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Research Article

Performance of dredged sediments based controlled low-strength material

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ABSTRACT

The process of depleting the natural sources of virgin sand and aggregate makes it challenging to satisfy the demand for construction work. Therefore, in a context of sustainable construction, this study examined the feasibility of utilizing dredged sediments (DS) as a substitute for sand in non-structural controlled low-strength materials (CLSM). A total of two types of dredged sediments, coarser and finer, were collected from two different sources. Then, nine CLSM mixtures were prepared by using different proportions of natural sand (virgin sand) and dredged sediments. Each mixture was tested for flowability, unconfined compressive strength, density and excavatability. Flow consistency decreased with the amount of dredged sediments and presence of finer material in CLSM. Strength results were found within required specification for all nine CLSM tested in this study. Overall, flow consistency, strength and excavatability were found dependent on the characteristics of dredged sediments. This study showed that up to 50% of substitution of sand with DS in CLSM improved strength and density. Furthermore, flow consistency was found to decrease with increase in the amount of DS in CLSM mixtures.

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1. INTRODUCTION

Dredging of sediments is a critical operation to maintain and improve the global and national water navigation [1], recreation, and defense systems [2]. Additionally, this operation is of great significance for flood prevention by reducing sea level [3], and coastal protection [4]. The materials excavated from waterbodies including waterways and harbors through dredging activities are recognized as dredged sediments (DS). DS is composed of high amount of water and various sizes of solid particles. In terms of the DS's physical and chemical properties, it is significantly different from the natural sand used for construction due to its content of not only salt, but the presence of heavy metals and organic matter [5]. Specifically, DS consists of a mixture of solid particles, organic/inorganic matter, contaminants (heavy metals and toxic substances), and a high content of liquid (interstitial water). The solid particles include sand, silt, clay, and shells. Moreover, heavy metals (e.g., mercury, cadmium, arsenic, etc.) and toxic substances (e.g., benzene, dioxins, pesticides, naphthalene, etc.) have also been found in DS [6].

According to the United States Army Corps of Engineers [7], the average annual quantity of material removed from waterways and channels in the United States is approximately 152 million m^3 (212 million yd^3) during fiscal years 2008–2012. In many countries, dredged sediments are considered as waste material. In most of the countries, only about 10% of dredged materials were reused, and 90% were either dumped into the sea or used for land reclamation [5, 8, 9].

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According to McNeil [10], USACE dredge 152 million m^3 (200 million yd^3) of DS per year nationwide to maintain channels' navigation. Approximately, 38 million m^3 (50 million yd^3) DS are beneficially reused and 116 million m^3 (150 million yd^3) provide opportunity [10]). This 116 million m^3 (150 million yd^3) DS are enough for covering 1 m (1.1 yard) of approximately 10,918 soccer fields. Some of the beneficial applications of dredged material are for beach nourishment, topsoil creation/enhancement, land creation/enhancement, habitat restoration and construction materials [11].

Literature review indicates that several researchers studied beneficial use of DS as a sand substitute in concrete materials. However, DS has not been widely used in concrete materials in the US. There appears to be three barriers. Barrier #1) The first is that concrete utilized in pavements or structures must meet tight specifications/standards, and only frequently tested/used materials are relied upon to meet those specifications/standards. Barrier #2) Contamination of DS could potentially impact performance of concrete materials. If DS is used directly then low pH and high salinity may corrode the reinforcement and increase the possibility of chloride attack [12, 13]. Barrier #3) The variability of DS due to spatial location, dredging operation, and material placement is also a concern in receiving consistent quality of material for reusing in concrete [14]. Physically, DS particles can range from sand to fine clay sizes. Chemically, DS may be clean or may contain any variety of contaminants as well as valuable nutrients [11].

The current research investigated an innovation that has the potential to address all four of these barriers from environmental and economic standpoints. Controlled low-strength material (CLSM) (also known as "flowable fill") is a concrete material which is used for backfilling utility trenches and excavations. It is applied as a flowable liquid, allowing voids to be easily filled and avoiding labor costs associated with compacted fill, yet is sufficiently low in strength to allow easy re-excavation [15]. Any ready-mix concrete plant can produce CLSM. These characteristics have resulted in increasing popularity of flowable fill [16].

The use of DS in CLSM could potentially address all three aforementioned barriers of utilizing dredged material in construction. First, CLSM mix is non-structural and specified by contractors or local agency [15]. Therefore, use of DM in CLSM imposes less risk compared to structural concrete. This will allow ready-mix plants to gain confidence and experience with DS, encouraging its use in other concrete mixtures in future. Second, CLSM requires low performance standards due to which it could tolerate contaminated DS materials. Third, inferior quality of sand that do not meet structural and pavement concrete standards are often acceptable in CLSM [15].

2. BRIEF REVIEW OF PREVIOUS STUDIES

Tarabadkar [17] created artificial aggregates using the accelerated carbonation technique, in which a mixture of sediments, water, and Portland cement were carbonated in a 100% carbon dioxide atmosphere. The accelerated carbonation technique improved the material's properties by facilitating carbon dioxide sequestration. Various artificial aggregate mixtures were analyzed using a statistical technique. Small scale experiments were carried out to determine the key process parameters for process optimization. The optimal mixture was composed of 55% sediments, 25% Portland cement, and 20% water. The mixture was carbonated in a tumbler for 2 hours to produce artificial aggregates. Full-scale experiments on the optimal mixture were carried out while key process parameters were considered. Artificial aggregates were uniformly graded, according to particle size analysis. Scanning Electron Microscopy (SEM) and thermogravimetric analysis revealed that a higher percentage of clay in the sediments caused the formation of two distinct layers in an aggregate, obstructing the uniform formation of $CaCO_3$. The results of the pH-dependent leaching tests revealed that metals were released at a lower rate in carbonated artificial aggregates than in uncarbonated raw sediments. Finally, it was determined that artificial carbonation of contaminated sediments can produce artificial aggregates that can be used for beneficial purposes.

Kim and Pradhan [18] evaluated stabilized organic dredged soils by conducting unconfined compression tests, pH tests, and seed germination experiments. To assess the impact of the organic content on the mechanical and germination characteristics of the stabilized soils, several mixtures with organic contents ranging from 0 to 30% by mass and binder contents ranging from 5 to 15% were prepared. It was found that a stabilized organic soil's strength and pH fall as its organic content rises, creating ideal germination circumstances. With an increase in organic content, both the germination rate and plant growth rate dramatically increased. The soil's strength was boosted by adding binder to mixtures, but the pH was also raised. As the organic content increased, the stability of the soils became weaker. This was explained by humic acid's affinity for the calcium in the soil. Increased soil nitrogen concentration was associated with a lower pH. Higher seed germination rates in mixtures with more organic material resulted in plants with more height and biomass overall. Shorter seed germination rates brought for plants with lower heights and less total biomass when binder levels were higher. This was related to both the increased soil strength, which inhibits root growth, and the decreased availability of nutrients at the higher pH with increased binder levels.

Kaliannan et al. [19] demonstrated that the addition of ground granulated blast furnace slag could minimize the cement content in solidification of dredged marine soils. Dredged marine soils had extremely low stiffness, low load-bearing capacity, high compressibility, and low permeability in the absence of solidification. The properties of the dredged marine soil were enhanced by the cement and slag mixture. The mix containing binder content of 3% cement and 7% slag was found to show greatest solidification outcome.

Rabbanifar [20] stabilized dredged material using hydrated lime (HL) and fly ash (FA) type F. The mechanical and physiochemical properties of the dredged material stabilized with HL and FA were evaluated after 7, 28, and 90 days of curing. The results revealed that the combination of HL and FA could effectively increase the compressive strength and decrease plasticity index of stabilized dredged material. SEM imaging revealed formation of gel covers on smaller particles, holding them together to form larger clusters. New compounds were formed, according to X-ray diffraction tests. A non-linear multi variable model was developed based on the experimental results of the study using the software R (R Studio) for predicting properties such as density and strength of the stabilized dredged material mix. The findings showed that dredged material could be successfully stabilized using HL and FA with predictable properties, transforming it into an environmentally friendly high-quality construction material.

Do et al. [21] investigated CLSM developed using a blend of natural sand, marine dredged soil (MDS), and binders, in geothermal systems. This study looked at flowability, fresh density, unconfined compressive strength, thermal conductivity, bleeding rate, and environmental impacts, among other factors. To evaluate total cost, a bleeding-rate-based volume compensation premise for an actual large-scale geothermal system was described. In terms of general and environmental properties, all the prepared CLSM mixtures performed well. Furthermore, the developed CLSM-based grout showed significantly higher thermal conductivity than conventional grouts. More importantly, an extremely positive effect of MDS was discovered: an appropriate addition of MDS to CLSM-based grout can result in a significant reduction in bleeding rate, resulting in only a small volume compensation of required boreholes.

In a recent study, Abidi et al. [22] investigated the viability of employing different percentages of dredged sediments from the Bouhanifia dam as an additive to calcareous tuff which is a natural material commonly used in road construction in Algeria. The physical, chemical, and mineralogical features of the sediments and tuff, as well as short-term mechanical performance tests, were used to make a general estimate of their long-term mechanical behavior. The study suggested that tuff admixed sediments could be used as an embankment or subgrade material; however, long-term mechanical behavior testing of these materials is required, and mechanical stabilization is recommended to improve their geomechanical behavior, as sediments are expected to have lower strength than tuff.

In another recent study, Shi et al. [23] investigated the effects of moisture content, maximum steel slag particle size, curing age, and cement and steel slag ratio on the compressive strength of dredged silty clay in a plastic flow condition. By contrasting the results of relevant earlier investigations, the performance enhancement of dredged silty clay stabilized with cement and steel slag was examined. Microstructural observation was used to investigate the strengthening process of dredged soils stabilized with cement and steel slag. The findings demonstrated that the strength qualities of dredged silty clay stabilized by cement and steel slag could guarantee the minimum requirements of the project larger than 100 kPa when the ratio of cement to steel slag was 9:6; specifically, utilizing steel slag to replace 40% of cement. The stabilizing effect improved with increasing steel slag particle fineness. With particle sizes of less than 0.075 mm, dredged silty clay stabilized with cement and steel slag showed compressive strengths that were 1.06, 1.10, and 1.16 times greater than those of 0.25 mm, 1 mm, and 2 mm, respectively. Additionally, the compressive strength increased linearly over curing ages up to 28 days. Dredged silty clay stabilized by cement and steel slag showed a compressive strength that was 2.44 times, 1.59 times, and 1.36 times greater than that of 3, 7, and 14 days, respectively. Due to the formation of more calcium silicate hydrate and other agglomerated flocculent gel materials because of the continued reaction between steel slag and cement hydration products, the structural compactness of dredged soil.

3. MATERIALS AND METHODS

3.1 Dredged Sediments and Natural Sand

The DS samples were obtained from two sources in coordination with USACE. The first sample, called as DS#1 in this study, was randomly collected from stockpiles located close to Illinois River in Glasford, Illinois. It was sitting in two piles with approximate height of forty feet. The top of the pile was washed away by rain revealing large quantities of clam shells, but the collection of material was deeper into the pile to make sure not to get washed-out material. The second sample, called as DS#2 in this study, was the stockpile next to Calumet Harbor (south side of Lake Michigan) in Chicago, Illinois. Specifically, DS#2 samples were collected from three separate stockpiles and then remixed in the laboratory before testing.

The sand used was naturally collected, not manufactured, from a pit located in Heyworth, IL. This sand was named as natural sand (NS) in this study. NS was collected by dredging under water and then sieved on US#200 (0.075 mm) for removing fines. Other than this, the sand is kept natural in most part. Figure 1 shows a photographic view of NS, DS#1 and DS#2. It is evident from Figure 1 that NS looks coarser than DS. Also, chunks of clumped clayey material are visible in DS#2.

Figure 1. Leftmost pan shows natural sand, middle pan shows DS#1 and rightmost pan shows DS#2.

For gradation analysis, sieve analysis was performed on two samples of NS, DS#1 and DS#2 in accordance with ASTM C136 test method. The results were compared to the upper limit (UL) and lower limit (LL) sieve sizes recommended by the Illinois Department of Transportation (IDOT) (2016) for CLSM sand (fine aggregates), called as FA-1 by IDOT. Figure 2 shows gradation of NS, DS#1 and DS#2. Additionally, IDOT UL and LL are also plotted for comparison on Figure 2. It is evident from Figure 2 that NS gradation is within IDOT's LL and UL ranges, as expected. However, DS#1 and DS#2 gradation is out of limits established by the IDOT for the FA-1 material. Specifically, for percent passing#200 sieve (0.075 mm size), DS#2 passed more through this sieve (7.6%) compared to natural sand and DS#1. This indicates that DS#2 has more finer clayey type material compared to natural sand. For percent passing#10 sieve (2 mm size), DS#1 passed more through this sieve (99.6%) compared to natural sand (86.2%). This indicates that DS#1 is finer than natural sand.

Besides above-mentioned materials, other materials used were Portland cement Type 1 and class C fly ash which were collected from Prairie Materials, a local ready-mix concrete plant, located in Normal, Illinois.

3.2 Mix Design

In this study, a total of nine CLSM mixtures, containing different amount of cement, fly ash, NS, DS#1 or DS#2, and water. The proportions of each ingredient was selected based on IDOT (2016) CLSM specifications, as presented in Table 1. In accordance with ACI229R, the amount of water was selected based on the flow consistency of CLSM mixtures. One control CLSM was prepared by mixing only cement, fly ash, NS and water (no DS). A total of four mixtures (three specimens in each group) were prepared by substituting 25%,

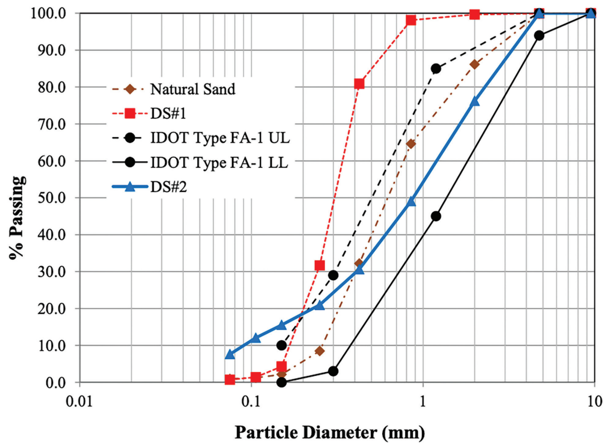

Figure 2. Sieve analysis results.

50%, 75% and 100% of natural sand with DS#1 by weight. Further, four mixtures were prepared by substituting 25%, 50%, 75% and 100% of natural sand with DS#2 by weight.

3.3 Specimen Preparation and Testing

All nine mixtures were prepared by adding required amount of dry ingredients in a five-gallon stationary vertical mixer (Fig. 3a). Then, all ingredients were mixed for 7 minutes followed by a 3 minutes rest, followed by a 5 minutes final mixing. The flow consistency of all nine CLSM mixtures was evaluated just after mixing in accordance with ASTM D 6103 test method. In this test, a 7.62 cm (3 in) by 15.24 cm (6 in) open-ended cylinder is used to spread CLSM on a flat non-absorbent surface and diameter of spread is measured.

For evaluating unconfined compressive strength (UCS) of CLSM mixtures, cylindrical specimens 10 cm x 20 cm (4 in x 8 in) were casted in accordance with ASTM D 4832 test method. To keep low strength CLSM specimens intact during preparation, special plastic molds were designed and manufactured in the laboratory (Fig. 3b). These molds can be split open into two halves for easy extraction of hardened CLSM specimen. Plastic molds were tied to a wooden board for easy transportation and handling. A total of three replicates were casted using each CLSM mixture. After casting, specimens were placed inside a plastic box under controlled temperature of 21°C (69.8 °F) and relative humidity of greater than 95% for four days. Then,

Table 1. Design of flowable fill mix proportions

Tag	% Natural sand	% DS	Cement (kg)	Fly ash (kg)	NS (kg)	DS (kg)	Water (kg)	Water/ cementitious
CONTROL (NS-100 DS-0)	100	0	0.41	1.22	10.61	0.00	2.40	5.9
NS-75 DS-25	75	25	0.41	1.22	7.96	2.65	2.40	5.9
NS-50 DS-50	50	50	0.41	1.22	5.31	5.31	2.40	5.9
NS-25 DS-75	25	75	0.41	1.22	2.65	7.96	2.40	5.9
NS-0 DS-100	0	100	0.41	1.22	0.00	10.61	2.40	5.9

Figure 3. **(a)** CLSM mixer; **(b)** Specimen mold; and **(c)** Unconfined compressive strength test setups.

Table 2. A summary of results of dredged sediment containing specimens

Mix#	Tag	% DS	Flow		Compressive strength		Density		Excavatability (RE)
			inch	cm	psi	kPa	psi	kN/m³	
1	Control	0	13.5	34.3	72.3	498.3	117.6	1885	0.95
2	NS-75 DS#1-25	25	12.8	32.4	84.3	581.0	116.3	1863	0.98
3	NS-50 DS#1-50	50	9.0	22.9	132.1	909.8	119.6	1916	1.31
4	NS-25 DS#1-75	75	9.5	24.1	102.7	707.9	117.9	1889	1.14
5	NS-0 DS#1-100	100	8.0	20.3	78.2	538.7	117.5	1882	0.97
6	NS-75 DS#2-25	25	9.0	22.9	85.6	589.9	113.7	1822	0.96
7	NS-50 DS#2-50	50	9.0	22.9	130.3	898.0	116.6	1869	1.25
8	NS-25 DS#2-75	75	9.5	24.1	65.9	454.2	112.8	1807	0.84
9	NS-0 DS#2-100	100	0.0	0.0	76.3	525.8	114.9	1841	0.93

specimens were demolded, wrapped with plastic film and then placed back in the storage box until the time of testing. Specimens were tested after 28 days of curing using a Universal Testing Machine in accordance with ASTM D 4832 test method (Fig. 3c). Specifically, specimens were subjected to load at a constant rate such that the cylinder failed in not less than 2 min.

4. RESULTS AND DISCUSSIONS

Table 2 shows a summary of results of all specimens tested in this study. A total of three replicates were tested for each mix and average was reported in Table 2.

4.1 Flow Consistency

Flow consistency enables CLSM to flow into a void and be self-consolidating which is a major benefit of CLSM compared to conventional fill materials. Variation of flow consistency with percent dredged material substitution is graphically presented in Figure 4 and tabulated in Table 2. In general, introducing more dredged sediments showed a decrease in the flow consistency values. Mixtures prepared by using 100% DS#1 and DS#2 substitution showed decrease in flow consistency by 14 cm (5.5 in) and 34.3 cm (13.5 in), respectively. One of the reasons for decrease in flow could be increase in finer particles in DS containing CLSM mixtures. As discussed in Materials and Methods section, gradation

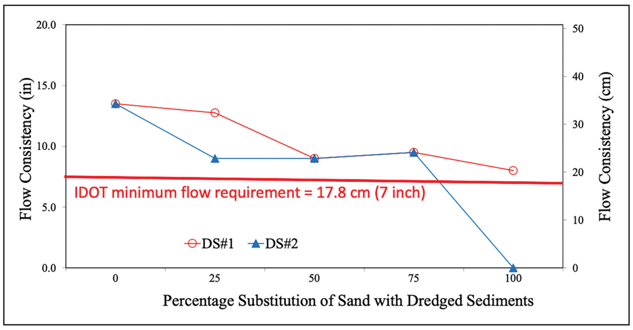

Figure 4. Variation of flow consistency with percentage substitution of sand with dredged sediments.

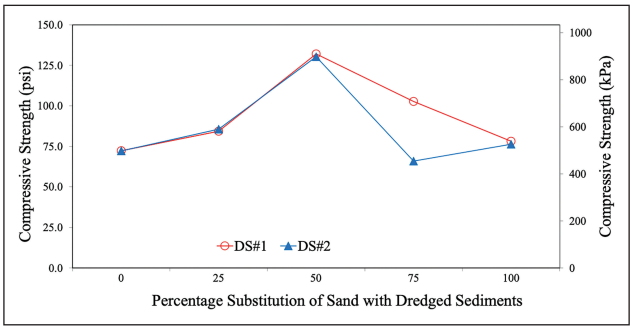

Figure 6. Variation of unconfined compressive strength with percentage substitution of sand with dredged material.

analysis showed relatively higher amount of fines in DS compared to NS. More fines results in larger surface area which will require more water for lubrication and flow of particles. Further, all CLSM mixtures tested, except Mix#9 prepared by substituting 100% sand with DS#2, showed a flow consistency of greater than 17.8 cm (7 in), as required by IDOT [24] specification for CLSM. According to ACI 229R [25], flowability can be expressed based on the diameter of CLSM material spread: low flowability (less than 15.2 cm, i.e., 6 in), normal flowability (15.2 cm to 20.3 cm, i.e., 6 to 8 in), and high flowability (greater than 20.3 cm, i.e., 8 in). Based on the results presented in Table 2 and Figure 4, all mixtures showed high flowability except Mix#5 (normal flowability) and Mix#9 (no flowability). Figure 5 shows photographic comparison of flow consistency of control mix (Mix#1), mix containing 100% DS#1 (Mix#5) and 100% DS#2 (Mix#9). It is evident from Figure 5 that control mix is highly flowable compared to 100% dredged sediments containing mixes. Bleeding of water in Mix#5 and caky type behavior of Mix#9 with no flow is visible from Figure 5. In general, water is released to the CLSM surface (i.e., owing to its high water content) as bleed water or absorbed by dredged sediments (Fig. 5b). More interestingly, an outstandingly positive effect of DS#2 was discovered: The addition of DS#2 to the CLSM decreased bleeding rate, as shown in Figure 5c. This could be attributed to finer and more cohesive nature of DS#2 which could hold excess amount of capillary water, leading to a reduction in the bleeding water.

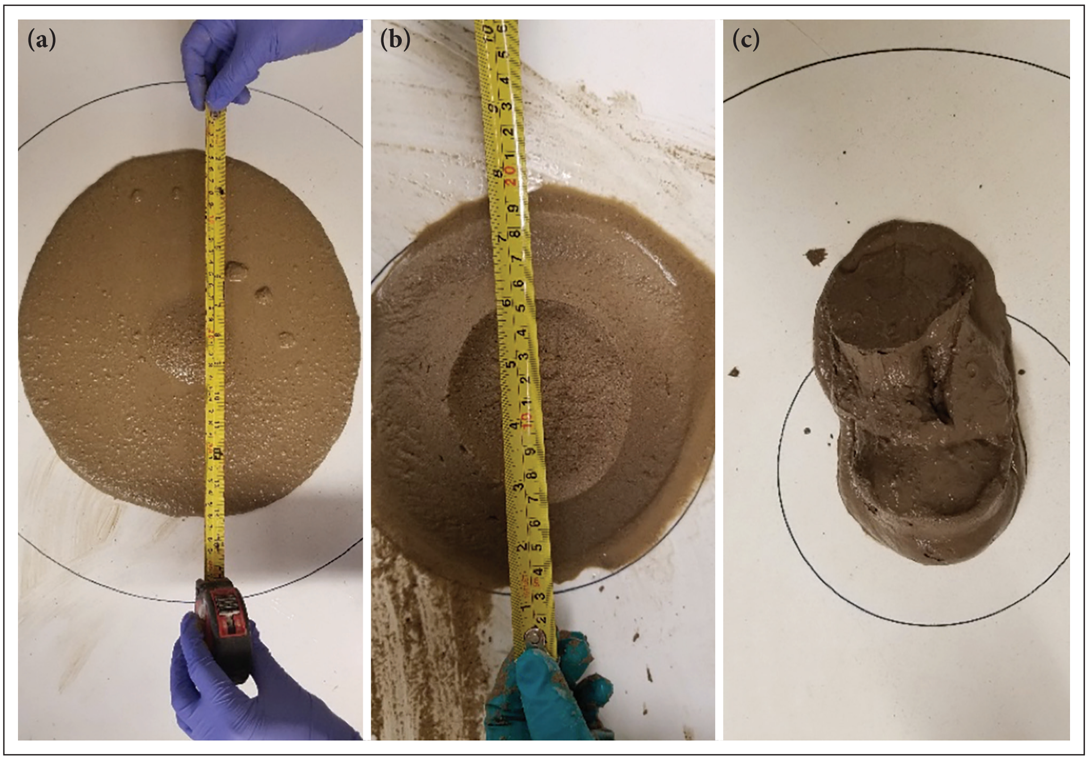

Figure 5. Photographic view of **(a)** Control (Mix#1), **(b)** 100% DS#1 containing (Mix#5) and **(c)** 100% DS#2 containing (Mix#9) containing mixes.

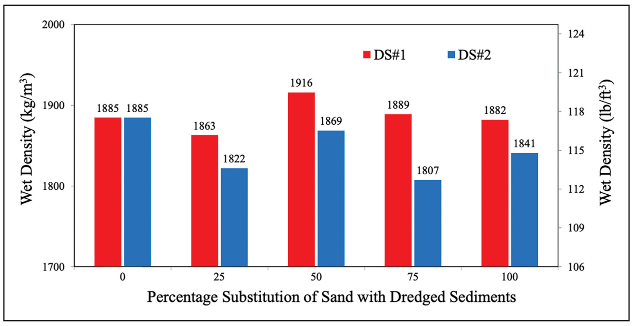

Figure 7. Variation of wet density with percentage substitution of sand with dredged material.

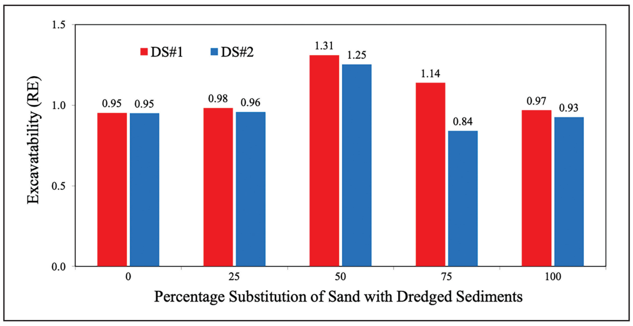

Figure 8. Variation of excavatability with percentage substitution of sand with dredged material.

4.2 Unconfined Compressive Strength

CLSM is designed with low unconfined compressive strengths which is a major objective for projects where later excavation is needed. Figure 6 shows UCS results of all mixes tested in this study. The strength values of CLSM specimens increases with percent substitution of NS with DS up to 50%. Beyond 50% substitution of NS with DS, decrease in strength of CLSM specimens was noticed. For example, substitution of sand with 50% DS#1 and 50% DS#2 provided an increase in strength by approximately 83% and 80%, respectively. Similar observations were reported by Do et al. [21] where strength of CLSM mixture decreased with increase in the amount of marine dredged sediments. This behavior of decrease in strength of CLSM mixtures with increase in DS was attributed to very small particle size of marine dredged sediments.

The behavior of increase in strength up to 50% can be rationalized using density of casted CLSM specimen, as shown in Figure 7. The CLSM containing 50% NS and 50% DS provided maximum density in case of both DS#1 and DS#2 which resulted in highest strength among all the mixtures tested in this study. The compressive strength of all CLSM mixtures tested in this study was found within IDOT requirements. Specifically, IDOT [24] specifies compressive strength value between 207 kPa (30 psi) and 1034 kPa (150 psi) for CLSM mixtures.

4.3 Density and Excavatability

Wet density results of all nine CLSM mixtures are presented in Figure 7. It is evident from Figure 7 that wet density of all nine mixtures varies between 1807 and 1916 kg/m³ (113 and 120 lb/ft³) which is within the range recommended by ACI 229R [25]. According to ACI 229R [25]), wet density of CLSM in place is in the range of 1840 to 2320 kg/m³ (115 to 145 lb/ft³). Further, it was found that wet density improved with percentage of substitution of NS with DS up to 50% beyond which decrease in wet density was noticed. However, all mixtures prepared by substituting sand with DS#2 showed wet density lower than control. This could be attributed to finer clayey nature of DS#2 which resulted in lower density values.

The ability to excavate in future is an important property of CLSM. In general, CLSM with a compressive strength of 0.7 MPa (100 psi) or less can be excavated manually. According to ACI 229R [25], a removability modulus (RE) can be used to determine the excavatability of CLSM. The RE can be calculated as follows in metric units:

$$RE=(W^{1.5}x0.619xC^{0.5})/106 \quad (1)$$

Where, W is the dry mass density in kg/m³ and C is the 28-day unconfined compressive strength in kPa. If the RE is less than 1.0, the CLSM is removable, while CLSM with RE values greater than 1.0 are not easily removed. The type and content of cementitious materials is important in determining excavatability of CLSM. Literature review shows that acceptable long-term performance can be achieved with cement contents from 24 to 59 kg/m³ (40 to 100 lb/yd³) and class F fly ash quantity up to 208 kg/m³ (350 lb/yd³) [25].

RE values of all nine mixtures are plotted in Figure 8. A total of three out of nine mixtures showed RE values of greater than 1.0. Specifically, Mix#3, Mix#4 and Mix#7 resulted in RE values of 1.31, 1.14 and 1.25, respectively. This could be attributed to higher compressive strength values (greater than 700 kPa, i.e., 100 psi) of Mix#3, Mix#4 and Mix#7. According to ACI 229R [25], CLSM with a compressive strength of 700 kPa (100 psi) or less can be excavated manually.

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the results presented in this study following conclusions could be drawn:

1) Flow consistency decreased with the amount of DS and presence of finer material in CLSM.
2) Unconfined compressive strength and wet density was found to improve with amount of DS in CLSM up to 50% beyond which strength and wet density started decreasing.
3) Based on flow consistency, unconfined compressive strength, wet density and excavatability, 100% substitution of sand with DS#1 and 75% substitution of sand with DS#2 could be used in preparing CLSM mixtures.

As noticed in this study, source and gradation of dredged sediments could influence the properties of CLSM. Therefore, it is recommended to investigate properties of DS in the laboratory before using it for CLSM projects.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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PEER-REVIEW

Externally peer-reviewed.

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