In Situ Stabilization/Solidification (ISS) in the Power Industry and Applications for Coal Combustion Products (CCP)

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INTRODUCTION

In situ stabilization/solidification (ISS) is a remediation technology that may offer an effective alternative for reducing leachability and improving geotechnical stability in coal combustion product (CCP) management applications. Over the last 10 years ISS has increasingly become a more economical remedy as design and construction expertise has developed, and costs are approaching the point where they are competitive with excavation and off-site disposal.

ISS technology is an important and powerful tool for environmental remediation because it:

- Is highly effective on previously difficult to remediate sites
- Has continued to gain community and regulatory acceptance
- Has developed a history of documented effectiveness

ISS applications completed to-date are relatively small in scale compared to most CCP management facilities. However, ISS technology has advanced to the point where it is now a viable consideration from a cost perspective when remediation of CCP management sites is necessary. One remaining limiting factor is that there are few examples demonstrating the effectiveness of ISS in CCP applications. This paper helps fill that void by highlighting the current state of the practice, and providing results of bench and pilot scale applications using ISS on CCPs.

OVERVIEW OF ISS

What is ISS?

Solidification and stabilization are names applied to two technologies that are closely related in that both use chemical or physical processes to reduce potential adverse effects to the environment from contaminated soil, sediment, and sludge. Solidification and stabilization are often used and occur together depending on the type, distribution, and concentration of contaminants. These technologies usually do not destroy contaminants. Instead, they slow or prevent contaminants from migrating into the surrounding environment. Each of these technologies is defined below:

- Solidification: This is primarily a physical process whereby the contaminated media (soil, sediment, or sludge) is converted into a solid, monolithic material that is more resistant to physical degradation and less susceptible to leaching than the untreated material. Constituents of concern (COC) are encapsulated and immobilized in the solidified matrix to reduce long-term mobility and toxicity.
- Stabilization: Stabilization is a chemical process whereby the soil's hazard potential is reduced by converting the constituents of concern into less soluble, mobile, or toxic forms. This process is applicable to constituents such as metals that have the ability to chemically bond or react with the stabilizing reagent to reduce long-term mobility or toxicity.

The ISS process is typically accomplished by mixing targeted soils with binders such as Portland cement and/or other pozzolan mixtures. Pozzolans are siliceous or aluminous materials which in and of themselves are not cementitious but when mixed with water and calcium hydroxide form compounds with cementitious properties (e.g., Class F fly ash). Some materials are both pozzolanic and cementitious such as ground granulated blast furnace slag (GGBFs), cement kiln dust, and Class C fly ash. (Ramme and Tharaniyil, 2004 [1]) Additives such as bentonite, organoclay, and plasticizers are sometimes blended with binders to further reduce hydraulic conductivity and leachability of targeted materials. For many applications the most commonly used reagents consist of GGBFS, Portland cement, and bentonite. An example of ISS treated material is provided below:

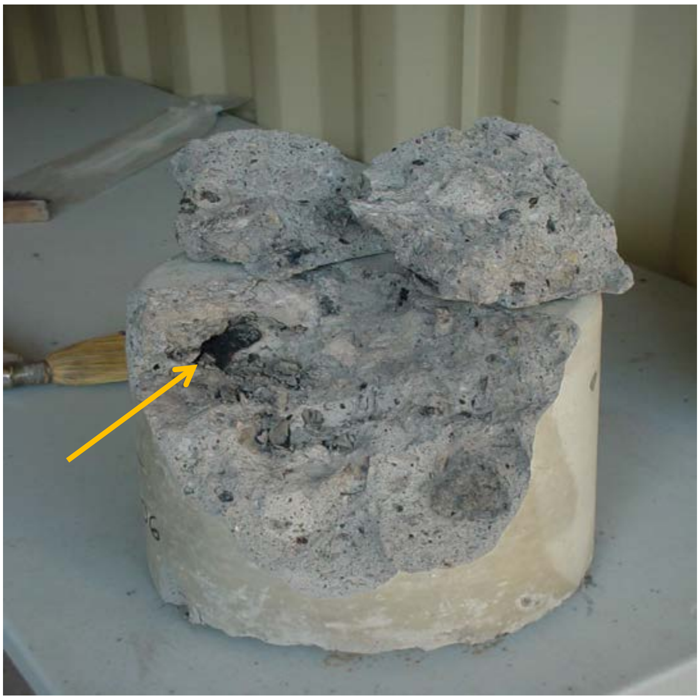

Figure 1 – Example of Solidified/Stabilized Material with Coal Tar Inclusion

The material in Figure 1 has a concrete-like appearance with little resemblance to the original soil matrix prior to mixing with reagents. On the left side of the sample, an inclusion of coal tar residuals is visible which is illustrative of the solidification process.

Criteria typically used to assess ISS performance include:

- Leachability: The preferred laboratory method is American Nuclear Society (ANS) method 16.1 to evaluate leaching of constituents from ISS material under laboratory conditions. Sample molds are cured a minimum of 28 days prior to leachability testing. The molds are then placed in a bath with demineralized water undisturbed to simulate full scale conditions where the monolith is surrounded with groundwater. During testing, samples of leachate are collected at set time intervals and submitted for laboratory analysis for a period of up to 90 days in accordance with method protocols. This test is different from other types of leaching tests such as the Synthetic Precipitation Leaching Procedure (SPLP) and the Toxicity Characteristic Leaching Procedure (TCLP) which require destructive sample preparation as part of the laboratory method, and are therefore not reflective of full scale conditions for a monolith.
- Unconfined Compressive Strength (UCS): Strength is measured using American Society of Testing and Materials (ASTM) methods D2166 or D1633. A typical minimum specified design strength is 50 pounds per square inch (psi).
- Hydraulic Conductivity: Hydraulic conductivity is measured using ASTM method D5084. Typical design permeabilities are in the range of $1x10^{-6}$ to $1x10^{-8}$ centimeters per second (cm/s).

Leachability is typically evaluated during the bench and pilot scale design phases. UCS and hydraulic conductivity are evaluated during the bench and pilot scale phases, and are the primary performance criteria typically measured during full scale construction. Leachability, UCS, and hydraulic conductivity results are correlated during the bench and pilot scale phases to provide a high level of confidence that measured values for UCS and hydraulic conductivity obtained during full scale construction will provide acceptable indicators for long term leachability.

Current State of the Practice

The use of ISS as a primary remediation technology has gained significant support from the USEPA but is less consistent on a state by state level. Some states have been very aggressive whereas some states are still relatively young in their understanding of the process. Consequently, the familiarity and experience with the ISS technology varies considerably. Presently, 26 states have reported implementing ISS (ITRC, 2011 [2]). In addition, the USEPA has documented that ISS is one of the most common *in situ* technologies used at CERCLA sites (USEPA, 2010 [3]). ISS has demonstrated effectiveness for remediation of various organics contaminants (VOCs, SVOCs, PAHs, and PCBs) and inorganic contaminants (trace metal and radioactive materials). It has been used by a variety of different industries, including the power industry at former manufactured gas plant (MGP) sites.

With regard to CCP applications, ISS implementation has been limited and specialized, as discussed in selected case study examples highlighted in this paper. Limiting factors include:

- The need for active remediation at CCP management sites has not been extensive. In many cases, simply closing and capping the facility provides effective remediation.
- CCP landfills and impoundments can be quite large and logistically challenging for implementing ISS due to the potential large volumes of material that would require mixing.
- Until recently, cost has been a limiting factor for ISS when active remediation is required, and other technologies such as pumping and treating groundwater have proven more cost effective.
- The effectiveness of ISS on CCPs, particularly in limiting leachability, is still being evaluated.

ISS Construction Applications and Techniques

The first step in a successful ISS construction application is to clearly establish data collection objectives as part of a bench scale study to evaluate critical aspects of full scale ISS construction. Pre-bench scale data collection objectives require careful assessment of the variable subsurface soil conditions. Soil type, select geotechnical parameters, moisture content, and dry density data will serve as the basis for estimating the amount of appropriate reagent addition during full scale ISS operations. It is therefore critical to collect samples in a manner that accounts for heterogeneities at the bench scale level and are representative of field mixing operations.

A number of different types of specialized mixing equipment are available for ISS construction (see Figures 2 and 3 below). In many applications, *in situ* mixing equipment consists of a drilling rig equipped with large diameter augers fitted with grout injectors. Specialized applications may use different types of backhoe mounted mixing tools such as rotary head (e.g., Lang Tool) or rake type injectors. Using the auger method, the augers are slowly advanced though the soil matrix while at the same time injecting and mixing the reagent grout into the soil. Multiple vertical passes may be required through the entire column to effectively mix the reagent grout and soil into a uniform mass. In general, mixing effectiveness may be as equally important to achieving performance criteria as having the proper mix design.

During the treatment program, columns are overlapped to construct a monolithic low permeability structure. Using current technology, back-hoe mounted mixing equipment is capable of mixing to depths of 20 feet below ground surface (bgs). In some applications greater depths can be achieved depending on the subsurface conditions.

Materials surpassing depths of 35 feet bgs have been achieved using crane and hydraulic drill rig mixing methods.

Figure 2 – Large Diameter Auger Mixing Using a Crane Mounted Drilling Platform

Figure 3 – Large Diameter Auger Mixing Using a Hydraulic Drilling Rig with Telescoping Boom

Reagents for mixing are typically mixed at an on-site batch plant to form slurry with specific water to reagent ratio derived from bench and pilot test results. Accurate reagent densities prepared at the batch plant are needed for establishing appropriate water to reagent ratios, reagent delivery rates, and mixing effort in the treatment zone. Once the reagent grout is prepared, it is delivered from the batch plant to the mixing equipment using high pressure progressive cavity grout pumps.

During construction, a number of parameters are monitored that include both geotechnical and qualitative index type parameters. Discrete samples of freshly mixed material are collected throughout the treatment zone. Samples are placed in molds and allowed to hydrate under humid conditions for a minimum of several days prior to geotechnical testing. An on-site field geotechnical laboratory can also be established for assessment of field parameters such as moisture content and slump.

ISS APPLICATIONS FOR CCP

Applicability of ISS for CCP

ISS has the potential to be an effective technology/construction technique for addressing a number of challenges associated with both historic and current CCP management. The technology’s ability to both improve strength and decrease permeability of CCP materials provides benefits for CCP management including:

- Improved geotechnical stability and material strength
- Decreased leaching of potential CCP COCs

These two properties of a properly constructed ISS application are directly relevant to a variety of common CCP environmental challenges such as:

- Leaching of potential COCs from legacy or active CCP landfills and impoundments that include sulfate, boron, and trace metals. For example, CCPs placed below the water table at legacy sites for backfill at former quarries.
- Constructing *in situ* low permeability containment for unlined legacy CCP landfills and impoundments.
- Providing an alternative to excavation, transportation, and landfill relocation/disposal of historic CCP fill sites when extreme remedial measures are required.
- Mitigating geotechnical stability concerns for CCP impoundments adjacent to surface water and rivers.
- Enhancing stability for Class F fly ash amended with soda ash (e.g., trona™).

Of these challenges, the application of ISS for reducing leachability of CCPs placed below the water table may pose the greatest potential benefit because capping alone is not effective under these circumstances and if untreated, the CCPs below the water table may leach for decades.

ISS Design Considerations Relative to the Unique Physical Characteristics of CCP

The discussion that follows is focused on fly ash, because testing has been performed on this material. This does not imply that ISS is not applicable to other types of CCPs such as bottom ash, boiler slag or FGD sludge. From a geotechnical standpoint, fly ash could be classified as a silty sand or sandy silt with low particle densities. Fly ash is well sorted with a consistency of fine powder, which is directly related to how it is collected from the flue gasses of coal fired power plants. Physical and chemical properties will vary depending on the type of coal used and the power plant process. Based on these characteristics, fly ash may be suitable for ISS, but poses a unique set of challenges that include:

- Particle Size: The presence and abundance of extremely small, uniform well rounded particle sizes could result in significant volume expansion during mixing. Volume expansion, or “swell”, occurs due to the displacement of the material with reagent and water during mixing. Swell is also a factor of the higher specific surface area that will be required for mixing in comparison with coarser grained materials. From a geotechnical standpoint, specific surface area is defined as the surface area of a particle divided by its volume. Larger particles have smaller surface areas per unit of volume and correspondingly smaller specific surfaces than smaller particles. For example, previous ISS applications in soil with high percentages of clay or silt (i.e., greater than 50 percent less than the #200 sieve) have resulted in swell volumes exceeding 40 percent of the total treated volume whereas for coarse grained soils swell volumes are more typical in the range of 15 to 20 percent.
- Particle Uniformity: Fly ash consists of mostly spherical particles that are often fairly uniform and well sorted that may yield lower UCS and higher hydraulic conductivity than poorly sorted materials during ISS construction. Poorly sorted materials with particles of different sizes and angularity can more effectively interlock to reduce interstitial void space and may result in higher UCS and lower hydraulic conductivity. Accordingly, greater void spaces could require higher reagent concentrations to achieve similar UCS and hydraulic conductivity to that of poorly sorted materials using lower reagent concentrations.
- Coal Source: Characteristics of fly ash can change significantly at power plants where conversions have been performed to change the grade of coal burned, for example from bituminous to subbituminous coal. A fly ash landfill or impoundment that has a history of CCP management with different coal sources may require characterization of the chemical and physical properties of the CCP’s by coal source, requiring development or application of multiple ISS mix designs.
- CCP Management Method: The method used for placement of the CCP could have a direct effect on the amount of reagent grout required for mixing. Sluiced

fly ash may require less reagent then ash that are managed dry. Virtually all water in the coal evaporates during combustion, and if the fly ash is managed dry, final moisture contents will be lower when placed than sluiced ash. In other words, dry management will result in significantly lower moisture contents that will require larger quantities of reagent grout to effectively deliver the correct quantities of water needed to hydrate reagents and meet design objectives.

- Particle Gradation: Fly ash is fine-grained and well sorted; however, it is common practice to manage other CCPs, such as bottom ash and boiler slag, that have larger particle sizes, in CCP landfills and impoundments. Conditions where there are larger percentages of coarse grained materials (e.g., bottom ash) could pose greater challenges for mixing equipment performance and increase the frequency for equipment repair. ISS mixing in coarse grained materials can quickly degrade mixing equipment components such as augers and pose additional strain due to the higher amounts of torque required to deliver the necessary mixing energy.
- Type of CCP (Class F vs. Class C CCP): Both Class F (low calcium) and C (high calcium) are pozzolans with the distinction that Class C is also cementitious. A Class C fly ash may require lower reagent concentrations to achieve desired UCS and hydraulic conductivity versus Class F fly ash.
- Moisture Sensitivity: Due to its consistent particle size, fly ash tends to be moisture sensitive. When placed at or near optimum moisture content, fly ash can exhibit a highly durable hard surface that will quickly destabilize with addition of moisture. Because of this moisture sensitivity, fly ash that is not self-cementitious may be subject to slope instability under high moisture or saturated conditions. It may also exhibit lower shear strength in comparison to other materials, such as poorly sorted sand or clay, and may result in low interface friction angles. Application of ISS can be effective in reducing stability concerns but should be evaluated with regards to the construction sequence and approach near embankments, slopes, or structures to maintain stability during mixing that will require addition of water with reagent.
- Amended CCPs: For example, some power plants inject trona™ to treat flue gas. The trona™ is then captured with fly ash and depending on the volume of injected, the captured material can exhibit different physical properties than the unamended fly ash. Fly ash mixed with trona™ and landfilled can become unstable after contact with water which can disrupt landfill operations (see case study below). It is important to understand how amendments can affect the physical properties of CCP when considering the types of reagents and reagent mix designs for ISS as a remedy.

To illustrate ISS applicability for adjusting the physical characteristics of fly ash, a comparison of geotechnical testing for two different reagent mix designs was conducted for this paper on samples of Class F fly ash:

Parameter	**Test Results**	
Mix Design	10% Portland Cement/0.5% Bentonite	7.5%GGBFS/2.5% Portland Cement
Tested at Number of Days	14	14
% Percent passing # 200	55	55
Moisture Content (%) (pretreatment)	31	31
Bulk Density (lbs/ft^3) (pretreatment)	102	102
Unconfined Compressive Strengh (psi)	221	184
Hydraulic Conductivity (cm/sec)	4.1 x 10^{-7}	1 x 10^{-6}

Figure 4 – Comparison of Geotechnical testing Results Using Two Different Mix Designs on Class F CCP

The results from this limited test suggest that acceptable UCS can be easily achieved when ISS is applied to fly ash. The acceptability of the hydraulic conductivity value will be application dependent, and in some cases, additional testing with different reagent mixtures and additives may be required to develop a mixture with lower hydraulic conductivity.

ISS Design Considerations Relative to CCP Constituents of Concern

Common COCs leached from fly ash and other CCPs include boron, sulfate, and inorganic trace elements. The relative solubility and leachability of the inorganic constituents will vary based on pH and other geochemical conditions that may be altered when an ISS reagent is applied. The relative leachability of COCs with respect to ISS is evaluated at the bench scale level and will be dependent on the reagent mix design, (e.g., relative ratios of reagents and/or additives), the percentage of reagent mixed with the CCP, and groundwater conditions where the CCP is to be treated.

From a full scale viewpoint, the ISS process creates a large monolithic mass with a hydraulic conductivity lower than the original material, and typically lower than the surrounding native material. Hydraulic conductivity values for fly ash have been observed in the range of $1x10^{-4}$ to $1x10^{-5}$ cm/s (EPRI, 1993 [4]), whereas ISS monoliths can have hydraulic conductivity values as low as $1x10^{-8}$ cm/s. The low hydraulic conductivity will greatly reduce contact of water with inorganic constituents stabilized/solidified within the ISS matrix. Furthermore, groundwater will flow around or beneath the monolith and the primary area for leaching is from the surface of the monolith that is in direct contact with the groundwater. Therefore, the amount of material actually exposed to leaching will be lower than prior to ISS treatment. This conceptual model illustrates why testing methods such as the ANS method 16.1 is a more representative method for assessing post ISS leachability then methods such as the TCLP because it simulates the presence of the undisturbed monolith surrounded in groundwater. With respect to pH, CCP is generally alkaline and the additions of reagents such as portland cement and/or GGBFS which are also alkaline are less likely to change pH. The effect of pH on leachability would need to be evaluated on a consistent specific basis during bench scale testing.

CASE STUDIES

Two case studies are presented that demonstrate bench and full scale ISS applications for CCP. The first study summarizes results of bench scale testing for an ISS application proposed to address leaching of fly ash placed below the water table at a Midwestern fly ash landfill. The second highlights a full scale application where ISS was used to stabilize CCP mixed with trona™ that was posing geotechnical stability concerns at an eastern CCP landfill.

Midwest CCP Landfill Bench Scale Test

A power company was investigating a groundwater plume associated with an off-site, former fly ash landfill located in a suburban setting. The landfill was located in a former sand and gravel quarry and portions of the fly ash were below the water table. Investigation identified elevated levels of sulfate, boron, and other inorganic constituents in two distinct aquifers beneath and downgradient from the former ash landfill. Private wells in the vicinity of the site showed sufficiently elevated levels of some ash constituents to warrant remedial actions. A remedial plan was developed to address the groundwater issues, which had the following site-specific challenges with regard to ISS:

- Saturated fly ash located at a depth of 33 to 39 feet.
- Estimated treatment volume of 42,000 cubic yards (7,000 CY in the saturated zone, 35,000 CY overburden).
- Groundwater impacted with sulfate, boron, and other inorganic constituents.

Treatability testing for ISS of the saturated fly ash was performed as part of the remedial options evaluation. Specific ISS treatment goals of the treatability testing included:

- Performance criteria for UCS greater than 50 psi, hydraulic conductivity less than 1×10^{-7} cm/sec.
- Reduce leachability below groundwater standards for sulfate, boron, selenium, and molybdenum using the ANS 16.1 leach method.
- Minimize volumetric swell to less than 30%.

Reagents tested for the ISS treatability study included Portland cement, GGBFS, bentonite, sodium silicate, gypsum, and TECT 350™ (a proprietary product). Two final mix designs were selected during the studies that were equally effective at meeting the treatment goals:

- 25% Type I/II Portland cement / 35% water blended with the fly ash.
- 15% Type I/II Portland cement / 0.4% bentonite / 35% water blended with the fly ash.

The two final mix designs met the leachability criteria for all constituents, exhibited UCS greater than 50 psi after 7 days of curing, and exhibited hydraulic conductivity values lower than 1×10^{-7} cm/sec. However, the final mix designs exhibited higher than desired volumetric expansion ranging from 42% to 60%.

The study also revealed the following useful information for application of ISS to fly ash:

- The final mix designs exhibited excellent durability (< 1% mass loss) when subjected to wet/dry and freeze/thaw testing.
- Site groundwater with elevated sulfate concentrations (600 to 800 mg/L) was used in the mix designs to determine potential interference with cement hydration during the curing process. No sulfate interference was apparent during the treatability testing.
- pH and alkalinity were elevated by the cement chemistry of the process, which could affect long term leachability of COCs (e.g., selenium).

In summary, the testing demonstrated that ISS could be an effective remedial technology for reducing the leachability of sulfate, boron, selenium, and molybdenum from the saturated ash at the former landfill. Ultimately, ISS was not selected for remediation of the landfill based on the following factors:

- Cost prohibitive compared to excavation at the time of construction (1999).
- Would have required ISS of overburden and significant volume expansion.
- Concerns remained for long term leaching of selenium due to elevated pH.

CCP landfill in Eastern Region (DeGrood, 2012 [5])

Several months after a generating station began using trona™ to reduce sulfur dioxide emissions, the station's landfill began experiencing difficulties with its CCP. Specifically, severe erosion and stability issues began to occur after placement in the landfill. These problems were attributed to the presence of trona™. It was concluded that when the trona™ mixed with CCP came into contact with water (e.g., storm events) it became highly unstable, which led to significant disruption in in the landfill management operations (e.g., heavy equipment operation and placement of CCP).

Bench scale testing was initiated to identify a method to stabilize the CCP. Performance criteria included UCS greater than 20 psi, hydraulic conductivity less than 1×10^{-5} cm/sec and reduced leachability for inorganic constituents. Several rounds of bench scale testing were conducted. The initial round used a lime (calcium hydroxide) as the stabilizing reagent. Additional rounds used a combination of calcium chloride, Portland cement, and GGBFS. The initial testing indicated the following:

- Cemented material disintegrated in contact with water
- Sodium hydroxide was formed with pH greater than 12.5 (hazardous) that had a gel-like material
- It was concluded that the sodium hydroxide formation was a result of a chemical reaction between sodium based salts and lime

Additional phases of testing concentrated on moderating pH by using calcium chloride in lieu of calcium hydroxide. Additional testing also included various combinations of Portland cement, and a proprietary reagent (Terra-Bond™). Based on the additional testing results, a final mix design was selected that consisted of Terra-Bond™ with GGBFS and Portland cement mixed at a 3:1 ratio.

The construction project entailed stabilizing the upper sixteen inches of fly ash across the landfill's surface, thereby creating a crust that is resistant to erosion and dissolution. Reagents were added by spreading them on the surface of the ash and then mixing them into it using a soil stabilizer (i.e., rake type injector; Figure 5). The cutting depth of the soil stabilizer was set at 16 inches. Work progressed in a counter-clockwise direction beginning in the southwest corner of the site. After the ash had been mixed with reagents a smooth drum vibratory compactor was used to compact the treated material and to form a smooth surface. An earthen cover was then placed over the stabilized CCP.

Figure 5 - Reagent Mixing Operations on CCP with Trona™

CONSIDERATIONS FOR FUTURE APPLICATIONS

This paper describes the current state of the art for ISS, and introduces its potential for CCP applications. Information available to-date indicates that ISS has merit as a remedial alternative in some CCP applications, capable of increasing strength and decreasing hydraulic conductivity. Limited testing has also shown a reduction in leachability, although additional site and material specific testing is always necessary to confirm all of these criteria. Testing to-date suggests that Portland cement and GGBFS are effective reagents, although more testing is needed to explore other options.

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