116	80	33
Max. Dry Density (γ_{dmax})	g/cm^3	ASTM D698	1.31	1.52
Optimum Moisture Content (ω_{opt})	%	ASTM D698	30	25
Liquid Limit (LL)	%	ASTM D4318	90	70
Plastic Limit (PL)	%	ASTM D4318	32	24
Plasticity Index (PI)	%	ASTM D4318	58	46
Sand	%	ASTM D422	5	18
Silt	%	ASTM D422	58	40
Clay	%	ASTM D422	37	42
Organic Content	%	ASTM D422	12	8
USCS	–	ASTM D2487	CH to OH	CH to OH

considered the minimum moisture content at which soils have an undrained shear strength of approximately 2.5 kPa (Casagrande 1932), and it is the minimum moisture content meeting the VHMS definition. The 100 % moisture content was also tested as it is commonly used in similar studies on VHMS (Howard and Carruth 2015, Bazne, Howard, and Vahedifard 2017). At 100 % moisture, VHMS has equal parts water and solids by mass.

TESTING MATRIX AND SAMPLE PREPARATION

The UC testing matrix included PLC and OPC at three cement content levels (C_{dry}) of 2.5, 5, and 10 % of dry soil mass, which translates to 1.3–5.9 % on a slurry mass basis and ranges from exceptionally low cement dosing to modest exceedance of the LC-VHMS definition. Dry mass cement dosing allowed for consistency between soil and moisture content combinations. Both soils were tested with two moisture content levels (LL and 100 %) and at four test ages in triplicate, for a total of 288 UC specimens. The majority of the cases tested in this study did not have measurable flow, as defined by ASTM D6103, *Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)*, and as such placement via positive displacement pumps would likely not be as desirable as bucket loaders and trucks.

UC specimens were prepared in a 165-mm tall by 76-mm diameter plastic mold, which was fitted with a thin aluminum plate for specimen removal. Stabilized slurry was added in 3 lifts with the mold tapped 25 times around the side between each lift. Specimens were covered with a plastic cap and stored in a curing room with 100 % relative humidity at approximately 22°C.

A total of 192 UU specimens were also prepared from 2 soils (ME, MO), 2 moisture contents (LL, 100 %), 2 cement types (OPC, PLC), 2 cement contents (5, 10 %), 3 confining pressures (10 to 120 kPa), 4 test ages (7, 28, 56, 115 days), and no replication. LC-VHMS was molded in PVC molds (95-mm tall and 100-mm diameter). The UU molds were filled in 3 lifts by tapping the molds 25 times around the side after placing each lift. The UU molds were covered with aluminum foil and stored in 100 % humidity at approximately 22°C. Because the groups with 2.5 % C_{dry} showed little or no strength gain during the UC testing, UU tests were not performed for groups containing 2.5 % C_{dry}.

TESTING PROCEDURES

After curing, UC specimens were extruded from the molds and tested (**Fig. 1a** and **1b**) according to ASTM D2166, *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*, with a strain rate of 1 %/min, 0.5 % strain past the maximum force, and using the corrected area for stress and strain determination. After 90 days of curing, moisture content (w_f), dry density (γ_d), void ratio (e), and Atterberg limits were measured on the UC specimens and the average values were reported. Void ratio was determined using wet and dry densities, and moisture contents were measured on representative portions of the specimens after testing. Before running the Atterberg limit tests, the soil was allowed to air dry for three days, processed over a No. 40 sieve, and evaluated as per the ASTM D4318, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*, multipoint procedure.

After curing, three specimens (70-mm tall by 35-mm diameter) were extruded from each 100-mm diameter UU mold and tested according to ASTM D2850, *Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils* (**Fig. 1c**). Confining pressures ranged from 10–120 kPa. Low confining pressures were chosen to be representative of low ground pressure construction applications. The maximum deviator stress was considered as the failure criterion for specimens tested.

Test Results and Discussion

Results and pertinent discussion are presented in the following three subsections for index property, UC, and UU results. Further analysis of the data was also presented in a sponsor report

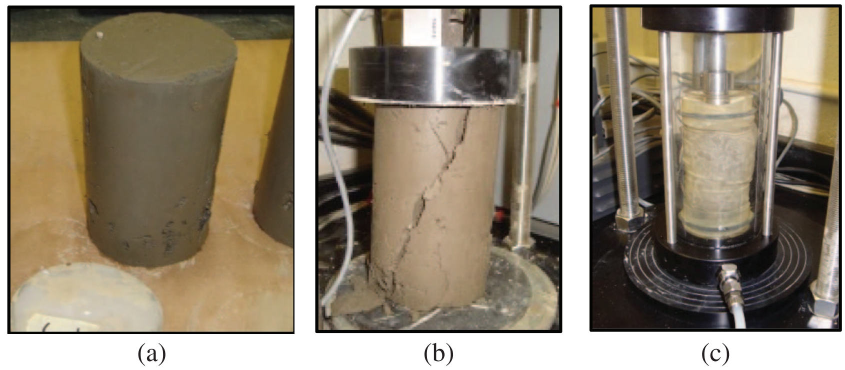


FIG. 1
Photographs of specimens and testing: (a) extruded UC specimen; (b) tested UC specimen; (c) tested UU specimen.

(Vahedifard et al. 2015) and a dissertation (Bazne 2016), in which assessments omitted a few strength measurements based on engineering judgment. The analysis presented herein makes use of all measurements, and in a few cases the structure of the analysis is slightly different than that of Vahedifard et al. (2015) and Bazne (2016). However, all interpretations lead to the same overall assessment.

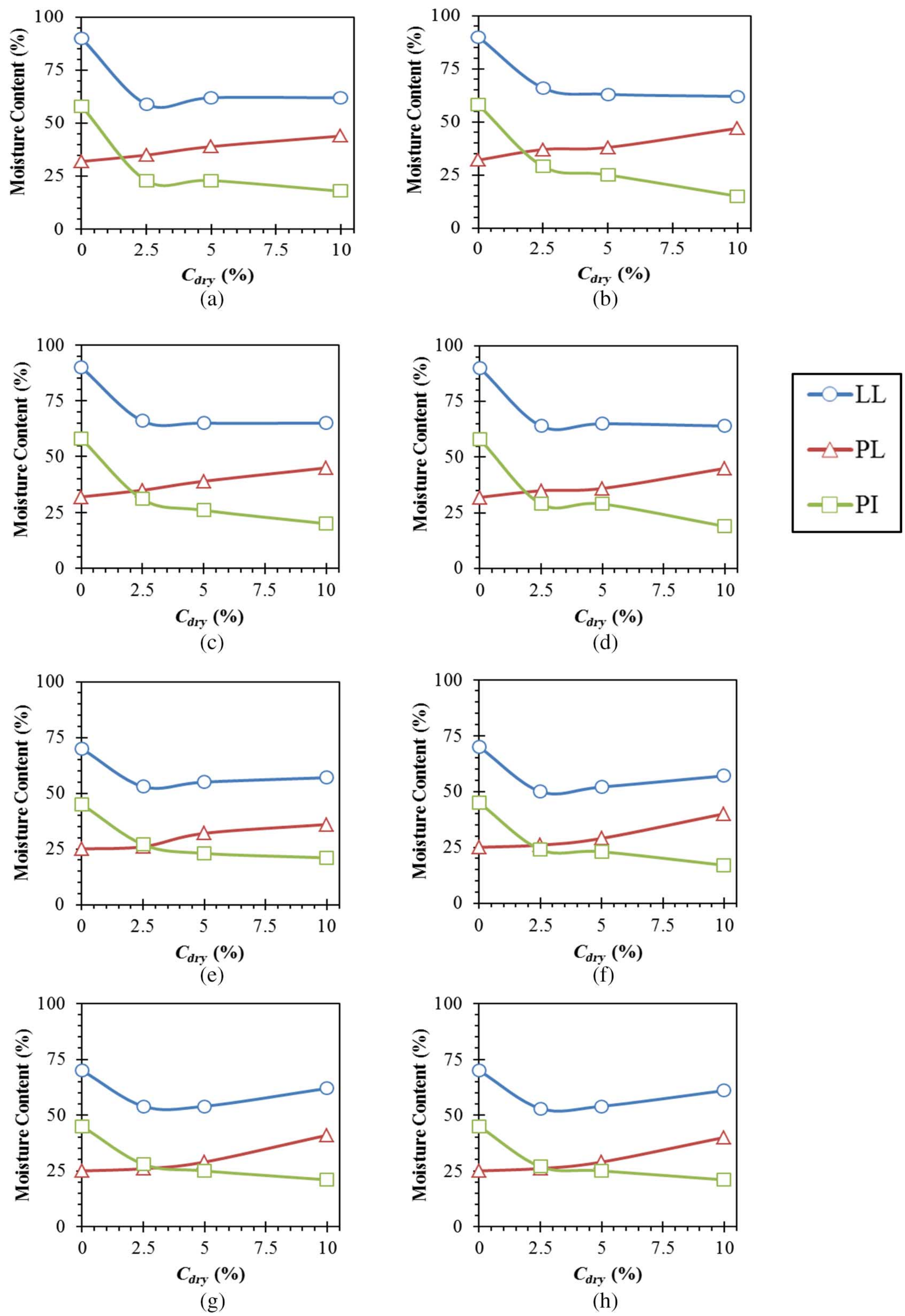
INDEX PROPERTY RESULTS

Moisture content, dry density, and void ratio results are provided in **Table 2**. As expected, cement addition reduced moisture and increased dry density. As shown, ME dry densities ranged from 0.74 to 0.82 g/cm^3, while MO dry densities ranges from 0.70 to 1.00 g/cm^3. For reference, untreated ME soil at 100 % moisture content leads to a theoretical dry density of 0.73 g/cm^3, and adding cement increases the dry density. Moisture content decreased from 2 to 17 % relative to values at the time of specimen preparation. At 2.5, 5, and 10 % cement content, moisture reduced by 2 to 8 %, 5 to 13 %, and 8 to 17 %, respectively. These results were generally expected, as others have reported similar results (Kamon and Nontananandh 1991; Chew, Kamruzzaman, and Lee, 2004; Bergado et al. 2006).

TABLE 2. Moisture content, dry density, and void ratio test results.

Soil	w_c (%)	Cement	C_{dry} (%)	w_f (%)	γ_d (g/cm^3)	e
ME	90	PLC	2.5	82.6	0.80	0.83
			5	81.7	0.81	0.82
			10	81.2	0.82	0.81
ME	100	PLC	2.5	91.6	0.75	0.92
			5	91.2	0.76	0.91
			10	90.7	0.78	0.91
MO	70	PLC	2.5	65.9	0.95	0.66
			5	64.4	0.96	0.64
			10	57.7	1.00	0.58
MO	100	PLC	2.5	91.3	0.70	0.91
			5	91.2	0.78	0.91
			10	83.1	0.81	0.84
ME	90	OPC	2.5	87.9	0.78	0.88
			5	84.3	0.80	0.84
			10	82.1	0.81	0.82
ME	100	OPC	2.5	92.9	0.74	0.93
			5	87.0	0.79	0.85
			10	83.3	0.81	0.83
MO	70	OPC	2.5	66.0	0.94	0.66
			5	65.0	0.95	0.65
			10	57.5	0.98	0.57
MO	100	OPC	2.5	92.9	0.77	0.93
			5	91.5	0.77	0.92
			10	84.3	0.81	0.84

FIG. 2 Atterberg limit test results. (a) 90 % w_c, PLC, ME soil. (b) 90 % w_c, OPC, ME soil. (c) 100 % w_c, PLC, ME soil. (d) 100 % w_c, OPC, ME soil. (e) 70 % w_c, PLC, MO soil. (f) 70 % w_c, OPC, MO soil. (g) 100 % w_c, PLC, MO soil. (h) 100 % w_c, OPC, MO soil.



After 90 days of curing, pozzolanic reactions tend to decrease moisture content and void ratio while increasing dry density. Because pozzolanic behavior of OPC versus PLC is largely unexplored in soil, **Table 2** was used to compare their properties. The moisture content decrease relative to the specimen preparation time was very similar for PLC- and OPC-stabilized soils (9 % for PLC and 8.8 % for OPC). Dry density and void ratio differences between OPC- and PLC-stabilized soils were also insignificant. Average dry density and void ratio values from **Table 2** were 0.83 g/cm^3 and 0.81 g/cm^3 for OPC and PLC, respectively. Ranges of values were slightly different between OPC and PLC, but the ranges mostly overlapped.

Atterberg limit results are plotted in **Fig. 2**. LL decreased noticeably and plastic limit (PL) increased marginally to decrease the plasticity index (PI) for all cases where 2.5 % cement was added to raw dredged soil. Additional cement content increases had modest effects on LL, while PL steadily increased with cement content additions. There were no meaningful or statistically significant overall differences for LL or PL between OPC- and PLC-stabilized soils. Paired t-testing found mean LL and PL differences of less than 0.3 % with p-values of 0.75–0.88.

UNCONFINED COMPRESSION (UC) TEST RESULTS

Average LC-VHMS unconfined compressive strength (q_u) relationships are presented in **Figs. 3** and **4** for ME and MO soils, respectively. Prior to interpreting **Figs. 3** and **4**, the data were benchmarked in terms of overall properties and variability relative to past studies. One soil tested by Howard, Carruth, and Cost (2015) was from Mobile and had similar properties to the MO soil tested herein. Unconfined compressive strengths at 100 % moisture and 10 % cement by dry mass was 100–150 kPa for 7 different cements after 7 days of curing. These results are in reasonable agreement with the 135–165 kPa strengths shown in **Fig. 4** for 10 % cement and 100 % moisture. **Table 3** compares coefficient of variation (COV) (i.e., standard deviation divided by the mean) of the data from **Figs. 3** and **4** versus the results reported by Howard, Carruth, and Cost (2015). It is noted that Howard, Carruth, and Cost (2015) used generally shorter testing times and higher cement dosages than the current effort. As seen, 87 % of the current data have COV values of less than 15 %, and the current data are less variable than previously published data sets with VHMS. As such, the following analysis incorporated some statistical assessments, but these assessments should be

FIG. 3 Unconfined compressive strengths for ME specimens with initial moisture content at LL (90 %) and 100 % (Note: the x-axis shows "water content," "cement content," and "cement type" for each mixture).

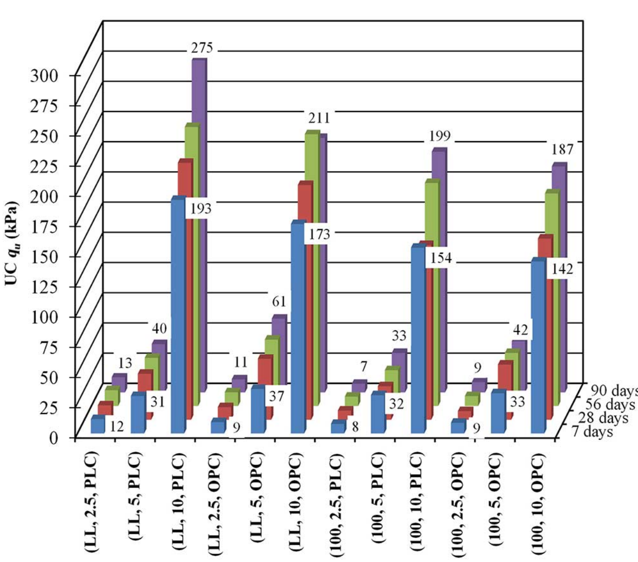


FIG. 4 Unconfined compressive strengths for MO specimens with initial moisture content at LL (70 %) and 100 % (Note: the x-axis shows "water content," "cement content," and "cement type" for each mixture).

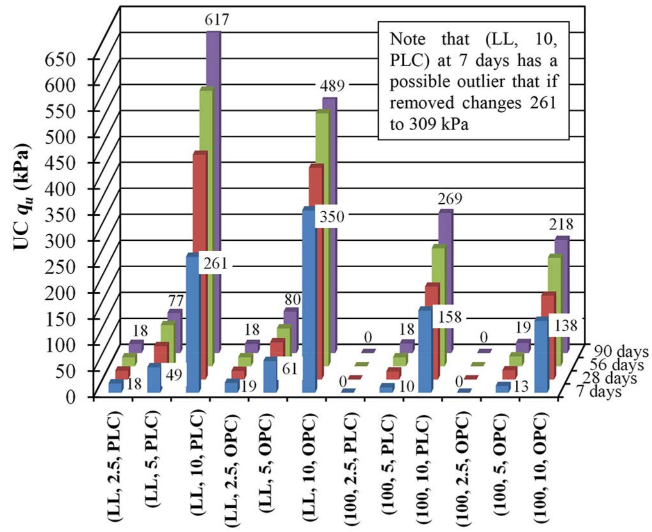


TABLE 3. Variability benchmarking.

	Coefficient of Variation (COV) Relative Frequency (%)	
Bin	Howard, Carruth, and Cost (2015)	Figs. 3 and 4
<5	9	42
5.1 to 10.0	30	31
10.1 to 15.0	20	14
15.1 to 20.0	25	8
20.1 to 25.0	7	4
25.1 to 30.0	6	0
>30	3	1

Notes: Howard, Carruth, and Cost (2015) tested VHMS with 5–15 % cement by slurry mass and contained approximately 200 variability sets that had 3–36 replicates each, in which average UC strengths ranged from 5 to 370 kPa. **Figs. 3** and **4** have 96 variability sets with 3 replicates each, and is the data analyzed in the current paper.

interpreted in the context that only three replicate tests were performed.

ME soil achieved 13 kPa or less at 2.5 % cement, and 61 kPa or less at 5 % cement (**Fig. 3**). At 5 % cement, OPC modestly outperformed PLC. Much higher strengths were observed for ME soil treated with 10 % cement for both cement types. PLC specimens cured for 90 days had higher q_u than OPC for both moisture contents.

As shown in **Fig. 4**, there was no strength gain for MO specimens treated with 2.5 % cement at 100 % moisture and very little strength gain with 5 % cement and 100 % moisture. Modest strengths were produced with 5 % cement at 70 % moisture. Strengths that were easily a half-order of magnitude more than 5 % cement were observed when the cement content was doubled to 10 %.

The data in **Figs. 3** and **4** were used to conduct an analysis of variance with factorial arrangements of treatments and a response variable q_u. Most calculations were performed using the statistical package SAS. Different cure times were considered as block effects, while factors of cement content, cement type, and initial moisture content were considered as treatments. Cure time produced statistically different values for q_u, and two factor interactions were present in some cases. As such, multiple comparison procedures were used to statistically rank treatment groups (**Table 4**). For ME soil at 10 % cement and LL moisture content, PLC produced a statistically significant strength improvement of 27 kPa, whereas for MO soil, PLC also produced a strength improvement of 27 kPa, but it was statistically insignificant.

Hydraulic and pozzolanic behaviors can be evaluated by comparing compressive strength results from 7 to 28 days and 56 to 90 days, respectively. Hydraulic behavior refers to the formation of calcium silicate hydrate due only to portland cement and water reactions. Pozzolanic behavior refers herein to free lime produced from portland cement reacting with water that subsequently reacts with clay minerals. Testing was performed for 90 days largely to compare relative hydraulic and pozzolanic behaviors between OPC and PLC cements. Compressive strengths at 28 days being meaningfully different from 7 days indicates the likelihood of hydraulic reactions, whereas compressive strengths at 90 days being meaningfully different from 56 days indicates the likelihood of pozzolanic reactions.

To evaluate trends of q_u with cure time, four completely randomized statistical evaluations were performed on specimens with 10 % cement content in which soil source and cement type were constant. Interaction was present between moisture content and cure time for MO, but not for ME. **Tables 5** and **6** provide pertinent results from this analysis in which ME data are consolidated into cure time but MO is separated into cure time and moisture content due to interaction being present.

OPC strengths increased from 14 to 57 kPa from 7 to 28 days, and all but one of the cases was statistically insignificant. OPC strengths increased no more than 10 kPa from 56 to 90 days, which was statistically insignificant. OPC strength gain became progressively less over time, indicating primarily hydraulic reactions. PLC strengths increased from 5 to 171 kPa from 7 to 28 days, and all but one of the cases was statistically insignificant. The increase of 171 kPa was for MO soil at 70 % moisture (LL). It is noted that there was one questionable specimen that if removed from consideration changes the increase from 171 to 123 kPa (the difference is significant in either case). PLC strengths increased from 29 to 87 kPa from 56 to 90 days, which was only statistically significant in one case. PLC strength gain was meaningful even at later ages, indicating a combination of hydraulic and pozzolanic reactions.

Fig. 5 is an equality plot comparing all OPC data to all PLC data in **Figs. 3** and **4**. Overall, PLC produced 9 % higher strength than OPC based on regression with an R^2 of 0.97. If the

TABLE 4. Ranking of cement content, cement type, and initial water content with respect to q_u from UC test results of LC-VHMS.

Memphis					Mobile				
Cement Type	C_{dry} (%)	w_c (%)	Mean q_u (kPa)	t-group	Cement Type	C_{dry} (%)	w_c (%)	Mean q_u (kPa)	t-group
PLC	10	90	228	A	PLC	10	70	460	A
OPC	10	90	201	B	OPC	10	70	433	A
PLC	10	100	171	C	PLC	10	100	208	B
OPC	10	100	164	C	OPC	10	100	181	B
OPC	5	90	51	D	OPC	5	70	71	C
OPC	5	100	41	DE	PLC	5	70	67	C
PLC	5	90	37	E	OPC	2.5	70	18	D
PLC	5	100	30	E	PLC	2.5	70	17	D
PLC	2.5	90	12	F	OPC	5	100	17	D
OPC	2.5	90	11	F	PLC	5	100	15	D
OPC	2.5	100	8	F	OPC	2.5	100	0	D
PLC	2.5	100	8	F	PLC	2.5	100	0	D

TABLE 5. Ranking of ME UC test results for cure time investigation.

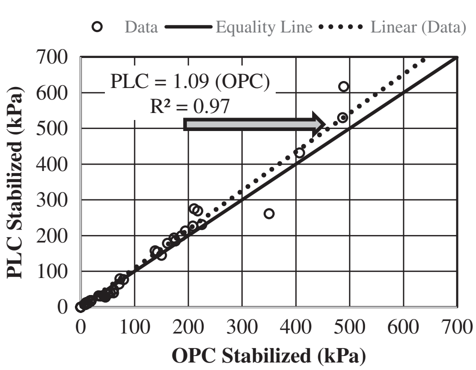
10 % OPC			10 % PLC		
Cure Time (days)	Mean q_u (kPa)	t-group	Cure Time (days)	Mean q_u (kPa)	t-group
56	201	A	90	237	A
90	199	A	56	208	B
28	172	B	28	179	C
7	158	B	7	174	C

TABLE 6. Ranking of MO UC test results for cure time investigation.

10 % OPC				10 % PLC			
Cure Time (days)	w_c (%)	Mean q_u (kPa)	t-group	Cure Time (days)	w_c (%)	Mean q_u (kPa)	t-group
90	70	489	A	90	70	617	A
56	70	487	A	56	70	530	A
28	70	407	B	28	70	432	B
7	70	350	C	90	100	269	C
90	100	218	D	7	70	261	CD
56	100	208	D	56	100	227	CDE
28	100	161	E	28	100	178	DE
7	100	138	E	7	100	158	E

Note: Two-way interaction of treatments prevented analyzing results for Mobile specimens based solely on cure time.

FIG. 5 Unconfined compression equality plot comparing OPC to PLC.



questionable 7-day PLC data point in **Fig. 4** is changed from 261 to 309 kPa, PLC produces 10 % higher strength than OPC with an R^2 of 0.98. These data suggest PLC produced modestly improved unconfined compressive strengths at a reduced environmental impact relative to OPC.

UU TRIAXIAL TEST RESULTS

Figs. 6 and **7** summarize maximum deviator stresses (D) results in which D is the average value from three different confining pressures (σ_3) from 10 to 120 kPa that varied with cement content and curing age. These figures should be interpreted in the context of the confining pressures used for each group of data. Consistent with reported trends in the literature (Wang and Miao 2009), **Figs. 6** and **7** depict that cement content and confining pressure significantly increased shear strength.

FIG. 6 UU triaxial results (maximum deviator stress): ME soil. Confining pressures tested: 10, 20, and 40 kPa for 7 days; 15, 30, and 45 kPa for 28 days and 56 days; 15, 30, and 45 kPa for 5 % C_{dry} at 115-day specimens; and 15, 60, and 120 kPa for 10 % C_{dry} at 115-day specimens (Note: the x-axis shows "water content," "cement content," and "cement type" for each mixture).

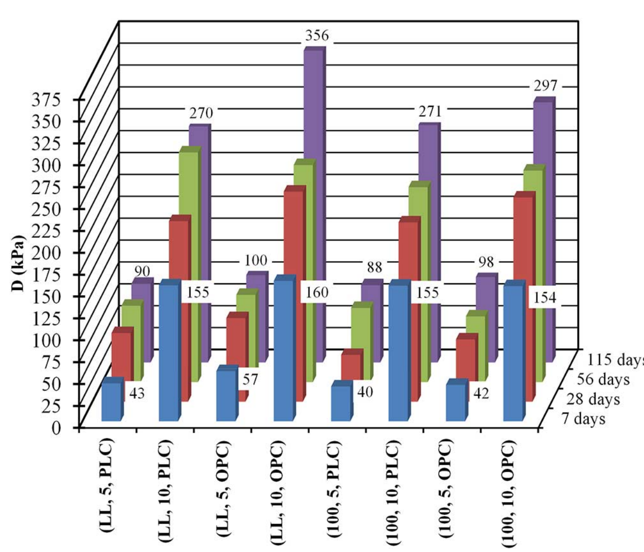


FIG. 7 UU triaxial results (maximum deviator stress): MO soil. Confining pressures tested: 10, 20, and 40 kPa for 7 days; 15, 30, and 45 kPa for 28 days and 56 days; 15, 30, and 45 kPa for 5 % C_{dry} at 115-day specimens; and 15, 60, and 120 kPa at 10 % C_{dry} for 115-day specimens (Note: the x-axis shows "water content," "cement content," and "cement type" for each mixture).

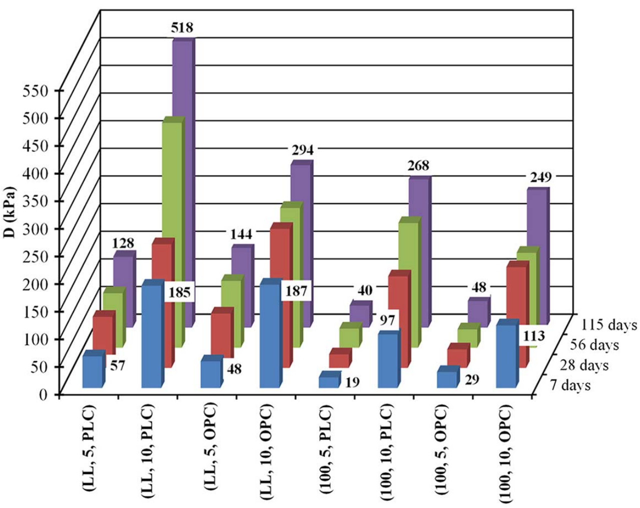
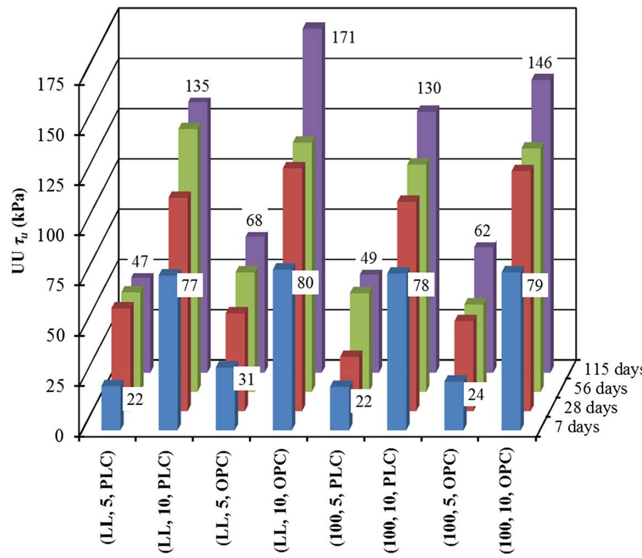


FIG. 8 Shear strengths for ME specimens with σ = 150 kPa (Note: the x-axis shows "water content," "cement content," and "cement type" for each mixture).



Mohr-Coulomb failure envelopes were produced (Vahedifard et al. 2015) to determine undrained cohesion (c_u) and undrained angle of internal friction (ϕ_u) with results shown in **Table 7**. The results indicate that c_u increased with higher cure time and cement content. With other factors constant, cohesion increased as moisture decreased. Additional cure time leads to the formation of more cement bonds, which further adhere particles together. In a similar manner, a higher cement content creates additional cement bonds. On the contrary, higher moisture means more space is filled by water, increasing the spacing between the soil particles. Cement addition was found to have a modest effect

TABLE 7. Variation of undrained cohesion and friction angle of ME and MO soils with different curing periods.

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

[a] Each ID represents "water content," "cement content," and "cement type."

FIG. 9 Shear strengths for MO specimens with σ = 150 kPa (Note: the x-axis shows "water content," "cement content," and "cement type" for each mixture).

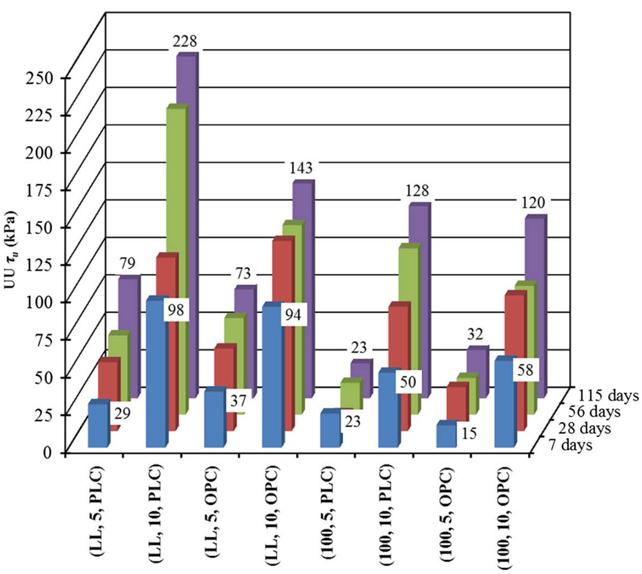
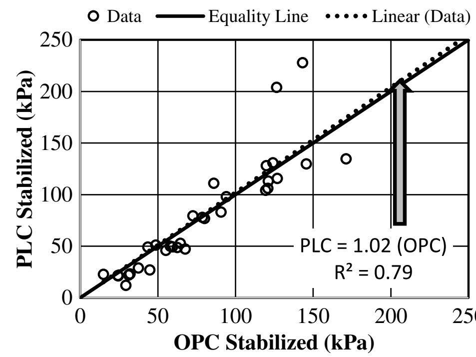


FIG. 10 Shear strength (σ = 150 kPa) equality plot comparing OPC to PLC.



of angle on internal friction. The latter is because ϕ_u is primarily controlled by interactions between fine particles and does not always increase with an increase in cement content. Other studies have reported similar results (Okyay and Dias 2010; Miao et al. 2013).

Shear strength (τ_u) from UU testing is presented in **Figs. 8** and **9**, in which τ_u is for a normal stress (σ) of 150 kPa (a representative normal stress for low ground pressure construction applications). At 5 % cement, OPC produced greater shear strengths than PLC for ME soil, and as much or more shear strength for MO soil. UU findings at 5 % cement generally agree with UC findings. UU results at 10 % cement did not fully agree with UC testing. MO soil treated with 10 % PLC produced higher late age shear strength than 10 % OPC, whereas 10 % OPC produced higher early age shear strength in some cases. ME soil treated with 10 % cement resulted in higher strengths at early and late ages from OPC (at early ages, strengths were only slightly higher with OPC). UC strengths did not align with these results and suggested PLC outperformed OPC by a noticeable margin at 10 % cement. These discrepancies may be attributed to the effect of confining pressure.

Fig. 10 is an equality plot of shear strength data comparing OPC- to PLC-stabilized soils for all combinations tested. PLC was 2 % stronger than OPC overall, though there was much more scatter than for UC (R^2 of 0.79). There is no meaningful difference between OPC and PLC based on this figure for the overall data set, though as the scatter shows, OPC performed better in some cases and PLC performed better in other cases.

Conclusions

This study investigated engineering properties of lightly cemented dredged VHMS for reuse in low ground pressure applications. A primary focus was to compare properties achievable with OPC versus the more sustainable PLC. This paper evaluated lower cement dosages than those typically used for stabilizing fine-grained dredged soil at moisture contents at or above their LL.

Results showed that LC-VHMSs attained suitable strength for some low ground pressure applications in which cement dosages were 5–10 % by dry soil mass. Lightly cementing VHMS improved index properties as well. PLC performed at least comparably to OPC within LC-VHMS; there were no meaningful overall performance differences between OPC and PLC. PLC outperformed OPC in some cases, OPC outperformed PLC in some cases, and they equally performed in some cases. The key finding from this study was that PLC can offer a sustainable stabilization alternative for fine-grained dredged soil in LC-VHMS, which appears feasible for low ground pressure applications. The potential for enhanced later age pozzolanic reactions with PLC should be explored in more detail.

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