Construction Considerations for ISS Bench Scale Studies and Field Scale Monitoring Programs

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ABSTRACT

In situ solidification / stabilization (ISS) projects require a significant amount of characterization, sampling, and bench scale testing in the design or feasibility phase to ensure a successful project. During this phase, the proposed construction methods need to be considered, taking into account such things as slurry proportions, untreated soil type / density, treated soil consistency, and soil / contaminant variability. As the project moves from the preconstruction phase into the construction phase, the results of the design phase are used to refine key project objectives which may include target improvements for permeability, strength, and / or leachability. A quality control / quality assurance monitoring program, which may include a combination of process controls, in-situ testing, and laboratory testing on grab samples, is then developed to confirm that the key project objectives are achieved. Process controls provide immediate feedback, but generally do not directly measure the target properties. Many of the available in situ testing methods were not developed for ISS mixtures and are therefore limited for use in this application. Finally, many of the laboratory tests conducted on field collected grab samples, specifically leachability tests, require long lead times and therefore provide limited real time feedback. In order to account for the advantages and disadvantages of each monitoring method, the quality control / quality assurance monitoring program should include a combination

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of short and long turnaround testing to be used collectively to predict the long term performance of the improved material.

SUBJECT HEADINGS

Construction Methods, Grouting, Quality Control, Solidification, Soil Cement, Soil Stabilization, Test Procedures, Waste Treatment

INTRODUCTION

In situ solidification / stabilization (ISS) has been used to reduce the impact of contaminated soil on groundwater in the United States since the late 1980s. ISS generally refers to the stabilization and / or solidification (S/S) of contaminated media performed in place, i.e. in situ, using various forms of soil mixing. The types of soil mixing equipment, construction methods, and even design approaches used for ISS projects have been the subject of numerous publications (Andromalos et al. 2012; Bates 2010a, b; Larson 2005). However, despite the industry’s advancement since the initial applications and the wide array of articles on the subject, ISS designs and bench scale studies are often still developed without proper consideration given to the construction components of this work. In this paper, the authors’ provide 40 combined years of lessons learned in ISS field applications to present construction considerations that should be given attention during the design phase of ISS projects.

FULL SCALE APPROACHES FOR ISS

Once ISS is established as the selected remedial approach, the Engineer, Contractor, or combined construction team, depending on the contract structure, should select the full scale
ISS method based on his understanding of the site conditions and constraints. Important considerations at this stage include site working room constraints, soil type, groundwater level, contaminant makeup and concentration, and target performance objectives. The full scale ISS method may be adjusted at a later date, based on additional investigations or the results of the bench scale study, but an informed decision at this stage will be helpful in structuring the bench scale study and monitoring strategy approaches. The four most common ISS construction methods, the advantages and disadvantages of each, and important construction related design considerations for each are identified below, in order of increasing complexity.

Bucket Mixing

Soil mixing performed using excavator buckets, a.k.a. bucket mixing (Fig. 1), is performed using conventional hydraulic excavators equipped with standard or modified excavator buckets to break apart and mix the soils with reagents added at the surface in a slurry (wet) or powder (dry) form. Bucket mixing is the most basic ISS method which results in the lowest unit cost, but also the least robust quality control (QC) in that bucket mixing affords little opportunity to accurately control vertical and horizontal distribution within a mixed cell and has the lowest mixing energy of available systems thereby making it difficult to break apart soil clods. Although it has been used in deeper applications, bucket mixing is most effective for shallow applications, less than 5 meters below ground surface (BGS), on sites with granular soils and a deep groundwater table. As with all ISS construction approaches, except jet mixing, bucket mixing use is limited around subsurface utilities. In all cases, bucket mixing operations must be closely monitored to ensure depth of treatment, proper keying into adjacent, previously treated cells, and even distribution of the binder or reagent.

Rotary Drum Mixing
Rotary drum mixing, a.k.a backhoe operated soil stabilization (BOSS), is performed using a hydraulically driven horizontal drum equipped with multiple cutting edges or teeth that rotate at high speeds to mix soils with either wet or dry reagents. This method of ISS is suitable for use in a variety of soil types with increased QC in comparison to bucket mixing through increased reagent distribution control and a higher mixing energy, but, like bucket mixing, the BOSS is limited to applications that are approximately 5 meters BGS. Generally, the BOSS unit is attached to the stick of a conventional excavator (Fig. 2) and is powered by the excavator’s hydraulic system. If additional power is needed, as may be necessary in dense, stiff, or plastic soils, then the unit is run through an auxiliary hydraulic power pack. Rotary drum mixing also offers a cost effective solution for the mass S/S of soft ground, such as sludge, peat, or soft clay. Like bucket mixing, the introduction of the binder and/or reagent to the treatment zone can be achieved through addition at the surface. However, unlike bucket mixing, many BOSS systems are capable of reagent administration through the mixing tool. Pneumatic pressure can even be used to add dry reagents at the tool head which can be beneficial for use in high moisture content soils, e.g. peat, or sludge, e.g. settlement lagoons.

Auger Mixing

Auger mixing is performed using crane (Fig. 3a) and excavator (Fig. 3b) mounted drill rigs, originally developed for the deep foundations industry, fitted with large diameter mixing augers to mix soils. Wet reagent slurries, or even dry reagents, are pumped through a Kelly bar, out of ports on the mixing auger, and are subsequently mixed with the soils in at least two passes, where a pass is the operation of the auger blades from the ground surface to the target depth and back to the ground surface. Auger diameter and drill size can be adjusted for work in a range of soil types to depths up to approximately 18 meters BGS or greater. Auger mixing is
also effective for use well below the groundwater table. Crane mounted drill rigs with a single large diameter auger were the most prevalent setup for the first 10 – 15 years of ISS auger mixing. The use of comparatively more mobile excavator mounted systems, still fitted with large diameter single auger setups, is more widespread now due to equipment advances. Multi auger systems are really only cost effective on projects requiring linear installations such as cutoff walls. Auger mixing affords the best QC of the methods presented here through increased horizontal and vertical reagent distribution control and monitoring, a comparatively higher mixing energy, and more robust construction monitoring systems. In the authors' opinion, auger mixing is the recommended approach for most ISS projects.

Jet Mixing

Jet mixing is performed using high pressure streams, i.e. jets of fluid to erode and mix the soil. In this approach, the high pressure fluid jet(s) are discharged from ports on the side of a grouting monitor (Fig. 4). This form of mixing is most effective in highly erodible soils, such as loosely packed cohesionless soils. Because jet mixing uses fluid jets to erode and mix the soils rather than mechanical mixing arms, it is the most suitable ISS method for use around and beneath underground obstructions and utilities or where augers cannot physically reach such as for the stabilization of thin contaminated deposits sitting immediately above bedrock. When used in conjunction with ISS, jet mixing is best suited for use in limited access areas where ISS is required around and beneath underground obstructions. Jet mixing is by far the most expensive ISS method and should really only be considered if site constraints (obstructions, utilities, working room) necessitate its use.

CONSTRUCTION CONSIDERATIONS FOR BENCH SCALE STUDIES
After the full scale approach has been selected, the bench scale study is developed with the proposed full scale ISS approach in mind. The bench scale study should be used to develop clear conclusions and recommendations that can be applied directly to the full scale work. The Engineer should be cognizant at this stage of the project to not inadvertently over specify or create competing constraints.

**Soil Sample Selection, Collection, and Conditioning**

Successful field implementation of ISS begins in the early phases of site assessment when the site soil properties and contamination makeup / concentration are studied. Results of these studies, generally used to select the remedial method and later to delineate the surface extent and depth of treatment zones, should also be considered during bench scale study sample collection and study composite selection. Composite samples developed for use in the bench scale study should be representative of the range of soils that may be encountered in the full scale work. Important considerations at this stage are soil property variability across the site and with depth, and soil and groundwater contamination makeup and concentration variability across the site and with depth. Samples selected should bracket the expected range of properties for each of these categories and the Engineer should be careful not to select samples strictly from worst case or “hot” zones. Studies conducted using only worst case conditions, although sometimes required by regulatory bodies, are unnecessarily conservative. Rather, the Engineer, with input from the Contractor if one is involved at this stage of the project, should use his / her engineering judgment and the results of the bench scale study to recommend a mixture that should reasonably achieve the project objectives. If site soil or contaminant conditions are known to vary substantially across the site, a zoned treatment approach may be required which will also require a bench scale study tailored to developing a suitable mixture for each zone. For ease of construction, the authors recommend that the Engineer select 1 to 3 horizontal
zones and only 1 vertical zone. It is difficult, and subsequently costly, to vary reagent dosage with depth.

Even after a rigorous selection and collection process, soil samples collected for use in the study will need to be conditioned prior to use in order to ensure the sample soil properties are representative of expected in situ properties. First, the composites selected for use in the bench scale work must be carefully homogenized prior to bench scale mixing. Homogenization at this stage is important to ensure that differences in performance results are due to differences in the formulas, not variations in the soil properties. The most common properties that require conditioning are moisture content, particle size, and contaminant concentration and/or makeup. Most full scale ISS work is performed beneath the water table so the soil samples selected for use in the bench scale study should be consistent with saturated site soils. To this end, the Engineer should confirm that moisture loss, between sample collection and laboratory testing, or due to sample collection procedure limitations, has not made the soil samples unrepresentative of saturated soils. If moisture loss is evident, then the samples must be moisture conditioned back to a moisture content representative of the in situ condition, prior to use in the study. Furthermore, the impact of particle size on laboratory tests must be considered when selecting the maximum particle size for use in the bench scale work. Laboratory and ASTM standard testing procedures generally outline the maximum particle size that can be used. Finally, sometimes due to the limitations inherent to subsurface sampling, soil samples may need to be spiked with an “ideal” mixture of contaminants that are representative of the contaminants known to exist at the study site. The Engineer will need to use his judgment in selecting the target properties for sample conditioning.
After suitably representative soils have been selected and collected for use in the bench scale work, the Engineer must then select or develop the study procedures. Most of the publicly available standards utilized in the ISS bench scale study industry, published by ASTM, American Petroleum Institute (API), Interstate Technology and Regulatory Council (ITRC) and other standard governing bodies, were developed for soils or for concrete and are therefore not necessarily ideal for creating or testing soil-reagent mixtures that are stronger than soil, but weaker than concrete. Many of the consultants involved in the creation, curing, and testing of soil-reagent mixtures understand the limitations of the available standards and use modified versions of those standards or internal procedures to perform these studies. The Engineer should use his knowledge of the site soils, understanding of the individual study procedures, and judgment to develop conclusions and recommendations that account for the inherent variability of these studies, understanding that, as with all subsurface work, no study will ever be fully representative of the true in situ condition.

Although the Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders (ASTM D4832) is widely specified for preparing and testing soil-reagent mixtures, it is not developed for use in this application and should be used only when modified to account for differences between controlled low strength material (CLSM) and soil-reagent mixtures. In lieu of a published standard, the authors recommend the following general procedure for the preparation of the soil-reagent samples:

1. Sieve the soil sample material to remove unrepresentatively large particles. Generally a 12.7mm (0.5 in.) sieve is used in this application.
2. Mix an appropriate volume of slurry using mixing procedure that mimics field application, e.g. high shear mixer for bentonite vs. low shear paddle mixer for cement, etc. Set aside.
3. Measure appropriate amount of soil.

4. Add slurry from Step 2 to soil from Step 3.

5. Mix slurry with soil by hand, or using table mounted mixer, until material is visually homogeneous. Depending on soil and slurry characteristics, this generally requires 5+ minutes of continuous effort. Be careful not to break particles apart that do not readily break apart as these particles will not break apart in the field.

6. In an effort to reduce overall sample preparation, measure slump using a laboratory sized mini slump cone (Fig. 5) (Malusis et al., 2008) or use visual indicators to determine if soil-reagent mixture is suitably workable. For soil mixing, suitably workable materials generally have a slump that is greater than 127mm (5 in.) measured using a conventional slump cone with a height of 305mm (12 in.). Rule of thumb: if the mixture closes a 12.7mm (0.5 in.) gap under its own weight, then it’s suitably workable. If the mixture is not suitably workable, add slurry to improve workability. Note: The authors do not recommend adding water directly to the mixture as this is not common in the field. The preferable approach is to add slurry, grout, or to remix the mixture using a higher water to solids ratio slurry or grout.

7. Create individual soil-reagent test specimens by casting soil-reagent mixture in plastic cylinders. Cylinder size should be selected based on the geotechnical laboratories criteria for each desired test. For example, most labs prefer to run permeability tests on 76.2mm (3 in.) diameter specimens and unconfined compressive strength (UCS) tests on 50.8mm (2 in.) diameter samples. Steps 8 through 16 are devoted to the casting procedure.

8. Fill 1/3 of the cylinder with the wet soil-reagent mixture.

9. In an effort to remove the air voids, not to compact the specimen, rod the wet mixture in the cylinder 20 – 25 times using a rod with a diameter that is 10% - 15% of the cylinder diameter.
10. Tap the 1/3 full cylinder against a hard surface 20 – 25 times.

11. Fill the cylinder to 2/3 full.

12. Repeat rodding and tapping sequence from Steps 10 and 11.

13. Fill the remaining 1/3.

14. Repeat rodding and tapping sequence from Steps 10 and 11.

15. Screed the surface of the cylinder using a trowel or other sharp edge.

16. Cap the cylinder.

17. Label the cylinder with the sample identification and cast date.

18. Place the recently cast cylinders in an insulated cooler with free water to cure, undisturbed, prior to testing. Other curing environments may be used if equally or more representative of in situ conditions.

The Engineer and Contractor should modify the procedure presented above to be consistent with the proposed full scale approach. Once the soil-reagent mixtures are created, cured and the desired laboratory tests are conducted, the Engineer must then select testing procedures. The three most important properties of ISS mixtures are the strength, permeability, and leachability of the ISS monolith. Strength and permeability improvement are almost universally specified for ISS performance monitoring and leachability is becoming more common. The standards that are most widely utilized for strength and permeability are ASTM D1633 and ASTM D5084, respectively. Both of these standards are suitably applicable to testing soil-reagent mixtures. Prior to the development of the new Leaching Environmental Assessment Framework (LEAF) testing methods, EPA Methods 1313-1316 (USEPA 2012a, b), there was no consensus opinion about which, if any, of the available leaching standards was most representative of the true condition. Although the LEAF methods are not widely employed, the authors believe that most in the industry agree that these new tests address many of the issues that made the other available tests, to varying degrees, unrepresentative of the in situ condition.
The main leachability standards that were, and arguably are, historically used on ISS work in the US were EPA Test Methods 1311 and 1312, TCLP and SPLP, respectfully, and American Nuclear Society Test Method ANS 16.1 (USEPA 1992; USEPA 1994; ANSI 2003). For various reasons, these standards are no longer preferable unless the Engineer or Contractor is intimately familiar with these standards and how to properly evaluate the results, the authors do not recommend their use for characterizing the leaching behavior of an ISS monolith. The new LEAF test methods are recommended for use in this application because the data collected highlights the contaminant’s leaching dependence on pH and liquid to solid ratio, there are separate procedures for testing particulate materials (soils) and monolithic materials (ISS mixtures), and the information can be used to model contaminant concentrations at points of compliance. EPA Method 1315 is specifically designed to provide mass transfer rates of ISS materials in a monolithic form and thus should be the preferred method for bench scale and monitoring of ISS mixtures. Unfortunately only a handful of laboratories and consultants are currently qualified to perform and analyze the LEAF tests, and, given their relatively recent acceptance and publication, the actual application of these methods in bench scale studies and for full scale evaluations has thus far been limited, but, as the standards are used more widely, the authors expect that these standards will become the consensus industry choice in this application.

Developing Recommendations and Conclusions for Use at Full Scale

When the soil-reagent mixtures have been tested and the results are being evaluated, the Engineer, or Contractor if one is involved, must ensure that the recommended grout / slurry mixture is pumpable via conventional pumping methods and that, when the appropriate amount of grout is added to the soils, the resulting soil-reagent mixture is suitably workable. In the
author’s experience, a pumpable grout or slurry is generally defined as a mixture of reagent particles suspended in water that has a Marsh funnel viscosity less than 50 seconds. Thicker slurries, or slurries with larger particle diameters (greater than 100 micrometers), may be pumpable via less conventional equipment, but this will likely drive up the construction cost. If the recommended reagent dosage or water to reagent ratio is different than that tested in the bench scale, then the Engineer must confirm that, when the appropriate amount of slurry is added, the soil-reagent mixture is essentially liquefied. In the author’s experience and as outlined above, generally a soil-reagent mixture with a slump greater than 127 mm (5 in.) is suitably workable, but site conditions may necessitate more fluid and the Engineer should not place tight controls on this as variable results should be expected. For example, deep ISS applications in dense soils may require more fluid lubrication, i.e. additional slurry. In these situations, the bench scale study program and Engineer’s recommendations should consider the implications (positive or negative) of additional slurry or higher water to reagent ratios in the slurry. The Engineer or Contractor must also consider the additional swell material that will be generated as a result of a higher slurry addition rate or higher water to reagent slurry.

Finally, when the bench scale study is complete, the Engineer, with input and recommendations from the Contractor, should use his knowledge and understanding of the entire process to account for limitations of the proposed field method(s). The recommendations and conclusions in the bench scale study report should be structured to prevent avoidable failures achieving the project objective. This is best accomplished by incorporating factors of safety that help to account for inherent variability. In order to make reasonable assumptions at this stage of the study, the study itself must be structured to provide information about the impact of statistically significant field variability that may be reasonably expected. In developing the recommendations, the project specifications, and the bid documents, the design Engineer should consider the available or proposed field performance verification procedures, i.e. process
controls vs. in situ testing vs. laboratory testing of grab samples, and recommend a suitable combination of available methods that prove project objectives are met. If highly variable field performance verification tests, such as leachability testing on field collected grab samples, which are sensitive to variations in contaminant level and makeup across a project site, can be justifiably eliminated based on the bench scale results, or even replaced with less variable verification methods like process controls, from which the Contractor can easily identify and quickly correct issues, then the Engineer can help to reduce construction team risk, construction issues, and ultimately cost. Lastly, the Engineer must consider the field performance verification method turnaround time in drawing the conclusions. The final recommended approach should be a combination of real-time monitoring with immediate feedback and offsite performance testing.

QUALITY CONTROL / QUALITY ASSURANCE MONITORING PROGRAM

Specification Development

Once the bench scale study is complete and the project approach is finalized, the Engineer must develop a document that outlines the objectives that must be met or how to perform the work. This document is generally in the form of a specification or series of specifications that are included in the contract. In the development of this document, the Engineer must choose whether it will be performance or method based. An educated decision about which requirement approach is best for each project is based on an understanding of the risk, cost, and schedule implications of each approach.

If the specifications will be performance based, i.e. the specifications outline the objectives that must be met, but not the procedures to be used to achieve those objectives, then the Engineer
must select reasonable property improvement objectives that are based on the bench scale study results. The performance approach places a large amount of the liability for the project in the construction phase and therefore generally results in the highest construction cost and longest field schedule. In order to reduce the cost and schedule, the Engineer should use his understanding of the project and regulatory requirements, and of results of the site characterization and bench scale study to minimize construction team project risk by eliminating unnecessary specifications. There is no need to specify extraneous requirements if there is no tangible benefit to the project or if the site characterization and bench scale study results are proof enough. For instance, a 345 kPa (50 psi) unconfined compressive strength is often specified when, in reality, a lesser strength of say 241 kPa (35 psi) would be sufficient for future site access and only 138 kPa (20 psi) is required to perform the EPA 1315 test. Strict leachability improvement objectives are also sometimes included when even a robust bench scale study is only representative of a small range of soil properties and locations across a site. Strict leachability requirements result in an increased project cost associated with the inherent risk that is borne solely by the construction team. In the author's opinion, leachability testing on field collected samples, if specified, should be conducted for documentation purposes, not for performance verification due to the long turnaround times for such testing (EPA 1315 is 63 days post curing).

Performance specifications should be written to outline minimum requirements with built-in flexibility. For example, the most common strength improvement objective is “The ISS mixture shall achieve an unconfined compressive strength of greater than or equal to 345 kPa (50 psi) after 28 days of curing”. A more flexible specification, consistent with ITRC guidelines, that achieves a similar objective would be “The ISS mixture shall have an average unconfined compressive strength of 345 kPa (50 psi) after 28 days (or longer) of curing with no individual sample less than 241 kPa (35 psi)”.
In summary, if insufficient characterization and up-front bench-scale testing and difficult performance criteria are specified, there is a higher likelihood that any of the following contractor bid response issues may arise:

- Construction teams will price in significant contingencies to cover the uncertainty, resulting in a significant increase in the overall cost of the project;
- Additional time may be needed either prior to the bid or after the bid for the bidders or selected construction team to perform additional characterization and bench-scale testing, resulting in months of delay to the start of the project;
- Given the additional liability, some of the more experienced construction teams may elect to not bid the project or will provide significant conditions with their pricing making bid comparisons difficult;
- If performance requirements are not achieved, then the likelihood of disputes based on changed conditions (i.e. variability of contaminant concentrations) becomes much greater;
- If performance objectives are not achieved, the question becomes, what corrective action will be required? Excavation and removal of cured ISS will be expensive and challenging.

In the author’s experience, the most reasonable ISS performance criteria for a performance-based specification are strength (typically unconfined compressive strength due to the cost and ease of testing) and permeability.

Alternatively, if the specifications are to be method based, i.e. the specifications will outline a general approach, details to be filled in by the Contractor in pre-construction work plan submittals, that meets how the work will be performed, not what objectives must be met, then the Engineer must outline an approach that meets the project objectives with a suitable factor of
safety. The method approach results in the least risk to the Contractor during construction and subsequently the lowest overall cost and schedule. The reduction in risk to the Contractor during the construction phase comes from more detailed design work and generally more responsibility to the design Engineer. However, a knowledgeable and experienced ISS Engineer overseeing this phase will generate a design that results in a better overall project approach with a reasonable set of technically sound goals. Also, if the design Engineer is involved throughout, from design into construction, then he can help to negotiate a reasonable set of acceptance criteria with the responsible regulatory agency, a very important aspect of all ISS projects. Often, an experienced Engineer will involve an experienced ISS Contractor to assist in the bench-scale testing and provide constructability input throughout the design phase.

In a method based specification approach, the Engineer needs to specify that the Contractor is to perform and document that the correct mix design is injected and properly blended. The reagent addition rates are specified by the Engineer and the contract usually includes unit prices for the various reagent materials (such as cement), so that the Engineer can adjust the mix if variations in site conditions are observed during construction. In this case, the project is performance based in that the Contractor’s performance is measured by their ability to add the prescribed amount of reagent(s).

Many contract documents include a combination of method and performance requirements. In many of these cases the requirements are contradictory or redundant. Combined method and performance requirements are sometimes a necessity, but, in these limited cases, the Engineer and Contractor must understand and protect themselves from litigation that may result from describing how to perform the work without taking responsibility for the performance. For instance, many specifications identify a recommended mix design, generally based on bench scale study results performed by the Engineer or a design subcontractor, as well as field
performance objectives, most commonly strength and permeability. Unless ample time exists between the bid and construction phase, which is rarely the case, the Contractor is forced to move forward with the specified mix, even in instances where, after review of all available information, the Contractor disagrees with the bench scale approach and representativeness of the results.

An important aspect of the specification development phase of an ISS project is the development of a full scale monitoring approach that ensures and documents that the final work product meets the overall objectives. The quality control / quality assurance (QC / QA) monitoring program should be applicable to the selected full scale approach and a combination of process controls including intermediate QC tests, laboratory tests on field collected “grab” samples, and, when necessary and feasible, in situ tests. In order to identify problems quickly, the program must include the means for immediate feedback indicative of long term performance, e.g. early strength and permeability test results used to predict 28-day compliance results or process controls used to verify that field procedures are resulting in a mixture consistent with the bench scale study results and / or design.

Process Controls

Process controls are the QC and documentation procedures used by the construction team to monitor the ISS process from reagent slurry creation to the delivery of the reagent slurry into the soil mass. These may include the methods to control and document the volume or weight of each reagent per unit volume of slurry, the volume of slurry added to a unit volume of contaminated soil, and the distribution of slurry in a mixed column or cell.
Reagent addition control at the batch plant is generally controlled by weight. Automated batch plants (Fig. 6), capable of simultaneously handling multiple dry and liquid reagents, can be programmed to automatically batch by weight of each component. The resulting reagent slurry has a known weight of reagent per volume of slurry. Alternatively, a batch plant operator can manually control the weight of each component added and document the weight added per batch. Regardless, daily QC documentation at the batch plant should include the weight of each component added to each batch (or series of batches in a continuous mixing approach), the total weight of reagents, including water, used over the course of a day, and the properties, namely viscosity and density, of the mixed slurry. The construction team can then assess on a daily basis whether or not the correct amount of reagent was used for the volume of soil treated. The density measurements can be used to monitor variability of the slurry over the course of the day from an absolute volume calculation to ensure that the measured density is continuously higher than the theoretical density. Measured density should be compared to the theoretical density obtained from an absolute volume calculation.

After the batch plant has accurately produced the reagent slurry with a known amount of reagent weight per volume of slurry, the construction team can easily calculate the required volume of slurry for each discrete mix column or cell. Previously treated overlapping sections of the cell or column can be subtracted to reduce redundant reagent addition. The theoretical minimum slurry volume for each mix cell or column is based on the recommended addition rates from the bench scale study, generally presented in a % of reagent to soil (by weight), converted to a volume of reagent slurry using the known reagent weight per volume of slurry and an assumed in situ soil density. The Engineer should provide the construction team the in situ density for use in this calculation. Calibrated flow meters, capable of reading the flow of fluids with high suspended particle contents, should be used to control the volume of reagent slurry added at each mixing location. Monitoring of reagent slurry volume at the mixing rig is
recommended. Available systems for auger mixing allow the drill rig operator to monitor the slurry flow rate, the volume of slurry added over discrete depth intervals (normally 0.6 m increment), the number of mixing passes, the drill mast inclination, the auger rotation speed, the hydraulic pressure on the rotary head (drilling difficulty), and the current and maximum depth of the bottom of the auger. All of this information is collected by an onboard computer system that converts the real-time information into a drill “rig report” that summarizes the drilling activity at each unique location. These rig reports (Fig. 7), along with operator notes, are then used to prepare a portion of the daily QC report. These onboard monitoring systems are most widely available for excavator mounted auger rigs, but many of the same parameters can also be monitoring on crane mounted auger rigs as well.

Grab Samples

Most ISS projects rely on laboratory tests conducted on grab samples to verify that the final ISS product meets or exceeds performance criteria. As described in the bench scale study discussion, the most common properties measured for performance verification are strength, permeability, and leachability. In the author’s experience, the results of strength and permeability testing can vary by ±25%-50% solely due to specimen inconsistency as leachability results can also vary by orders of magnitude, depending on the contaminant concentration distribution. When coupled with inherent mix inhomogeneity across the site and with depth, the results of these tests can be unrepresentatively misleading. For this reason, the authors feel that it is prudent for the Engineer to incorporate flexibility into the requirements in order to ensure that the mixture, including inherent variability, meets the minimum requirements in order to protect the project from unnecessary litigation associated with unrealistic objectives. The Engineer should allow the construction team to propose the grab sampling method as each available method applies to a different set of site conditions, but must verify that the proposed
procedure results in a sample that is representative of the mixed material. Various sampling tools and methods are available for collection of grab samples of the freshly mixed soil-reagent mixture. Samplers can be used to collect samples at specific depths within a specific column or cell. Sampling with an excavator is suitable for near surface samples, i.e. for samples collected less than 5 meters BGS. Hydraulic or mechanical samplers (Fig. 8a, b) that can be opened and closed from the ground surface are recommended for the collection of deep samples. Once the sample has been retrieved, the specimens should be cast using a procedure similar to that described for creating bench scale study specimens. Laboratory testing, after appropriate curing period, is performed according to the standards used in the bench scale study (see above for common standards for this application). The authors recommend Bates (2010a, p. 113) for additional information regarding strategies for performance sampling and testing of solidified materials through the use of ISS methods.

In Situ Sampling or Testing

Although not commonly performed and, in the author’s experience, rarely recommended, there are methods available for collecting samples of the in situ material after it has cured or for testing the material in place. If in situ samples are desired, then the Engineer, with the advice from the selected Contractor, must use his understanding of the available coring methods and soil-reagent properties to ensure that the collected cores are representative of the in situ material. It is widely understood that conventional coring methods can introduce fractures into the ISS material during core collection. Depending on the severity of the fracturing, these sample disturbance effects can cause the measured values of strength and permeability to be respectively lower and higher respectively than the actual condition. The underlying issue with the currently available in situ sampling methods is that they were developed for collecting samples of very strong material, i.e. rock or concrete with UCS strengths in the range of 7,000
kPa, or for collecting very weak material, i.e. soil. No method currently available was developed for soil-reagent mixtures with a compressive strength range in-between that of soil and rock, 200 – 3,500 kPa. Coring methods are often specified where soil mixing is being utilized for structural and geotechnical applications where strengths are typically much higher and then inappropriately applied to ISS.

CLOSING REMARKS

ISS is being increasingly used for the cost effective S/S of numerous waste types in a variety of soils. A large amount of research and development has been dedicated to the technology which has contributed to a wider understanding and has further increased its application. Despite the numerous publications devoted to all facets of the technology there are still misunderstandings prevalent in the transfer from ISS designs to construction. The design Engineer must consider the full scale ISS approach when developing the approach for the site investigation, bench scale study, and full scale quality control / quality assurance monitoring program. If the full scale approach is considered at all stages, the resulting recommendations and conclusions will be easily applied to the construction and will result in the highest probability of a successful remediation project. Experienced ISS design Engineers understand the importance of including construction considerations in the design and often include experienced ISS Contractors on the design team to improve the design constructability review.

REFERENCES


Liquid-to-Solid Ratio in Solid Materials Using a Parallel Batch Procedure


The original Final Draft ended at line 593. The figures have been added here to complete the presentation.

Fig. 1. Bucket mixing
Fig. 2. Rotary mixing
Fig. 3(a). Crane supported drill rig

Fig. 3(b). Excavator mounted drill rig
Fig. 4. Jet mixing
Fig. 5. Miniature slump cone
Fig. 6. Automated batch plant
Single Auger Soil Mixing
4.5 ft. Diameter Auger
Drill Rig Report

Job Site Data:
- Project name: Sample
- Area: Sample
- Client: Sample
- Contractor: Sample
- Machine: 

Data for Pile No: U33p
- Date: 3/29/2010
- Start time: 12:49:33 PM
- End time: 12:58:14 PM
- Total time: 00:08:41
- Pausetime: 00:00:00
- Pile length: 19.1 ft
- Total Volume: 469 gal
- Strokes: 4
- Inclination (°/°): 0.2° / 0.2°

Timediagram

Depthdiagram

Fig. 7. Rig report
Fig. 8(a). Hydraulic sampling device
Fig. 8(b). Mechanical sampling device