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STABILIZATION/SOLIDIFICATION

OF

HAZARDOUS WASTE

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Based on a Technical Handbook Prepared for the U.S. EPA

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs, and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments, and the needs of both large and small business in handling their wastes responsibly and economically.

This paper presents a summary of the EPA Handbook on Stabilization/Solidification Alternatives for Remedial Action and was developed as a resource document for a joint USEPA/Spain Seminar on the treatment and disposal of hazardous waste to be held in Spain in May 1986.

For further information, please contact the Land Pollution Control Division of the Hazardous Waste Engineering Research Laboratory.

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ABSTRACT

A technical handbook for stabilization/solidification of hazardous waste has recently been developed for EPA by the U.S. Army Engineer Waterways Experiment Station. This document is intended to serve as a guide to stabilization/solidification technologies for individuals responsible for preparing and reviewing remedial action plans. The handbook provides detailed discussion of the chemistry of commonly used stabilization/solidification techniques, highlighting their advantages and disadvantages. It provides suggested methodologies for waste and site characterization, as well as for laboratory and bench/pilot-scale testing. Planning and executing of full-scale treatment operations are also discussed, along with four different treatment scenarios from which cost and other comparisons can be made. The handbook also provides guidance on site safety, site cleanup, and site closure and monitoring.

TABLE OF CONTENTS

Tables

STABILIZATION/SOLIDIFICATION OF HAZARDOUS WASTE

INTRODUCTION

Over the last decade, there has been an increased interest in the stabilization and solidification of hazardous wastes and contaminated soils and sediments. In response to this growing interest, the Land Pollution Control Division of EPA'a Hazardous Waste Engineering Research Laboratory has produced a technical handbook on the subject. This handbook provides details of the materials and equipment in common use, and outlines methodologies for applying these techniques to hazardous waste problems. Among the subjects covered are waste and site characterization, laboratory testing and leaching protocols, bench and pilot scale testing, and full-scale operations. Four stabilization/ solidification scenarios are presented to illustrate advantages and disadvantages of different mixing techniques. Cost factors for the four techniques are also presented and discussed.

For this handbook, the terminology associated with these techniques is defined as follows: (1) Stabilization refers to those techniques which reduce the hazard potential of a waste by converting the contaminants into their least soluble, mobile, or toxic form. The physical nature and handling characteristics of the waste are not necessarily changed by stabilization. (2) Solidification refers to techniques that encapsulate the waste in a monolithic solid of high structural integrity. The encapsulation may be of fine waste particles (microencapsulation) or of a large block or container of wastes (macroencapsulation). Solidification does not necessarily involve a chemical interaction between the wastes and the solidifying reagents, but may involve mechanically binding the wastes into the monolith. Contaminant migration is restricted by vastly decreasing the surface area exposed to leaching, and/or by isolating the wastes within an impervious capsule.

Considerable impetus has been given to stabilization/solidification by both the Resource Conservation and Recovery Act (RCRA), including the 1984 amendments, and by the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). These techniques are often the basis for delisting* petitions under RCRA, and can be employed to satisfy the prohibition on the landfilling of liquids. Under CERCLA, solidification and encapsulation are specifically cited in the NCP (40 CFR 300) as methods to be considered during the feasibility study for remedying releases from contaminated soils and sediments.

STABILIZATION/SOLIDIFICATION TECHNIQUES

Most stabilization/solidification systems available today are proprietary processes involving the addition of absorbents and solidifying agents to a waste. Often the process is changed to accommodate specific types of wastes.

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*Delisting. The approval given by the U.S. EPA that a waste is no longer hazardous following a specific treatment process.

Most processes fall within a few generic types with proprietary additives added by different companies. The exact degree of performance observed in a specific system may vary widely from its generic type, but the general characteristics of a process and its products can be discussed.

Waste stabilization/solidification systems that have potentially useful application for hazardous waste to be discussed in detail here include:

- Sorption
- Lime-fly ash pozzolan processes
- Pozzolan-portland cement processes
- Thermoplastic microencapsulation
- Macroencapsulation

Sorption

Sorption involves the adding of dry, solid substance to a liquid or semi-liquid waste to take up free liquid and improve waste handling characteristics. The sorbent may hold the fluid as capillary liquid, or react chemically with it. Common natural sorbents include:

- Soil
- Fly ash
- Bottom ash
- Cement kiln dust
- Lime kiln dust

Physical and chemical properties of these and other natural sorbents are shown in Table 1.

A number of synthetic sorbents are also available, but due to their relatively higher cost, are less commonly used as presolidification agents. Table 2 lists some synthetic sorbents and the wastes that are effectively treated by them.

Sorbents, especially natural ones, are in wide use at hazardous waste landfills to eliminate free liquid and improve waste handling characteristics. In many cases, however, the sorbed wastes remain subject to leaching, and the landfill liner and leachate collection system are relied on to prevent contaminant migration. Sorbents that act like sponges and only soak up the liquids are not recommended.

Mixing requirements and equipment for sorption are job specific. For many jobs, a mixing pit and backhoe will suffice. If greater control of sorbent/waste ratios or mixing thoroughness is required, pug mills or ribbon blenders may be used. In any case, each batch of natural sorbent should be tested with the waste to ensure optimum mix ratios are employed.

Lime-Fly Ash Pozzolan Process

This process involves mixing wastes with natural or artificial silicic material and hydrated lime. Natural pozzolana include some volcanic tuffs and

TABLE 1. TYPICAL PHYSICAL AND CHEMICAL PROPERTIES OF COMMONLY USED NATURAL SORBENTS

Sorbent	Bulk density (kg/m^3)	Cation-exchange capacity (meq/100 gms)	Anion-exchange (meq/100 gms)	Slurry pH	Major mineral species present
Fly ash, acidic	1187	--	--	4-5	Amorphous silicates, hematite, quartz, mullite, free carbon
Fly ash, basic	1187	--	--	9-10	Calcite, amorphous silicates, quartz, hematite, mullite, free carbon
Kiln dust	641-890	--	--	9-11	Calcite, quartz, lime (CAO) anhydrite
Limestone screenings	--	--	--	6-7	Calcite, dolomite
Clay minerals (soils)	1519	--	--	--	Various, e.g., illite
Kaolinite	--	5-15	6-20	--	Can be relatively pure kaolinite
Vermiculite	--	100-500	4	--	Can be relatively pure
Bentonite	--	100-120	--	--	Smectite, quartz illite, gypsum, feldspar, kaolinite, calcite
Zeolite	1543	100-300	--	--	Zeolite (e.g., heulondite, laumonite, stilbite, chabazite, etc.)

TABLE 2. SYNTHETIC SORBENTS USED WITH HAZARDOUS WASTES

Sorbent	Waste treated effectively
Activated alumina	Sorbs fluoride in neutral wastes
Activated carbon	Sorbs dissolved organics
Hazorb* (foamed glass)	Sorbs water and organics
Locksorb† (treated clay)	Reportedly effective with oil emulsions
Imbiber beads# (cross-linked polymer)	Reportedly useful in spills of inert spirits-type liquids (cyclohexane)

* Product of Diamond Shamrock Corporation.

† Product of Radecca Corporation, Austin, TX.

Product of Dow Chemical Company, Midland, MI.

diatomaceous earth. Artificial pozzolana include blast furnace slag, ground brick, and some fly ashes from the burning of powdered coal. The wastes, often prestabilized, are mixed with the pozzolanic material to a pasty consistency. Calcium hydroxide (hydrated lime) is then blended into the fly ash-waste mixture. In order to produce a mechanically strong solid, from 20 to 30 percent lime is often required, depending on the wastes and type of fly ash used. The fly ash-waste-lime mixture is then placed in a landfill and compacted to increase its density. Alternately, the moist mixture may be compacted into molds and allowed to cure and pass specific tests prior to disposal.

Lime-fly ash solidification has several advantages. The materials and equipment required are readily available at relatively low cost. The resultant waste-lime-fly ash mixture sets into an easily handled solid product with reduced permeability. Among the disadvantages of this technique are the increased volume of material requiring disposal, and a relatively high leaching loss of potential contaminants from the solidified wastes, thus requiring secure disposal. A number of compounds, including sodium borate, calcium sulfate, potassium bichromate, and carbohydrates, can interfere with the setting reaction. Also, high oil and grease in the wastes can physically coat waste, fly ash, and lime particles, preventing them from reacting.

Pozzolan-Portland Cement Processes

A number of waste treatment processes employ portland cement as the solidifying agent, often with a pozzolanic material (such as fly ash) added to improve strength and increase durability. A variety of other additives, such as other forms of silica, and clays, may also be employed to alter the performance of these processes.

The type of portland cement can be selected to favor particular cementation reactions, thus avoiding interference from incompatible compounds. The five major types of portland cement include:

° Type I:	Common portland cement
° Type II:	Low alumina cement, moderately sulfate resistant
° Type III:	Rapid set cement, high early strength
° Type IV:	Long set cement for large mass pouring
° Type V:	Very low alumina cement, sulfate resistant

Due to its relatively low cost and wide availability, Type I is the most commonly used for solidification of wastes. Types II and V are used to a much lesser extent. Subject to availability, lower cost cement kiln dust may also be used, but larger quantities are generally required.

Many types of water-based waste-fly ash slurries may be mixed directly with cement using conventional cement mixing equipment. Large solidification projects may make the use of concrete batch mixing plants advantageous. Extremely hazardous waste may require the use of controlled, in-drum mixing equipment.

The suspended solids in a waste slurry become incorporated into the hardened concrete matrix. Most multivalent toxic metals will be transformed into their low solubility hydroxides or carbonates by the high pH of the cement mixture. Some metal ions may become integrated into the mineral crystals within the cement. Some materials in a waste can increase the strength and durability of a waste. These include sulfides (except sodium sulfide), asbestos, and latex.

A number of compounds can interfere with the solidification process. Some, such as soluble salts of manganese, tin, zinc, copper, and lead, can increase setting times and greatly decrease physical strengths. Impurities such as organic matter, silts, and some clays, can cause significant delays in setting. These impurities and other insoluble materials, fine enough to pass a No. 200 mesh sieve, can coat larger particles and weaken the waste/cement bond.

Cement-fly ash solidification techniques, with or without waste-specific additives, are among the most common offered by solidification vendors. Due to their relatively higher cost, they are less commonly used than lime-fly ash techniques.

Thermoplastic Microencapsulation

Thermoplastic microencapsulation involves mixing dried wastes with materials such as bitumen (asphalt), paraffin, polyethylene, polypropylene, or sulfur amended asphalt, and placing the mixture in some sort of container or mold. The most commonly employed material is asphalt. These techniques, developed originally for radioactive waste disposal, are adaptable to highly soluble toxic substances which are not amenable to lime or cement-based techniques.

Many waste types should not be considered for asphalt microencapsulation. Combustible materials such as solid hydrocarbons or sulfur, can ignite or explode at the elevated temperatures (130° to 260°C) employed for mixing. Borate salts can cause sudden hardening and clog equipment. Some solvents can prevent hardening while others, such as toluene and xylene, can readily migrate from the asphalt mixture. For wastes that are compatible with these techniques, however, the resultant product has a very low loss of contaminants to leaching fluids.

The greatest limitations to use of these techniques are relatively high cost, and the need for specialized mixing equipment and trained operators. Also, the wastes must be dried before mixing with the heated thermoplastic. Consequently, these techniques are generally used to achieve complete containment of special waste types in cases where costs are not a seriously limiting factor.

Macroencapsulation

Macroencapsulation, often referred to as jacketing, is a technique for isolating wastes by completely surrounding them with a durable, impermeable coating. One such technique involves sealing the wastes in a polyethylene, or polyethylene-lined, drum. Another involves drying the wastes, mixing them with polybutadiene, and compressing the mixture into a block. The block is then placed in a mold, surrounded by powdered polyethylene, and heated under pressure. The resultant product is a block with a thin polyethylene coating fused to it.

These techniques may be employed to contain very soluble toxic wastes, such as nonoxidizing mineral acids. The containment of the wastes is complete and assured for the life of the coating material. The polyethylene drum sealing technique can be used to over-pack damaged or leaky drums during both immediate removals and remedial actions.

The disadvantages of this technique include the expense of materials, specialized equipment, and energy, especially for fused-coating systems. Skilled labor is required and volatilization and combustion are an important consideration for wastes considered for these techniques.

Other Techniques

Other less common specialty systems are briefly discussed in the following paragraphs:

Two other solidification techniques show promise for selected wastes and situations. Self-cementation can be applied to wastes containing large amounts of calcium sulfate or calcium sulfite, such as flue-gas cleaning sludges or desulfurization sludges. A portion of the waste, usually 8 to 10 percent by weight, is calcined and then remixed with the waste along with proprietary additives. Fly-ash may be used to absorb excess moisture. The resultant product is an easily handled stable solid. The major drawbacks of this technique are waste specificity, energy and equipment expenses, and the need for skilled labor.

Another solidification technique is vitrification. Wastes are mixed with silica and heated to extremely high temperatures, and allowed to cool into a glass-like solid. A variation of this technique, using graphite electrodes driven into buried wastes, allows in-situ vitrification. All vitrification systems employ some type of hood to capture and treat the fumes and vapors given off during operation. Because these systems are very energy intensive, thus costly, they are generally considered only for radioactive or extremely dangerous wastes.

PRETREATMENT

Pretreatment systems, which overlap with stabilization and sorption processes, can be used to achieve a number of results that condition the waste to ensure better and more economical containment after the remaining materials have been stabilized and solidified. These include:

- Destruction of materials (such as acids or oxidizers) that can react with solidification reagents (lime or portland cement)
- Reduction of the volume of waste to be solidified (using processes such as settling or dewatering)

- Chemical binding of specific waste constituents to solid phases added to scavenge toxic materials from solution and hold them in solids

- Techniques for improving the scale on which waste processing can be done, for example, bulking and homogenizing waste to allow a single solidification system to be used without modification on a large volume of waste

Neutralization, oxidation or reduction, and chemical scavenging stabilize the waste in that they bring the chemical waste into an inert or less soluble form. Dewatering, consolidation, and waste-to-waste blending are also useful pretreatment methods which reduce the waste volume or numbers of different waste forms requiring treatment.

WASTE CHARACTERIZATION

A thorough physical and chemical characterization of a waste is essential to determine the most suitable stabilization/solidification method, as well as any special pretreatment or material handling methods that may be required. Physical characterization focuses mainly on transport, storage, and mixing considerations, while chemical characterization focuses mainly on interfering compounds, hazard assessment, and compatibility. These issues are discussed below.

Physical Characterization

Tests performed to characterize the physical properties of a waste will vary with the specific wastes and the stabilization/solidification techniques proposed for them. The physical determinations most commonly employed for stabilization/solidification are:

- Moisture content
- Suspended solids content
- Bulk density
- Grain-size distribution
- Atterberg limits
- Cone index
- Unconfined compressive strength

Moisture content is the ratio of the weight of water to the weight of solids expressed as percent. This value is used to determine if pretreatment is necessary, and for designing the stabilization/solidification process to be employed. A standard method for making this determination is given in ASTM method D 2216-80.

Suspended solids content is used to determine the best method for handling the waste and for estimating the amount of volume decrease due to consolidation or dewatering. Table 3 gives general consistency categories based on approximate suspended solids content. The EPA Standard Method for Settleable Matter is often used for this determination.

TABLE 3. HAZARDOUS WASTE CONSISTENCY CLASSIFICATION

Consistency Category	Characteristics
Liquid waste	<1% suspended solids,* pumpable liquid, generally too dilute for sludge dewatering operation
Pumpable waste	<10% suspended solids,* pumpable liquid, generally suitable for sludge dewatering
Flowable waste	>10% suspended solids,* not pumpable, will flow or release free liquid, will not support heavy equipment, may support high flotation equipment, will undergo extensive primary consolidation
Nonflowable waste	Solid characteristics, will not flow or release free liquids, will support heavy equipment, may be 100% saturated, may undergo primary and secondary consolidation

*Suspended solids ranges are approximate.

Bulk density of a waste is defined as the weight of a known waste volume to the weight of the same volume of water. This weight per unit volume, or bulk density, expressed in grams per cubic centimeter (g/cc) is used to convert waste weight to volume for materials handling calculations.

Because fine-grained wastes can cause problems with several solidification techniques, grain-size distribution measurements are important. These are made using ASTM Standard Method for Particle-size Analysis of Soils (ASTM D 422-63[72]).

Atterberg limits are the moisture contents which mark the boundaries between a materials liquid and plastic states. The liquid limit of a material is the moisture content below which it will flow as a viscous liquid. This is determined by ASTM Standard Method for Liquid Limit of Soils (ASTM D 423-66[72]). The plastic limit is the moisture content at the boundary between the plastic and semisolid states. It is determined by ASTM Standard Method for Plastic Limit and Plasticity Index of Soils (ASTM D 424-59[71]). The plasticity index is the difference of moisture content between the liquid limit and the plastic limit. These data are used to estimate such properties as compressibility, strength, and swelling characteristics, to provide an indication of how the waste material will behave when stresses are applied.

The cone index test involves forcing a standard cone-shaped device into the material to be tested, and measuring the penetration resistance offered by the material. This test is used to measure the in-situ strength of the wastes. ASTM Standard Method for Deep, Quasi-Static, Cone and Friction-Cone Penetration Tests for Soils (ASTM D 3441-79), may be used.

Unconfined compressive strength tests are used to measure shear strength of cohesive soils. These, in turn, may be used to predict the stability and ultimate bearing capacity of the wastes. ASTM Standard Method for Unconfined Compressive Strength of Cohesive Soil (ASTM D 2166-66[79]), is used for this determination.

Chemical Characterization

The purposes of chemical characterization are to determine the hazards associated with waste handling, to determine if interfering materials are present, and to examine waste/waste and waste/process compatibilities. The hazard potential, used to develop worker health and safety plans and equipment requirements, may be determined by analysis for hazardous pollutants. Tests to determine the presence of compounds deleterious to the intended stabilization/solidification processes may be used to identify necessary pretreatment measures. Compatibility testing is used to determine if wastes can be mixed into larger bulks for treatment, and to determine if the wastes are amenable to various stabilization/solidification techniques.

PROCESS SELECTION

The first measure taken in determining the feasibility of a stabilization/solidification technique as a remedial alternative, is to complete a thorough characterization of the wastes, and to calculate their volume. From this, a determination of the need to pretreat the wastes can be made. Flammable, corrosive, reactive, and infectious wastes are among those that should not be considered for solidification without some form of pretreatment. If more than one pretreatment measure is required, as may be the case with complex wastes, some method other than solidification may become more cost-effective.

Another use for the waste characterization is to assess the degree of hazard associated with handling the wastes. The equipment and time needed to protect workers and nearby residents while extremely hazardous wastes are being processed, may become prohibitively expensive.

An additional process selection measure is to characterize the site where the solidified wastes will be disposed. Because all solidification techniques result in increased volumes for disposal, and transportation costs are significant, wastes are usually solidified at the site where they will be disposed. Consequently, wastes are either excavated and hauled to a suitable site (often first stabilized), or the existing site is made suitable through modifications. Many uncontrolled sites can be made suitable to accept solidified wastes through the installation of a liner, leachate collection system, or other engineered measure. As with the costs of pretreatment processes, the costs of site modifications for secure burial may become limiting.

Another step in selecting a suitable process is to develop the specifications the solidified wastes must meet. Such specifications should include:

- Leachability
- Free liquid content
- Physical stability and strength
- Reactivity
- Ignitability
- Resistance to biodegradation
- Permeability

Standards for testing stabilized/solidified wastes have not yet been developed. The specifications and testing procedures outlined below constitute a minimum suggested program.

There are essentially three types of leachability tests performed on hazardous materials intended for landfilling: tests for regulatory compliance, tests for maximum hazard assessment; and tests for landfill and landfill facility design.

The regulatory compliance test most commonly applied to stabilized/solidified wastes is the Extraction Procedure (EP) toxicity test required under RCRA (40 CFR Part 261.24). This involves subjecting a waste sample to leaching by dilute acetic acid for 24 hours, and analyzing the resultant leachate for eight toxic metals and six pesticides. The allowable level of these toxics in the leachate is 100 times their Interim Primary Drinking Water Standard level. If this limit is exceeded, the stabilized waste is still considered hazardous and must be disposed of in a licensed hazardous waste facility.

A number of tests to assess the maximum hazard of a solidified waste have been proposed. Most involve subjecting finely-ground waste to leaching by water, followed by successive leaching of fresh waste with recycled leachates. This results in a solution that is saturated with respect to the component contaminants. Although no specific levels of contaminants in the leachate have been established for guidance, levels of concern can be identified and possibly counteracted by alternation to the treatment process.

Leachability tests conducted for engineering purposes are generally for use in the design of leachate collection and treatment systems. The most commonly employed is the Uniform Leaching Procedure (ULP) developed for assessing solidified low-level radioactive wastes. This procedure involves leaching a set volume of wastes with a set volume of leaching medium (usually water) which is changed regularly. Based on the surface area of the waste sample and contaminant concentrations in the leachate, contaminant losses by diffusion from the mass may be calculated. These values may be used to predict the degree of containment required of the disposal site.

The free liquid content of solidified waste is an important consideration. USEPA regulations currently prohibit landfilling of wastes containing free liquids. Several tests have been developed for measuring the free liquid content of solidified materials. Most involve placing a block or cylinder of waste of specific dimensions and weight between two filters. This sample is then loaded to pressures equal to the anticipated landfill overburden pressures. Any exudate collected on the filters is weighed to calculate its amount.

Physical stability and strength are important for solidified wastes intended for landfilling. The wastes must be able to support the weight of construction equipment without significant consolidation and settling. The amount of allowable settlement is largely governed by landfill design. Flexible membrane covers, for example, are less tolerant of settlement than earthen covers. The most commonly used tests for physical stability and strength are unconfined, triaxial shear, or plate loading, compressive strength tests. Often these tests are run on saturated and unsaturated samples to determine if saturation results in lower strength.

Samples of solidified waste should be tested for both reactivity and ignitability if there is a possibility that they would exhibit these properties. Reactivity testing is employed to assess the compatibility of the solidified wastes with landfill liner material and with other wastes. Ignitability testing is generally reserved for wastes that are solidified with thermoplastics or biodegradable wastes which could generate methane.

An assessment of a solidified waste's ability to support biologic activity may be important. Microbial activity can produce acids which can attack and weaken lime and cement. ASTM Standard Methods G 21 and G 22 can be used for this purpose.

Measuring the permeability of solidified wastes can yield predictions of the rate at which contaminants could be leached out of the solid. Low permeability equates to low contaminant mobility. Typically, a falling head permeability test conducted in a back-pressured triaxial chamber is used. The normal range of permeabilities for solidified wastes ranges from 10^{-4} to 10^{-8} cm/sec.

PROCESS SCREENING

Assuming that one or more stabilization/solidification processes are identified as feasible by the selection procedures described above, bench-scale or pilot-scale studies can be used to choose and refine the most suitable technique. Areas of concern investigated by these studies include:

- Safe waste handling procedures
- Waste uniformity
- Mixing and pumping properties
- Processing parameters
- Process control procedures
- Volume increases

A large stabilization/solidification operation has the potential to present many safety concerns. Heat generation, volatilization, and dust propagation are among the potential hazards. Also, the rapid addition of a reactive pretreatment or solidification agent such as lime, could cause a flash fire by rapid volatilization of organic chemicals. Many solidification reactions are exothermic, and an evaluation of the heat transfer characteristics of the treatment system is essential. The effects of heat transfer on reaction rates as the system is scaled up must also be evaluated. ASTM Standard Method C 186, Test for Heat of Hydration of Hydraulic Cements, is often employed in these evaluations. Like many of the tests used to assess stabilization/solidification processes, modifications may have to be made to assess the generation of fumes during treatment.

Waste uniformity and the mixing and pumping qualities at various points within the treatment system should also be studied. Serious problems can be caused by rapid viscosity increases within the system and must be evaluated, along with performance evaluations of the pumps, mixers, or other equipment to be used.

Process parameters, including mix ratios, mix and set times, and volume increases, are among the most important results of bench- or pilot-scale testing. Due to the heterogeneity of wastes and many commom treatment materials (such as fly ash), many of the process parameters will be determined by trial and error. Moisture content of wastes or treatment agents can show wide variability and significantly alter mix ratios.

There is no substitute for a pilot study to evaluate a solidification program and develop production techniques in large-scale solidification projects. Pilot studies also provide large samples of material required for more accurate, realistic testing, and permit resolution of equipment and material handling problems. Pilot studies can also be used to train equipment operators on the characteristics of the waste and the solidified product. Although quite expensive and time-consuming, pilot studies can reduce the possibility of a major accident, reduce work stoppages, and increase product consistency and process reliability, paying for themselves many times over in large-scale projects.

PROCESS OPERATION

Full-scale operation of a solidification process requires detailed planning and cost comparisons. The first planning step involves the characterization, testing, and process selection efforts described above. The second phase of planning involves the development of the operations plan, including equipment requirements, work sequence and scheduling, and cost estimation for the specific site. These are briefly discussed below.

Equipment requirements are largely determined by the type of mixing to be employed in the process. For the purpose of this discussion, four types of mixing are discussed: in-drum, in-situ, plant, and area.

In-drum mixing is best suited for application to highly toxic wastes that are present in relatively small quantities. This technique may also be applicable in cases where the waste is stored in drums of sufficient integrity to allow rehandling. In-drum mixing is typically the highest cost alternative when compared to in-situ, mobile plant, and area mixing scenarios. Quality control also presents serious problems in small batch mixing operations; complete mixing is difficult to achieve and variations in the waste between drums can cause variations in the characteristics of the final product.

In-situ mixing is primarily suitable for closure of liquid or slurry holding ponds. In-situ mixing is most applicable for the addition of large volumes of low reactivity, solid chemicals. The present state of technology limits application of in-situ mixing to the treatment of low solids content slurries or sludges. Where applicable, in-situ mixing is usually the lowest cost alternative. Quality control associated with in-situ mixing is limited with present technology.

Mobile mixing plants can be adapted for applications to liquids, slurries, and solids. This technique is most suitable for application at sites with relatively large quantities of waste materials to be treated. It gives best results in terms of quality control. Mobile plant mixing is applicable at sites where the waste holding area is too large to permit effective in-situ mixing of the wastes or where the wastes must be moved to their final disposal area.

Area mixing consists of spreading the waste and treatment reagents in alternative layers at the final disposal site and mixing in place. It is applicable to those sites where slurries with high solids content or where contaminated soils or solids must be treated. Area mixing requires that the waste materials be handled by construction equipment (dumptrucks, backhoes), and is not applicable to the treatment of liquids. Area mixing is land-area intensive in that it requires relatively large land areas for mixing. Area mixing presents the greatest possibility for fugitive dust, organic vapor, and odor generation. Area mixing ranks below in-drum and plant mixing in terms of quality control.

Project sequencing and scheduling is largely determined by the type of mixing technique employed. The first step generally involves preparation of the site and construction of any necessary facilities. These could include excavation of an inground mixing pit, or construction of a disposal site to receive the processed waste. This is often followed by any needed evaluation of the wastes including such things as drum integrity or phase separation. The actual processing of the wastes then takes place, along with the process control monitoring. This is followed by waste curing and final disposal. Variations to these sequences are likely due to process and site-specific factors.

Cost estimations for a full-scale processing operation must take into account costs for:

- Treatment reagents
- Labor
- Materials
- Equipment (and mobilization)
- Cleanup
- Overhead and profit

These will depend on the solidification technique employed, the amount of wastes to be processed, and many other site-specific constraints. For comparative purposes, Table 4 shows the costs for solidification of 500,000 gallons of waste with 30 percent portland cement and 2 percent sodium silicate, based on the four mixing methods described above. As shown, in-situ mixing is the least costly, and in-drum mixing is nearly an order of magnitude more costly. This illustrates why in-drum mixing and disposal is generally reserved for highly toxic wastes where the secondary containment in drums is needed to lower the migration potential.

The number of waste processing, handling, and mixing technologies is highly varied, as is the number of treatment reagent-waste formulations. Waste and site characteristics, and reagent cost and availability are the major factors which must be weighed in project planning to ascertain the most cost-efficient and reliable containment strategy. This section has discussed a sampling of possible stabilization/solidification scenarios, all of which are commercially available. This is intended to give the reader an appreciation of the wide diversity of applicable technology now in use.

SUMMARY

A technical handbook for stabilization/solidification of hazardous waste has recently been developed for EPA by the U.S. Army Engineer Waterways Experiment Station. This document is intended to serve as a guide to stabilization/solidification technologies for individuals responsible for preparing and reviewing remedial action plans. The handbook provides detailed discussion of the chemistry of commonly used stabilization/solidification techniques,

TABLE 4. SUMMARY COMPARISON OF RELATIVE COST OF STABILIZATION/
SOLIDIFICATION ALTERNATIVES
(U.S. Dollars)

Parameter	In-drum	In-situ	Plant Mixing		Area Mixing
			Pumpable	Unpumpable	
Metering and mixing efficiency	Good	Fair	Excellent	Excellent	Good
Processing days required	374	4	10	14	10
Cost/ton					
Reagent	$23.58 (9%)*	$20.50 (63%)	$20.50 (53%)	$20.50 (42%)	$20.50 (49%)
Labor and Per Diem	58.88 (23%)	1.36 (4%)	3.83 (10%)	6.93 (14%)	6.35 (15%)
Equipment Rental	42.82 (17%)	1.38 (4%)	3.93 (10%)	7.54 (16%)	4.07 (10%)
Used drums @ $11/drum	55.55 (21%)	--	--	--	--
Mobilization-demobilization	18.08 (7%)	1.58 (5%)	1.43 (4%)	2.26 (5%)	1.20 (3%)
Cost of treatment processes	$198.91	$24.82	$29.69	$37.23	$32.12
Profit and overhead (30%)	59.67 (23%)	7.45 (23%)	8.91 (23%)	11.17 (23%)	9.63 (23%)
TOTAL COST/TON	$258.58	$32.27	$38.60	$48.40	$41.75

* % of total cost/ton for that alternative.

NOTE: In all cases, 500,000 gal (2,850 tons) of waste treated with 30% portland cement and 2% sodium silicate with on-site disposal; costs include only those operations necessary for treatment. All costs are per ton of waste treated.

highlighting their advantages and disadvantages. It provides suggested methodologies for waste and site characterization, as well as for laboratory and bench/pilot-scale testing. Planning and executing of full-scale treatment operations are also discussed, along with four different treatment scenarios from which cost and other comparisons can be made. The handbook also provides guidance on site safety, site cleanup, and site closure and monitoring.

REFERENCE

Cullinane, M. J., Jr. and L. W. Jones, "Draft Technical Handbook for Stabilization/Solidification of Hazardous Waste," Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS., under contract to the Land Pollution Control Division, Hazardous Waste Engineering Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH, September 1984.

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16. ABSTRACT

In response to the growing interest in stabilization and solidification of hazardous wastes and contaminated soils and sediments, the Land Pollution Control Division of EPA's Hazardous Waste Engineering Research Laboratory has produced a technical handbook on the subject. This handbook provides details of the materials and equipment in common use, and outlines methodologies for applying these techniques to hazardous waste problems. Among the subjects covered are waste and site chacterization, laboratory testing and leaching protocols, bench and pilot scale testing, and full-scale operations. Four stabilization/solidification scenarios are presented to illustrate advantages, disadvantages and costs for different mixing techniques.

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