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Technology Performance Review: Selecting and Using Solidification/Stabilization Treatment for Site Remediation

National Risk Management Research Laboratory
Office of Research and Development
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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and groundwater; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's Engineering Technical Support Center (ETSC) provides technical support to EPA Headquarters and Regional Office personnel for innovative approaches for site remediation. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

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Sally Gutierrez, Director
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Disclaimer

The document was subjected to the Agency's peer and policy review and was approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Technology Performance Review: Selecting and Using Solidification / Stabilization Treatment for Site Remediation

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Abstract: Solidification/Stabilization (S/S) is a widely used treatment technology to prevent migration and exposure of contaminants from a contaminated media (i.e. soil, sludge and sediment). Solidification refers to a process that binds a contaminated media with a reagent changing its physical properties. Stabilization refers to the process that involves a chemical reaction that reduces the leachability of a waste.

S/S treatment and application is primarily used at hazardous waste sites. This Technology Performance Review (TPR) includes a discussion on several sites, and addresses important factors to consider in the selection of S/S treatment. Each S/S case study has a brief project description, regulatory status, S/S treatment process that includes binder materials used, and a summary of the performance data. Estimated treatment costs and maintenance activities are also included when available. Estimated costs must be adjusted for inflation and current material price increases.

This TPR is not an authoritative or original source of research on S/S treatment and is intended to provide a summary of the S/S process and its potential applicability across multiple sites and conditions. This document should not be used as the sole basis for determining this technology's applicability to a specific site.

Additional Key Words: solidification, stabilization, remediation, remedial technology, S/S

ABBREVIATIONS AND ACRONYMS

ASR	Annual Status Report
BTEX	Benzene, Toluene, Ethylbenzene, Xylenes
cm/s	Centimeters per Second
cy	Cubic Yard
DNAPL	Dense Non-Aqueous Phase Liquid
ETSC	Engineering Technical Support Center
EPRI	Electric Power Research Institute
ROD	EPA Record of Decision
LEED™	Leadership in Energy and Environmental Design
LNAPL	Light Non-Aqueous Phase Liquid
MGP	Manufactured Gas Plant
MCL	Maximum Contaminant Level
µg/L	Micrograms per Liter
mg/kg	Milligrams per Kilogram
NAPL	Non-Aqueous Phase Liquid
NRML	National Risk Management Research Laboratory (U.S. EPA)
NPL	National Priorities List
ORD	Office of Research and Development
PCB(s)	Polychlorinated Biphenyl
PAH(s)	Polycyclic Aromatic Hydrocarbon
PRP	Potential Responsible Party
PCP	Pentachlorophenol
PSI	Pounds per Square Inch
ROD	Record of Decision (CERCLA)
RCRA	Resource Conservation and Recovery Act
RPMs	Remedial Project Managers
S/S	Solidification/Stabilization
STL	Superfund and Technology Liaison
SPLP	Synthetic Precipitation Leaching Procedure
TPR	Technology Performance Review
TCLP	Toxicity Characteristic Leaching Procedure
TSP	Trisodium Phosphate
UCS	Unconfined Compressive Strength
EPA	U.S. Environmental Protection Agency
VOC(s)	Volatile Organic Compound

1.0 Introduction

This Technology Performance Review (TPR) focuses on solidification/stabilization (S/S) treatment and includes its application primarily at CERCLA (Superfund) sites, but also includes a brief discussion of Brownfields, RCRA and other federal facility sites. The scope of this document is to provide basic information about S/S treatment. Use of this technology must follow applicable federal, state and local regulations. The document discusses important factors to consider in the selection of S/S treatment, such as treatability studies and S/S specifications to evaluate performance, type of contaminants to be treated, cost considerations, and long-term permanence. The Treatment Technologies for Site Cleanup: Annual Status Report (ASR), 12th Edition, establishes that S/S is among the most frequently used established (where cost and performance is often available) treatment technologies for on- and off-site remedies. According the ASR, S/S was used in 217 Superfund projects from 1982 to 2005.

Several S/S projects, from EPA and the states, were reviewed as part of this TPR, and most are used as either exhibits or case studies throughout this document. The site-specific case studies illustrate where this technology has been successfully applied and reliability versus where there are limitations. The TPR is intended to provide assistance to decision makers such as Remedial Project Managers (RPMs), remediation practitioners, researchers, and other interested parties in evaluating S/S as a treatment option for their sites.

Each S/S case study in this TPR has a brief project description, regulatory status, S/S treatment process that includes binder materials used, and a summary of the performance data. Estimated treatment costs and maintenance activities are also included when available.

This TPR is not an authoritative or original source of research on S/S treatment. It is intended to briefly describe the S/S process and its potential applicability across multiple sites and conditions. This document cannot be used as the sole basis for determining this technology's applicability to a specific site, because that decision is based on many factors and must be made on a case-by-case basis. Technology expertise must be applied and treatability studies conducted to support a final remedy decision.

2.0 Solidification/Stabilization

S/S is a widely used treatment technology to prevent migration and exposure of contaminants from a contaminated media (i.e. soil, sludge and/or sediments). Solidification refers to a process that binds a contaminated media with a reagent changing its physical properties by increasing the compressive strength, decreasing its permeability and encapsulating the contaminants to form a solid material. Stabilization refers to the process that involves a chemical reaction that reduces the leachability of a waste, so it chemically immobilizes the waste and reduces its solubility; becoming less harmful or less mobile. S/S treatment typically involves mixing a binding agent into the contaminated media or waste. These techniques are done either in-situ, by injecting the binder agent into the contaminated media or ex-situ, by excavating the materials and machine mixing them with the agent.

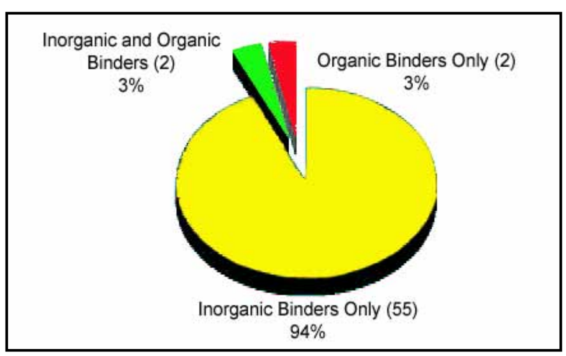

Figure 2-1. Binder Materials Used for Solidification/Stabilization Application

Common types of binder materials used are organic binders that include asphalt, organophilic clay, or activated carbon; and inorganic binders that may include cement, fly ash, lime, phosphate, soluble silicates, or sulfur. Figure 2-1 shows percentage of binder materials used based on input from EPA and State project managers on various S/S applications at Superfund sites in the past. The resulting product from the treatment process is a monolithic block of waste that is either excavated and disposed of in a landfill or re-used on site to support redevelopment.

Another S/S treatment process is vitrification (in-situ or ex-situ). The treatment process uses an electric current, direct-fired kiln, or other heat source to melt soil or other earthen materials at extremely high temperatures (1,600 - 2,000°C or 2,900 - 3,650°F). The treatment process is used to immobilize most inorganics and to destroy organic pollutants by pyrolysis. Inorganic pollutants are incorporated within the vitrified glass and crystalline mass. Water vapors and organic pyrolysis combustion products are captured by an off-gas treatment system for additional processing prior to discharge. Superfund Record of Decision (ROD) data collected from the EPA ASR 12th Edition shows that vitrification has only been selected three times in RODs and construction completed at only one Superfund site as of 2005. The energy requirements and, in cases where ex-situ is used, costs for transportation of materials have precluded use of vitrification as a viable treatment option. Therefore, this document focuses on binder material uses in S/S treatment only.

3.0 Types of Sites and Contaminants Treated By Solidification/Stabilization

There is potential to use S/S under a wide variety of site conditions. Some types of sites at which S/S has been applied or evaluated include: manufacturing gas plants (MGP), wood preserving sites, industrial and municipal landfills, military bases, ammunition plants, waste oil recycling facilities, plating facilities, oil refineries, and battery disposal facilities. Physical and chemical tests must be completed on contaminated material from these sites prior to implementation of S/S treatment. Leaching and extraction tests assist in determining the amount of hazardous contaminants that can leach from the treated waste under a worst-case scenario. Physical tests such as compressive strength can be used to determine absence of free liquids in treated material and also construction properties if treated material is intended for reuse or land disposal. Physical tests of solidified material are also used as indicators of the longevity of the solidification including resistance to freeze/thaw. These tests are described in more detail in Section 4.0.

S/S has been tested and evaluated for its effectiveness in containing and treating a wide array of contaminants, such as metals including lead, arsenic and chromium, and organic contaminants, such as creosote and petroleum products found at sites. For metals, S/S is most often selected for treatment of these contaminants because metals form insoluble compounds when combined with appropriate additives, such as Portland cement. According to the EPA ASR 12th Edition, S/S treatment was selected for source treatment of metals on 180 projects from 1982 to 2005.

In applying S/S for treating organic contaminants, the use of certain materials such as organophilic clay and activated carbon, either as a pretreatment or as additives in cement, can improve contaminant immobilization in the solidified/stabilized wastes. Some organic contaminants have a detrimental effect on the properties of cementitious materials and may not be immobilized by S/S treatment. These organic contaminants should be remediated by some other treatment process, such as thermal or biological processes, prior to performing S/S. Table 3-1 lists S/S treatment effectiveness in treating general contaminant groups.

Table 3-1. Effectiveness of Solidification/Stabilization on General Contaminant Groups for Soil and Sludges

Contaminant Group	Effectiveness
Organic	
Halogenated Volatiles	▲
Non-halogenated Volatiles	▲
Halogenated Semivolatiles	■
Non-halogenated Semivolatiles and Non-volatiles	■
Polychlorinated Biphenyls	■
Pesticides	■
Dioxins/Furans	●
Inorganic	
Non-volatile Metals	■
Radioactive Materials	■

■ = Demonstrated Effectiveness ▲ = No Expected Effectiveness ● = Potential Effectiveness

Superfund S/S Application

S/S is frequently selected as a source control treatment option at EPA Superfund remediation sites. Based on Superfund RODs from FY 1982 through FY 2005, 23 percent of selected source control remedies for these sites included the use of S/S (see Figure 3-1). For S/S, 18 percent of these source control projects were ex-situ treatment with only 5 percent being in-situ treatment. EPA has also identified S/S treatment as Best Demonstrated Available Treatment Technology for at least 50 commonly produced Resource Conservation and Recovery Act (RCRA) hazardous wastes.

Exhibit 3-1 provides an example of a successful S/S remedy at the Peak Oil Superfund Site in Tampa, Florida.

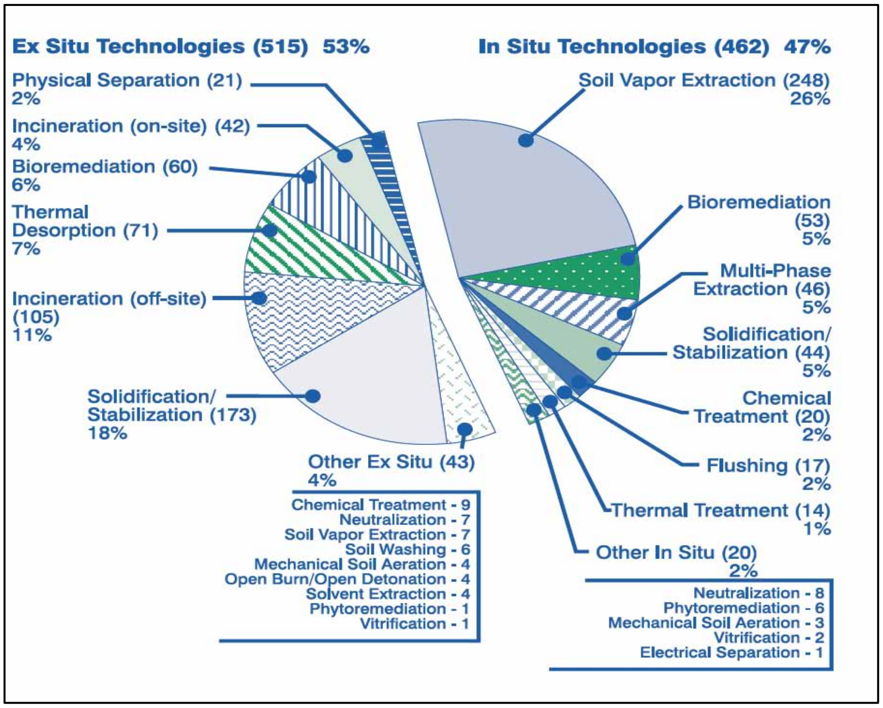

Figure 3-1. Source Control Treatment Technologies (FY 1982-2005)

Exhibit 3-1. Peak Oil Superfund Site in Tampa, Florida

Figure 3-2. Ex-Situ Soil Mixing at the Peak Oil Site

The Peak Oil Superfund site a former waste oil recycling plant site, covered 15.5 acres and soil was contaminated with waste oil products, including polychlorinated biphenyls (PCBs), lead, and bis (2-ethylhexyl) phthalate. As a result of a previous remediation attempt (infrared heat treatment), a stockpile of contaminated ash mixed with soil was also present. The underlying lithology was made up of variable drift and included sand, silt, clay, and peat. This area also had a shallow water table with a low hydraulic gradient to the west.

The treatment method at the site involved excavation of contaminated soil and backfilling the void to a height of 8 to 12 inches above the water table with clean soil. The excavated oil-contaminated soil and ash were blended together and treated with trisodium phosphate (TSP) granules to further immobilize the lead. The material was then screened and fed through a pugmill where it was mixed with the cement binder agent (see Figure 3-2). An estimated 19,300 cy of material was treated.

<u>Brownfields Solidification/Stabilization Application</u>

One of the more optimal applications of S/S remediation is as a containment technology for remediation of contaminated industrial properties. S/S has been implemented at a number of Brownfields sites across the country. The treated material can often be reused on site as part of the redevelopment efforts since S/S treatment can improve the physical characteristics of the material.

Exhibit 3-2 provides an example of a successful Brownfields project that used S/S treatment to remediate contamination at a former MGP site. This project earned the regional Phoenix Award at the EPA-sponsored Brownfields 2006 Conference and also received certification under the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED™) program.

Exhibit 3-2. Kendall Square Redevelopment Project in Cambridge, Massachusetts

Kendall Square is a former MGP site that covered 10-acres in East Cambridge, Massachusetts. Byproducts from the MGP operations led to soil impacted with coal tar and petroleum residues. As a temporary cleanup remedy, a previous owner of the property capped the subsurface contamination with a parking lot, which remained in place for about 30 years. Revitalization of the area surrounding the property made it attractive for redevelopment. The results of an environmental investigation found 4 acres of soil impacted with polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs), from 0 to 20 feet below grade; and a 3-acre non-aqueous phase liquid (NAPL) plume that consisted of: dense non-aqueous phase liquid (DNAPL) present at the groundwater/clay interface about 20 feet below grade and light non-aqueous phase liquid (LNAPL) on the groundwater surface about 10 feet below grade.

Figure 3-3. In-Situ Treatment Using Shallow Soil Mixing Method at Former MGP Site

Excavation and disposal was chosen as the remediation strategy for the parcels of the property outside the NAPL plume. In-situ S/S was selected to treat the NAPL plume and contaminated soil. A mixture of Portland cement, bentonite and water was mixed and injected into the impacted soil, immobilizing free-phase NAPL in the subsurface. In-situ soil mixing was accomplished using a 10-foot, crane-mounted auger system. The mixed soil columns were overlapped by 35 percent, ensuring that all impacted soil was treated (see Figure 3-3). S/S treatment resulted in immobilization of contaminants of concern within a 20-foot thick monolithic, solidified mass with a volume over 100,000 cy.

<u>Other Examples of Solidification/Stabilization Applications</u>

S/S remediation projects have also been conducted by federal agencies, such as the U.S. Department of Defense and U.S. Department of Energy, to manage munitions constituents from unexploded ordnance- and radioactive-impacted sites. For example, S/S was used at the former Fernald Uranium Processing Facility in Cincinnati, Ohio to treat low-level production waste that was stored in two silos on site. About 8,900 cubic yards of material containing radium and thorium radionuclides was removed from the two silos, treated with S/S, and shipped off-site for disposal. S/S treatment involved a cement-rich mix design consisting of 20 percent waste and 80 percent of cement and other supplemental cementitious materials to not only produce a monolithic block of waste but also to shield from radioactivity.

Table 3-2 lists types of sites that S/S has been employed with some level of success in remediating the sites. The table provides only a sample of sites and contaminants.

4.0 Solidification/Stabilization Treatment Evaluation

Specifications for S/S projects generally fall into the physical or chemical categories. Typical S/S specifications are provided in Table 4-1. The commonly specified physical tests in project performance standards include hydraulic conductivity and unconfined compressive strength (UCS).

The most commonly specified chemical test is the Toxicity Characteristic Leaching Procedure (TCLP). The TCLP is applied because it is linked to regulations in the EPA RCRA program. However, there has been discussion about the appropriateness of applying TCLP to S/S treated waste when this treated waste is managed other than in a municipal landfill. The TCLP procedure relies on extracting sample waste with a diluted organic acid, simulating conditions of mixed waste (including organic waste) disposal, such as in a municipal landfill. Many S/S-treated wastes are disposed in monofills or treated in situ and left in place. The TCLP procedure may not be the appropriate simulation of these disposal scenarios. To address this, the Synthetic Precipitation Leaching Procedure (SPLP) may be applied in place of the TCLP. The SPLP is designed to simulate waste exposure to acid rain. Decision makers should consider the final disposal environment of treated waste to determine the appropriate test.

Table 3-2. Selected Solidification/Stabilization Projects

Contaminant(s)	Purpose	Media	Mechanism	S/S Binding Agent(s) and Formula	Site/Name/Location	Point of Contact
PCBs, lead and arsenic	Stabilize contaminated soil in monolith per remedy in the EPA ROD	144,00 cy of soil	Ex- situ treatment and capping the processed monolith	Cement and fly ash	Pepper Steel and Alloys, Inc. Superfund site/Medley, FL	Jan Rogers, U.S EPA (561) 616-8868 rogers.jan@epa.gov
Arsenic, PAHs, and dioxin	To meet industrial risk-based, soil remedial goals specified in the ROD	45,000 cy of soil	Ex- situ treatment then backfilled, compacted, and capped on site	5% Cement, 1.3% powdered carbon, and 4.5% fly ash	American Creosote Works Superfund site/Jackson, TN	Femi Akindele, U.S. EPA (404) 562-8809 akindele.femi@epa.gov
PCBs	Pilot-scale study to evaluate suitability of treating contaminated sediment and reusing treated material for construction purposes	10,000 cy of sediment	Ex-situ treatment after harbor sediment was dredged and dewatered	13% Cement	New Bedford Harbor Superfund site/New Bedford, ME	Dave Dickerson, U.S. EPA (617) 918-1329 dickerson.dave@epa.gov Erik Matthews, USACE (978) 318-8365 erik.w.matthews@usace.army.mil
Lead, PAHs, and PCBs To achieve remedial goals and chemical/physical performance standards specified in the ROD amendment	To achieve remedial goals and chemical/physical performance standards specified in the ROD amendment	40,000 cy of soil and sludge	In-situ treatment with crane auger and soil capped	Agricultural limestone (pretreatment), cement, and fly ash	South 8th Street Landfill Superfund site/West Memphis AR	Vincent Malott, U.S. EPA (214) 665-8313 malott.vincent@epa.gov
PAHs and DNAPL	To create a more cohesive layer less susceptible to erosion and eliminate contaminant exposure to benthic community in river sediment as specified in ROD	2,450 cy of sediment	In-situ treatment using marsh excavator to mix upper 2 feet of sediment with cement-based grout	Cement and proprietary additives	Koppers Co. Ashley River Superfund site/Charleston, South Carolina	Craig Zeller, U.S. EPA (404) 562-8827 zeller.craig@epa.gov
Arsenic and creosote	To meet cleanup standard for reuse of material as sub base and base course for pavement constructed on site	Soil	24,000 cy treated by in-situ mixing of deep soil with in-situ blender/27,000 cy treated ex-situ using pugmill equipment	8% Cement	Former Wood Treating Facility - Brownfields site/Port Newark, New Jersey	Eric Stern, U.S. EPA (212) 637-3806 stern.eric@epa.gov

There are other chemical tests used to assess the leachability of S/S treated waste including the semi-dynamic leaching test, American Nuclear Society (ANS) 16.1, originally developed for nuclear waste but has also been adopted for S/S treated waste.

Table 4-1. Typical Solidification/Stabilization Specifications

Parameter	Units	Average Value [(1)]	Test Method
Unconfined Compressive Strength	Pounds per Square Inch	>50	ASTM D1633
Hydraulic Conductivity	Centimeters per Second	$<1x10^{-6}$	ASTM D5084
Leaching Tests	Milligrams per Liter	Site Specific	TCLP and SPLP
[1] - Usually stated as "the average value of all treated must equal" (usually a 20% allowance is permitted for individual samples.			
TCLP - Toxicity Characteristic Leashing Procedure SPLP - Synthetic Precipitation Leashing Procedure			

The ratio of reagents to unstabilized material to achieve target goals is typically determined by bench-scale treatability studies. While some information regarding implementability is also generated from bench-scale treatability studies, field treatability studies are completed to develop more information relative to the implementability and cost of a S/S technology.

An important component of the S/S procedure is mixing of the unstabilized material and reagents. Reagents can either be added in a dry state, with water subsequently added as necessary, or in a slurried state. The method that is selected may be inherent to a specific treatment method (e.g., in-situ drilling or ex-situ slurry mixing) and can be optimized during the bench-scale phase. In any method, mixing to achieve a homogenous condition is preferred.

A general logic diagram for treatability testing is provided on Figure 4-1. A tiered approach to treatability is often advantageous to evaluate the predetermined target goals. Tier I screening criterion are usually related to physical performance goals, such as permeability or compressive strength. The chemical concentrations in leachates are also considered. Usually the reagent dosages include multiple formulations such that the unstabilized material is under- and over-treated. Tier II, where all target goals are analyzed, further evaluates and refines reagent dosages using larger quantities of the unstabilized materials. Subsequent iterative tiers can then be performed to further evaluate or optimize a selected Tier II reagent mix that meets the treatability study goals.

Subsequent to bench-scale testing, a pilot-scale test may be performed to confirm the bench-scale results and to refine or revise the process as needed. The pilot-scale testing commonly includes the proposed full-scale equipment, or equipment that most closely simulates that proposed process.

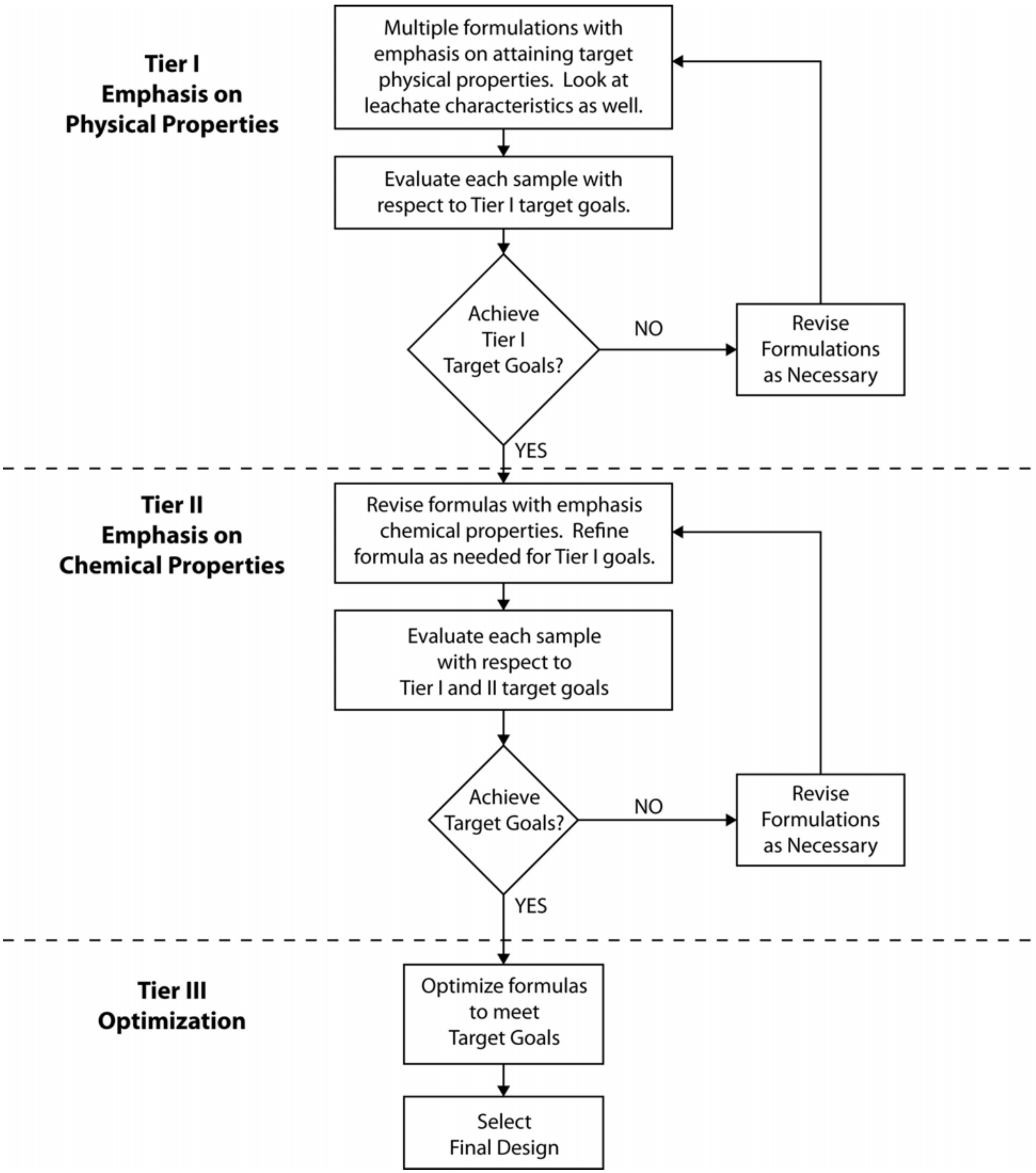

Figure 4-1. Conceptual Model Treatability Study

The sampling approach is also critical to the treatability study to insure representative soil samples of less impacted to highly contaminated areas are collected from the site. This step is necessary so the selected reagent formula will work across the entire S/S treatment area. The soil samples collected for testing:

- Should represent worst case for full-scale treatment
- Should be field screened using soil gas, photoionization detector, metals screening (x-ray fluorescence), and/or PCB/PCP test kits to confirm contaminants present at sample locations
- Should be verified through homogenization by analyses of a minimum of 3 sets of grab samples
- Should be used to research/develop initial formulations

Exhibit 4-1 provides an example of a full-scale cleanup where performance standards were achieved for the South 8th Street Landfill Superfund site in Memphis, Arkansas. A treatability study was completed to develop optimal S/S treatment formula prior to full-scale remediation of the site.

Exhibit 4-1. South 8th Street Landfill Superfund Site in West Memphis, Arkansas

The South 8th Street Landfill was a 16.3 acre site located on the floodplain between the Mississippi River and the St. Francis Levee in West Memphis, Arkansas. The site was first used for waste disposal sometime after 1957. Between 1970 and 1980, a 2.6 acre pit at the site was used for disposal of waste oil sludge from a re-refining process. Between 1981 and 1988, EPA conducted investigations and found the site contaminated with PAHs, PCBs, benzene, toluene, ethyl benzene, and xylene (BTEX), pesticides, and metals. The principal threat was the waste pit, primarily due to the low pH of the wastes which were corrosive and could have caused severe burns.

Figure 4-2. In-Situ Treatment of Sludge Pit Wastes

The ROD specified ex-situ S/S treatment of the waste. Subsequent treatability testing by the PRP group demonstrated that the waste could be treated in-situ and was successful in meeting the following performance standards:

- UCS > 50 pounds per square inch (psi)
- Hydraulic conductivity less 1×10^{-6} centimeters per second (cm/s)
- Leaching of lead < 15 micrograms per liter (µg/L) as determined by SPLP

Augers were used to mix the reagent and sludge (see Figure 4-2). Approximately 40,000 cy of sludge were treated. The treatment formula was as follows:

- 64.5 percent sludge
- 16.1 percent limestone for pretreatment
- 12.9 percent Portland cement
- 6.5 percent fly ash

Average cost was about $106 per cy.

5.0 Cost of Solidification/Stabilization

Costs presented in this section are based on data collected from 1982 to 2005 at National Priorities List (NPL) sites and some of these sites are presented as case studies in this document. S/S costs vary according to site, contaminants, and ex-situ or in-situ treatment. Ex-situ S/S is used to treat excavated soil, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil to be treated. Processing typically would be done on site in a mobile unit. Average costs for small-scale, ex-situ treatment (approximately 1,000 cy) range from $125 to $185 per cy. Large-scale treatment (approximately 50,000 cy) generally cost in the range of $70 to $145 per cy. Table 5-1 provides an example of major bid cost components vs. actual costs for S/S ex-situ treatment of soil at the American Creosote Works Superfund site in Jackson, Tennessee.

Major cost drivers for ex-situ treatment include the following:

- Moisture content
- Contaminant types
- System size

These 3 factors are important in determining costs for S/S treatment. Higher percent moisture content will increase amount of reagent required for treatment. Contaminant concentration and type determine the amount and type of reagents added to the waste to attain the required treatment standards. Excessive addition of reagents can increase volume resulting in higher treatment and disposal costs. Selecting the correct size mobile s/s system to adequately handle throughput of waste volume is also an important cost consideration.

Table 5-1. Major Bid Cost Components vs. Actual Costs for Solidification/Stabilization Treatment at American Creosote Works in Jackson, TN

Item	Cost Per Unit	Total Cost ($)
Mobilization and Reports	--	142,000
Demolition/Debris	--	34,000
NAPL recovery	System	124,000
Cutoff wall	$9 linear foot	20,000
Drainage Trenches	$14.90 cy	75,000
Excavate, Treat and Replace Soil	$44.25 cy	1,996,000
Water Treatment	$0.68 gallon	20,000
Creosote Disposal	$3.05 gallon	47,000
CAP (GCL plus 2 ft. soil)	$50,460 acre	363,000
Site Restoration and Demobilization	--	55,000
Other	--	10,000
Total Bid	**--**	**2,886,000**
Actual Total Paid	**46,700 cy**	**3,200,000**

In-situ treatment typically uses augers or injector head systems to mix reagents with soil to immobilize contaminants. Reagents are applied through nozzles at the bottom of the augers as they turn, mixing and drilling into the soil. Grout injection involves forcing reagent into the soil porosity using high-pressure grout injection pipes forced into the soil. Average costs for auger treatments range from $40 to $60 per cy for shallow applications and $150 to $250 per cy for deeper applications.

Costs for in-situ treatment vary widely according to project size, subsurface soil characteristics, chemical nature of contaminants, and additives or reagents used and their availability. Most reagents and additives are relatively inexpensive industrial commodities and are widely available. However, the method requires large volumes of bulk reagents and additives be transported to the site. The transport costs can increase where local material sources are unavailable.

The volume of reagent required for in-situ or ex-situ treatment can range from 5 to 30 percent per volume of soil treated. The quantity of reagent to be added is determined through the treatability study process conducted on the subject waste or medium. Table 5-2 presents selected results of the American Creosote Works treatability study and cost of reagent per ton of untreated soil to meet target remediation goals.

Table 5-2. Selected Results of the American Creosote Works Treatability Study

Parameter	Units	Untreated	Treated \$39/ton[1]	Treated \$62/ton[1]	Target
PCP					
Total	Milligrams per kilogram (mg/kg)	200	-	-	-
SPLP (pH)	Micrograms per liter (µg/L)	8,200 (7.0)	120 (11.8)	12 (11.8)	200
Dioxins					
Total	Micrograms per kilogram	50	-	-	-
SPLP (pH)	µg/L	320 (7.0)	12 (11.8)	14 (11.8)	30
PAHs					
Total	mg/kg	29	-	-	-
SPLP (pH)	µg/L	2.8 (7.0)	<2.8 (11.8)	<2.8 (11.8)	10
Physical Properties[2]					
UCS	Pounds per Square Inch	-	1,435	1,240	>100
Permeability	Centimeters per Second	-	1.1×10^{-6}	4.1×10^{-7}	$<1.0 \times 10^{-6}$

[1] - Cost of reagent only per ton of untreated soil using different composition.
[2] - 28 day cure time.
SPLP - Synthetic Precipitation Leaching Procedure
UCS - Unconfined Compressive Strength

6.0 Long-Term Permanence

Future use of the site and environmental conditions may erode materials used to stabilize contaminants, which may impact their capacity to immobilize contaminants. Cement-based S/S stabilized wastes, for example, are vulnerable to the same physical and chemical degradation processes as concrete and other cement-based materials. SS-treated material using concrete as part of the reagent mix may differ from conventional concrete. Conventional concrete for use in building material uses properly proportioned gravel, stone and sand selected strictly for their durability and compressive strength properties. In S/S treatment, mix designs are based on the properties of the contaminated media that is being treated so selection of aggregate material is generally not an option. Concrete used in building materials typically have a minimum UCS of 4,000 psi or greater, S/S-treated materials usually have UCS performance standards starting at 50 psi.

Treatability testing cannot simulate all real world conditions to which S/S treated waste may be exposed, and there is limited information currently available regarding the long-term permanence of S/S products' durability. It is important that long-term monitoring be completed to insure that contaminants have not been re-mobilized. Five-year reviews for cases studies presented in this document indicate monitoring groundwater and/or surface water downgradient of S/S treated source area was the selected remedy for long-term monitoring. This is the case with most remediation projects that result in a form of constructed containment (e.g., cap, road bed material, structural, fill, etc.). In these cases, it may be difficult to complete chemical tests (leachate) and physical tests (strength and permeability) without compromising the structural integrity of the remedial construction work. The EPA five-year review reports on NPL sites should be considered as a source for future information on long-term permanence of S/S remedies as more information on monitoring techniques becomes available.

The Electric Power Research Institute (EPRI) recently completed a study on the long-term effectiveness of S/S treatment on soils impacted by former MGP operations at a site in Columbus, Georgia. The EPRI study evaluated the structural integrity and geo-chemical nature of the treated soils 10 years after S/S treatment. The site was redeveloped into a park with a river walk along the Chattahoochee River. The study is discussed in more detail in Section 7.0, Case Studies.

In-situ S/S treatment of impacted soils at the MGP site was completed in June 1993. In 2003, cored samples of the treated soil were evaluated to identify chemical and physical deterioration. Results of the study concluded that after 10 years the S/S treated material solidified mass at the site continues to exceed original performance standards. The results of the 10-year study are summarized below:

- Groundwater has not penetrated the solidified mass
- All samples surpassed geotechnical pre-remediation performance standards
- The liner integrity has remained in place
- Solid phase geochemistry did not show physical or chemical deterioration
- Groundwater monitoring has shown that leaching has not occurred
- Results from Remedial Options Assessment Modeling have shown there is low potential for leaching in future

7.0 Case Studies

This section discusses select case studies that illustrate the testing and application of S/S at various sites.

7.1 American Creosote Works Superfund Site, Jackson, TN

Site Type: Wood Preserving

Scale: Full-scale, ex-situ treatment.

Site Description: The 60-acre American Creosote Works (ACW) site was a wood treatment plant that operated from the early 1930s until late 1981. The plant used coal tar creosote (PAHs) and pentachlorophenol (PCP) to preserve wood. Groundwater underlying the facility, on-site soils, surface water, and sediments were contaminated with VOCs, PAHs, and metals.

Figure 7-1. Ex-Situ Treatment at ACW

Solidification/Stabilization Design: Soil from a 7-acre area of the ACW site (45,000 cy) was excavated for treatment (see Figure 7-1). The soil was mixed by pugmill and the S/S formula was as follows: 89.2 percent waste, 5 percent cement, 4.5 percent fly ash, and 1.3 percent powdered carbon. The treated material was buried on site covered with a geosynthetic clay liner and capped with clean soil.

Performance Data: Industrial risk-based, soil remedial goals specified by the ROD in milligrams per kilogram (ppm) were: arsenic, 225; benzo (a) pyrene, 41.5; dibenzo (a,h) anthracene, 55; PCP, 3,000; and dioxin, 0.00225. The following table summarizes strength, permeability, and leaching analyses and the average results for tested samples:

	Average	**Allowance**	**Method**
Strength (UCS- Pounds per Square Inch)	>100	>80	ASTM D 1633
Permeability (Centimeters per Second)	<1x10-6	<1x10-5	ASTM D 5084
Leaching:	--	--	SW 846
Arsenic (µg/L)	<50	<75	(MTD 1312)
PAHs (µg/L)	<10	<15	(SPLP)
Dibenzo(a,h)anthracene (µg/L)	<4.4	<6.6	-
PCP (µg/L)	<200	<300	-
Dioxins (pg/L)	<30	-	-
µg/L = Micrograms per liter Pg/L = Picograms per liter			

Major Cleanup Milestones: Final Remedy Selected – 9/30/1996; Construction Complete – 5/15/2000.

Regulatory Status: Treatment was conducted from 1999 to 2000. EPA's five-year review from 2004 concluded that the soil remediation conducted at the site was protective of human health for industrial use purposes.

Maintenance Activities: Institutional controls were required at the ACW site prohibiting potable use of area groundwater and excavation where treated soil is buried. Damaged fencing around the site and low spots and bare areas on the treated and capped soil was noted during the 2004 five-year review.

Cost: Cost was $3.2 million for the S/S treatment, which included demolition/debris removal, NAPL recovery, drainage, soil treatment, water treatment, creosote disposal, capping with 2 feet of soil, and site restoration.

Point of Contact: Femi Akindele, EPA RPM - Phone: (404) 562-8809/Email: akindele.femi@epa.gov

7.2 Pepper Steel and Alloys, Inc. Superfund Site, Medley, FL

Site Type: Battery Manufacturing

Scale: Full-scale treatment of 85,000 cubic yards.

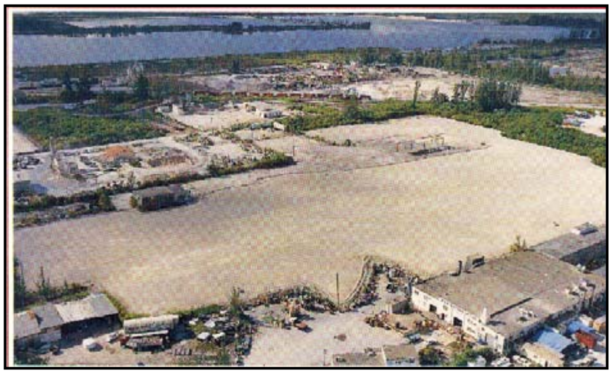

Figure 7-2. Overview of PSA Site

Site Description: The Pepper Steel and Alloys, Inc. (PSA) site consists of three 10-acre tracts. PSA operations were conducted on one of the 10-acre tracts. Operations at the site included manufacture of batteries, pre-cast concrete products and fiberglass boats, and repair of heavy equipment and service trucks. All three tracts are believed to have received waste from PSA. The terrain is naturally flat and underlain by, in ascending order, organic loam and peat, sand, and limestone. Groundwater occurs at about 6 feet bgs.

The site was added to the NPL in 1983 (see Figure 7-2). Subsequent remedial investigations documented soil contaminated with arsenic, lead, and PCBs at concentrations high enough to pose a threat to public heath, welfare, and environment.

Solidification/Stabilization Design: Approximately 85,000 cy of soil were excavated and mixed with cement, fly ash, and water (proportions not provided) and pumped back into the excavation.

Performance Data: Performance criteria were as follows:

- UCS > 20.9 psi
- Hydraulic conductivity < $1x10^{-6}$ (cm/s)
- Leachates below EP Tox criteria

Major Cleanup Milestones: Final Remedy Selected – 3/12/86; Construction Complete – 9/28/93.

Maintenance Activities: The five-year review from 2007 indicated that EPA entered into a Cooperative Agreement with the PRP for O&M activities, including clearing trees from the site, repairing the cover after tree removal, and inspecting the drainage collar for any necessary repairs.

Regulatory Status: Complete. Groundwater quality monitoring is ongoing.

Cost: Not provided.

Point of Contact: Jan Rogers, EPA RPM – Phone: (561) 616-8868/Email: rogers.jan@epa.gov

7.3 Schuylkill Metals Corporation Superfund Site, Plant City, FL

Site Type: Battery Recycling

Scale: Full-scale treatment of 150,000 tons of soil.

Figure 7-3. Schuylkill Metals Wastewater Holding Pond

Site Description: Prior to 1972, the 17.4 acre Schuylkill Metals Corporation (Schuylkill) was primarily marsh. Beginning in 1972, Schuylkill began operations as a battery recycling plant. Schuylkill subsequently filled and developed the site including 2.3 acres of processing area and a 2.2 acre wastewater holding pond (see Figure 7-3). Between 1972 and 1986 Schuylkill recycled more than 20,000 batteries.

The site is underlain by, in descending order, a surficial aquifer system 8 to 20 feet thick, an intermediate depth aquifer system 36 to 55 feet thick, and a deep bedrock aquifer system over 1,000 feet thick.

The Site was added to the NPL in 1982. Remedial investigations and feasibility studies conducted between 1987 and 1990 documented soil and groundwater contaminated with lead, cadmium, chromium, and antimony.

Solidification/Stabilization Design: Ex-situ mixing in proportions as follows:

- Soil 88 percent
- Cement 10 percent
- TSP 2 percent

The treated soils were consolidated in a 5-acre plot on the northern portion of the site.

Performance Data: Performance criteria were as follows:

- UCS > 50 psi
- Hydraulic conductivity < $1x10^{-6}$ cm/s
- Lead in TCLP leachate < 5 milligrams per liter (mg/L)
- Lead in SPLP leachate < 1 mg/L

Major Cleanup Milestones: Final Remedy Selected – 9/28/90; Construction Complete – 9/15/98.

Regulatory Status: Complete.

Cost: Estimated $40 per ton.

Point of Contact: Galo Jackson, EPA RPM – Phone: (404) 562-8937/Email: jackson.galo@epa.gov

7.4 Selma Pressure Treating Superfund Site, Selma, CA

Site Type: Wood Preserving

Scale: Full-scale, ex-situ treatment.

Figure 7-4. Overview of SPT Site

Site Description: The Selma Pressure Treating (SPT) site was a former wood treating facility, located approximately 15 miles south of the City of Fresno, in Selma, California (see Figure 7-4). The SPT site occupied approximately 18 acres, which included a paved area where the former wood treatment and storage facility operated, percolation ponds, a building housing a water treatment facility, and a capped soil impoundment area. The following chemical contaminants were detected in the soil: chromium, arsenic, copper, dioxins/furans, and PCP. Arsenic, dioxins/furans, and PCP were found at concentrations that posed a risk to human health through exposure to soil.

Solidification/Stabilization Design: Silicate Technology Corporation's (STC) S/S process was demonstrated at this site. An initial treatability study determined the amount of STC's proprietary liquid silicate reagent to be used. Contaminated soil was first excavated and pre-screened to separate course material prior to treatment. The course material was sent through a shredder to reduce the grain size to less than 3/8-inch. The screened material was then processed through a batch plant where it was weighed and reagent was added. The material was then mixed and allowed to cure. The treated material was placed in an on-site impoundment and capped.

Performance Data: The following table summarizes ranges of concentrations by TCLP analysis:

Constituent	Ranges of Concentrations by TCLP Analysis (ppm)		Percent Reduction
	Raw Waste	Treated Waste	
Arsenic (TCLP)	1.06-3.33	0.086-0.875	35-92
Copper (TCLP)	1.38-9.43	0.062-0.103	90-99
PCP (total)	2,000-8,300	80-170	91-97

Major Cleanup Milestones: Final Remedy Selected – 9/24/88; Construction Complete – 1/26/05.

Regulatory Status: According to the five-year review completed in 2006, the remedial action objectives set forth in the ROD for soils at the SPT site have been met.

Maintenance Activities: Institutional controls at the SPT site prohibited potable use of area groundwater and digging or excavation where treated soil was buried. The capped areas were reported to be in good condition during the 2006 five-year review.

Cost: $190 to $330 per cy of raw waste.

Point of Contact: Charnjit Bhullar, EPA RPM – Phone: (415) 972-3960/Email: bhullar.charnjit@epa.gov

7.5 Reuse of New York Harbor Sediments - Brownfields, New York Port Authority

Site Type: Shipping Port

Scale: Full-scale, ex-situ treatment.

Figure 7-5. Dredged Sediment Undergoing Treatment in Barge

Site Description: The New York/New Jersey Harbor is a major commercial shipping port and must be dredged to maintain navigability. Due to concerns regarding contamination, federal regulations restrict ocean disposal of sediments dredged from the harbor and land-based disposal options are required. Contamination in the sediment includes metals, dioxins, PAHs, and PCBs.

Solidification/Stabilization Design: During the testing phase, dredged material was transported by barge to a pier (see Figure 7-5), and cement was mixed into the sediment while it remained in the barge. Portland cement was used as the binding reagent. The mixing method used an excavator-mounted mixing head. Sediments were then processed in a stationary pugmill. Portland cement was added at a rate of 8 percent of the wet weight of dredged sediment.

Performance Data: The treated material removed from the barge was used as structural fill at two properties. Both properties were designated for Brownfields redevelopment. Treated sediment was used to cover 20 acres of a municipal landfill and a shopping center was constructed. Over 1.5 million cy covered a former coal gasification and wood preservation facility.

Regulatory Status: Brownfields. No further action has been completed.

Cost: Not provided.

Point of Contact: Eric Stern, EPA Region 2 – Phone: (212) 637-3806/Email: stern.eric@epa.gov

7.6 South 8th Street Landfill Superfund Site, West Memphis, AR

Site Type: Industrial and Municipal Waste Landfill

Scale: Full-scale treatment of 40,000 cy.

Figure 7-6. Performance Sampling at South 8th Street Landfill

Site Description: The 30-acre site was located on the flood plain between the Mississippi River and the St. Francis Levee in West Memphis, Arkansas. Formerly, the site was excavated for gravel deposits resulting in a series of borrow pits. Sometime after 1957 the pits were used for disposal of industrial and municipal wastes. Between 1960 and 1970, a 2.6 acre parcel was used for the disposal of waste-oil-sludge from a nearby re-refining process.

Between 1981 and 1988, EPA conducted borings in and near the waste-oil-sludge pit. Soil was found to be contaminated with PAHs, PCBs, and lead. The site was proposed for listing on the NPL in 1991.

Solidification/Stabilization Design: In-situ mixing with augers in the following proportions:

- Soil 64.5 percent
- AG limestone 16.1 percent
- Portland cement 12.9 percent
- Fly ash 6.5 percent

Performance Data: The following table summarizes the performance criteria per the ROD (see Figure 7-6):

Parameter	Value	Comment
pH	7.0 < pH < 11.5	
UCS	50 psi @ 28 days	Average of all samples
	40 psi @ 28 days	Minimum of any sample
	25 psi @ 3 days	Average of all samples
Hydraulic Conductivity	1×10^{-6} cm/s @ 28 days	Average of all samples
	1 x 10-5 cm/s @ 28 days	Maximum of any sample
Wet/Dry Durability	<30% loss of mass after 12 cycles	

Major Cleanup Milestones: Final Remedy Selected – 7/22/98; Construction Complete – 9/19/00.

Regulatory Status: A five-year review of the site was completed in June 2004. Sampling during the remedial action confirmed that in-situ S/S of the oily sludge pit and ancillary soils achieved the remedial goals and the chemical and physical performance standards as specified in the ROD.

Cost: Estimated $106 per cy.

Point of Contact: Vincent Malott, EPA RPM – Phone: (214) 665-8313/Email: malott.vincent@epa.gov

7.7 Georgia Power Company and Electric Power Research Institute, Columbus, GA

Site Type: Manufactured Gas Plant

Scale: Full-scale, in-situ treatment.

Site Description: The former Columbus MGP was located in the central business district of Columbus, Georgia, adjacent to the Chattahoochee River. The plant was in operation from the 1850s until it was decommissioned in 1931. Soil and groundwater contamination from the plant operations was assessed from 1990 to 1991. Contaminants included PAHs, BTEX, and cyanide.

Figure 7-7. In-Situ Soil Mixing at MGP Site

Solidification/Stabilization Design: The S/S treatment was initiated in February 1992 and completed in June 1993. The soils were solidified by pumping cement slurry thru 2.4-meter diameter hollow-stem augers (see Figure 7-7). A 10 percent mixture of binding agent was used for the majority of the site, and a 25 percent mixture was used adjacent to the Chattahoochee River to act as a barrier wall and to facilitate construction of the river walk and park.

Performance Data: Post-remediation groundwater monitoring began in 1993 and, based on analytical results, was discontinued in 1998. A study was conducted in 2002 and 2003 to evaluate structural integrity of the solidified soils and to evaluate the 10-year effectiveness of S/S with respect to immobilizing the contaminants. The study included collection of drill cores from the site for geotechnical characteristics, geochemistry, and contaminant analysis. Leachability testing and groundwater modeling were also conducted. The study determined that the structural integrity and geochemical nature of the solidified mass continues to exceed the original performance standards established prior to implementation of S/S.

Performance criteria were as follows:

- All samples exceeded the performance criteria established for the site for both the 25 percent cement mixture ($1x10^{-6}$ cm/s) and 10 percent cement mixture ($1x10^{-5}$ cm/s)
- All samples met the performance criteria for UCS of 60 psi
- Leachability study identified naphthalene and acenapthene as most commonly detected compounds. Naphthalene was only constituent that exceeded Federal Maximum Contaminant Levels and State of Georgia Drinking Water Standards

Regulatory Status: An evaluation of remedial alternatives was performed in 1991 and S/S was selected. Prior to implementation, a treatability study, feasibility study, and risk assessment were conducted. Based on these studies, performance criteria were presented to and agreed upon by the Georgia Environmental Protection Division.

Cost: Not provided.

Point of Contact: Andrew Coleman, EPRI Principal Investigator – Phone: (650) 855-2000

8.0 Additional Information

For EPA staff requiring site-specific assistance, consult the U.S. Environmental Protection Agency's (EPA) Office of Research and Development's (ORD) Engineering Technical Support Center (ETSC) at http://www.epa.gov/nrmrl/lrpcd/rr/etsc/index.html or consult your regional Superfund and Technology Liaison (STL) at http://www.epa.gov/OSP/hstl.htm. The Supporting Resources in Section 9.0 of this document presents more detailed information on S/S treatment.

9.0 Supporting Resources

Table 9-1 presents a list of references including Internet sites, documents, and presentations used to prepare this document and a general guide to the subject matter included in each reference.

Table 9-1. References by Topic

References	What is Solidification and Stabilization	Examples of Solidification and Stabilization	Advantages and Considerations in Selecting Solidification and Stabilization	Significance of Treatability Testing
A Citizen's Guide to Solidification/Stabilization. Office of Solid Waste and Emergency Response. EPA 542-F-01-024. December 2001. Website: http://www.epa.gov/tio/download/citizens/s-s.pdf.	■		■	
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Evaluation of the Effectiveness of In-Situ Solidification/Stabilization at the Columbus, Georgia Manufactured Gas Plant Site. Electrical Power Research Institute. September 2003.		■		
Wilk, C. *Principles and Use of Solidification/Stabilization Treatment for Organic Hazardous Constituents in Soil, Sediment, and Waste,* presented at the WM Conference in Tucson, AZ. Portland Cement Association. February 2007. Website: http://www.cement.org/waste/pdfs/Radwaste%20paper.pdf	■	■	■	■
Cement.ca Internet website (particularly for Effectiveness of Cement-Based Applications). 2007.	■	■	■	
Cement.org Internet website (particularly for Solidification/Stabilization Waste Treatment Overview and Case Studies). 2007.	■	■	■	■
http://cfpub.epa.gov/asr Internet website (particularly for Annual Status Report data for Superfund Case Studies). 2007.		■		
http://cfpub.epa.gov/fiveyear Internet website (particularly for 5-yr Reviews on Superfund Case Studies). 2007.		■		