United States Environmental Protection Agency | Office of Emergency and Remedial Response Washington, DC 20460 | Office of Research and Development Cincinnati, OH 45268

Superfund | EPA/540/S-92/015 | May 1993

EPA

Engineering Bulletin
Solidification/Stabilization of Organics and Inorganics

Purpose

Section 121(b) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) mandates the Environmental Protection Agency (EPA) to select remedies that "utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable" and to prefer remedial actions in which treatment "permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances, pollutants, and contaminants as a principal element." The Engineering Bulletins are a series of documents that summarize the most current information available on selected treatment and site remediation technologies and related issues. They provide summaries of and references for this information to help remedial project managers, on-scene coordinators, contractors, and other site cleanup managers understand the type of data and site characteristics needed to evaluate a technology for potential applicability to their Superfund or other hazardous waste site. Those documents that describe individual treatment technologies focus on remedial investigation scoping needs. Addenda are issued periodically to update the original bulletins.

Abstract

Solidification refers to techniques that encapsulate hazardous waste into a solid material of high structural integrity. Encapsulation involves either fine waste particles (microencapsulation) or a large block or container of wastes (macroencapsulation) [1, p. 2]*. Stabilization refers to techniques that treat hazardous waste by converting it into a less soluble, mobile, or toxic form. Solidification/Stabilization (S/S) processes, as referred to in this document, utilize one or both of these techniques.

S/S technologies can immobilize many heavy metals, certain radionuclides, and selected organic compounds while decreasing waste surface area and permeability for many types of sludge, contaminated soils, and solid wastes. Common S/S agents include: Type 1 Portland cement or cement kiln dust; lime, quicklime, or limestone; fly ash; various mixtures of these materials; and various organic binders (e.g., asphalt). The mixing of the waste and the S/S agents can occur outside of the ground (ex situ) in continuous feed or batch operations or in the ground (in situ) in a continuous feed operation. The final product can be a continuous solid mass of any size or of a granular consistency resembling soil. During in situ operations, S/S agents are injected into and mixed with the waste and soil up to depths of 30 to 100 feet using augers.

Treatability studies are the only means of documenting the applicability and performance of a particular S/S system. Determination of the best treatment alternative will be based on multiple site-specific factors and the cost and efficacy of the treatment technology. The EPA contact identified at the end of this bulletin can assist in the location of other contacts and sources of information necessary for such treatability studies.

It may be difficult to evaluate the long-term (>5 year) performance of the technology. Therefore, long-term monitoring may be needed to ensure that the technology continues to function within its design criteria.

This bulletin provides information on technology applicability, the limitations of the technology, the technology description, the types of residuals produced, site requirements, the process performance data, the status of the technology, and sources for further information.

Technology Applicability

The U.S. EPA has established treatment standards under the Resource Conservation and Recovery Act (RCRA), Land Disposal Restrictions (LDRs) based on Best Demonstrated Available Technology (BDAT) rather than on risk-based or health-based standards. There are three types of LDR treatment standards based on the following: achieving a specified concentration level, using a specified technology prior to disposal, and "no land disposal." Achieving a specified concentration level is the most common type of treatment standard. When a concentration level to be achieved is specified for a waste, any technology that can meet the standard may be used unless that technology is otherwise prohibited [2].

The Superfund policy on use of immobilization is as follows: "Immobilization is generally appropriate as a treatment alternative only for material containing inorganics, semi-volatile and/or non-volatile organics. Based on present information, the Agency does not believe that immobilization is an appropriate treatment alternative for volatile organic compounds (VOCs). Selection of immobilization of semi-volatile compounds (SVOCs) and non-volatile organics generally requires the performance of

*[reference number, page number]

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a site-specific treatability study or non-site-specific treatability study data generated on waste which is very similar (in terms of type of contaminant, concentration, and waste matrix) to that to be treated and that demonstrates, through Total Waste Analysis (TWA), a significant reduction (e.g., a 90 to 99 percent reduction) in the concentration of chemical constituents of concern. The 90 to 99 percent reduction in contaminant concentration is a general guidance and may be varied within a reasonable range considering the effectiveness of the technology and the cleanup goals for the site. Although this policy represents EPA's strong belief that TWA should be used to demonstrate effectiveness of immobilization for organics, other leachability tests may also be appropriate in addition to TWA to evaluate the protectiveness under a specific management scenario. "To measure the effectiveness on inorganics, the EPA's Toxicity Characteristic Leaching Procedure (TCLP) should be used in conjunction with other tests such as TCLP using distilled water or American Nuclear Society (ANS) 16.1 [3, p. 2].

Factors considered most important in the selection of a technology are design, implementation, and performance of S/S processes and products, including the waste characteristics (chemical and physical), processing requirements, S/S product management objectives, regulatory requirements, and economics. These and other site-specific factors (e.g., location, condition, climate, hydrology, etc.) must be taken into account in determining whether, how, where, and to what extent a particular S/S method should be used at a particular site [4, p. 7.92]. Pozzolanic S/S processes can be formulated to set under water if necessary; however, this may require different proportions of fixing and binding agents to achieve the desired immobilization and is not generally recommended [5, p. 21]. Where non-pumpable sludge or solid wastes are encountered, the site must be able to support the heavy equipment required for excavation or in situ injection and mixing. At some waste disposal sites, this may require site engineering.

A wide range of performance tests may be performed in conjunction with S/S treatability studies to evaluate short- and long-term stability of the treated material. These include total waste analysis for organics, leachability using various methods, permeability, unconfined compressive strength (UCS), treated waste and/or leachate toxicity endpoints, and freeze/thaw and wet/dry weathering cycle tests performed according to specific procedures [6, p. 4.2] [7, p. 4.1]. Treatability studies should be conducted on replicate samples from a representative set of waste batches that span the expected range of physical and chemical properties to be encountered at the site [8, p. 1].

The most common fixing and binding agents for S/S are cement, lime, natural pozzolans, and fly ash, and mixtures of these [4, p. 7.86] [6, p. 2.1]. They have been demonstrated to immobilize many heavy metals and to solidify a wide variety of wastes including spent pickle liquor, contaminated soils, incinerator ash, wastewater treatment filter cake, and waste sludge [7, p. 3.1] [9]. S/S is also effective in immobilizing many radionuclides [10]. In general, S/S is considered an established full-scale technology for nonvolatile heavy metals although the long-term performance of S/S in Superfund applications has yet to be demonstrated [2].

Traditional cement and pozzolanic materials have yet to be shown to be consistently effective in full-scale applications treating wastes high in oil and grease, surfactants, or chelating agents without some form of pretreatment [11] [12, p. 122]. Pretreatment methods include pH adjustment, steam or thermal stripping, solvent extraction, chemical or photochemical reaction, and biodegradation. The addition of sorbents such as modified clay or powdered activated carbon may improve cement-based or pozzolanic process performance [6, p. 2.3].

Regulations promulgated pursuant to the Toxic Substances Control Act (TSCA) do not recognize S/S as an approved treatment for wastes containing polychlorinated biphenyls (PCBs) above 50 ppm. It is EPA policy that soils containing greater than 10 ppm in public/residential areas and 25 ppm in limited access/occupational areas be removed for TSCA-approved treatment/disposal. However, the policy also provides EPA regional offices with the option of requiring more restrictive levels. For example, Region 5 requires a cleanup level of 2 ppm. The proper disposition of high volume sludges, soils, and sediments is not specified in the TSCA regulations, but precedents set in the development of various records of decision (RODs) indicate that stabilization may be approved where PCBs are effectively immobilized and/or destroyed to TSCA-equivalent levels. Some degree of immobilization of PCBs and related polychlorinated polycyclic compounds appears to occur in cement or pozzolans [15, p. 1573]. Some field observations suggest polychlorinated polycyclic organic substances such as PCBs undergo significant levels of dechlorination under the alkaline conditions encountered in pozzolanic processes. Recent tests by the EPA, however, have not confirmed these results although significant desorption and volatilization of the PCBs were documented [13, p. 41] [14, p. 3].

Table 1 summarizes the effectiveness of S/S on general contaminant groups for soils and sludges. Table 1 was prepared based on current available information or on professional judgment when no information was available. In interpreting this table, the reader is cautioned that for some primary constituents, a particular S/S technology performs adequately in some concentration ranges but inadequately in others. For example, copper, lead, and zinc are readily stabilized by cementitious materials at low to moderate concentrations, but interfere with those processes at higher concentrations [12, p. 43]. In general, S/S methods tend to be most effective for immobilizing nonvolatile heavy metals.

The proven effectiveness of the technology for a particular site or waste does not ensure that it will be effective at all sites or that treatment efficiencies achieved will be acceptable at other sites. For the ratings used in Table 1, demonstrated effectiveness means that at some scale, treatability tests showed that the technology was effective for that particular contaminant and matrix. The ratings of "Potential Effectiveness" and "No Expected Effectiveness" are both based upon expert judgment. When potential effectiveness is indicated, the technology is believed capable of successfully treating the contaminant group in a particular matrix. When the technology is not applicable or will probably not work for a particular combination of contaminant group and matrix, a no expected effectiveness rating is given.

Table 1
Effectiveness of S/S on General Contaminant Groups for Soil and Sludges

	Contaminant Groups	Effectiveness Soil/Sludge
Organic	Halogenated volatiles	❑
	Nonhalogenated volatiles	❑
	Halogenated semivolatiles	■
	Nonhalogenated semivolatiles and nonvolatiles	■
	PCBs	▼
	Pesticides	▼
	Dioxins/Furans	▼
	Organic cyanides	▼
	Organic corrosives	▼
Inorganic	Volatile metals	■
	Nonvolatile metals	■
	Asbestos	■
	Radioactive materials	■
	Inorganic corrosives	■
	Inorganic cyanides	■
Reactive	Oxidizers	■
	Reducers	■

KEY:
- ■ Demonstrated Effectiveness: Successful treatability test at some scale completed.
- ▼ Potential Effectiveness: Expert opinion that technology will work.
- ❑ No Expected Effectiveness: Expert opinion that technology will/does not work.

Another source of general observations and average removal efficiencies for different treatability groups is contained in the Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions," (OSWER Directive 9347.3-06FS, September 1990) [16] and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions," (OSWER Directive 9347.3-06BFS, September 1990) [17]. Performance data presented in this bulletin should not be considered directly applicable to other Superfund sites. A number of variables such as the specific mix and distribution of contaminants affect system performance. A thorough characterization of the site and a well-designed and conducted treatability study are highly recommended.

Other sources of information include the U.S. EPA's Risk Reduction Engineering Laboratory Treatability Database (accessible via ATTIC) and the U.S. EPA Center Hill Database (contact Patricia Erickson).

Technology Limitations

Tables 2 and 3 summarize factors that may interfere with stabilization and solidification processes respectively.

Physical mechanisms that can interfere with the S/S process include incomplete mixing due to the presence of high moisture or organic chemical content resulting in only partial wetting or coating of the waste particles with the stabilizing and binding agents and the aggregation of untreated waste into lumps [6]. Wastes with a high clay content may clump, interfering with the uniform mixing with the S/S agents, or the clay surface may adsorb key reactants, interrupting the polymerization chemistry of the S/S agents. Wastes with a high hydrophilic organic content may interfere with solidification by disrupting the gel structure of the curing cement or pozzolanic mixture [11, p. 18] [18]. The potential for undermixing is greatest for dry or pasty wastes and least for freely flowing slurries [11, p. 13]. All in situ systems must provide for the introduction and mixing of the S/S agents with the waste in the proper proportions in the surface or subsurface waste site environment. Quality control is inherently more difficult with in situ products than with ex situ products [4, p. 7.95].

Chemical mechanisms that can interfere with S/S of cement-based systems include chemical adsorption, complexation, precipitation, and nucleation [1, p. 82]. Known inorganic chemical interferants in cement-based S/S processes include copper, lead, and zinc, and the sodium salts of arsenate, borate, phosphate, iodate, and sulfide [6, p. 2.13] [12, p. 11]. Sulfate interference can be mitigated by using a cement material with a low tricalcium aluminate content (e.g., Type V Portland cement) [6, p. 2.13]. Problematic organic interferants include oil and grease, phenols [8, p. 19], surfactants, chelating agents [11, p. 22], and ethylene glycol [18]. For thermoplastic micro- and macro-encapsulation, stabilization of a waste containing strong oxidizing agents reactive toward rubber or asphalt must also be avoided [19, p. 10.114]. Pretreating the wastes to chemically or biochemically react or to thermally or chemically extract potential interferants should minimize these problems, but the cost advantage of S/S may be lost, depending on the characteristics and volume of the waste and the type and degree of pretreatment required. Organic polymer additives in various stages of development and field testing may significantly improve the performance of the cementitious and pozzolanic S/S agents with respect to immobilization of organic substances, even without the addition of sorbents.

Volume increases associated with the addition of S/S agents to the waste may prevent returning the waste to the landform from which it was excavated where landfill volume is limited. Where post-closure earthmoving and landscaping are required, the treated waste must be able to support the weight of heavy equipment. The EPA recommends a minimum compressive strength of 50 to 200 psi [7, p. 4.13]; however, this should be a site-specific determination.

Environmental conditions must be considered in determining whether and when to implement an S/S technology. Extremes of heat, cold, and precipitation can adversely affect S/S applications. For example, the viscosity of one or more of the

Table 2.
Summary of Factors that May Interfere with Stabilization Processes *

Characteristics Affecting Processing Feasibility	*Potential Interference*
VOCs	Volatiles not effectively immobilized; driven off by heat of reaction. Sludges and soils containing volatile organics can be treated using a heated extruder evaporator or other means to evaporate free water and VOCs prior to mixing with stabilizing agents.
Use of acidic sorbent with metal hydroxide wastes	Solubilizes metal.
Use of acidic sorbent with cyanide wastes	Releases hydrogen cyanide.
Use of acidic sorbent with waste containing ammonium compounds	Releases ammonia gas.
Use of acidic sorbent with sulfide wastes	Releases hydrogen sulfide.
Use of alkaline sorbent (containing carbonates such as calcite or dolomite) with acid waste	May create pyrophoric waste.
Use of siliceous sorbent (soil, fly ash) with hydrofluoric acid waste	May produce soluble fluorosilicates.
Presence of anions in acidic solutions that form soluble calcium salts (e.g., calcium chloride acetate, and bicarbonate)	Cation exchange reactions - leach calcium from S/S product increases permeability of concrete, increases rate of exchange reactions.
Presence of halides	Easily leached from cement and lime.

* Adapted from reference 2

Table 3.
Summary of Factors that May Interfere with Solidification Processes *

Characteristics Affecting Processing Feasibility	*Potential Interference*
Organic compounds	Organics may interfere with bonding of waste materials with inorganic binders.
Semivolatile organics or poly-aromatic hydrocarbons (PAHs)	Organics may interfere with bonding of waste materials.
Oil and grease	Weaken bonds between waste particles and cement by coating the particles. Decrease in unconfined compressive strength with increased concentrations of oil and grease.
Fine particle size	Insoluble material passing through a No. 200 mesh sieve can delay setting and curing. Small particles can also coat larger particles, weakening bonds between particles and cement or other reagents. Particle size >1/4 inch in diameter not suitable.
Halides	May retard setting, easily leached for cement and pozzolan S/S. May dehydrate thermoplastic solidification.
Soluble salts of manganese, tin, zinc, copper, and lead	Reduced physical strength of final product caused by large variations in setting time and reduced dimensional stability of the cured matrix, thereby increasing leachability potential.
Cyanides	Cyanides interfere with bonding of waste materials.
Sodium arsenate, borates, phosphates, iodates, sulfides, and carbohydrates	Retard setting and curing and weaken strength of final product.
Sulfates	Retard setting and cause swelling and spalling in cement S/S. With thermoplastic solidification may dehydrate and rehydrate, causing splitting.

* Adapted from reference 2

Table 3
Summary of Factors that May Interfere with Solidification Processes * (continued)

Characteristics Affecting Processing Feasibility	*Potential Interference*
Phenols	Marked decreases in compressive strength for high phenol levels.
Presence of coal or lignite	Coals and lignites can cause problems with setting, curing, and strength of the end product.
Sodium borate, calcium sulfate, potassium dichromate, and carbohydrates	Interferes with pozzolanic reactions that depend on formation of calcium silicate and aluminate hydrates.
Nonpolar organics (oil, grease, aromatic hydrocarbons, PCBs)	May impede setting of cement, pozzolan, or organic-polymer S/S. May decrease long-term durability and allow escape of volatiles during mixing. With thermoplastic S/S, organics may vaporize from heat.
Polar organics (alcohols, phenols, organic acids, glycols)	With cement or pozzolan S/S, high concentrations of phenol may retard setting and may decrease short-term durability; all may decrease long-term durability. With thermoplastic S/S, organics may vaporize. Alcohols may retard setting of pozzolans.
Solid organics (plastics, tars, resins)	Ineffective with urea formaldehyde polymers; may retard setting of other polymers.
Oxidizers (sodium hypochlorite, potassium permanganate, nitric acid, or potassium dichromate)	May cause matrix breakdown or fire with thermoplastic or organic polymer S/S.
Metals (lead, chromium, cadmium, arsenic, mercury)	May increase setting time of cements if concentration is high.
Nitrates, cyanides	Increase setting time, decrease durability for cement-based S/S.
Soluble salts of magnesium, tin, zinc, copper and lead	May cause swelling and cracking within inorganic matrix exposing more surface area to leaching.
Environmental/waste conditions that lower the pH of matrix	Eventual matrix deterioration.
Flocculants (e.g., ferric chloride)	Interference with setting of cements and pozzolans.
Soluble sulfates >0.01% in soil or 150 mg/L in water	Endangerment of cement products due to sulfur attack.
Soluble sulfates >0.5% in soil or 2000 mg/L in water	Serious effects on cement products from sulfur attacks.
Oil, grease, lead, copper, zinc, and phenol	Deleterious to strength and durability of cement, lime/fly ash, fly ash/cement binders.
Aliphatic and aromatic hydrocarbons	Increase set time for cement.
Chlorinated organics	May increase set time and decrease durability of cement if concentration is high.
Metal salts and complexes	Increase set time and decrease durability for cement or clay/cement.
Inorganic acids	Decrease durability for cement (Portland Type I) or clay/cement.
Inorganic bases	Decrease durability for clay/cement; KOH and NaOH decrease durability for Portland cement Type III and IV.

* Adapted from reference 2

materials in the mixture may increase rapidly with falling temperatures or the cure rate may be slowed unacceptably [20, p. 27]. In cement-based S/S processes the engineering properties of the concrete mass produced for the treatment of the waste are highly dependent on the water/cement ratio and the degree of hydration of the cement. High water/cement ratios yield large pore sizes and thus higher permeabilities [21, p. 177]. This factor may not be readily controlled in environmental applications of S/S and pretreatment (e.g., drying) of the waste may be required.

Depending on the waste and binding agents involved, S/S processes can produce hot gases, including vapors that are potentially toxic, irritating, or noxious to workers or communities downwind from the processes [22, p. 4]. Laboratory tests demonstrate that as much as 90 percent of VOCs are volatilized during solidification and as much as 60 percent of the remaining VOCs are lost in the next 30 days of curing [23, p. 6]. In addition, if volatile substances with low flash points are involved, the potential exists for fire and explosions where the fuel-to-air ratio is favorable [22, p. 4]. Where volatization problems are anticipated, many S/S systems now provide for vapor collection and treatment. Under dry and/or windy environmental conditions, both ex situ and in situ S/S processes are likely to generate fugitive dust with potentially harmful impacts on occupational and public health, especially for downwind communities.

Scaleup for S/S processes from bench-scale to full-scale operation involves inherent uncertainties. Variables such as ingredient flow-rate control, materials mass balance, mixing, and materials handling and storage, along with the weather compared to the more controlled environment of a laboratory, all may affect the success of a field operation. These potential engineering difficulties emphasize the need for a field demonstration prior to full-scale implementation [2].

Technology Description

Waste stabilization involves the addition of a binder to a waste to immobilize waste contaminants effectively. Waste solidification involves the addition of a binding agent to the waste to form a solid material. Solidifying waste improves its material handling characteristics and reduces permeability to leaching agents such as water, brine, and inorganic and organic acids by reducing waste porosity and exposed surface area. Solidification also increases the load-bearing capacity of the treated waste, an advantage when heavy equipment is involved. Because of their dilution effect, the addition of binders must be accounted for when determining reductions in concentrations of hazardous constituents in S/S treated waste.

S/S processes are often divided into the following broad categories: inorganic processes (cement and pozzolanic) and organic processes (thermoplastic and thermosetting). Generic S/S processes involve materials that are well known and readily available. Commercial vendors have typically developed generic processes into proprietary processes by adding special additives to provide better control of the S/S process or to enhance specific chemical or physical properties of the treated waste. Less frequently, S/S processes combine organic binders with inorganic binders (e.g., diatomaceous earth and cement with polystyrene, polyurethane with cement, and polymer gels with silicate and lime cement) [2].

The waste can be mixed in a batch or continuous system with the binding agents after removal (ex situ) or in place (in-situ). In ex situ applications, the resultant slurry can be 1) poured into containers (e.g., 55-gallon drums) or molds for curing and then off- or onsite disposal, 2) disposed in onsite waste management cells or trenches, 3) injected into the subsurface environment, or 4) re-used as construction material with the appropriate regulatory approvals. In in situ applications, the S/S agents are injected into the subsurface environment in the proper proportions and mixed with the waste using backhoes for surface mixing or augers for deep mixing [5]. Liquid waste may be pretreated to separate solids from liquids. Solid wastes may also require pretreatment in the form of pH adjustment, steam or thermal stripping, solvent extraction, chemical reaction, or biodegradation to remove excessive VOCs and SVOCs that may react with the S/S process. The type and proportions of binding agents are adjusted to the specific properties of the waste to achieve the desired physical and chemical characteristics of the waste appropriate to the conditions at the site based on bench-scale tests. Although ratios of waste-to-binding agents are typically in the range of 10:1 to 2:1, ratios as low as 1:4 have been reported. However, projects utilizing low waste-to-binder ratios have high costs and large volume expansion.

Figures 1 and 2 depict generic elements of typical ex situ and in situ S/S processes, respectively. Ex situ processing involves: (1) excavation to remove the contaminated waste from the subsurface; (2) classification to remove oversize debris; (3) mixing; and (4) off-gas treatment. In situ processing has only two steps: (1) mixing; and (2) off-gas treatment. Both processes require a system for delivering water, waste, and S/S agents in proper proportions and a mixing device (e.g., rotary drum paddle or auger). Ex situ processing requires a system for delivering the treated waste to molds, surface trenches, or subsurface injection. The need for off-gas treatment using vapor collection and treatment modules is specific to the S/S project.

Process Residuals

Under normal operating conditions neither ex situ nor in situ S/S technologies generate significant quantities of contaminated liquid or solid waste. Certain S/S projects require treatment of the offgas. Prescreening collects debris and materials too large for subsequent treatment.

If the treated waste meets the specified cleanup levels, it could be considered for reuse onsite as backfill or construction material. In some instances, treated waste may have to be disposed of in an approved landfill. Hazardous residuals from some pretreatment technologies must be disposed of according to appropriate procedures.

Figure 1.
Generic Elements of a Typical Ex Situ S/S Process

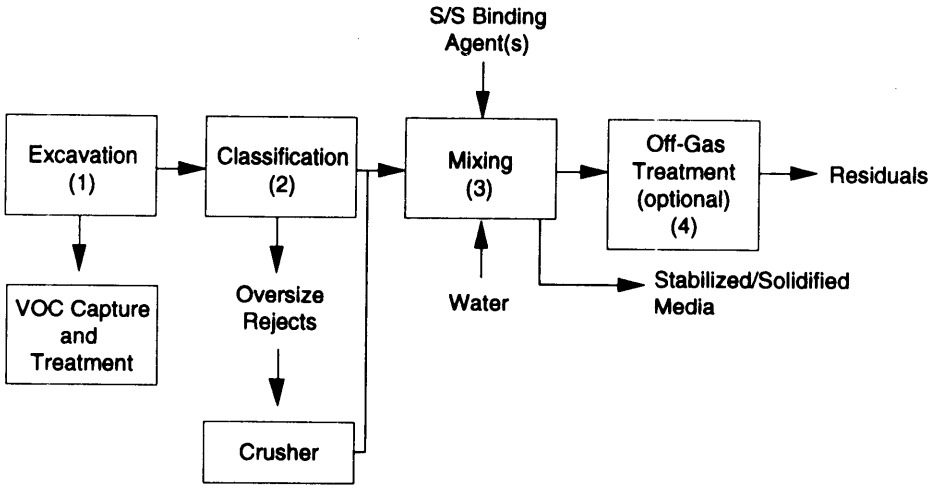
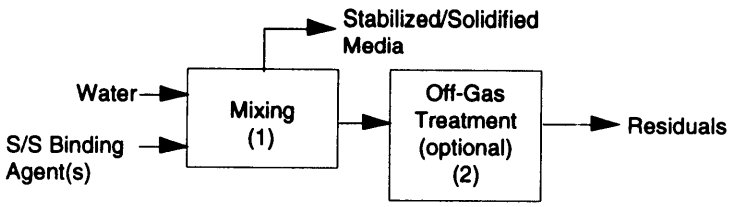


Figure 2.
Generic Elements of a Typical In Situ S/S Process



Site Requirements

The site must be prepared for the construction, operation, maintenance, decontamination, and ultimate decommissioning of the equipment. An area must be cleared for heavy equipment access roads, automobile and truck parking lots, material transfer stations, the S/S process equipment, set up areas, decontamination areas, the electrical generator, equipment sheds, storage tanks, sanitary and process wastewater collection and treatment systems, workers' quarters, and approved disposal facilities (if required). The size of the area required for the process equipment depends on several factors, including the type of S/S process involved, the required treatment capacity of the system, and site characteristics, especially soil topography and load-bearing capacity. A small mobile ex situ unit could occupy a space as small as that taken up by two standard flatbed trailers. An in situ system requires a larger area to accommodate a drilling rig as well as a larger area for auger decontamination.

Process, decontamination, transfer, and storage areas should be constructed on impermeable pads with berms for spill retention and drains for the collection and treatment of stormwater runoff. Stormwater storage and treatment capacity requirements will depend on the size of the bermed area and the local climate. Standard 440V, three-phase electrical service is usually needed. The quantity and quality of process water required for pozzolanic S/S technologies are technology-specific.

S/S process quality control requires information on the range of concentrations of contaminants and potential interferants in waste batches awaiting treatment and on treated product properties such as compressive strength, permeability, leachability, and in some instances, contaminant toxicity.

Performance Data

Most of the data on S/S performance come from studies conducted for EPA's Risk Reduction Engineering Laboratory under the Superfund Innovative Technology Evaluation (SITE) Program. Pilot scale demonstration studies available for review during the preparation of this bulletin included: Soliditech, Inc. at Morganville, New Jersey (petroleum hydrocarbons, PCBs, other organic chemicals, and heavy metals); International Waste Technologies (IWT) process using the Geo-Con, Inc. deep-soil-mixing equipment, at Hialeah, Florida (PCBs, VOCs); Chemfix Technologies, Inc., at Clackamas, Oregon (PCBs, arsenic, heavy metals); Im-Tech (formerly Hazcon) at Douglassville, Pennsylvania (oil and grease, heavy metals including lead, and low levels of VOCs and PCBs); Silicate Technology Corporation (STC), at Selma, California (arsenic, chromium, copper, pentachlorophenol and associated polychlorinated dibenzofurans and dibenzo-p-dioxins). The performance of each technology was evaluated in terms of ease of operation, processing capacity, frequency of process outages, residuals management, cost, and the characteristics of the treated product. Such characteristics

included weight, density, and volume changes; UCS and moisture content of the treated product before and after freeze/thaw and wet/dry weathering cycles; permeability (or permissivity) to water; and leachability following curing and after the weathering test cycles. Leachability was measured using several different standard methods, including EPA's TCLP. Table 4 summarizes the SITE performance data from these sites [20] [24] [25] [26] [27] [28].

A full-scale S/S operation has been implemented at the Northern Engraving Corporation (NEC) site in Sparta, Wisconsin, a manufacturing facility which produces metal name plates and dials for the automotive industry. The following information on the site is taken from the remedial action report. Four areas at the site that have been identified as potential sources of soil, groundwater, and surface water contamination are the sludge lagoon, seepage pit, sludge dump site, and lagoon drainage ditch. The sludge lagoon was contaminated primarily with metal hydroxides consisting of nickel, copper, aluminum, fluoride, iron, and cadmium. The drainage ditch which showed elevated concentrations of copper, aluminum, fluoride, and chromium, was used to convey effluent from the sludge lagoon to a stormwater runoff ditch. The contaminated material in the drainage ditch area and sludge dumpsite was then excavated and transported into the sludge lagoon for stabilization with the sludge present. The vendor, Geo-Con, Inc., achieved stabilization by the addition of hydrated lime to the sludge. Five samples of the solidified sludge were collected for Extraction Procedure (EP) toxicity leaching analyses. Their contaminant concentrations (in mg/l) are as follows: Arsenic (<.01); Barium (.35 - 1.04); Cadmium (<.005); Chromium (<.01); Lead (<.2); Mercury (<.001); Selenium (<.005); Silver (<.01); and Fluoride (2.6 - 4.1). All extracts were not only below the EP toxicity criteria but (with the exception of fluoride) met drinking water standards as well.

Approximately three weeks later UCS tests on the solidified waste were taken. Test results ranged from 2.4 to 10 psi, well below the goal of 25 psi. One explanation for the low UCS could be due to shear failure along the lenses of sandy material and organic peat-like material present in the samples. It was determined that it would not be practical to add additional quantities of lime into the stabilized sludge matrix because of its high solids content. Therefore, the stabilized sludge matrix capacity will be increased to support the clay cap by installing an engineered subgrade for the cap system using a stabilization fabric and aggregate prior to cap placement [29].

The Industrial Waste Control (IWC) Site in Fort Smith, Arkansas, a closed and covered industrial landfill built in an abandoned surface coal mine, has also implemented a full-scale S/S system. Until 1978 painting wastes, solvents, industrial process wastes, and metals were disposed at the site. The primary contaminants of concern were methylene chloride, ethylbenzene, toluene, xylene, trichloroethane, chromium, and lead. Along with S/S of the onsite soils, other technologies used were: excavation, slurry wall, french drains, and a landfill cover. Soils were excavated in the contaminated region (Area C) and a total of seven lifts were stabilized with flyash on mixing pads previously formed. A clay liner was then constructed in Area C to serve as a leachate barrier. After the lifts passed the TCLP test they were taken to Area C for in situ solidification. Portland cement was added to solidify each lift and they obtained the UCS goal of 125 psi. With the combination of the other technologies, the overall system appears to be functioning properly [30].

Other Superfund sites where full scale S/S has been completed to date include Davie Landfill (82,158 yd^3 of sludge containing cyanide, sulfide, and lead treated with Type I Portland cement in 45 days) [31]; Pepper's Steel and Alloy (89,000 yd^3 of soil containing lead, arsenic, and PCBs treated with Portland cement and fly ash) [32]; and Sapp Battery and Salvage (200,000 yd^3 soil fines and washings containing lead and mercury treated with Portland cement and fly ash in roughly 18 months) [33], all in Region 4; and Bio-Ecology, Inc. (about 20,000 yd^3 of soils, sludge, and liquid waste containing heavy metals, VOCs, and cyanide treated with cement kiln flue dust alone or with lime) in Region 6 [34]. All sites required that the waste meet the appropriate leaching test and UCS criteria. At the Sapp Battery site, the waste also met a permeability criterion of 10^{-6} cm/s [33]. Past remediation appraisals by the responsible remedial project managers indicate the S/S technologies are performing as intended.

RCRA LDRs that require treatment of wastes based on BDAT levels prior to land disposal may sometimes be determined to be Applicable or Relevant and Appropriate Requirements (ARARs) for CERCLA response actions. S/S can produce a treated waste that meets treatment levels set by BDAT but may not reach these treatment levels in all cases. The ability to meet required treatment levels is dependent upon the specific waste constituents and the waste matrix. In cases where S/S does not meet these levels, it still may in certain situations be selected for use at a site if a treatability variance establishing alternative treatment levels is obtained. Treatability variances may be justified for handling complex soil and debris matrices. The following guides describe when and how to seek a treatability variance for soil and debris: Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions" (OSWER Directive 9347.3-06FS) [16], and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions" (OSWER Directive 9347.3-06BFS) [17]. Another approach could be to use other treatment techniques in conjunction with S/S to obtain desired treatment levels.

Technology Status

In 1990, 24 RODs identified S/S as the proposed remediation technology [35]. To date only about a dozen Superfund sites have proceeded through full-scale S/S implementation to the operation and maintenance (O&M) phase, and many of those were small pits, ponds, and lagoons. Some involved S/S for off-site disposal in RCRA-permitted facilities. Table 5 summarizes these sites where full scale S/S has been implemented under CERCLA or RCRA [7, p. 3-4].

More than 75 percent of the vendors of S/S technologies use cement-based or pozzolanic mixtures [11, p. 2]. Organic polymers have been added to various cement-based systems to enhance performance with respect to one or more physical or

Table 4. Summary of SITE Performance Data

Site	Vendor Technology	Pretreatment	Post Treatment
Imperial Oil Co. / Champion Chemical Co. Morganville, NJ	Soliditech: Urrichem reagent, water, additives, Type II Portland cement	Bulk density: 1.14 to 1.26 g/cm^3 Permeability: Not determined UCS: Not determined Lead-TCLP Extract: 0.46 mg/l	Bulk density: 1.43 to 1.68 g/cm^3 Permeability: 8.9x10^{-9} to 4.5x10^{-7} cm/s UCS: 390 to 860 psi Lead-TCLP extract: <0.05 to <0.20 mg/l
GE Electrical Service Shop Hialeah, FL	IWT-DMS/Geo-Con: In situ injection of silicate additive	Bulk density: 1.55 g/ml Permeability: 1.8x10^{-2} cm/s UCS: 1.2 to 1.85 psi	Bulk density: 1.88 g/ml Permeability: 0.24x10^{-7} to 21x10^{-7} cm/s UCS: 300 to 500 psi
Portable Equipment Salvage Co. Clackamas, OR	Chemfix: polysilicates and dry calcium containing reagents	TCLP-Extractable (Pb, Cu, Zn): 12 to 880 mg/l Hydraulic cond. (CSS-13): 2.4 x10^{-6} to 2.7x10^{-4} cm/s Bulk density: 2.0 to 2.6 g/cm^3	TCLP-Extractable (Pb, Cu, Zn): 0.024 to 47 mg/l Hydraulic cond. (CSS-14): 4.6x10^{-7} to 1.2x10^{-6} cm/s Bulk density: 1.6 to 2.0 g/cm^3 USC (14, 21, 28 days): 131, 136, 143 psi Immersion UCS (30, 60, 90 days): 177, 188, 204 psi
Douglasville Douglasville, PA	Imtech (Hazcon): Chloranan™, water and cement	Bulk density: 1.23 g/ml Permeability: 0.57 cm/s TCLP-Extractable Pb: 52.6 mg/l	Bulk density (7, 28 days): 1.95, 1.99 g/ml Permeability (7, 28 days): 1.6x10^{-9}, 2.3x10^{-9} cm/s TCLP-Extractable Pb (7, 28 days): 0.14, 0.05 mg/l UCS (7,28 days): 1447,113 psi
Selma Pressure Treating Wood Preserving Site Selma, CA	Silicate Tech Corp.: alumino-silicate compounds	Arsenic-TCLP: 1.06 to 3.33 ppm Arsenic-Distilled H_20 TCLP: 0.73 to 1.25 ppm PCP-TWA: 1983 to 8317 ppm Bulk density: 1.42 to 1.54 g/cm	Arsenic-TCLP: 0.086 to 0.875 ppm Arsenic-Distilled H_20 TCLP: < 0.01 to 0.012 ppm PCP-TWA: 14 to 158 ppm Bulk density: 1.57 to 1.62 g/cm Permeability: 0.8x10^{-7} to 1.7x10^{-7} cm/s UCS: 259 to 347 psi

UCS - Unconfined Compressive Strength
TCLP - Toxicity Characteristic Leaching Procedure
TWA - Total Waste Analysis

Table 5. Summary of Full Scale S/S Sites

Site	Contaminant	Physical Form	Binder	Percentage Binder(s) Added	Treatment (batch/ continuous In Situ)
Independent Nail, SC	Zn, Cr, Cd, Ni	Solid/soils	Portland cement	20%	Batch Plant
Midwest, US Plating Company	Cu, Cr, Ni	Sludge	Portland cement	20%	In Situ
Unnamed	Pb/soil 2-100 ppm	Solid/soils	Portland cement and proprietary ingredient	Cement (15-20%) proprietary (5%)	In Situ
Marathon Steel, Phoenix, AZ	Pb, Cd	Dry-landfill	Portland cement and silicates	Varied 7-15% (cement)	Concrete batch plant
Alaska Refinery	Oil/oil sludges	Sludges, variable	Portland cement and proprietary ingredient	Varied 50+	Concrete batch plant
Unnamed, Kentucky	Vinyl chloride Ethylene dichloride	Sludges, variable	Portland cement and proprietary ingredient	Varied 25+	In Situ
NE Refinery	Oil sludges, Pb, Cr, As	Sludges, variable	Kiln dust (high CaO content)	Varied, 15-30%	In Situ
Velsicol Chemical	Pesticides and organics (resins, etc.) up to 45% organic	Sludges, variable	Portland cement and kiln dust, proprietary ingredient	Varied (cement 5-15%)	In Situ
Amoco Wood River	Oil/solids Cd, Cr, Pb	Sludges	Proprietary ingredient	NA, proprietary	Continuous flow (proprietary)
Pepper Steel & Alloy, Miami, FL	Oil saturated soil Pb-1000 ppm PCBs-200 ppm As-1-200 ppm	Soils	Pozzolanic and proprietary ingredient	~30%	Continuous feed (mixer proprietary design)
Vickery, Ohio	Waste acid PCBs (<500 ppm) dioxins	Sludges (viscous)	Lime and kiln dust	~15% CaO ~5% kiln dust	In Situ
Wood Treating, Savannah, GA	Creosote wastes	Sludges	Kiln dust	20%	In Situ
Chem Refinery, TX	Combined metals, sulfur, oil sludges, etc.	Sludges (synthetic oil sludges)	Portland cement and proprietary ingredient	NA	Continuous flow
API Sep. Sludge, Puerto Rico	API separator sludges	Sludges	Portland cement and proprietary ingredient	50% cement ~4 % proprietary	Concrete batch plant
Metaplating, WI	Al-9500 ppm Ni-750 ppm Cr-220 ppm Cu-2000 ppm	Sludges	Lime	10-25%	In Situ

chemical characteristics, but only mixed results have been achieved. For example, tests of standardized wastes treated in a standardized fashion using acrylonitrile, vinyl ester, polymer cement, and water-based epoxy yielded mixed results. Vinyl and plastic cement products achieved superior UCS and leachability to cement-only and cement-fly ash S/S, while the acrylonitrile and epoxy polymers reduced UCS and increased leachable TOC, in several instances by two or three orders of magnitude [36, p. 156].

The estimated cost of treating waste with S/S ranges from $50 to 250 per ton (1992 dollars). Costs are highly variable due to variations in site, soil, and contaminant characteristics that affect the performance of the S/S processes evaluated. Economies of scale likely to be achieved in full-scale operations are not reflected in pilot-scale data.

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Acknowledgments

This bulletin was prepared for the US Environmental Protection Agency, Office of Research and Development (ORD), Risk Reduction Engineering Laboratory (RREL), Cincinnati, Ohio, by Science Applications International Corporation (SAIC) under contract No. 68-C8-0062 (WA 2-22). Mr. Eugene Harris served as the EPA Technical Project Manager. Mr. Gary Baker was SAIC's Work Assignment Manager. This bulletin was written by Mr. Larry Fink and Mr. George Wahl of SAIC. The authors are especially grateful to Mr. Carlton Wiles and Mr. Edward Bates of EPA, RREL and Mr. Edwin Barth of EPA, CERI, who have contributed significantly by serving as technical consultants during the development of this document.

The following other EPA and contractor personnel have contributed their time and comments by participating in the expert review meetings or peer reviews of the document:

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Dr. Jeffrey Means	Battelle
Ms. Mary Boyer	SAIC-Raleigh
Mr. Cecil Cross	SAIC-Raleigh
Ms. Margaret Groeber	SAIC-Cincinnati
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