OVERVIEW OF U.S. INDUSTRY PRACTICE FOR SOIL MIXING IN CONTAMINATED SOILS

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ABSTRACT

Soil mixing has been used around the world for geotechnical construction for nearly 50 years. After its introduction into the United States market in the late 1980s, soil mixing was gradually adopted for environmental remediation driven by increasing environmental regulations and clean-up needs. Since these early applications, soil mixing has grown into a widely accepted method to stabilize, solidify, and treat a variety of wastes. In this paper, the authors draw from decades of experience in the environmental soil mixing market to provide an overview of the U.S. industry practice, including discussions of major industries served, waste types remediated, and trends in construction. The paper also includes descriptions of recent applications throughout to reinforce the high level discussions.

INTRODUCTION

In United States (U.S.) practice, the term soil mixing generally refers to the in-situ mixing of soils with a binder and/or other materials to improve the geotechnical or environmental properties of the soil. In geotechnical applications, the primary objectives include shear strength improvement and permeability reduction used to achieve various goals including liquefaction potential reduction, slope stability, or bearing capacity improvement. In environmental applications, soil mixing is used to stabilize or solidify impacted soils to reduce the impact of wastes on the surrounding soil and groundwater. In environmental applications, soil mixing can also be used to treat contaminated soils with oxidizing or reducing agents. For many waste types, soil mixing is a preferred technology for environmental applications to accomplish stabilization, solidification, or treatment objectives. Compared to another common method of remediation, excavation and off-site disposal of impacted soils, soil mixing offers numerous benefits, including eliminating a need for excavation support systems, temporary dewatering, or temporary treatment of impacted groundwater, reducing exposure of employees and the public to air-borne contaminants, eliminating or reducing trucking and disposal costs, eliminating or reducing risk of exposure to the public from trucks hauling waste, improved sustainability, and reducing or eliminating the purchase and placement of imported clean backfill.

SCOPE, PURPOSE, AND AUDIENCE

This paper is meant to convey an overview of soil mixing practice in the U.S. Due to space constraints, most of the topics are not covered in great detail and would normally be deserving of further discussion. General practitioners will find benefit in the broad discussion of topics and experienced ISS practitioners will find benefit in the detailed discussions section.
OBJECTIVES FOR ENVIRONMENTAL SOIL MIXING

**Containment**
One of the first environmental applications of soil mixing was for the creation of vertical barriers to contain impacted soil and wastes from the surrounding groundwater. One of the main advantages of using soil mixing in lieu of the more conventional approach of slurry trench excavating methods is it minimizes the potential exposure of contaminants that are harmful to human health. An example of this application was where soil mixing with a multi-axis soil mix rig was used to successfully install an environmental barrier for isolation of tritium contaminated soils in 2010 at a U.S. Department of Energy facility in Southeastern United States (Fig. 1).

**In Situ Solidification / Stabilization**
Soil mixing is often used to achieve in situ stabilization/solidification (ISS) objectives. In these applications, the soil mixing method is used to inject a fluid grout with binding reagents into the soil to improve the strength, reduce the permeability, and often improve (reduce) the leachability characteristics of the soils. Commonly specified objectives for ISS completed via soil mixing include a target unconfined compressive strength (UCS) of greater than 345 kPa (50 pounds per square inch (psi)) and a target hydraulic conductivity of less than $1 \times 10^{-6}$ cm/sec. Reagents for ISS are selected based upon their binding and adsorption/absorption characteristics. Binding reagents improve the strength and reduce the permeability while adsorption/absorption reagents aid in leachability reduction and sometimes reduce the permeability. Common binding reagents are Portland cement, blast furnace slag, flyash, cement kiln dust, and lime. Portland cement is used in over 90% of ISS applications because of its excellent binding properties, its relatively low cost and its wide availability in large quantities. Common adsorption/absorption reagents are activated carbon, organophillic clay, and attapulgite clay. Bentonite clay is sometimes used in conjunction with Portland cement mixes to reduce the permeability of the treated ISS material.

**In Situ Treatment**
In addition to ISS, soil mixing can also be used to deliver reagents selected for gross contaminant mass reduction. For the purposes of this paper, the authors separately refer to this technique as in situ treatment (IST) although technically speaking these techniques are a form of stabilization accomplished with or without solidification. Unlike ISS, IST is used to target chemical reactions that reduce the contaminant concentration or alter the contaminant(s) into less harmful constituents. The main chemical reactions used in these applications include chemical reduction, referred to as in situ chemical reduction (ISCR), or chemical oxidation, referred to as in situ chemical oxidation (ISCO). After IST, most sites are also solidified using a second pass of soil mixing to allow for a stable subgrade for potential future development or placement of a soil cap. The reagents utilized for IST depend on the contaminants of concern (COCs) and site remedial objectives, but common reagents used in this application include sodium persulfate, calcium peroxide, potassium permanganate, and zero valent iron (ZVI).

**In Situ Air and Steam Stripping**
Although much less common, thermal remediation by injection of hot air and steam can also be utilized to remove volatile organic compounds (VOCs) and semi volatile organic compounds (SVOCs) respectively. Once vaporized, these compounds are collected under a negative air pressure shroud and then captured...
using ex-situ vapor phase treatment equipment. This application has been successfully utilized on multiple full scale and pilot study projects over the past 15 years. The steam and hot air is injected during mechanical mixing to increase permeability and raise the temperature in the subsurface to approximately 65° to 95° C. These temperatures volatilize the COCs and the hot air conveys the desorbed contaminants to the surface. At the surface, the vapors are captured beneath a shroud and immediately passed through a vapor conditioning and treatment system. Typically, the in situ thermal technology using steam and hot air has removal efficiencies of 90-99 percent for VOCs and 50 to 90 percent for SVOCs (La Mori, et al 2010). In addition to the thermal treatment, a polishing step is often performed to extend the treatment. For chlorinated solvents, the addition of a ISCR agent such as ZVI can be mixed into the soils to further reduce COC concentrations over time.

MAJOR APPLICATIONS & COMMON CONTAMINANTS REMEDIATED

Former Manufactured Gas Plants
From the 1800’s to the early 1960’s, thousands of manufactured gas plants (MGPs) operated in various cities and towns across the U.S. and all over the world. These plants converted coal into gas for lights and furnaces. Unfortunately the process of gasifying the coal produced a variety of by-products, including coal tar, which contain harmful chemical constituents such as VOCs and polynuclear aromatic hydrocarbons (PAHs). Typical remediation options for MGP sites in the early 1990s included excavation and disposal, thermal treatment, encapsulation, and in-situ stabilization (Dennis 1999). Now in-situ stabilization/solidification (ISS) is a favorable alternative to meet the primary remediation objectives of mitigating COCs, controlling off-site contaminant migration, and protecting human health and the environment. The first successful application of ISS at a MGP site was in 1992 in Columbus, Georgia. At the time, this was the largest use of deep mixing ISS with a treated volume of about 90,000 cubic yards treated (Dennis 1999). The remedial objectives of reducing VOC and PAH concentrations and migration were met.

Another successful early execution of ISS for MGP impacted soils was implemented in 2000 at a site in Cambridge, Massachusetts (Andromalos and Carr 2016). The MGP site was contaminated with both dense non-aqueous phase liquid (DNAPL) and light non-aqueous phase liquid (LNAPL). Soil mixing at this site was performed using a containment hood for odor and VOC control. The hood was deployed around the active area being mixed and air was constantly drawn out of the hood and run through a treatment system where the vapors were treated before discharge to the atmosphere. Today, foam suppression techniques are more commonly utilized to control VOC and odor emissions in the areas of active treatment.

The use of ISS at MGP sites across the U.S. represents the largest application of environmental soil mixing today. The method is widely accepted as the preferred technology for the remediation of these sites. To date, ISS has been used to remediate several million cubic yards of MGP impacted soil in more than 11 states.

Wood Treating Facilities
Coal tar, a by-product of the MGP process and the coke making process used in the production of steel has been used for decades to manufacture creosote, a common wood treating chemical used to treat wood for use as railroad ties or utility poles. Given that these sites have a similar waste stream to MGP sites, ISS has logically also been an effective remediation technique for wood treating sites. Even soil impacted with other
common wood treating processes such as chromated copper arsenate (CCA) have been effectively treated with ISS.

**Metals**
The above ground stabilization of metal contaminated soil and waste at environmental clean-up sites and treatment, Storage and Disposal Facilities (TSDFs) has been performed for over 40 years in the U.S. As a result, more is known about metal stabilization than most any other hazardous constituent group. This knowledge can and has been directly applied to the use of ISS for metal impacted soils. Most metals and metal compounds can be effectively treated with cement-based ISS techniques, with or without any additional additives. Some metals and metal compounds may require pre-treatment or other reagents (Conner 1997).

**Chlorinated Solvents**
A highly successful and widely applied reducer of chlorinated solvents is zero-valent iron (ZVI). In 2002, the first application of in-situ treatment (IST) with ZVI and clay was performed at the DuPont Chemical site in Martinsville, Virginia. ZVI was used to treat carbon tetrachloride while the clay additive was used primarily to reduce the permeability of the treated zone to prevent groundwater flow through the area. The ZVI-clay application was executed again in 2005 at a site in Camp Lejeune, North Carolina that was contaminated with Perchloroethylene (PCE), TCE, and other DNAPLs (Andromalos and Carr 2016). Soil mixing was used at that site to deliver the reagents to the contaminated soils so that the contaminants could be degraded into the daughter products Dichloroethane (DCE) and vinyl chloride. A 99% reduction in parent product concentrations was achieved a year post-treatment (Olson et. al., 2012). Recently there has even been progress with PCB reduction with emulsified ZVI (EZVI) (Olson 2014).

A variety of oxidants are also useful for treating chlorinated solvents, such as TCE and PCE, and other contaminants like naphthalene and pyrene. Two such oxidants are potassium permanganate and sodium persulfate. Being such a strong oxidant, potassium permanganate is best reserved for sites that contain DNAPL source zones and organics. An example of ISCO via soil mixing with potassium permanganate was completed in 2010 at a former glassware manufacturing facility located in Northern New Jersey. The contaminant of concern, TCE, was treated with potassium permanganate which was allowed to oxidize the contaminants for one to three days before the soil was mixed with Portland cement to increase the strength of site soils and decrease the hydraulic permeability (Andromalos and Ruffing 2014). Sodium persulfate is also used to treat chlorinated solvents and other contaminants. For example, in 2011 sodium persulfate was used to treat xylene and pesticides at a former chemical manufacturing facility located near Robbinsville, New Jersey. At that site, the sodium persulfate was catalyzed with hydrated lime to improve the oxidation reaction (Andromalos and Ruffing 2014).

**EMERGING APPLICATIONS**

**Sediments**
Impacted river sediments have typically been remediated through the use of dredging to excavate and dispose of the impacted materials. However, the method of dredging causes excess turbidity in the water body while removing the impacted sediments. This can cause further contamination of the water body. In
addition, dredging is a time consuming and costly operation. In the last decade, ISS has started to be considered as an option for remediating water-laden impacted sediments.

With this increased focus on the remediation of contaminated river sediments using ISS, the Electric Power Research Institute (EPRI) investigated this technique in a pilot study in Springfield, Massachusetts in 2013. The purpose of the study was to determine the feasibility of ISS for solidification of MGP wastes in saturated sediments with minimized disturbance to the environment. The setup of the mixing rig was on a barge, allowing the rig to reach the sediments in the river. The project was successful in achieving the UCS and permeability requirements, as well as mobility reduction of the contaminants as assessed with the LEAF leachability assessment method (EPRI 2014). Turbidity was monitored and adequately controlled throughout the mixing process.

Also, in 2015, at a project site on the Gowanus Canal near Brooklyn, New York, an ISS test program was performed instead of dredging to remediate river sediments. Gowanus Canal historically has been a hot spot for contaminated sediments, but dredging has not been performed due to the potential for sediment dispersion, high contaminant concentrations, and limited disposal options. The pilot test succeeded in demonstrating that full-scale mixing of sediments from a barge is feasible and that the performance goals established during the bench-scale study can be met with several different reagent mixtures (Olean, et al 2016). As a result of the pilot study success, full-scale use of ISS for sediment remediation at this site is currently slated to begin in 2021 on the canal.

The results of these studies conclude that ISS is a viable technology for the solidification and stabilization of impacted river sediments and may be a more environmentally effective technology than dredging as soil mixing minimizes the dispersion of impacted sediments throughout treatment. With the increased focus on sediment remediation and the cost and issues associated with dredging, soil mixing along with capping of the sediments will become more common for remediating water-laden impacted sediments.

**Coal Ash**

Regulations put out by the U.S. EPA in 2014 have classified coal ash (the by-product of all coal-fired power plants) as a waste. These regulations require that all current coal ash impoundments comply with the new regulations similar to those required at all U.S. Resource Conservation and Recovery Act (RCRA) regulated waste management facilities. In a combination of both an environmental and geotechnical application, soil mixing is a technology that can be applied to strengthen and improve these impoundments through the construction of in-situ shear walls or to isolate these wastes through the construction of soil-mixed barrier walls or even to stabilize and solidify the entire impoundment. A few applications of soil mixing at coal ash facilities have been completed and soil mixing is being evaluated for one or more uses on several projects in design.

**PFAS**

Per- and poly-fluoroalkyl substances (PFAS) are a large class of compounds that have been used in a variety of industrial and residential applications since the 1950s for such things as firefighting and food packaging materials. These widespread substances are part of a group of emerging contaminants that were not previously monitored in the environment, but have been recognized by the US EPA and other worldwide organizations to pose human health risks. Recently, some proprietary products containing aluminum hydroxide, activated carbon, kaolinite clay, and/or chemically modified clays have been demonstrated to...
immobilize these contaminants (AquaBlok 2019). A few pilot studies using soil mixing as the delivery method have been successfully completed and this is anticipated to be a large use of soil mixing in the future.

**RECENT INDUSTRY ACTIVITY & CASE STUDY**

As discussed above, soil mixing has become a preferred remediation tool for a variety of industries and waste types. With personal involvement in 10+ projects per year and exposure to at least 5 times as many bids, these authors estimate that there are approximately 40 to 70 active ISS projects per year in the US. These projects range from pilot studies to full scale site remediation where ISS is just a component of the overall site work.

A case study in New Jersey completed in 2019 highlights a common application of ISS as well as the versatility of soil mixing to work in limited space and to achieve multiple site objectives. The project site was the former location of a MGP that operated from the 1870s to the 1920s. The current site use is a parking lot for a police department and a municipal park. The ISS portion of the project (see Fig. 5) included soil mixing of 52,000 cubic meters (CM) (68,000 cubic yards (CYs)) of impacted soils to a depth of 9 meters (30 feet) below a work platform established at 3 meters (10 feet) below existing street level, i.e. soil mixing was performed from 3 meters (10 feet) to 15 meters (40 feet) below existing grade. Soil mixing for the interior columns was performed using a single axis mixing tool to deliver a Portland cement and blast furnace slag mixture to achieve a target UCS of greater than 345 kPa (50 psi) and target permeability of less than 1x10^{-6} cm/s. In addition to the cement and slag, activated carbon was added to the perimeter columns to improve protection of the surrounding environment through contaminant leachability reduction via absorption. Given the close proximity of nearby structures (police station, roads, park) and the presence of the ISS drill rig, the designers chose to install a 3 meter (10 feet) high perimeter gravity wall excavation support system via soil mixing. For these perimeter columns, the cement dosage was increased to achieve a higher target strength of 720 kPa (100 psi). Overall the project was considered a technical and practical success by all parties and ultimately resulted in a significant time and schedule savings relative to having to excavate and dispose of all the impacted material.

**IMPLEMENTATION DISCUSSIONS**

**Coring**

On some environmental sites and specifically in some U.S. states, regulatory stakeholders have begun to push for the collection of in situ samples in an attempt to evaluate the in situ sample homogeneity of soil mixed materials. This is a logical, albeit misunderstood, extension of the practice of coring for the recovery of in situ samples on geotechnical soil mixing sites. In addition, new requirements associated with this trend include strict tolerances for visual indicators of contaminant, maximum contaminant particle sizes, and core recovery. The authors have numerous concerns related to this practice. First, coring of relatively low strength soil mixed composites is difficult and often the resulting findings are not representative of the true in situ condition. For instance, in certain soil conditions, i.e. soils with gravel or cobbles, coring may be nearly impossible as the gravel/cobbles particles can spin within the core and destroy the sample. If coring is going to be widely specified for soil mixing on environmental sites, then the strength objective will inevitably (and unnecessarily) need to be increased to something closer to 2 MPa (290 psi), which is...
considered the lower bound strength for successful coring. This will come with an increased reagent cost, increased spoil volumes, and potentially other issues associated with material re-work and/or future site access. Second, it is dangerous to start assigning responsibility for maximum particle size or the presence of contaminants to soil mixing Contractors. For example, if ISS is the primary objective, the ISS process is not meant to change the nature of the contaminants, but rather to encapsulate the contaminants in a low permeability, moderate strength monolith which reduces the contaminants’ impact on the surrounding soils and groundwater. Finally, many of the visual indicators will be qualitative in nature and therefore the performance verification will rely on opinions. Anytime an opinion is relied upon, the door is open to interpretation which inevitably increase the frequency and magnitude of claims.

If coring is used to supplement wet grab samples (discussed in the next section), it should be used for visual confirmation of adequate mixing (no large unmixed zones) and confirmation of no un-encapsulated free-product (i.e. DNAPL). In order to maximize core recovery, coring should be performed by an experienced driller using triple-tube coring techniques including bentonite slurry as the coring fluid. If low core recovery is experienced (often due to washing out of the sample during coring), the use of a down-the-hole borehole camera is helpful to evaluate ISS integrity. Due to the likelihood of micro fracturing of this low strength material during the coring process, permeability and even strength testing should not be performed on these core samples.

**Representing Macro Performance Using Wet Grab Samples**

Because it is cost prohibitive and difficult to test a full scale soil mixed column, it is common in the industry to assess full scale performance using small samples, generally wet “grab” samples, of the soil mixed material. These samples are collected from discrete depths within a recently mixed column using a hydraulic or mechanical sample collection tool that can be opened and closed from the ground surface. When evaluating the validity of using these samples to model the full scale mixed material, it is important to consider 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 the right (macro) scale. Visual observation of soil mixed elements will show the mixture contains soil mixed with cement, soil, hardened cement grout, watery soil, pockets of unmixed contaminants (if present) and even possibly small air voids. However, when viewed from a larger scale, the soil mixed material 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 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 mixed sample is sieved prior to casting in the cylinder, there are inevitably inclusions in these cylinders that will have an effect on the performance of the specimens. The photos in Figure 6 show cross sections of soil mixed cylinders.

**Figure 6. Cross section photographs of specimens from grab samples showing inclusions**
If the performance of these cylinders with 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 0.6 m (2 feet) (inclusions are up to 1.3 cm (0.5 inch) in a 5 cm (2 inch) diameter cylinder, so 25% of the diameter for a 3 m (9.8 foot) column equals 0.75 m (2.46 feet)). 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. Recognizing this known inhomogeneity that inevitably exists within a soil mixed mass is important so that factors for the inhomogeneity can be incorporate in the design in an attempt to account for scaling in the development of sampling, casting, and testing procedures for determining acceptance.

**Determination of Pay Volumes**

The pay quantity for soil mixed volumes is a highly debated topic, varies considerably from site to site, and is not always easy to calculate. For example, circular soil mixed columns are often used to mix along straight lines or in rectangular areas and the depth of treatment can vary across the site, even element to element. Depending on how the contract is setup, the site Owner or Contractor may have to take all of the risk associated with overtreatment to meet minimum treatment areas. Obviously the larger the treatment area, the more it costs, and the more complicated the treatment is, the more it costs. The lowest cost and simplest approach to addressing this issue is to leave the little gaps left between circular elements along the perimeter alone (see Figure 7). From a technical standpoint this approach also makes sense since the treatment area perimeter is often selected by interpolating, hopefully conservatively, between a relatively small amount of data so it’s actually irrational to expect that leaving small gaps around the perimeter results in a lower amount of protection. Generally, the most expensive approach is to use jet grouting or smaller diameter mix tools to fill those small gaps, followed by overtreatment (larger columns extended outside the minimum area), followed by abnormal or larger overlaps between columns (columns shifted to minimize treatment outside the minimum area). Some site Owners prefer to place all of the risk associated with overtreatment (increased quantities) with the Contractor using language like, “The Contractor is responsible for developing a column layout that ensures 100% coverage of the treatment zone. Payment will be made according to the neat line volumes shown.” This requires the Contractor to determine the column layout ahead of time and price in the work outside the neat lines into the base neat line contract units. Other contracts are structured to pay according to the actual effective volume treated, as calculated from QC/as-built information. From the Contractor’s standpoint, overtreatment on the “grid” pattern with pay quantity calculated from actual effective volume treated is the most fair and technically sound approach. This method is fair to both parties and provides complete coverage of the minimum area. However, depending on how the design was developed and who is overseeing the remediation, it can also make sense to leave the untreated areas alone around the perimeter.

**Spoils Handling and Payment**

On any ISS project, the handling and disposition of spoils must be considered. The amount of spoils produced is dependent on the gradation of the material being mixed and the type and amount of reagent being added. Typically, the spoils generated can be between 15% and 30% of the volume of material being treated, but spoils can be as low as 5% and as high as 100%. A sand/gravel with no fines will produce minimal spoils, on the order of 10%, while a high fines content hard clay will produce a high volume of 50%.
spoils, as high as 100%. Also, the higher the volume of grout being added, the more spoils will be produced. A rough estimate of spoils can be determined during the mix design phase.

Ideally, the site will allow for removal of some overburden from the soil mix footprint prior to mixing. Removing this material may allow for the swell to be left in place. However, consideration must be given to the equipment performing the soil mixing. A work platform that is too close to the water table may cause stability problems for the soil mixing rig. As a general rule, it is best to leave the work platform at least a meter (~3 feet) above the high water table to provide a suitable work platform.

If the spoils are to be left onsite, it is best to have payment for spoils handling included in the soil mixing unit price. Should the project require spoils to be hauled off and disposed of, then a separate unit price should be provided. Some projects include spoils management and disposal as a lump sum item with all risk on the Contractor. Generally, this encourages the Contractor to add contingencies in the bid which increases the cost to the Owner.

**Leachability**
A variety of testing procedures exist to test the contaminant reduction post-ISS. Common tests include the Toxicity Characteristic Leaching Procedure (TCLP), Synthetic Precipitation Leaching Procedure (SPLP), and the more recently developed Leaching Environmental Assessment Framework (LEAF) methods. TCLP was introduced in 1990 by the U.S. Environmental Protection Agency (EPA) as a method to simulate leaching from landfill conditions and determine contaminants identified by RCRA and their concentrations from the leachate based on a single-point pH test (Hattaway et al., 2013). Another single-point pH test is the SPLP, introduced in 1986 by the EPA as a method to simulate leachate that precipitates from rainfall on material in situ. Like the TCLP, the SPLP method can determine RCRA soil contaminants and their concentrations in the leachate. However, as a single-point test there are limitations on modelling long term effects of the remediation. In addition, both the TCLP and SPLP methods involve the pulverization of the sample prior to testing, which is not representative of a solidified ISS monolith. Another previously used method is the ANS 16.1 method that was initially developed for the testing of stabilized nuclear wastes.

In 2010, the EPA introduced LEAF as an additional analytical procedure to model leaching behavior. Unlike the TCLP and SPLP methods, the LEAF methods can be used to assess leachability across pH, liquid to solid ratio, rate of mass transport, and transport kinetics in order to model the physical and chemical behavior of leachate for more informed remedial decisions (Kosson 2012). Due to cost and turn-around times associated with analytical testing, most leach testing is performed during the selection of design mix(e)s and not as an acceptance criteria during full-scale production work. Occasional testing, for reference purposes, may be performed during production work.

**Design Mixes**
With the advancement of soil mixing for ISS and IST as a successful and cost-effective remediation technology, well conducted pre-construction design mix studies are of high importance. Design mix studies are used to assess feasibility of technology implementation, including identifying effective reagents for site contaminants, and dosages to minimize cost and meet site remedial objectives. For ISS, strength improvement and permeability reduction are typical objectives achieved with Portland cement and other additives. For environmental applications the objectives may be more complicated and site specific, for example leachability testing may be conducted. For ISCO and ISCR, design mix studies are used to study contaminant reduction and reaction time by simulating soil mixing field conditions. In order to prevent issues in translating the results of a design mix bench scale study to the full scale, construction considerations and impacts must be considered at all stages of the design mix development.
CONCLUSIONS

Since its creation in the 1950s soil mixing has developed from a geotechnical application to an environmental remediation application. Due to driving factors from environmental law and regulations, soil mixing development for environmental stabilization and treatment of contaminants has been swift and widespread. ISS is now a proven and cost-effective remediation alternative for MGP and many other contaminated sites, while ISCO and ISCR are continuing to become popular replacement options vs. excavation and disposal and thermal treatment remediation alternatives. The technique is regularly being applied or considered for a number of emerging contaminants or new applications such as the recent successful use of soil mixing for remediation of river sediments. Implementing site treatability studies prior to soil mixing implementation has proven to be an effective standard of practice in the field to cost effectively choose reagent types and dosages to meet remedial objectives.

REFERENCES


