

IN SITU REMEDIATION AND STABILIZATION OF CONTAMINATED SOILS AND GROUNDWATER USING SOIL MIXING TECHNIQUES WITH VARIOUS REAGENTS

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ABSTRACT

In situ soil mixing, in various forms, has been utilized in the geotechnical field for over 40 years. Originally, the primary applications of soil mixing were for the construction of foundation support elements and earth retention structures. Soil mixing techniques were first applied to environmental applications in the late 1980's and early 1990's. Increasingly, soil mixing is being used in the United States to cost effectively treat a range of waste types in a variety of applications.

This paper presents an overview of soil mixing as it relates to environmental remediation, highlights the differences between stabilization and treatment, and presents recent soil mixing case studies specifically chosen to emphasize common soil mixing reagents and applications.

RESUMO

A mistura de solo *in situ* (Soil Mixing) tem sido utilizada no campo geotécnico por mais de 40 anos. Originalmente, as principais aplicações da mistura de solo foram para a construção de suporte de fundações e estruturas de contenção de solo. As técnicas de "Soil Mixing" foram primeiramente usadas para a aplicação na área ambiental no final dos anos 80 e início dos anos 90. Cada vez mais, a técnica de mistura de solo tem sido utilizada nos Estados para um custo efetivo de tratamento de uma variedade de tipos de resíduos, e para diversas aplicações.

O artigo apresenta uma visão geral sobre a técnica de mistura de solo *in situ*, aplicado à remediação de áreas contaminadas, destacando-se as diferenças entre a técnica de estabilização e o tratamento dessas áreas. O artigo apresenta também, os recentes casos de estudo sobre mistura do solo, especificamente escolhidos para enfatizar os reagentes em comum e suas aplicações.

INTRODUCTION

In situ soil mixing, in various forms, has been utilized in the geotechnical field for over 40 years. Soil mixing was first introduced in the United States (US) in the 1950s, was primarily developed in Europe and Japan in the 1960's, 1970's, and 1980's and has been further refined in the US since its reintroduction in the late 1980's. Originally, the primary applications of soil mixing were for the construction of foundation support elements and earth retention structures (Ryan and Walker, 1992^[1]).

Soil mixing techniques were first applied to environmental applications in the late 1980's and early 1990's. Increasingly soil mixing is being considered a technically sound and cost effective method for remediating a variety of waste types. Techniques utilizing soil mixing to remediate contaminated sites have seen significant development and soil mixing has become an efficient means of *in situ* remediation in the US accepted by the U.S. EPA and numerous other agencies in a range of applications.

Soil mixing may be defined as any technique that is used to mechanically mix soils with or without the addition of additives. Commonly, in both geotechnical and environmental applications, soil mixing refers to processes by which reagents are injected and mixed with soil (Day and Ryan, 1995^[2]). The processes vary widely from *in situ* to *ex situ*, dry mixing to wet mixing as shown in Larsson (2005^[3]), auger mixing to rotary drum mixing, single auger to multi auger, but generally the purpose remains the same; the efficient creation of a soil-reagent composite with improved properties relative to the *in situ* soils. Soil mixing on environmental remediation projects is primarily performed *in situ* using large diameter single auger soil mixing with wet reagent injection. In this method a reagent slurry is used as the drilling lubricant and the final soil additive. The reagent slurry is pumped through a hollow drill stem as a large (0.9 m to 3.7 m diameter) auger is turned in the soil thereby creating treated columns of soil. The columns are installed in an overlapping pattern that ensures 100% coverage of the contaminated target area. Occasionally project or site conditions necessitate the use of dry mixing methods or the use of air as a drilling fluid. Soil mixing on environmental projects is typically used to accomplish one of two objectives; stabilization (aka *in situ* stabilization or ISS) or treatment (herein referred to as *in situ* treatment or IST) of impacted soils. ISS is more common than IST, but IST has seen an increase in use over the last half decade. The purposes of this paper are to define ISS and IST, highlight the similarities of ISS and IST, and finally to present recent case studies that emphasize the wide range of ISS and IST applications and reagents.

STABILIZATION

Stabilization (also referred to as solidification) refers to processes that utilize binding agents to alter the physical properties of impacted soil/sediment. On stabilization projects the contaminants are not chemically changed to less harmful forms, but are typically locked in low permeability matrices that reduce the contaminants' impacts on the surrounding soils and groundwater. Stabilization/solidification (S/S) is normally accomplished through the *in situ* addition of Portland cement (PC) to the soil (Adaske et al, 1998^[4]). Other additives that are common in S/S applications include blast furnace slag, flyash, cement kiln dust, activated carbon, bentonite clay, organophilic clay, and attapulgite clay. See Table 1 for a summary of reagents. Bench scale studies are commonly performed to determine an efficient combination of additives that accomplishes the project objectives (Andromalos and Ameel, 1995^[5], ITRC, 2011^[6]).

The most common project objectives are reduced permeability and increased strength, but occasionally S/S projects require tangible reductions in contaminant leachability. Commonly the project objectives are an unconfined compressive strength (UCS) greater than or equal to 0.344 Mpa and a permeability less than or equal to 1×10^{-6} cm/s. The ability of reagent combinations to cost effectively meet the project objectives is confirmed in the bench scale study and sometimes through full scale pilot tests.

TREATMENT

Treatment refers to processes that utilize reagents to actively promote a chemical change in the impacted material. On treatment projects the contaminants are chemically changed to less harmful constituents. Treatment is commonly performed using chemical reduction (commonly referred to as *in situ* chemical reduction, ISCR) or oxidation (commonly referred to as *in situ* chemical oxidation, ISCO). Treatment objectives vary from project to project depending on the site contaminants, contaminant concentration(s), and final site use. Reagent combinations are specifically designed to target the contaminants of concern (COC). Common reagents include zero valent iron (ZVI), potassium permanganate, sodium persulfate, ferrous sulfate (see Andromalos and Ameel 1994^[7]), calcium polysulfide, biological nutrients, and hot air. Often, additional reagents, in combination with the treatment reagent, are injected to facilitate the main reaction. One such instance would be for pH adjustment. These other reagents include lime, soda ash, quick lime, and phosphoric acid, amongst others. See Table 1 for a summary of reagents. Project objectives vary widely on treatment projects, but are generally centered around target contaminant destruction.

Table 1. Example ISS and IST Reagents

ISS or IST	Reagent	COCs Effectively Stabilized or Treated	Underlying Process
ISS	Portland cement	Numerous, MGP waste, gasoline and diesel range organics, metals	Binding
	Blast Furnace Slag	Numerous, MGP waste, gasoline and diesel range organics	Binding
	Flyash	Metals, organics and inorganics	Binding
	Cement Kiln Dust	Metals	Binding
	Activated Carbon	Organics, Phenolic Waste	Adsorption
	Bentonite Clay	Organics	Adsorption
	Organophillic Clay	Phenolic waste, organics	Adsorption
	Attapulgitic Clay	Acids Waste, Metals	Adsorption
IST	Lime	Inorganics, Metals	Binding
	Zero Valent Iron	TCE, Arsenic	Reduction
	Potassium Permanganate	TCE, Acetone, Pesticides, VOCs	Oxidation
	Sodium Persulfate	TCE, Acetone, Pesticides, VOCs	Oxidation
	Ferrous Sulfate	TCE, Acetone, Pesticides, VOCs	Oxidation
	Calcium Polysulfide	Chromium	Reduction
	Biological Nutrients	Acetone, Pesticides	Enhanced Bio-Degradation
Hot Air	VOCs	Volatilization	

Sources: ITRC (2011)^[6]; Gardner, F.G., et. al., (1998)^[8]; Irene M.C., (1996)^[9]; USEPA (2009)^[10]; U.S Department of Defense (2000)^[11]; U.K Environmental Agency (2004)^[12]; Raj, D.S.S; Rekha, C.A.P, Bindhu, V.H; Anjaneyulu, Y., (2005)^[13]; Conner, (1990)^[14].

STABILIZATION VS. TREATMENT

There are inherent advantages and disadvantages to ISS/IST compared to alternative site remediation technologies, but this discussion is focused on the comparison of these two approaches. The four main factors that dictate the remediation approach are cost, schedule, remediation efficacy, and constructability.

Cost

Cost is arguably the most important factor for any construction project and remediation construction projects are no exception. Fiscally responsible owners and public agencies are constantly looking for more efficient ways to clean up or reduce the long term environmental impacts of contaminated sites. The overall remediation cost may be divided into two main categories; construction cost and long term operation cost. The long term operation cost primarily consists of extended monitoring programs that are required on projects where the contaminants are not entirely removed or proven destroyed. Generally, IST projects have a higher construction cost than ISS projects, but the long term operation cost can be substantially lower. Budgetary construction cost ranges, developed from recent US project experience, are presented on Table 2.

Table 2. Budgetary Construction Cost Ranges for ISS and IST

Approach	Mobilization (\$ ¹)	Soil Mixing (\$ ¹ /m ³)	Reagents (\$ ¹ /m ³)
ISS	75k – 100k	38 – 53	8 – 15
IST	75k – 100k	45 – 61	8 – 76

¹ \$ = US dollars

As shown in Table 2, IST projects are normally more expensive to implement because of the health and safety concerns related to material handling and the higher reagent cost. On the other hand, IST projects typically require a less robust long term monitoring program than ISS projects. This is due to the fact that the contaminants are converted to less harmful constituents on treatment projects, but are left chemically unchanged on stabilization projects. In general, IST approaches are more expensive to implement than ISS approaches, especially in terms of capital costs.

Schedule

Schedule is often second only to cost in factors affecting the remedial approach choice. If the same numbers of reagents are used for a ISS and a IST project, then the soil mixing production rate will be identical or very similar and generally will fall in the range of 190 m³ – 380 m³ treated per day. Occasionally, material delivery lead times and inefficiencies associated with onsite material handling can increase the schedule on IST projects. Additionally, IST projects or projects utilizing a combination of ISS/IST may require multiple mixing passes with time for the reaction to take place between passes. For the most part IST and ISS projects will have similar construction schedules.

Remediation Efficacy

Post remediation goals vary widely and are influenced by numerous factors. Therefore, it's difficult to compare the efficacy of a stabilization approach and a treatment approach. On some projects, stabilization may be viewed as a well established, consistent means of reducing the long term impacts of contamination on the environment. For example, ISS is widely viewed as acceptable for use in the remediation of former manufactured gas plant (MGP) sites. Other projects, in different locales, may require aggressive remediation which typically includes contaminant concentration reduction, i.e. treatment. Broadly speaking IST is viewed as a more robust solution because it promotes active degradation of the contaminants, whereas ISS only reduces the contaminants' impacts on the surrounding subsurface. Remediation efficacy should be compared on a project specific basis because of the large number of variable that factor in to the comparison.

Constructability

IST and ISS approaches require similar sets of equipment and labor. However, IST projects are harder to implement because the post treatment soil is loose and/or extremely wet and tends to stay this way for extended periods of time. For this reason, IST projects are more difficult than ISS projects in terms of overall constructability. This is one of the contributing factors to the higher construction cost of IST approaches.

CASE STUDIES

In situ soil mixing for environmental remediation has been utilized on a number of recent projects that support its cost effectiveness and general acceptance amongst owners, engineers, and oversight agencies. Four select recent projects completed by Geo-Solutions, Inc. of Pittsburgh, PA (US) are presented here to highlight uses of ISS and IST in environmental applications. The projects were chosen to emphasize different reagent combinations and contaminants of concern.

Case Study 1 – *In Situ* Chemical Oxidation and Stabilization of TCE Contaminated Soils

In the spring/summer of 2010 large diameter single auger soil mixing was used for the *in situ* chemical oxidation and stabilization of trichloroethylene (TCE) contaminated soils in northern New Jersey. The soils were first treated with Potassium Permanganate (PP) followed by stabilization with PC. In total, approximately 5,700 m³ were treated and stabilized using a 2.7 m diameter soil mixing auger to depths up to 5.8 m below ground surface (bgs).

Preliminary bench scale studies and stoichiometric demand calculations indicated that a PP dosage greater than 6 mg PP / kg soil would result in a 99% reduction in TCE concentration. Using an assumed *in situ* dry soil density, this value was converted to a reagent weight per volume of soil, ~10,4 kg / m³ soil, for easier field application. Bench scale studies indicated that the reaction required 24 hours to take place and so the soils were allowed to react for a minimum of 1 to 3 days before being stabilized with PC. A low PC dose, 7% - 8% by dry soil weight, was injected mainly for future site access centered around development. Careful staging and execution of this project was important in order to allow continuous construction access to unfinished areas given the 1 to 3 day waiting period between PP and PC additions and the liquid nature of the PP treated soils. A photo of the PP injection and mixing is shown in Figure (1).

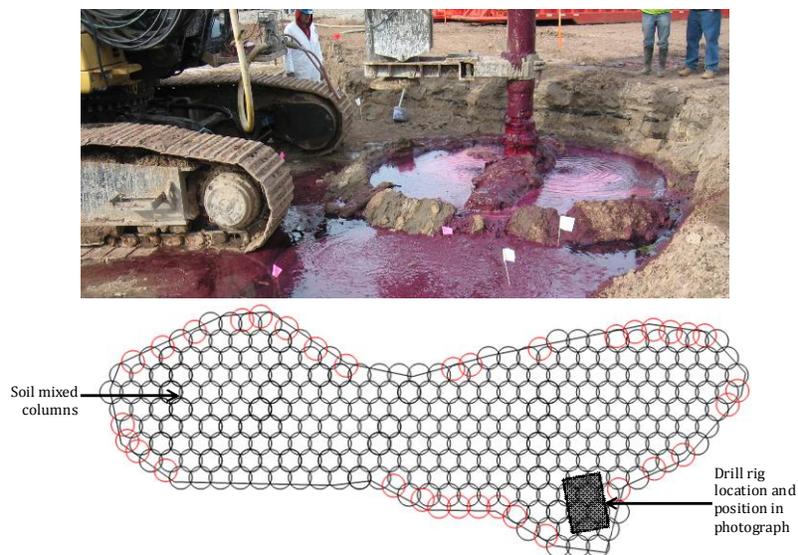


Figure 1. Treatment of TCE Impacted Soils in New Jersey

Post construction testing was centered on the observation of physical properties of wet grab samples. The wet grab samples exhibited an average permeability of 4.1×10^{-7} cm/s and an average unconfined compressive strength of 1.861 Mpa both after 28 days of curing. The work was completed over a 15 week timeframe, including mobilization, demobilization, and miscellaneous site preparation activities.

Case Study 2 – *In Situ Chemical Oxidation of Pesticide and Xylene Impacted Soils*

In the Summer of 2011 large diameter single auger soil mixing was used for the *in situ* chemical oxidation of pesticide and xylene impacted soils in central New Jersey. The soil was amended first with hydrated lime to adjust the pH followed by the injection of sodium persulfate. This two step procedure is also referred to as a base-catalyzed sodium persulfate treatment. In total approximately 2.100 m³ of soil were treated using a 2.7 m diameter soil mixing auger to depths up to 4.6 m bgs.

Preliminary studies indicated that a lime addition rate of 42,9 kg / m³ of soil would be sufficient to reduce the soil pH to a level that would allow for an efficient oxidation reaction and that a sodium persulfate addition of 16.7 kg / m³ of soil would be sufficient for the oxidation reaction. Reagents were delivered to the soils suspended in a water slurry. Vertical distribution within each column was monitored in two foot increments to ensure even distribution of the chemicals within the targeted treatment area. Process controls were employed as the main means of quality control. No post construction testing was performed as part of the construction contract.



Figure 2. Treatment of Acetone Impacted Soils in New Jersey

The work was completed over a 3 week timeframe including mobilization and demobilization.

Case Study 3 – *Stabilization of MGP Impacted Harbor Sediments*

In the summer/fall of 2011 large diameter single auger soil mixing was used to stabilize manufactured gas plant (MGP) impacted harbor sediments with Portland cement on a site located in southeastern Massachusetts. In total, approximately 5.000 m³ of dredged harbor sediments were stabilized using 0.9 m and 2.4 m diameter augers to depths up to 9.5 m bgs.

The project goals included a composite permeability less than 1×10^{-6} cm/s and a strength greater than 0.344 Mpa, both after 28 days of curing. Preliminary bench scale investigations indicated that these goals could be achieved using a cement addition rate of 15%-17% Portland cement calculated by the wet weight of soil. During construction approximately ~285 kgs of cement was added to each cubic meter of soil/sediment. The primary COCs on this site were coal tar byproducts, namely consisting of benzene, toluene, ethylbenzene, and

xylene (BTEX) and other related contaminants. A progress photograph of the stabilization and a site layout map is shown in Figure (3).

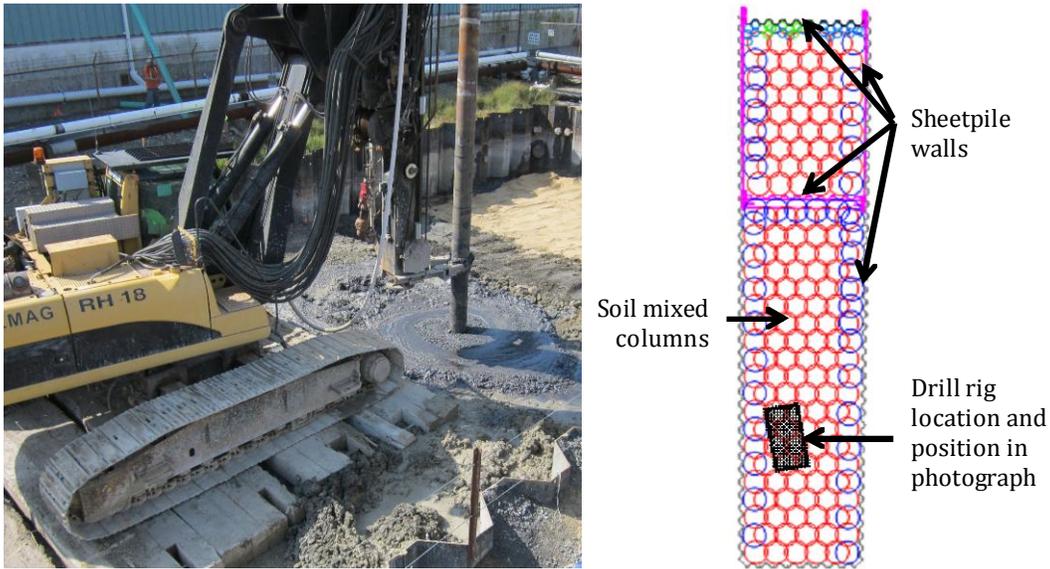


Figure 3. Stabilization of MGP Impacted Harbor Sediments in Massachusetts

All of the stabilization work was completed within sheetpile cells from atop timber crane mats. The work was completed over a period of 6 weeks, including mobilization to the site. Wet grab samples of the stabilized material exhibited strength and permeability values that far exceeded the project requirements.

Case Study 4 – *In Situ* Chemical Reduction of TCE Contaminated Soils

In the Fall/Winter of 2011 large diameter single auger soil mixing was used for the *in situ* chemical reduction of TCE contaminated soils in northeastern Illinois. A slurry consisting of zero valent iron (ZVI) and bentonite was injected and mixed with the TCE impacted soils. The ZVI was injected to chemically reduce the TCE to less harmful constituents and the bentonite was added to increase the residence time of groundwater travelling through the contaminated zone. In total approximately 6,500 m³ were treated using a 2.7 m diameter soil mixing auger up to depths of 7,2 m.

Bench scale studies indicated that a ZVI dosage between 1% and 3% would be sufficient for TCE reduction. Therefore field application was targeted around 2% ZVI addition based on the dry weight of soil. One percent bentonite clay by dry weight of soil was added to reduce the composite permeability of the primarily silty sands underlying the site. Magnetic separation tests were conducted on at least 1 column per day at two to three vertical locations per column. In order to confirm that the iron was properly distributed, the iron weight at each vertical location could not vary by more than 25% from the mean iron concentration in that column. Additionally, no column could have an iron concentration less than 1.5% of the dry soil weight. Through careful staging and distribution control the project was both a technical and financial success despite the less than perfect winter weather working conditions. A picture of the treatment in progress is shown in Figure (4).

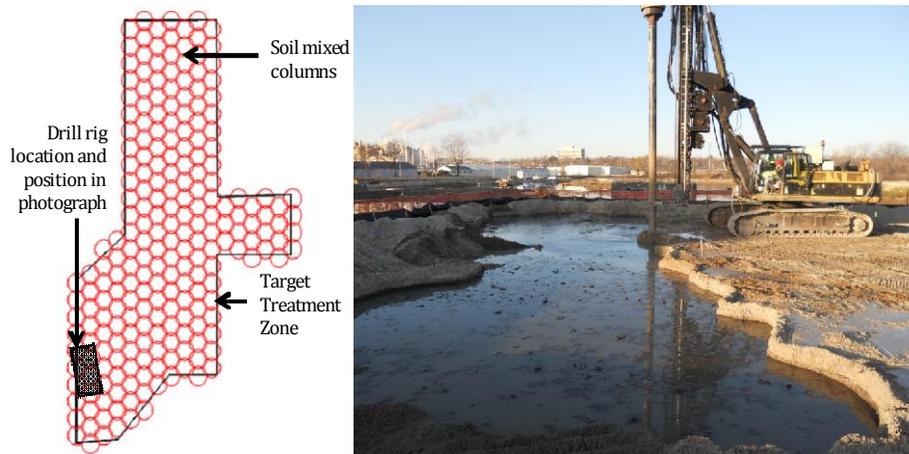


Figure 4. Treatment of TCE Impacted Soils in Illinois

The work was completed over a 7 week timeframe, including mobilization and demobilization.

CONCLUSIONS

Soil mixing has been applied to solve geotechnical problems for over 50 years. The technique was introduced in the United States, developed in Japan and Europe, and finally re-introduced in the US in the late 80s. More recently, soil mixing has seen significant use in the stabilization and treatment of a variety of impacted soil/sediments. The soil mixing remediation approach has become a technically viable and cost effective solution for the treatment or stabilization of numerous contaminants. Stabilization and treatment are similar in many ways, but also vary in a few key categories namely cost, remediation efficacy, and constructability. Selected recent case studies highlight the wide range of applications and contaminants that *in situ* soil mixing is being applied to. Each new application brings new challenges, but through careful quality control and safe work practices there is no end to the breadth of contaminated sites that may be cost effectively remediated using *in situ* soil mixing.

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