Geotechnical evaluation of Stabilized Dredged Material (SDM) from the New York/New Jersey Harbor

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Abstract

As a result of the 1997 ban on ocean dumping of dredged sediments, the States of New York and New Jersey have embarked on a rigorous program of seeking environmentally friendly solutions to the handling of dredged material, including the beneficial use of stabilized dredged material (SDM) in roadway applications. A pilot study was initiated in 1998 to construct two embankments on a site in Elizabeth, NJ, where SDM was successfully used as a cover for more than 100 acres of commercial development area. The pilot study included a laboratory phase for geotechnical evaluation of SDM, and a field phase for monitoring and evaluation of the construction process, as well as the performance of the fills following construction. The results of the laboratory study, as reported in this paper, demonstrate that SDM satisfies most of the geotechnical criteria for fill construction, except those for durability, requiring proper coverage and protection similar to those provided for fills constructed on cohesive soils.
Keywords: dredged material; contaminated sediments; beneficial use; embankments.

1 Introduction

The Port of New York and New Jersey is the largest Port on the East coast of the United States, situated in the metropolitan center of the Hudson Raritan Estuary complex. The New York / New Jersey Harbor complex is naturally shallow, with an average depth of 19 feet at low tide. Due to the Port’s strategic position in regional and international trade, the U.S. Army Corps of Engineers has

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provided some 250 miles of engineered waterways at depths ranging from 20 to 45 feet. Plans are underway to deepen the main channels to 53 feet during this decade. Maintenance of these waterways, crucial to safe navigation, requires dredging 4-6 million yd^3 of sediment, or “dredged material”, annually. Unfortunately, at least half of the material scheduled for removal is contaminated with industrial chemicals and trace metals from historical and ongoing sources, making management of the material challenging.

Historically, dredged materials from the channels and berths in the Port have been relocated to other parts of the Harbor, used to fill in shallows, or dumped in the ocean. Following the London Convention, the United States Environmental Protection Agency (USEPA) directed consignees to evaluate dredged material for its potential environmental impact prior to dredging. Materials found suitable for open water disposal were to be placed in one or more designated sites. In the case of the NY/NJ Harbor, this meant placing the material at a 2.2 square mile area off Sandy Hook, NJ, known locally as the “Mud Dump”. Starting in 1991, further modifications to the ocean disposal testing requirements resulted in strict restrictions on disposal at the site. In 1993, environmental groups began legally challenging even the most recent regulations, eventually resulting in an outright ban of disposal of dredged materials at the site by 1997. Today, only material considered to be completely free of potential to cause environmental harm is placed at the site, doubling as a cap of older, more contaminated materials. Unfortunately, these new regulations did nothing to slow the rate of sedimentation in the Harbor complex. Berths and channels in this heavily trafficked system require nearly continuous maintenance to ensure safe passage of commercial vessels. The Port community was unprepared for the loss of management options for dredged material. Managers were forced to either delay dredging or pay sums 15-20 times higher than usual. Dredging has all but ceased in the Port, threatening the maritime industry.

In response the States of New Jersey and New York, the U.S. Army Corps of Engineers (Corps) and the Port Authority of New York and New Jersey (PANYNJ) created teams to find alternative methods for management of contaminated dredged material. One of the alternatives considered was to seek beneficial use of stabilized dredged material (SDM) in upland disposal sites. This entails the stabilization of dredged material with pozzolanic admixtures to create structural and non-structural fills for various applications, including those in brownfield development projects and transportation infrastructure systems. The beneficial use of SDM as a fill has been demonstrated to be cost effective for high volume usage. For example, approximately 600,000 cubic yards of SDM were successfully used as structural fill for the construction of parking areas for the Jersey Gardens Mall in Elizabeth, NJ. In this project, the developer utilized dredged material amended with Portland cement for the grading, filling and capping required for the remediation of the landfill. Amending dredged material with Portland cement yields three benefits: it binds contaminants to the sediment particles, it removes excess water and it improves the structural characteristics of the silt and clay particles.

2 Objective

During the course of the Jersey Gardens development project, the Office of Maritime Resources of the New Jersey Department of Transportation (NJDOT) initiated a pilot study to evaluate the feasibility of SDM as a fill material for roadway embankments. Two embankments were constructed on existing municipal solid waste fills at the Jersey Gardens Mall site using SDM as the fill material. The project had two phases: a laboratory phase (phase I) consisting of a comprehensive geotechnical evaluation of SDM for beneficial re-use applications, and a field phase (phase II) consisting of performance evaluation of embankments following construction. This paper summarizes the first phase of the study.

3 Geotechnical properties of SDM

The controlling parameters for the laboratory investigation were the type and the content of admixtures (cement and fly ash) that were used in the field phase, as well as the sequence of mixing, curing and placement activities specific to the project. The preparation of SDM in the field was conducted on the Jersey Gardens site using a pugmill system. After preparation, the stabilized dredge material (SDM) was placed on various locations at the site for stabilization for curing. Unlike typical soil-cement mixtures in which the soil and cement are mixed and then immediately compacted, the SDM due to its high initial water content was placed on holding sites while it dried and cured, and the final site preparations were made. Once the SDM had cured, it was moved to the embankment sites for final placement, molding and compaction. As a result, a direct comparison between the SDM used in this project and typical soil-cement materials could not be made. However, soil-cement properties are used as point of reference for the evaluation of laboratory results.

Three different mixtures were prepared for the laboratory evaluation; each using raw dredged material (RDM), Portland cement and fly ash. The recipes were all mixed on a wet-weight basis. The three recipes used were: 1) RDM with 4% Portland cement, 2) RDM with 8% Portland cement, and 3) RDM with 8% Portland cement and 10% fly ash. The following tests were conducted to characterize each mixture:

- Unified Soil Classification ASTM D-1140, and D-422
- Shear Strength (tri-axial), ASTM D-4767, 2850-87
- Swell Pressure ASTM D-4546
- Consolidation Test ASTM D-2435
- Resilient Modulus AASHTO T274
- Hydraulic Conductivity (Permeability) ASTM D-5084
- Compaction Test ASTM D-1557
- Durability ASTM D-559
- Cement Content Determination ASTM D-806-96

3.1 Classification

The dredged material tested in this investigation is mostly silt with low percentages of fine sand and clay. Sediments dredged from navigational channels do not naturally contain coarse or medium sand (although incidental pieces of gravel were found in some samples), because sand will settle before it reaches still waters. In addition, these sediments cannot contain high percentages of clay, because clay particles will stay in suspension. However, deepening dredging in undisturbed areas might result in the generation of material containing significant amounts of gravel and rock mixed with fine material. This study did not address this type of material.

The SDM samples tested consisted, on average, of 66% silt, 14% clay and 16% fine and medium sand (12.1% fine, 3.9% medium). Gravel content was negligible except for one sample, which contained 6.5% gravel. The percentage of clay size particles was higher for those SDM samples that had been mixed with fly ash, presumably due to the fine nature of fly ash particles. The organic content of the raw dredge material was determined to be around 8%, according to ASTM D2974.The effect of increased curing time on particle size distribution was minimal. Any variation in particle size is attributable to size variation in the source material. In addition to the gradation test, SDM samples were also tested for plasticity index. Based on the Atterberg Limits, all the samples tested are below the A-line and to the right of the LL=50 line on the Plasticity Chart. Therefore, the SDM could be classified as Elastic Silt (MH).

3.2 Moisture-density relationship

According to the test results, maximum dry densities ranged from 76.6 pcf to 78.8 pcf (1.23 to 1.26 Mg/m^3), and optimum moisture contents ranged from 26% to 31.5%. A slight reduction in maximum dry density was observed when the percentage of cement and the curing time were increased prior to compaction of the material. This is similar to findings made by Kezdi [4], where the maximum dry densities of cement-treated silts were found to decrease slightly with increasing cement content.

3.3 Consolidation

Laboratory consolidation tests were conducted according to the ASTM D-2435 method. The samples were prepared using RDM amended with 4% Portland cement, 8% Portland cement, and 8% Portland cement with 10% fly ash. The SDM mix was remolded into a consolidometer with different compaction efforts applied. To determine the level of compaction achieved with each sample, a compaction test conforming to ASTM D-1557 was conducted for each recipe. According to the test results, samples were compacted to varying degrees ranging from 59% to 90% of their maximum dry density.

The moisture contents used when the test samples were remolded were chosen to represent the site's average and approved layers that did not meet the 85% Modified Proctor criteria. Samples were tested after one and six months of curing. The energy applied for remolding the sample prior to the test played a major role in the consolidation behavior of the material. The test results indicate pre-consolidation stresses (P_c) as high as 8.7 tsf (833 kPa) once the sample is compacted to 87% of its modified maximum dry density. This means that the compacted material will compress before experiencing 8.7 tsf (833 kPa) of overburden (equivalent to approximately 170 feet (52 m) of SDM, unit weight of 100 pcf (1.6 Mg/m^3), or 133 feet (40 m) of compacted granular fill unit weight of 130 pcf – 2.08 Mg/m^3). However, P_c as low as 1.32 tsf (126.4 kPa) was recorded for a sample compacted to 86% of its modified maximum dry density. The average value of $P_{c,}$ for samples compacted from 81% to 90% of their modified maximum dry density, is higher than 5 tsf (478 kPa).

The compression index (C_c) values range from 0.22 to 0.9. Both of these values were recorded for SDM with 8% Portland cement. In general, for all recipes tested, once compaction reaches 81%, the compression index will not exceed 0.5. In that case, a P_c of 2 tsf or more should be expected. The compression ratio ($C_R = C_c/1+e_0$) varied from 0.085 to 0.24. This value did not exceed 0.19 for samples compacted to 83% or above.

The results also show that based on consolidation settlement estimates, SDM embankments could be constructed to a height of 50 feet (15 m) with negligible settlement taking place within the SDM fill. This conclusion is supported by the results of the field settlement program. In the case of the two embankments in this study, and in similar cases where construction is proposed on marginal foundation soils, settlement is primarily a function of the foundation soil and its consolidation characteristics.

3.4 Permeability ASTM D-5084

Twenty-four samples were prepared and tested for permeability (hydraulic conductivity). Three different recipes for amending RDM were used in the sample preparation: 4% Portland cement, 8% Portland cement, and 8% Portland cement with 10% fly ash. The three different recipes were sampled at one month and at six months. Half of the samples were compacted to 85% and the other half were compacted to 90% of their maximum dry density, as determined by Modified Proctor (ASTM D-1557). The permeability results ranged from $1.25\text{x}10^{-6}$ cm/sec to $4.3\text{x}10^{-7}$ cm/sec. The lowest values were recorded for samples of RDM amended with 8% Portland cement and 10% fly ash. Also, samples amended with 4% Portland cement generally had lower permeability than did samples amended with 8% Portland cement. This may be due to the apparent effect of cementation on imposing a flocculated fabric arrangement in SDM. In general, tests results indicate that SDM could be considered for use as a low permeability layer in landfill cap applications. For roadway applications, however, building roadways on SDM would be similar to building on compacted fine-grained sub-grades, such as those used in arid regions like Arizona, Texas, etc. For roadway construction, proper coverage must be provided using an appropriate base or sub-base materials.

3.5 Shear strength

The strength parameters of SDM were evaluated for feasibility of SDM as a fill material, and specifically for the slope stability of the pilot embankments. The consolidated undrained (CU) shear condition was determined to best reflect the realistic field conditions both during construction and post-construction periods. Both one and six-month-old samples of the three different recipes for SDM were tested for shear strength characteristics under CU conditions (ASTM D-2850-87). The samples were compacted to 85% and 90% of their modified maximum dry density and total and effective strength parameters were determined for stability analysis.

The effective C and ϕ or (C′ and ϕ') were calculated after the Mohr circles for effective stresses were plotted. As expected, the effective friction angle values were generally larger than the total values for SDM. No significant change or trend in the magnitude of the frictional angle, and, with the addition of cement and fly ash could be observed. This is similar to previous findings by Balmer [1], Clough, et al. [2] and Van Riessen and Hansen [6]; where different soil types, amended with varying cement contents, were extensively tested and showed no significant change in frictional angle as a function of the varying amount of cement.

In general, an average angle of 34^{o} can be estimated for long-term stability analysis of embankments constructed with SDM. On average, there is an 8° increase in the effective friction angle compared with the total friction angle. Cohesion, however, decreases as the friction angle increases.

The test results also showed that compaction plays a significant role in the magnitude of strength parameters. For all the samples tested, a 5% increase in dry density resulted in increased strength. On average, the un-drained C values increased by 35%. Moreover, the average increases in ϕ' and C′ were 1 % and 50%, respectively. On this basis, it can be concluded that compaction is the most important physical stabilizer of SDM with respect to strength parameters.

A general comparison of SDM with typical soil-cement and cement-modified soils shows that with the same percentage of added cement, and similar compaction efforts (90% of optimum for SDM, and optimum for soil-cement) cement-modified soils are denser than SDM, have slightly higher friction angles, and have a much higher cohesion intercept under triaxial shear conditions.

3.6 Resilient modulus (AASHTO TP46-94)

The resilient modulus is a dynamic soil property used in the mechanistic design of pavements. The test provides a means of characterizing base, sub-base and sub-grade materials under simulated field loading conditions and is the basis for a deterministic approach to pavement design. In the resilient modulus test, the materials are tested under a variety of conditions, some of which include stress state, moisture content, temperature, gradation and density. A detailed description of the test and sub grade resilient properties of NJ soils is given by Maher, et al [5].

For this study, the resilient properties of SDM were determined for all the mixture types used. Table 1 summarizes the resultant resilient modulus values for SDM mixtures and those for three New Jersey sub-grade soils that currently underlie roadways in New Jersey. According to the table, SDM compares favourably to the soil taken from various subgrades in NJ, indicating sufficient resiliency under dynamic loads.

Table 1: Comparison of resilient modulus values between SDM and typical NJ base materials.

Sample Type	Stockpiling Period (months)	Compaction Effort (%)	Resilient Modulus (Psi)	Resilient Modulus (MPa)
4% PC	1	85	4827.5	33.28
		90	7720.2	53.22
4% PC	6	85	5167.9	35.62
		90	8752	60.34
8% PC	1	85	11911	82.12
		90	12326	84.98
8% PC	6	85	8432	58.13
		90	8945	61.67
8%PC + 10% FA	1	85	5610	38.68
		90	9254	63.80
8%PC + 10% FA	6	85	1498	10.32
		90	6601	45.51
Rt. 23 in NJ (medium to fine sand)		max dry density	9633	66.42
Rt. 295 in NJ (medium to fine silty sand)		max dry density	6405	44.16
Rt. 206 in NJ (silt with fine sand)		max dry density	6554	45.19

3.7 Swell potential

Samples of SDM were also tested for swell pressure in order to determine if SDM could be used in applications where the material would be in contact with structures sensitive to swell pressures and excessive deformations. For example, if SDM were used as a base material in roadways, excessive swell pressures and deformations will be detrimental to the integrity of the pavement.

For this study, samples of RDM were mixed with 4% Portland cement, 8% Portland cement, and 8% Portland cement plus 10% fly ash. Samples were cured in the laboratory for one month and for six months. These samples were then compacted to different densities in order to determine at what point the density level and moisture content would become critical in generating excessive swell pressure and deformation. Swell tests were performed in accordance with ASTM D-4546.

The laboratory data indicate several trends. The strain or percent swell was not significant for any of the samples tested. The strain values ranged from 0.1

to 1.2 percent, with an average of 0.6. The maximum strain belonged to the sample amended with 8% Portland cement plus10% fly ash (1.2%). This magnitude of volume change is considered low and, therefore, not detrimental to adjacent structures. The swell pressure, however, was high for samples compacted to 94% or higher of their maximum dry density with moisture contents on the dry side of optimum. For these samples, the overall average swell pressure was 1.005 tsf (96.25 kPa). The average for one-month old samples was slightly higher at 1.34 tsf (128.32 kPa), with an average strain of 1.1%. Although strains were not high for any of the samples tested, the swell pressure generated was moderate. For SDM that was mixed with 8% Portland cement and compacted to 95% of its maximum dry density, the swell pressure was measured as high as 1.96 tsf (187.69 kPa). However, considering low associated strains, SDM would not have any detrimental effect on adjacent structures.

For samples compacted on the wet side of their optimum moisture content, much lower swell pressures and strains were measured. The average swell pressure for those samples was 0.14 tsf (13.41 kPa), and the average strain was 0.3%. This is due to the fact that fine-grained soils have a flocculated structure at low moisture contents (below optimum moisture content). At moisture contents above optimum, the structure of the soil particles becomes more dispersed and layered. For dispersed structures, additional moisture does not result in significant volume changes.

3.8 Durability

The major durability concerns regarding SDM include potential strength loss due to freeze-thaw cycles and moisture variation. The freeze-thaw test simulates the internal expansive forces that result from the moisture in fine-grained soils. During freeze-thaw cycles, SDM experiences an increase in volume and a loss in strength. Some soil-cement mixtures have the ability to regain strength under certain conditions; specifically, the availability of reactive Calcium Oxide, adequate temperature and a high pH environment. For SDM, these conditions do not exist; therefore, any strength loss will be permanent.

In order to study the effects of freeze-thaw cycles on SDM, samples were prepared from the three different recipes. The testing was performed in accordance with ASTM D560. Samples were compacted to 85 and 90% of their maximum dry density, as determined by Modified Proctor. To provide a point of reference, a natural clay sample was also tested for its behavior during freeze-thaw cycles.

According to the test results, none of the samples could withstand more than three freeze-thaw cycles before failing. Significant volume change (ranging from 1.8% to 58%) was experienced during testing. Considering that the average volume change for the natural clay sample was 2%, it may be concluded that the freeze-thaw effect is several times more severe for SDM than it is for natural clay. As a result, all SDM should be protected against frost in order to maintain the cement contents within the percentages used for this project. Frost depth in New Jersey is approximately 2.5 to 3 feet (0.75 to 0.9 m). Under these conditions, SDM should be kept at least three feet below the surface. This should apply to both pavements and embankment slopes.

Wet-dry tests are conducted to simulate shrinkage forces in cement-modified or soil-cement specimens. Wet-dry cycle tests were conducted on the three different recipes of SDM. Tests were conducted according to ASTM D-559. All of the samples with the exception of one (8% PC @ 90% Modified Proctor) collapsed before experiencing 12 wet-dry cycles. Volume changes were in the range of 10% to 48% of the original volume. Therefore, SDM should be protected against frequent wet-dry cycles with placement of proper coverage for roadway applications, or low permeability layers in general fill applications. Furthermore, if SDM is compacted at moisture contents below the shrinkage limit, the potential for the development of tensile cracks and a consequent loss in strength could be minimized.

4 Conclusions and recommendations

Beneficial use of stabilized dredge material (SDM) has been shown to be a practical option for the management of navigational dredged material in the Port of NY and NJ. The laboratory study described in this paper evaluated the geotechnical properties of stabilized dredge material (SDM) from the NY/NJ Harbor for potential high volume applications in roadway construction. The study was the first phase of a two-phase pilot project sponsored by the New Jersey Department of Transportation for finding alternative methods for beneficial use of the 2-4 million yd^3 of contaminated sediments dredged annually, to maintain the maritime the transportation system that serves the Port.

The results of the laboratory study demonstrate that stabilized dredge material (SDM) satisfies most of the geotechnical criteria for construction of fills and embankments, except those for durability: freeze-thaw and wet-dry cycles. Proper coverage and protection need to be provided for SDM fills to address the durability problem, similar to those addressed in the construction fills with cohesive soils. A summary of the test results as described in the paper is as follows:

1. The raw dredged material from the NY/NJ Harbor is mostly silt with low percentages of fine sand and clay. The dredged material samples tested in this study consisted of 66% silt, 14% clay and 16% fine and medium sand (12.1% fine, 3.9% medium). The percentage of clay size particles was higher for those stabilized samples that had been mixed with fly ash. This is due to the fine nature of fly ash particles. The organic content of the raw dredge material was determined to be around 8% according to ASTM D2974. Based on the Atterberg Limits, all the samples tested are below the A-line and to the right of the LL=50 line on the Plasticity Chart, classifying SDM as Elastic Silt (MH).
2. The maximum dry densities for the different mixes tested ranged from 76.6 pcf to 78.8 pcf (1.23 to 1.26 Mg/m^3), and optimum moisture contents ranged from 26% to 31.5%. A slight reduction in maximum

dry density was observed when the percentage of cement and the curing time were increased prior to compaction of the material.

3. The compression index (C_c) values for SDM ranged from 0.22 to 0.9. and did not exceed 0.5 for any of the samples, once the samples had been compacted to 81% of their maximum dry density. Therefore, a P_c of 2 tsf (191.52 kPa) or more should be expected. The compression ratio ($C_R = C_c/1+e_0$) varied from 0.085 to 0.24. It can be concluded that SDM embankments up to 50 feet (15 m) in height could be constructed with only minimal settlement within the SDM fill.
4. The hydraulic conductivity (permeability) results ranged from $1.25\text{x}10^{-6}$ cm/sec to $4.3\text{x}10^{-7}$ cm/sec. SDM could, therefore, be considered for use as a low permeability layer in landfill cap applications. In roadway applications, however, building on SDM fills would be similar to construction on compacted fine-grained sub-grades, such as those in arid regions like Arizona, Texas, etc. Proper coverage must be provided using appropriate base or sub-base materials.
5. The addition of admixtures produced no significant change or trend in the frictional properties of SDM. In comparison to soil-cement and cement-modified soils, SDM has lower friction angle and much lower cohesion intercept under triaxial shear conditions mainly due to the sequence of sample preparation used in this study which followed the field operations. Temperature had a major effect on the curing process of SDM at temperatures below 40°F; it is recommended that SDM be placed during warm seasons (e.g., April through October in New Jersey).
6. The resilient modulus values for all of the samples tested compared well with three sub-grade soils that are currently under New Jersey roadways.
7. The strain or swell percentage was not significant for any of the samples tested. The strain values ranged from 0.1% to 1.2%, with an average of 0.6%. This magnitude of volume change is considered to be low and, therefore, not detrimental to adjacent structures.
8. The results from durability tests indicate that SDM is susceptible to frost action (several times more susceptible than natural clay) and should be placed below frost line. Based on the wet-dry tests, proper soil cover needs to be provided at all times to minimize strength loss due to erosion. Compacting SDM at moisture contents below the shrinkage limit would minimize the potential for tensile cracks and thereby minimize any further strength loss in the material.

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