A Case Study: Soil Mixing for Soft Ground Improvement at a Landfill

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ABSTRACT

Soil mixing with pozzolanic binders is widely used for the stabilization and solidification of a variety of wastes in environmental applications as well as for bearing capacity improvement, earth retaining structures, and slope stabilization in geotechnical applications. This paper summarizes a series of recent projects at the Seneca Meadows Landfill facility in Waterloo, NY that highlight a growing application of soil mixing; soft ground improvement beneath embankment slopes. Soil mixing at this facility has been used on three separate occasions over the last four years and will be used on an upcoming final phase of the work. The soil mixing performed at this facility is designed to improve the bearing capacity and shear strength of a very soft clay deposit to increase the stability of perimeter embankments during construction and placement of waste in the landfill. The design approach, construction processes, quality control, and lessons learned from these projects are discussed. Up to this point, the soil mixing at this facility has been successful as supported by the information collected during the completed projects.

INTRODUCTION AND SITE HISTORY

Seneca Meadows Landfill began operation in 1953. The facility's operations currently occupy approximately 600 acres and include stormwater and leachate management facilities, a tire recycling center, various clay mines, access roads, scales, and miscellaneous support facilities. The facility also consists of landfill cells, or "stages," in various phases of their lifecycle. These include capped landfills, operating landfills, stages under construction, and planned expansion stages. Figure 1 shows the overall layout of the landfill, including the stages.

Figure 1. Aerial photograph of the Seneca Meadows Landfill Facility

In 2004, two slope failures occurred during excavation for the subgrade and fill placement of the perimeter berms for a planned stage expansion at the Southeast Landfill (SELF). Subsequent subsurface exploration and laboratory testing programs were completed to explore the cause of the SELF failures. The engineer at the time concluded that the failures were caused by soft clayey deposits that did not have sufficient shear strength to resist the weight of the berm.

In response, the soft deposits at these locations were improved by installation of shear elements via jet grouting and the construction of the SELF was completed. This improvement appears to have been successful as the SELF has since been filled and capped, and no unexpected berm movements have been observed.

As the landfill has filled, additional stage construction has been completed. Seneca Meadows Inc. (SMI), the landfill operating company, began the planning and design of Stages 7 and 8 in 2011 and 2012, with construction beginning in 2013. Stages 7 and 8 are located adjacent to the landfill cell that experienced the slope failures in 2004 and Stage 7 was to share the perimeter berm that experienced one of the failures. The permit conditions stated that the landfill berms were required to have a "short-term" factor of safety (FS) of 1.3 and a "long-term" FS of 1.5.

SMI engaged McMahon & Mann Consulting Engineers, P.C. (MMCE) to explore and characterize the site geology and design an improvement program to facilitate the Stage 7 and 8 construction while meeting the minimum required FSs for stability.

SITE GEOLOGY

Through numerous investigation programs, hundreds of borings have been completed across the site. Observations in these exploratory programs generally show that the surficial geology follows a consistent pattern of glacial soil deposits above rock, as outlined below (surface down):

- Upper glacio-lacustrine (UGL)
- Upper glacial till (UGT)
- Lower glacio-lacustrine (LGL)
- Lower glacial till (LGT)

The lacustrine deposits (i.e., the UGL and LGL) are clayey silt or silty clay soil layers that were likely deposited in a low energy aquatic glacial environment. As a result, these deposits have little, or no, granular materials. The till deposits (i.e., the UGT and LGT), however, were likely deposited below advancing glaciers and are primarily silt with varying proportions of clay, sand, and gravel. With the exceptions described below, the deposits at the site are generally stiff or dense.

Most of the borings show that the UGL and UGT consist of two zones. The UGL has a stiff upper portion and a soft lower portion of higher plasticity. The upper portion of the UGT is generally soft and becomes stiffer with depth. The soft lower UGL and upper UGT exhibit similar strengths and are collectively referred to as the "soft zone" for the remainder of this paper. The major soil strata are pictorially represented in Figure 2.

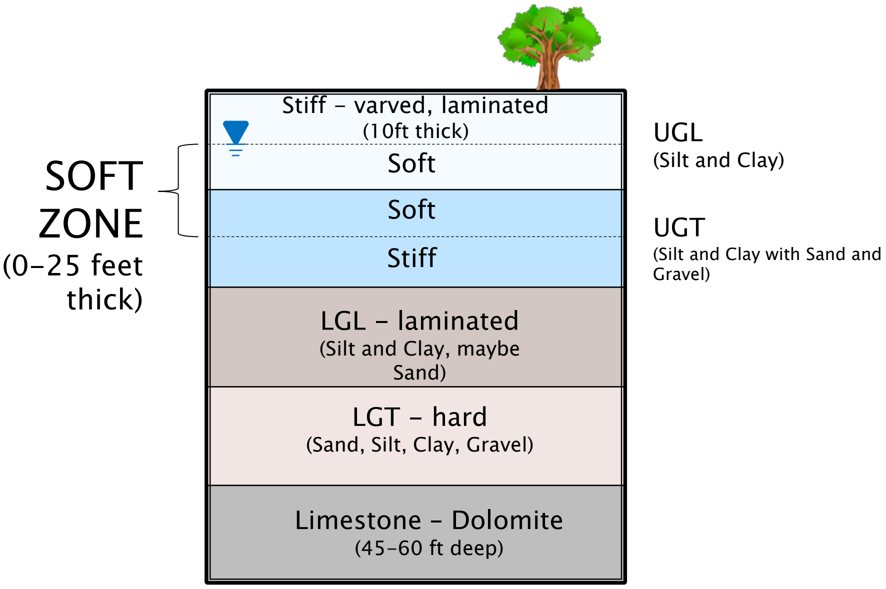

Figure 2. Idealized cross-section showing major soil strata

The limits of the soft zone were delineated based on Standard Penetration Test (SPT) N-values. The soft zone is generally characterized based on SPT N-values of 4 or less, with some exceptions made based on additional laboratory data or observations. However, the majority of the samples collected in this zone had N-values of 1 or less (i.e., weight of hammer or weight of rods).

SITE SOILS

As described above, the soft zone at the site consists of the lower UGL and the upper UGT, or a combination of both deposits. Figure 3 includes a photograph of a large block of soil removed from the UGL / LGL soft zone.

Figure 3. Photograph of soft soil from the lower UGL or upper LGL

Using the data from the available boring logs, MMCE created a three-dimensional model of the interfaces between the deposits across the entire site, including the top and bottom elevation (EL) of the soft zone.

The model shows that the thickness of the soft zone varies drastically across the site from 0 feet thick (i.e., not present) up to about 25 feet thick. Further, the model shows that the 2004 SELF failures were located over exceptionally thick areas of the soft zone (14 to 18 feet thick). This follows with the failure investigation conclusion that the shear strength of the soft zone is not adequate to support the perimeter berms at all locations.

Additional explorations were completed for the design of Stages 7 and 8 in 2011 and 2012. These included more borings, instrumentation, and field and laboratory testing. The field testing consisted of 16 vane shear tests completed in the soft zone. The laboratory testing included moisture content, Atterberg limits, consolidation tests, and a consolidated-undrained triaxial test with pore pressure measurements.

The laboratory test data show that the soft UGL is a plastic deposit with a liquid limit that typically ranges from 35 to 45. The moisture contents of the samples were typically at, or slightly above, the liquid limit. Further, testing showed that the UGL is slightly overconsolidated with OCRs typically ranging from 1.5 to 3.0.

Samples from the soft UGT deposits exhibited lower liquid limits, typically between 15 and 20, and moisture contents slightly lower than the liquid limit.

The strength of the soft zone was estimated using several methods. First, results of the laboratory testing were used with relationships developed by Skempton (1957), Ladd and Foott (1974), and the Mohr-Coulomb equation. Second, vane shear test results were used with corrections from Bjerrum (1972) in combination with correlated strengths from SPT N-values using NAVFAC (1982) and direct measurements from Cone Penetration Testing (CPT) completed after the 2004 failures.

The analysis resulted in 163 strength estimates of the soft zone materials. The overall interpretation of the data resulted in a summary approximation of the undrained shear strength (Su) of 400 pounds per square foot for the soft zone.

GROUND IMPROVEMENT DESIGN

In order to develop ground improvement recommendations, MMCE developed cross-sections through the planned excavations and berms for the landfill stages. The cross-section locations were selected based on the thickness of the soft zone identified in the model, the required depth of excavation, and the associated berm height. A software program, Slide 6.0 (software manufactured by Roc Science) was then used to perform a two-dimensional limit equilibrium slope stability analysis.

The stability of the cross-sections were first analyzed with no soil improvement. Analyses of the unimproved cross sections resulted in calculated FSs less than 1.3, with some less than unity. After this initial analysis, it became clear that some type of improvement would be required.

The analyses showed that portions of the soft zone behind the excavated slopes and below the perimeter berms would require an increase in shear strength from the existing 400 psf to between 1,000 and 1,500 psf to meet the minimum FSs. Based on the success of the SELF emergency improvement project and in general consideration of the problem / available solutions, MMCE recommended improving the soft zone by mixing a cementitious material with the soil to increase the shear strength. In general, the overall conceptual approach was to install overlapping improved columns perpendicular to the planned slope to act as a shear panels to resist the driving forces imposed during berm construction and increase the stability of the slope. Three methods were considered to accomplish this: wet soil mixing, dry soil mixing, and jet grouting.

Wet soil mixing involves mixing soil with a water based reagent grout (typically Portland cement suspended in water) to create a treated column. Dry soil mixing also involves creating treated columns. However, rather than a water based grout, dry reagent is injected into the soil and the moisture from the soil provides the water required for hydration. These columns typically have a smaller diameter than wet soil mixed columns. Finally, jet grouting involves inserting a nozzle at the bottom of a drill string and injecting a fluid (grout, water, and/or air) at high pressure to erode and mix the surrounding soils resulting in treated columns.

Ultimately wet soil mixing was selected because: 1) it is less sensitive to the moisture content of the surrounding soil (the UGL and UGT have moisture contents that can vary by over 30 percent), 2) the mixing apparatus and injection system is typically relatively rugged and therefore expected to be capable of penetrating into the stiff UGT, and 3) the anticipated soft clay soils are not ideal (difficult to erode) for jet grouting.

The required treatment was broken into discrete “zones”, (herein “areas” to distinguish from the soft soil zone) around the perimeter of Stages 7 and 8. Each area consisted of plan dimensions (length and width), top and bottom elevations (selected so that each column extended a minimum of 2 feet above and below the expected limits of the soft zone), and a required composite shear strength (1,000 or 1,500 psf). The composite shear strength is a weighted average of the entire improved soil mass with the soil strength conservatively neglected.

A minimum aerial coverage of 20 percent was included in the specifications. The intent of this requirement was to limit the potential for a contractor to install a small quantity of higher strength columns rather than a larger quantity of lower strength columns. More columns will provide some redundancy during construction to limit the effects of non-homogeneity inherent in the soil mixing process. The 20 percent requirement also limits the maximum possible spacing between rows of columns. After the Stage 7 and 8 projects, but prior to the Stage 6 construction (third phase of the work), a maximum center-to-center row spacing of 35’ was added to the project requirements.

Further slope stability analyses conducted on the improved cross-sections resulted in FSs of 1.3 to 1.7, all higher than the minimum FSs needed for temporary stability.

CONTRACTING

In late 2012, SMI began searching for construction companies interested in completing the Stage 7 ground improvement project. At the time, SMI was soliciting interest from firms capable of performing jet grouting and soil mixing. In early 2013, a formal request for proposal (RFP) was issued. In response to the RFP, four bids were submitted, all utilizing wet soil mixing. Based on its experience and approach, Geo-Solutions, Inc. (GSI) was selected as the contractor to perform the ground improvement using wet cement-soil mixing. GSI began its preparation for the work by performing a site specific mix design study.

BENCH SCALE STUDY

A site specific mix design study was developed to mimic the full scale application (i.e. soil mixing of soft clay soil with Portland cement) to improve the shear strength of the soft zone. The soil used for the mix design study was collected from an open excavation during a preconstruction site visit. A sample of available site water for use in grout preparation during full-scale work was collected from a stormwater retention pond. Upon arrival at the laboratory, a portion of the soil sample was taken to a local geotechnical laboratory (Geotechnics of East Pittsburgh) for soil index testing. The results of that soil index testing are included below on Table 1.

Table 1. Soil Index Test Results

Soil Sample ID	USCS Classification	Moisture Content (%)	Fines Content (%)	Organic Content (%)	Soil pH
Clay Composite	Lean Clay, CL	35.8	99.0	1.1	7.7

The results of the soil index testing were consistent with previous soil testing and the project team's understanding of the soft zone soils; i.e. the soft soil consists of predominantly fine soil particles, has a low organic content, neutral pH, and a high moisture content near the expected liquid limit.

After the soil index testing, GSI performed a qualitative study of the amount of water needed to turn the soft zone soil into a workable viscous liquid matrix with a viscosity approximately equal to a material with a slump of 7" to 9". Table 2 and Figure 4 show the results of this study.

Table 2. Water Addition vs. Workability

Photo #	Water* (%, by soil weight)	Description
1	5	Too dry
	10	More workable, but too dry
	15	Better consistency, but too dry
2	20	Potentially mixable, even consistency
3	25	Easily mixable, solid consistency
4	30	Easily mixable, approaching liquid consistency
5	35	Easily mixable, closer to muddy water than soil

*This does not include pore water, only added water

1 2 3 4 5

Figure 4. Photographs of water / soil mixes from bench scale study

The study showed that the added water component of the mix should optimally be between 20% and 35% (not including pore water), by total soil weight. After the water addition rate had been selected, eight (8) soil-cement mixtures were created to determine the Portland cement dosage. Portland cement dosages in these trial mixes ranged from 6% to 12%, by total soil weight. Water added at this stage ranged from 28% to 47%, by total soil weight, consistent with a base water addition of 20% to 35% (both assessed at each cement dosage) and an additional water addition of 6% to 12% (consistent with a 1:1 water to cement (W:C) grout). After 28 days, the soil-cement mixtures were subjected to unconfined compressive strength (UCS) testing and exhibited values of 70 to 150 psi. In general, the 28 day UCS was 1.7 times the 7 day UCS.

Conversion of Mix Design Conclusions to Field Scale Application. In order to utilize the information collected in the mix design at the full scale, a number of simplifying assumptions needed to be made. The project design called for two target composite shear strengths, 1,000 and 1,500 psf, and a minimum aerial replacement ratio (ratio of improved surface to unimproved surface) of 20%. Using the target composite shear strengths and the minimum aerial replacement ratio, the minimum shear strength of the soil-cement columns was calculated, 5,000 psf for 1,000 psf areas and 7,500 psf for the 1,500 psf areas. Furthermore, assuming a UCS to S_u ratio of 2, the target soil-cement UCS was calculated as 70 psi for the 1,000 psf areas and 105 psi for the 1,500 psf areas. Finally, using the strength results from the bench scale study and assuming an *in situ* total soil density of 105 psf (5% higher than any measured value), the cement dosages of 14 lbs / ft^3 for the 1,000 psf areas and 16 lbs / ft^3 for the 1,500 psf areas were selected.

CONSTRUCTION

Upon mobilization to the project site, GSI setup its batch plant and equipment, received materials, and began preparations for the test program. In mid-June 2013, 4 test columns were installed. Production column installation began immediately following test column installation. Moving to the production columns prior to final acceptance of the test program was GSI's decision and was done so at its own risk. Construction procedures for the Stage 7 ground improvement are described in GSI's submittal titled "Work Plan" dated May 2013 as well as in subsequent emails and other submittals. In general, GSI utilized a modified excavator mounted drilling rig originally designed for pile drilling fitted with a 9' diameter soil mixing auger for the soil mixing and an automated batch plant for cement-water grout preparation. Figure 5 shows the Stage 6 project site which has an identical equipment layout.

Figure 5. Photograph of Stage 6 site, showing drill rig (right) and batch plant (left)

In early July, core samples were taken from the test columns and the columns were exhumed for observation. Observations of the exhumed test columns revealed mixed results. One column, which was pre-drilled using water, looked clearly superior to the other columns that were not pre-drilled with water. Based on the results of the test program, the final selected mixing approach included a drilling and mixing stroke with water only followed by two mixing strokes through which the cement was added at the dosages described above in a water based grout with a W:C ratio of 1:1.

The improvement of 290,000 cf of soft soil was completed over approximately two months, including mobilization, site setup, site teardown, and demobilization. Due to the configuration of the final column layout, the actual aerial replacement ratio in the discrete areas ranged from 22% to 26%. The average UCS for the discrete areas ranged from 195 psi to 385 psi. Two additional ground improvement columns were added at the end of two shear walls to overcome a slightly reduced strength as determined by lower wet grab UCS results.

Because of the success of the Stage 7 project, SMI decided to move forward with the Stage 8 ground improvement project with the same project team through a change order to the Stage 7 work. The Stage 8 work was completed in the Fall of 2014. On the Stage 8 project, the improvement of 97,000 cf of soft soil was completed over approximately one month, including mobilization, site setup, site teardown, and demobilization. The actual aerial replacement ratio in the discrete areas ranged from 22% to 37%. The average UCS for the discrete areas ranged from 180 psi to 270 psi. No additional ground improvement elements were needed as elements passed requirements the first time around.

Finally, because of the success of the Stage 7 and Stage 8 projects, SMI decided to move forward with the Stage 6 ground improvement with the same project team. The Stage 6 ground improvement project began in June and was completed in October 2016. At the time of this writing, final quantities and strength results for Stage 6 are still being finalized. The final ground improvement project, Stage 5, is planned for the Spring of 2017.

QUALITY CONTROL

Quality control (QC) is of the utmost importance and often among the biggest challenges for specialty geotechnical projects. The QC program on these projects included a test program, process controls to monitor the work in real time, wet grab sampling of the mixed product for UCS testing of cast specimens, and *in situ* sampling. In addition to the QC performed by GSI, MMCE was onsite full time for this work serving in a QA / oversight capacity for SMI. The sections below briefly describe the major components of the QC program utilized on these projects.

Test Program. In order to confirm the proposed installation methodology at the full scale, a test program was incorporated in this work. The test program included installation of 4 columns in Stage 7 and 2 columns in Stages 8 and 6. In all cases, the columns were installed near the production areas to model performance in similar soil conditions, but far enough away to allow destructive examination of the full depth. Prior to full excavation, the test columns were subjected to wet grab and *in situ* sampling for comparison to productive column performance. Lessons learned in the test program were then used to refine or improve the full scale production processes. The photo in Figure 6a shows a column excavation in progress and Figure 6b shows the excavated column, both from the Stage 6 work.

Figure 6. Column Excavation (a) and exposed column (b) in Stage 6

Examination of the mixed product in the test program excavation focused on observed mix homogeneity and observed column limits. Qualitative observations of strength were obtained through conversations with the excavator operator(s) through discussions about relative (soil vs. soil-cement) excavation resistance.

Process Controls. In order to ensure that the intended amount of cement and water is added to each column, a series of process controls were utilized to monitor the mixing process in real time. The major aspects of the process control component of the overall QC program included reagent weight per batch, grout density & viscosity, total volume of grout added per column, volume of grout added per vertical mixing increment (2'), drill rig rotary head pressure (indirect measure of resistance), number of mixing passes completed per column, column top and bottom elevation, and column installation start and stop time.

To provide constant and immediate information to the drill rig operator, the drill rigs were equipped with on-board computers that provided the operator with information about the penetration rate (ft/min), auger rotation rate (RPM), grout injection pressure and flow rate, rotary head pressure, current and maximum drilling depth, and total grout injected for the column and in each discrete vertical increment. Batching of the cement-water grout was completed using an automated batch plant designed to automatically create batches of wet and dry reagent components based on preset target weights for each component. To constantly check and confirm the accuracy of the batch plant weigh scales, the operator takes periodic measures of the grout density for comparison to the density predicted through absolute volume calculations. The information collected in the process controls was used to biasedly select columns for wet grab sampling and/or *in situ* testing to purposefully assess suspected under performers and confirm compliance with the overall project goals.

Wet Grab Sampling & Testing. Because it is cost prohibitive and difficult to test a full scale soil mixed column for its *in situ* strength, it is common in the industry to assess full scale performance using wet "grab" samples of the soil-cement mixture. These samples are collected from a discrete depth within a recently mixed column using a hydraulic or mechanical sample collection tool that can be opened and closed from the ground surface. The collected sample is then run through a sieve to remove particles that would have an uncharacteristically large effect on the results of testing performed on the small sample cylinders. For 2" wide cylinders, the sieving step is generally used to remove particles greater than 0.5". Once the larger particles have been removed, the collected sample is cast in cylinders using a procedure that limits the entrapment of air. Generally, this procedure mimics the procedures used for concrete cylinder molding (i.e. a third of the cylinder (length) is filled with sample, the sample is rodded, the next third is added, the sample is rodded, and the final third is added and rodded (Andromalos et al 2015)). At the conclusion of the casting process, the top of the cylinder is smoothed and the cylinder is capped. The cast specimens are then placed in storage to cure undisturbed, typically in a cooler with free water kept in the job trailer. Once the specimens have cured for 3 to 5 days, they are sent to a geotechnical laboratory for UCS testing. Testing is generally performed after the specimens have cured 7, 14, and 28 days with further testing at 42 or 56 days performed if an understanding of additional strength gain is necessary. Sampling and testing on these projects was performed at a frequency of 1 sample set for every 4 columns (approximately 1 for every 150 CYs). The results of UCS testing on the wet grab samples were used as the primary acceptance criteria for the work.

In Situ Sampling. The original project specification included coring and strength testing of cored samples. Knowing the issues associated with coring and testing low strength soil-cement mixtures, GSI excluded core strength testing in its proposal and agreed to perform the coring for visual observation only. In selecting the coring methodology, GSI suggested the Acker Pitcher Sampler, see Figure 7.

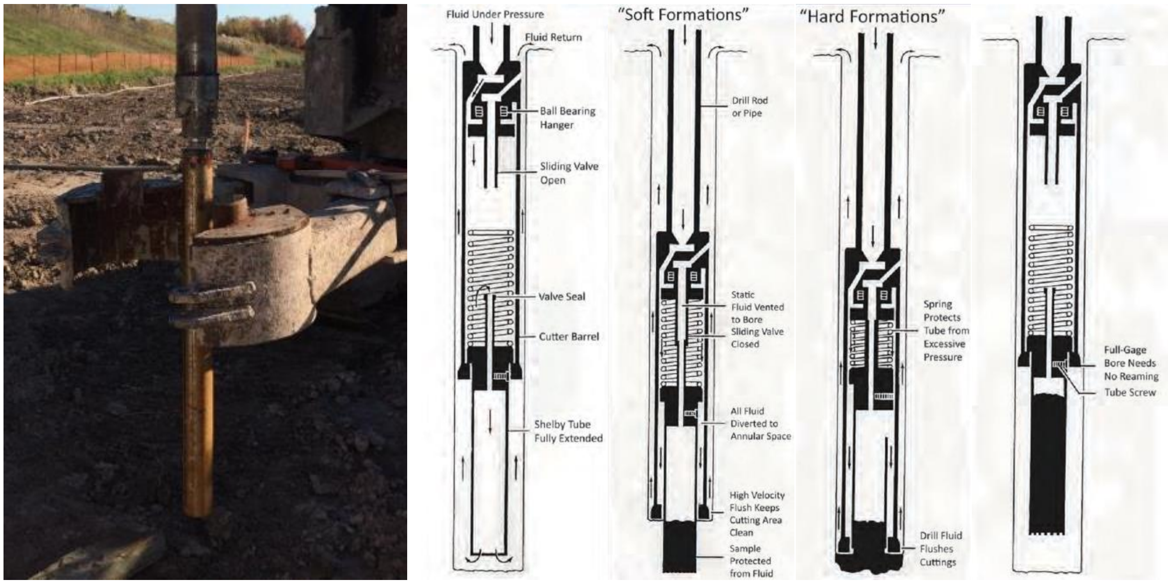

Figure 7. Photo of Acker Pitcher Sampler (left) mounted on a drill rig and schematics of the pitcher sampler (right) from Acker's brochure

The Pitcher Sampler is designed to allow the collection of Shelby tube samples in a range of soil types, from soft soil (see "Soft Formations" in Figure 4) to soft rock (see "Hard Formations" in Figure 4). The client and engineer agreed that this *in situ* sampling method seemed appropriate and this approach was ultimately selected *in lieu* of other, more conventional coring methods. *In situ* samples were collected at a frequency of 1 sample for every 4 columns (approximately 1 for every 150 CYs) for Stage 7 and 1 sample for every 10 columns (approximately 1 for every 375 CYs) for Stages 8 and 6. The individual Shelby tubes collected were cut open, photographed, subjected to pocket penetrometer testing, and the recovery was noted. Visual observation of the *in situ* samples was used as a secondary acceptance tool.

LESSONS LEARNED

As with any underground construction project, there were a number of lessons learned in the execution of the various phases of this work, but primarily in Stage 7. Through open communication, the project team was able to work through several concerns towards a successful resolution. This section focuses on the lessons learned in the Stage 7 work with reinforcement from the work on the Stage 8 and 6 projects.

Jet Grouting vs. Soil Mixing. The RFP did not specify the improvement type. Although soil mixing and jet grouting are similar (i.e., mixing of a reagent with soil) and can be used to accomplish the same overall objective, the processes differ substantially and therefore each require special considerations. Jet grouting inherently relies on the soil being easily erodible. Easily erodible soils are generally cohesionless soils with a maximum particle diameter of 3". Because jet grouting does not rely on physical displacement of the soils to accomplish mixing, the resulting soil-cement columns are often small and have variable diameters. This is especially true of sites with variable vertical or horizontal soil conditions or where plastic soils are present. For these reasons, wet soil mixing was ultimately selected as the desired approach and the project documents were modified to accommodate this selection.

Pre-drilling with water. In the exposure of the Stage 7 test columns, the project team learned that a clearly superior mixed column can be created by pre-drilling and mixing the soil column with water followed by cement addition via grout versus skipping the pre-drilling step and mixing only while injecting grout. Based on the Stage 7 observations, the procedures for subsequent work were adjusted to include two distinct processes for each column, drilling/mixing with water followed by additional mixing with grout.

Coring and *In Situ* Sampling of Low Strength Material. Although the Pitcher Sampler is more appropriate for use in low strength soil-cement than other *in situ* sampling methods, it has numerous limitations. Some of the limitations of this method observed in these projects include:

- This method is sensitive to relatively small (~3") cobbles. These cobbles can deform the bottom of the Shelby tube thereby preventing the sample from entering the tube or being destroyed as it moves into the tube. Cobbles can also get caught in the drill head teeth. If this happens, the cobble spins with the drill head destroying the sample as it enters the tube.
- Debris and/or water can become trapped in the top of the Shelby tube thereby preventing additional sample from entering the tube.
- Very hard layers can destroy the pitcher sampler drill head. When this happens, the bottom of the Shelby tube is generally destroyed and no sample is recovered. If a sample is recovered, it is not representative of the *in situ* condition.
- Very hard material can partially penetrate the Shelby tube and prevent additional material from entering the tube.

As with any sampling tool, it is very important to review the results of sampling with the Pitcher Sampler in the context of these known limitations. Although the construction team recognizes the limitations of the selected tool and feels that there may be other, potentially more appropriate, sampling tools available, the team has elected to continue using the Pitcher Sampler for ease of comparison to past projects and to maintain continuity for regulatory oversight. The discussions below provide some of the author's recommendations about *in situ* sampling of relatively low strength soil-cement mixtures.

Soil Mixing Homogeneity vs. Scale. Creating a fully homogeneous mixture using soil mixing is inherently infeasible. However, it is possible to create a nearly homogeneous mixture when viewed from a macro scale. Visual observation of soil mixed elements will show the mixture contains soil-cement, soil, hardened cement grout, watery soil, and possibly air voids. However, when viewed from a larger scale, the soil-cement mixture would appear to be homogeneous. As an analogy, milk appears to be a homogeneous white liquid when examined with the human eye, but when examined under a microscope, milk is clearly a colloidal suspension of fat, proteins, carbohydrates, vitamins, electrolytes, minerals, and bacteria in water. Designs incorporating soil mixing for ground improvement should take this known inhomogeneity into account. The standards of practice within the industry already account for this to some extent. Take for example the modeling of full scale soil mix column performance through the testing of small cylinders. Although the soil-cement mixture sample is sieved prior to casting in the cylinder, there is inevitably going to be inclusions in these cylinders that will have an effect on the performance of the specimen. The photos in Figure 8 show cross sections of soil-cement cylinders from these projects.

Figure 8. Specimen cross sections showing inclusions

If the premature crushing of these cylinders due to these inclusions can be directly scaled to the macro performance of the soil mixed elements, then these specimens would be representative of macro scale columns with soil or rock inclusions as large as 2' (inclusions are up to 0.5" in a 2" cylinder, so 25% of the diameter for a 9' column = 2.25'). Further, the number of inclusions in the small specimens is typically much larger and the spacing much tighter than the actual inclusions in the full scale elements. It is important to recognize the inhomogeneity that inevitably exists within a soil mixed mass, incorporate factors for that inhomogeneity in the design, and attempt to account for scaling in the development of sampling, casting, and testing procedures for determining acceptance.

RECOMMENDATIONS FOR FUTURE IMPLEMENTATIONS

Although soil mixing is already widely implemented for environmental remediation and geotechnical ground improvement, the authors expect the implementation of soil mixing to continue to grow as designers and owners recognize the advantages of this approach over alternate options. There are many ground conditions that lend themselves well to this approach. Some recent, key examples are the levee foundation improvement projects (e.g. around New Orleans, LA and Sacramento, CA) and numerous projects utilizing soil mixing for the geotechnical improvement of high moisture content or soft soils. Another expected large application of soil mixing is for the solidification and/or stabilization of fly ash. With the recent passing of the new coal combustion residual (CCR) regulations, designers are searching for innovative ways to cost effectively deal with existing CCR impoundments and new CCR waste streams. Soil mixing is well positioned for this new market to achieve both environmental remediation and geotechnical property improvement objectives.

As the use of soil mixing for ground improvement expands, it's imperative for designers, owners, and contractors to recognize the inherent limitations of the methodology and the associated QA/QC methods and address those limitations in the design and construction. One of the most important limitations to consider is inhomogeneity. With the recent large scale implementation of geotechnical soil mixing in New Orleans came a rush of research. One of the chief findings of this research confirms and details what many already knew, soil mixing properties can vary substantially in what most would consider "identical" conditions. For example, the coefficient of variability of the mix strength, or the ratio of the standard deviation to the mean, is known to vary from approximately 0.3 to 0.7 with an average of around 0.5 (Navin and Filz 2006). Practically speaking, this means that on a project with a mean strength of 100 psi, approximately 64% of the overall data set could fall within the range of 50 to 150 psi, but a sizable portion of the data set, approximately 18% will likely fall below 50 psi and above 150 psi. Typically, strength testing on cylinders cast from wet grab samples will exhibit a lower coefficient of variability and strength testing on *in situ* samples, for example cores, will have a higher coefficient of variability. However, given that soil properties are expected to vary somewhat across a site and with depth, the properties of the soil-cement mixture should also be expected to vary.

Another important consideration is the selection of an appropriate performance verification method. Although strength testing of cylinders cast from wet grab samples is the common choice, there is also a large amount of strength testing of core samples. Each of these approaches has advantages and disadvantages. Cylinders cast from wet grab samples are cast in a method that may or may not actually result in a representative (of the macro scale condition) specimen, are not cured in the same conditions as the subsurface mixed element, and are typically rather small in comparison to the full scale element. Specimens taken from cores may be damaged during collection and extraction, often include comparatively large inclusions, and are also small in comparison to the full scale element. Other *in situ* tests that can be used include the vane pullout, cone penetrometer test (CPT), standard penetration test (SPT), pressuremeter, and vane shear. However, these other *in situ* tests have not been widely used in this application. In the authors' experience, there are really no suitable coring approaches for very low strength materials, UCS less than 100 psi, and conventional approaches are very limited for moderate strength materials, UCS in the range of 100 to 250 psi. Even up to 400 or 500 psi, conventional coring approaches have variable effectiveness in certain soil types. Systems like the Pitcher sampler or sonic coring can be used to obtain samples of the *in situ* material, but both methods will result in disturbed samples and observations must be made with the sampling tool limitations in mind.

CONCLUSIONS

This paper summarizes recent ground improvement projects completed using soil mixing at a landfill facility in upstate New York. Topics discussed include the site history, the conditions leading to the need for ground improvement, site geology and soil properties, ground improvement design, construction methods, quality control processes, lessons learned, and recommendations for future implementations in similar applications. In summary, the success of the case study projects reinforces the usefulness of soil mixing for soft ground improvement in the right conditions. Lessons learned in the completion of these projects emphasize the need to account for the subtleties associated with soil mixing in the design and construction phases of these projects. Although no project is the same, the authors have tried to provide some recommendations for future implementations of soil mixing in soft soils, namely the need to recognize and account for known property variability and to select appropriate performance verification tools.

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