U.S. EPA Contaminated Site Cleanup Information (CLU-IN)

Solidification
Overview

- Overview
- Guidance
- Application
- Training
- Additional Resources
- Technology Focus Home
- Suggest Resource
- Comments

The term "solidification/stabilization" (S/S) refers to a general category of processes used to treat a wide variety of wastes, including solids and liquids. Solidification and stabilization are each distinct technologies.

- Solidification refers to processes that encapsulate a waste to form a solid material and/or coat the waste with low-permeability materials to restrict contaminant migration by decreasing the surface area exposed to leaching. Solidification can be accomplished by mechanical processes or by a chemical reaction between a waste and binding (solidifying) reagents, such as cement, kiln dust, or lime/fly ash (EPA 2000). The desired changes usually include an increase of the compressive strength, a decrease of permeability, and encapsulation of hazardous constituents (Wilk 2007).
- Stabilization refers to processes that involve chemical reactions that reduce the leachability of a waste. Stabilization chemically immobilizes hazardous materials or reduces their solubility through a chemical reaction. This process may or may not change the physical nature of the waste (EPA 2000). The desired changes for stabilization include converting contaminants into a less soluble, mobile, or toxic form (Wilk 2007).

Treatment reagents often both solidify and stabilize the contaminant matrix; hence, this treatment technology is frequently referred to as a solidification/stabilization process. For example, a treatment reagent such as cement can reduce the mobility of many metal contaminants by forming insoluble hydroxides, carbonates, and silicates with them (stabilization) as well as providing a solid encapsulation matrix to reduce leaching (solidification) (Wilk 2007). Also, in some S/S applications, a primarily stabilization reagent such as phosphate or organoclay can be used to enhance the ability of the binder to encapsulate the contaminants.

EPA's 2010 *Superfund Remedy Report* (thirteenth edition) of treatment technologies used at Superfund sites states that, based on project data, ex situ S/S was used in 170 projects and in situ S/S in 41 projects for source control over the period 1982-2004. An additional 33 ex situ and 15 in situ S/S actions were identified in 2005-2008 decision documents. A number of the ex situ S/S actions at National Priorities List (NPL) sites were conducted to stabilize contaminated soil prior to off-site disposal at a RCRA Subtitle D facility.

EPA's 2007 annual status report, *Treatment Technologies for Site Cleanup* (twelfth edition), breaks down the 207 S/S source treatment projects conducted during the period FY 1982-2005 by contaminant class treated: metals were treated in 180 projects, polycyclic aromatic hydrocarbons and other non-halogenated semivolatile organics in 35 projects, organic pesticides in 16 projects, PCBs in 35 projects, and other organic chemicals in 53 projects. Some cleanups addressed multiple contaminant types and the status report does not indicate whether they were primary or secondary targets of the S/S remedy.

Top of Page

Jump to a Subsection

Contaminant Treatment | Mixing Processes | Advantages | Limitations | General Resources | Inorganic Contaminants | Organic Contaminants

Contaminant Treatment

S/S contaminant treatment requires careful consideration of binders and additives. Binders, which generally have both stabilization and solidification capabilities, can be divided into inorganic or organic based materials. The inorganic binders are cementitious with the most common being Portland cement and **pozzolans**. Organic binders can be based on polymer, asphalt, or bitumen materials.

While these binders are often used as stand alone materials their performance can often be improved by using an additive material. For example phosphate, a stabilization agent, can be mixed with a soil or sludge prior to mixing with a cementitious binder to improve the stability of some metal contaminants through the formation of metal phosphate complexes. The low solubility phosphate complexes are then encapsulated when the cementitious binder sets up. Use of organoclays and activated charcoal additives can improve contaminant immobilization of some organic contaminants as they act as stabilization reagents either in a pretreatment step or by direct mixing with the cementitous binder. The organic compounds sorb to the organoclays or activated charcoal and are encapsulated by the binder.

Cementitious S/S treatment can result in monolithic-formed chunks or blocks or in a soil-like matrix. The method is most effective on metals and inorganic contaminants, and less effective with increasing concentrations of organic contaminants. Stabilization of heavy metals is mainly achieved by converting the heavy metals into insoluble precipitates. Without additives, organics usually are sorbed or encapsulated in the matrix pores, with leachability depending on the solubility of the compound in water and its diffusivity through the waste matrix. Generally, **hydrophobic organic compounds** do not react with the inorganic binders and may interfere with the hydration reactions of cement or pozzolanic materials and inhibit the setting of cement (Paria and Yuet 2006).

However, depending upon the specific chemical properties cementitious based materials have been used to treat soils/sludges contaminated with semivolatile organic contaminants (ITRC 2011, EPRI 2009, Barnett et al. 2009). While this process might involve some stabilization through sorption, it is primarily an encapsulation process and its success is dependent upon the concentration of the target contaminants in the soil sludge matrix and their solubility in water.

Table 1 provides a summary of the effectiveness of cementitious S/S techniques (with and without additives) on various contaminant groups.

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

Contaminant Group	Effectiveness
Organic	
Halogenated Volatiles	N
Non-Halogenated Volatiles	N
Halogenated Semivolatiles	D
Non-Halogenated Semivolatiles and Non-Volatiles	D
Polychlorinated Biphenyls	D
Pesticides	D
Dioxins/Furans	P
Inorganic	
Non-Volatile Metals	D
Radioactive Materials	D
D=Demonstrated Effectiveness **N**=No Expected Effectiveness **P**=Potentially Effective	

Source: Barnett et al. 2009
Some metals, such as arsenic(III), chromium(VI), and mercury, are not suitable for cement- and pozzolan-based treatments because they do not form highly insoluble hydroxides (Mulligan et al. 2001 cited in Paria and Yuet 2006), but with pretreatment or additives such as lime, this disadvantage can be overcome.

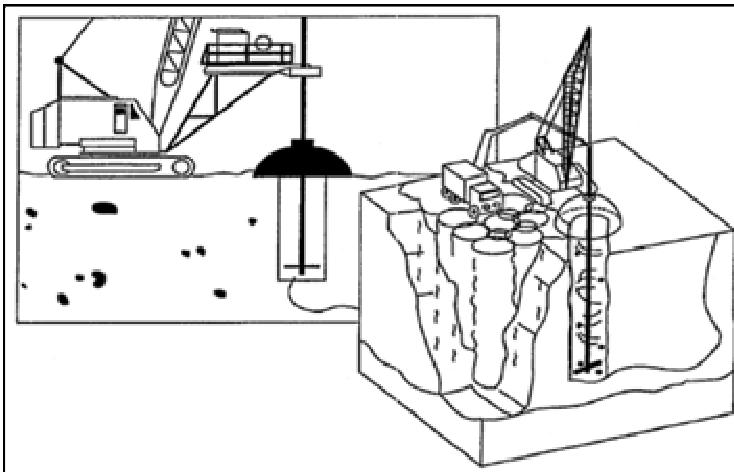
- **Binders**
- **Additives**

Top of Page

Mixing Processes

S/S processes can be implemented either in situ or ex situ.

In Situ. In situ S/S typically involves the addition of binding agents to an area of sludge or soils and addition of water where necessary, followed by repeated in-place mixing with the bucket of a backhoe or similar excavator to mix and stabilize the sludges or soils in place. The excavator also can be equipped with a mixing head. In addition, in situ mixing can be accomplished using large, flighted, rotary augers, 6 to 8 or more feet in diameter, that are capable of injecting slurry chemicals and water through the auger flights. The auger bores and mixes a large-diameter "plug" of the contaminated material. During augering, binders and water (if needed) are injected into the soils. After thorough mixing, the auger is removed, and the setting slurry is left in place. The auger is advanced to overlap the last plug slightly, and the process is repeated until the contaminated area is completed (USACE 2003). Augers generally are used for deep mixing and can be used to treat soils 60 to 100 feet deep (ITRC 2011 EPA 1997). The addition of binders and additives can increase the volume of the treated soils or sludges. The significance of the increase in volume needs to be considered in both shallow and deep mixing.



Deep in situ auger mixing

Shallow in situ mixing with mixing head

Ex Situ. Ex situ S/S field processes involve excavation and staging of the solids, screening to remove materials too large in diameter to be treated effectively (usually 2 inches in diameter or greater), blending the binding agents and water with solids (typically in a pug mill) when appropriate, and stockpiling treated solids for testing prior to shipment off site or placement back in the excavation. Ex situ S/S processing can be accomplished in drums, in a fixed plant, or in a mobile plant. A significant consideration in applying the ex situ technology is the "swell factor" in the solid volume created by the binding agent; this factor depends on the amount of reagents that must be added and can approach 50 percent in some cases. Due to the swell factor, it is possible that the treated material will not fit in the excavation from which it was removed without altering the natural grade (USACE 2003). Al-Tabbaa and Perera (2006) provide a detailed discussion of mixing technologies with accompanying photographs of the equipment.


Ex situ mixing operation

Top of Page

Advantages*

- Many S/S technologies can treat complex mixtures of different wastes.
- S/S can be effective in treating materials contaminated with some types of organic chemicals (e.g. coal tars). Treatment of volatile organics by S/S is problematic and has not found widespread use.
- Most binding agents are relatively inexpensive.
- Some NAPLs have been addressed through S/S treatment.
- The fixed treatment end point can be reached relatively quickly.
- S/S can improve structural properties of soil, waste, and sludge (e.g., strength) to facilitate consideration of land beneficial reuse.
- The technology is applicable to in situ or ex situ treatment.
- Applications include dry or wet conditions, thus reducing dewatering and waste management issues.
- Simple, readily available equipment and materials are used.
- On-site management of contaminated materials conserves landfill space with no transportation off site.
- Most S/S techniques require low levels of skill.
- Depending upon the site, S/S may be more cost effective than excavation and off-site disposal.

*Adapted from AEPI 1998 and ITRC 2011.

Top of Page

Limitations*

- Many S/S techniques do not decrease contaminant toxicity.
- Contaminants are not destroyed or removed; long-term stewardship may be required.
- Volume increases that occur in the treated mass may require management.
- Implementation requires removal of debris or underground obstructions prior to treatment.
- With heterogeneous distribution of contaminants in the subsurface, in situ mixing of waste and binder can result in uneven performance.
- S/S of sensitive areas may inhibit future more comprehensive restoration.
- S/S effectiveness for certain contaminants (e.g., some organic species such as volatile organics, or highly mobile species) may require additional measures in testing and design. Cementitious S/S processes alone are generally not effective in treating volatile organics or some metals (e.g. chromium (VI)) that do not form highly insoluble hydroxides.
- Potential changes in physical setting (e.g., groundwater flow, mounding) may need to be assessed.
- Uncertainties are associated with prediction of long-term behavior.
- Options for treatment or post-treatment modifications are limited by time for field performance testing and changed properties of treated material.

*Adapted from AEPI 1998 and ITRC 2011.

References:

Al-Tabbaa, A. and A.S.R. Perera. 2002. Binders & Technologies, Part I: Basic Principles.

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Paria, S. and P.K. Yuet. 2006. Solidification/stabilization of organic and inorganic contaminants using portland cement: A literature review. Environmental Reviews 14(4):217-255.

Reible, D.D. 2005. McCormick and Baxter Creosoting Company Portland, Oregon: Organoclay Laboratory Study. Oregon DEQ.

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Wilk, C. 2007. Principles and use of solidification/stabilization treatment for organic hazardous constituents in soil, sediment, and waste. Waste Management '07 Conference, 25 February-1 March 2007, Tucson, Arizona.

Top of Page

General Resources

Amending Soils with Phosphate as Means to Mitigate Soil Lead Hazard: A Critical Review of the State of the Science (Abstract)
Scheckel , G.L. Diamond , M.F. Burgess , J.M. Klotzbach , M. Maddaloni , B.W. Miller, C.R. Partridge, and S.M. Serda.
Journal of Toxicology and Environmental Health, Part B: Critical Reviews 16(6):337-380(2013)

Phosphate amendments have been studied as a means to mitigate risks from exposure to Pb in soil by promoting the formation of highly insoluble Pb species, such as pyromorphite. The formation of insoluble Pb species thereby reduces the risk of Pb leaching through soils into drinking waters and absorption by soil biota, and may make it less bioavailable during physiological transport in the human gastrointestinal tract following incidental ingestion. This paper provides a detailed description of phosphate chemistry and the goal of converting Pb into pyromorphite.

Cement Stabilization and Solidification (STSO): Review of Techniques and Methods
Maijala, A., J. Forsman, P. Lahtinen, M. Leppaenen, A. Helland, A.-O.H. Roger, and M. Konieczny.
Ramboll Norge AS, Oslo, Norway. Rap001-Id01, 57 pp, 2009

This review presents different types of STSO (i.e., S/S) techniques, mixing methods, and usages. The main techniques are column stabilization, mass stabilization, and layer stabilization. The different techniques serve different purposes, e.g., improving the strength of subsoil and/or preventing leaching of contaminants from soil. Different purposes require different stabilizers or mixtures of stabilizers and mixing technology.

Development of Performance Specifications for Solidification/Stabilization
ITRC, 162 pp, 2011

This document specifically focuses on processes and approaches for the treatment of contaminated materials on site, mixed with inorganic cementitious/pozzolanic reagents (the most common application of S/S) and cured in place to create a solid mass with a reduced potential for leaching and typically a lowered hydraulic conductivity. Therefore, the technology as discussed in this document is based on on-site, in situ S/S applications.

Regional Report: European Practice of Soil Mixing Technology
Massarsch, K.R. and M. Topolnicki.
International Conference on Deep Mixing: Best Practice and Recent Advances, 23-25 May 2005, Stockholm, Sweden. Report 13, Vol 1:3-10(2005)

The evolution and recent developments of deep and shallow soil mixing methods are presented, covering dry and wet mixing methods.

Review of Scientific Literature on the Use of Stabilisation/Solidification for the Treatment of Contaminated Soil, Solid Waste, and Sludges
Bone, B.D., L.H. Barnard, D.I. Boardman, P.J. Carey, C.D. Hills, H.M. Jones, C.L. MacLeod, and M. Tyrer.
Environment Agency, UK, Science Report SC980003/SR2, 343 pp, 2004

This is a companion document and reference resource to "Guidance on the Use of Stabilisation/Solidification for the Treatment of Contaminated Soil" (Environment Agency 2004).

Solidification/Stabilization of Organic and Inorganic Contaminants Using Portland Cement: A Literature Review
Paria, S. and P.K. Yuet.
Environmental Reviews 14(4):217-255(2006)

This survey focuses on (1) cement chemistry, (2) the effects of inorganic (heavy metals) and organic compounds on cement hydration, and (3) the mechanisms of immobilization of different organic and inorganic compounds. For heavy metals, cement-based S/S technology has been shown to be effective in immobilizing the contaminants, even without any additives. In applying cement-based S/S for treating organic contaminants, the use of adsorbents such as organophilic clay and activated carbon, either as a pretreatment or as additives in the cement mix, can improve contaminant immobilization in the solidified/stabilized wastes.

Stabilization and Solidification of Hazardous, Radioactive, and Mixed Wastes
Spence, R.D. and C. Shi.
Lewis Publishers/CRC Press, Boca Raton, FL. ISBN: 1566704448, 392 pp, 2004

This book provides comprehensive information on waste characterization, waste form design approaches, contaminant transport and leachability, testing methods for stabilized waste forms, case studies, and regulatory considerations. It covers all systems used for stabilization and solidification of wastes, discusses the interactions between contaminants and stabilizing components, and provides guidelines for the selection of bonding materials for stabilization. It also demonstrates how to design a stabilized waste form, covers test methods and protocols for treating wastes and evaluating treatment technology, and includes a section on statistical techniques for generating response surface models for large, complicated applications.

State of Practice Reports, UK Stabilisation/Solidification Treatment and Remediation

STARNET is a network program funded by the UK's Engineering and Physical Sciences Research Council. STARNET sponsored seven S/S state-of-practice reports published between 2002 and 2005. The reports identify knowledge gaps and future research needs in the practice of stabilizing and solidifying hazardous materials. The STARNET site also hosts the presentations from the International Conference on Stabilisation/Solidification Treatment and Remediation, held April 12-13, 2005, at Cambridge University, UK.

STARNET Reports

Technology Performance Review: Selecting and Using Solidification/Stabilization Treatment for Site Remediation
Barnett, F., S. Lynn, and D. Reisman.
EPA 600-R-09-148, 28 pp, 2009

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.

Treatability Study Report for In Situ Lead Immobilization Using Phosphate-Based Binders
Bricka, R.M., A. Marwaha, and G. Fabian.
ATC-9137195, ESTCP Project ER-0111, 195 pp, 2008

Phosphate-based binders marketed by four vendors were evaluated at Camp Withycombe, OR, for immobilization performance of Pb in small arms firing range soil. Variability in Pb stability was observed in all four soil treatments.

Top of Page

Inorganic Contaminants

- **General**
- **Arsenic**
- **Chromium**
- **Lead**
- **Mercury**
- **Research**
- **Sediment**

Top of Page

Organic Contaminants

- **General**
- **Manufactured Gas Plants**
- **Research**

Top of Page