Designation: E 2060 – 00

Standard Guide for Use of Coal Combustion Products for Solidification/Stabilization of Inorganic Wastes[1]

This standard is issued under the fixed designation E 2060; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers methods for selection and application of coal combustion products (CCPs) for use in the chemical stabilization of trace elements in wastes and wastewater. These elements include, but are not limited to, arsenic, barium, boron, cadmium, chromium, cobalt, lead, molybdenum, nickel, selenium, vanadium, and zinc. Chemical stabilization may be accompanied by solidification of the waste treated. Solidification is not a requirement for the stabilization of many trace elements, but does offer advantages in waste handling and in reduced permeability of the stabilized waste.

1.1.1 Solidification is an important factor in treatment of wastes and especially wastewaters. Solidification/Stabilization (S/S) technology is often used to treat wastes containing free liquids. This guide addresses the use of CCPs as a stabilizing agent without the addition of other materials; however, stabilization or chemical fixation may also be achieved by using combinations of CCPs and other products such as lime, lime kiln dust, cement kiln dust, cement, and others. CCPs used alone or in combination with other reagents promote stabilization of many inorganic constituents through a variety of mechanisms. These mechanisms include precipitation as carbonates, silicates, sulfates, etc.; microencapsulation of the waste particles through pozzolanic reactions; formation of metal precipitates; and formation of hydrated phases **(1-4)**.[2] Long-term performance of the stabilized waste is an issue that must be addressed in considering any S/S technology. In this guide, several tests are recommended to aid in evaluating the long-term performance of the stabilized wastes.

1.2 The CCPs that are suited to this application include fly ash, spent dry scrubber sorbents, and certain advanced sulfur control by-products from processes such as duct injection and fluidized-bed combustion (FBC).

1.3 The wastes or wastewater, or both, containing the problematic inorganic species will likely be highly variable, so the chemical characteristics of the waste or wastewater to be treated must be determined and considered in the selection and application of any stabilizing agent, including CCPs. In any waste stabilization process, laboratory-scale tests for compatibility between the candidate waste or wastewater for stabilization with one or more selected CCPs and final waste stability are recommended prior to full-scale application of the stabilizing agent.

1.4 This guide does not intend to recommend full-scale processes or procedures for waste stabilization. Full-scale processes should be designed and carried out by qualified scientists, engineers, and environmental professionals. It is recommended that stabilized materials generated at the full-scale stabilization site be subjected to testing to verify laboratory test results.

1.5 The utilization of CCPs under this guide is a component of a pollution prevention program; Guide E 1609 describes pollution prevention activities in more detail. Utilization of CCPs in this manner conserves land, natural resources, and energy.

1.6 This guide applies only to CCPs produced primarily from the combustion of coal. It does not apply to ash or other combustion products derived from the burning of waste; municipal, industrial, or commercial garbage; sewage sludge or other refuse, or both; derived fuels; wood waste products; rice hulls; agricultural waste; or other noncoal fuels.

1.7 Regulations governing the use of CCPs vary by state. The user of this guide has the responsibility to determine and comply with applicable regulations.

1.8 It is recommended that work performed under this guide be designed and carried out by qualified scientists, engineers, and environmental professionals.

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 114 Test Method for Chemical Analysis of Hydraulic Cement[3]

C 311 Test Method for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in

---

[1] This guide is under the jurisdiction of ASTM Committee E-50 on Environmental Assessment and is the direct responsibility of Subcommittee E50.03 on Environmental Risk Management/Sustainable Development/Pollution Prevention.

Current edition approved Feb. 10, 2000. Published April 2000.

[2] The boldface numbers in parentheses refer to the list of references at the end of the text.

[3] *Annual Book of ASTM Standards*, Vol 04.01.

Portland-Cement Concrete[4]

C 400 Test Methods for Quicklime and Hydrated Lime for Neutralization of Waste Acid[3]

D 75 Practice Sampling Aggregates[5]

D 422 Test Method for Particle-Size Analysis of Soils[6]

D 558 Test Method for Moisture-Density Relations of Soil-Cement Mixtures[6]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[6]

D 1129 Terminology Relating to Water[7]

D 1193 Specification for Reagent Water[7]

D 1556 Test Method for Density and Unit Weight of Soil in Place by the Sand-Cone Method[6]

D 1633 Test Method for Compressive Strength of Molded Soil-Cement Cylinders[6]

D 1635 Test Method for Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading[6]

D 2166 Test Method for Unconfined Compressive Strength of Cohesive Soil[6]

D 2216 Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock[6]

D 2922 Test Method for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth)[6]

D 2937 Test Method for Density of Soil in Place by the Drive-Cylinder Method[6]

D 3441 Test Method for Deep, Quasi-Static, Cone and Friction-Cone Penetration Tests of Soil[6]

D 3877 Test Method for One-Dimensional Expansion, Shrinkage, and Uplift Pressure of Soil-Lime Mixtures[6]

D 3987 Test Method for Shake Extraction of Solid Waste with Water[8]

D 4318 Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils[6]

D 4842 Test Method for Determining the Resistance of Solid Wastes for Freezing and Thawing[8]

D 4843 Test Method for Wetting and Drying Test of Solid Wastes[8]

D 4972 Test Method for pH of Soils[9]

D 5084 Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter[6]

D 5239 Practice Characterizing Fly Ash for Use in Soil Stabilization[9]

E 1609 Guide for the Development and Implementation of a Pollution Prevention Program[9]

3. Terminology

3.1 *Definitions*:

3.1.1 Definitions are in accordance with Terminology D 653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *advanced sulfur control (ASC) products*—by-products generated from advanced coal conversion technologies including FBC and gasification and by-products from advanced environmental emissions cleanup technologies such as duct injection and lime injection multiphase burners (LIMB).

3.2.2 *baghouse*—a facility constructed at some coal-fired power plants consisting of fabric filter bags that mechanically trap particulates (fly ash) carried in the flue gases.

3.2.3 *beneficial use*—projects promoting public health and environmental protection, offering equivalent success relative to other alternatives, and preserving natural resources.

3.2.4 *BDAT*—best demonstrated available technology.

3.2.5 *boiler slag*—a molten ash collected at the base of slag tap and cyclone boilers that is quenched in a water-filled hopper and shatters into black, angular particles having a smooth, glassy appearance.

3.2.6 *bottom ash*—agglomerated ash particles formed in pulverized coal boilers that are too large to be carried in the flue gases and impinge on the boiler walls or fall through open grates to an ash hopper at the bottom of the boiler. Bottom ash is typically grey-to-black in color, is quite angular, and has a porous surface texture.

3.2.7 *coal combustion products*—fly ash, bottom ash, boiler ash, or flue gas desulfurization (FGD) material resulting from the combustion of coal.

3.2.8 *DSC*—differential scanning calorimetry.

3.2.9 *DTA*—differential thermal analysis.

3.2.10 *DTG*—differential thermal gravimetry.

3.2.11 *electrostatic precipitator*—a facility constructed at some coal-fired power plants to remove particulate matter (fly ash) from the flue gas by producing an electric charge on the particles to be collected and then propelling the charged particles by electrostatic forces to collecting curtains.

3.2.12 *encapsulation*—complete coating or enclosure of a toxic particle by an additive so as to sequester that particle from any environmental receptors that may otherwise have been negatively impacted by that particle.

3.2.13 *ettringite*—a mineral with the nominal composition $Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$. Ettringite is also the family name for a series of related compounds, known as a mineral group or family, which includes the following minerals **(1)**:

Ettringite	$Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$
Charlesite	$Ca_6(Si,Al)_2(SO_4)_2(B[OH]_4)(OH)_{12}\cdot 26H_2O$
Sturmanite	$Ca_6Fe_2(SO_4)_2(B[OH]_4)(OH)_{12}\cdot 26H_2O$
Thaumasite	$Ca_6Si_2(SO_4)_2(CO_3)_2(OH)_{12}\cdot 24H_2O$
Jouravskite	$Ca_6Mn_2(SO_4)_2(CO_3)_2(OH)_{12}\cdot 24H_2O$
Bentorite	$Ca_6(Cr,Al)_2(SO_4)_3(OH)_{12}\cdot 26H_2O$

3.2.14 *flue gas desulfurization material*—a by-product of the removal of the sulfur gases from the flue gases, typically using a high-calcium sorbent such as lime or limestone. Sodium-based sorbents are also used in some systems. The three primary types of FGD processes commonly used by utilities are wet scrubbers, dry scrubbers, and sorbent injection. The physical nature of these by-products varies from a wet, thixotropic sludge to a dry powdered material, depending on the process.

3.2.15 *fly ash*—coal ash that exits a combustion chamber in the flue gas. Coal fly ashes are typically pozzolans. Some coal fly ashes also exhibit self-hardening properties in the presence of moisture.

---

[4] *Annual Book of ASTM Standards*, Vol 04.02.

[5] *Annual Book of ASTM Standards*, Vol 04.03.

[6] *Annual Book of ASTM Standards*, Vol 04.08.

[7] *Annual Book of ASTM Standards*, Vol 11.01.

[8] *Annual Book of ASTM Standards*, Vol 11.04.

[9] *Annual Book of ASTM Standards*, Vol 04.09.

3.2.16 *pozzolans*—siliceous or siliceous and aluminous materials that in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxides at ordinary temperatures to form compounds possessing cementitious properties.

3.2.17 *S/S*—solidification/stabilization.

3.2.18 *stabilization or fixation*—immobilization of undesirable constituents to limit their introduction into the environment. Toxic components are immobilized by treating them chemically to form insoluble compounds.

3.2.19 *solidification*—the conversion of soils, liquids, or sludges into a solid, structurally sound material for disposal or use, typically referring to attainment of 50 psi or strength of surrounding soil.

3.2.20 *XRD*—x-ray diffraction.

4. Significance and Use

4.1 *General*—CCPs can have chemical and mineralogical compositions that are conducive to use in the chemical stabilization of trace elements in wastes and wastewater. These elements include, but are not limited to, arsenic, barium, boron, cadmium, chromium, cobalt, lead, molybdenum, nickel, selenium, vanadium, and zinc. Chemical stabilization may be accompanied by solidification of the waste treated. Solidification is not a requirement for the stabilization of many trace elements, but does offer advantages in waste handling and in reduced permeability of the stabilized waste. This guide addresses the use of CCPs as a stabilizing agent without addition of other materials. S/S is considered the BDAT for the disposal of some wastes that contain metals since they cannot be destroyed by other means **(2)**.

4.1.1 *Advantages of Using CCPs*—Advantages of using CCPs for waste stabilization include their ready availability in high volumes, generally good product consistency from one source, and easy handling. CCPs vary depending on the combustion or emission control process and the coal or sorbents used, or both, and CCPs contain trace elements, although usually at very low concentrations. CCPs are generally an environmentally suitable materials option for waste stabilization, but the compatibility of a specific CCP must be evaluated with individual wastes or wastewater through laboratory-scale tests followed by full-scale demonstration and field verification. CCPs suitable for this chemical stabilization have the ability to incorporate large amounts of free water into hydration products. CCPs that exhibit high pHs (>11.5) offer advantages in stabilizing trace elements that exist as oxyanions in nature (such as arsenic, boron, chromium, molybdenum, selenium, and vanadium) and trace elements that form oxyhydroxides or low-solubility precipitates at high pH (such as lead, cadmium, barium, and zinc). Additionally, CCPs that exhibit cementitious properties offer advantages in solidifying CCP-waste mixtures as a result of the hydration reactions of the CCP. These same hydration reactions frequently result in the formation of mineral phases that stabilize or chemically fix the trace elements of concern.

4.2 *Chemical/Mineralogical Composition*—Since CCPs are produced under conditions of high temperature, reactions with water during contact with water or aqueous solutions can be expected. Mineral formation may contribute to the chemical fixation and/or solidification achieved in the waste stabilization process. One example of this type of chemical fixation is achieved by ettringite formation. Reduced leachability of several trace elements has been correlated with ettringite formation in hydrated high-calcium CCPs typically from U.S. lignite and subbituminous coal, FGD materials, and ASC by-products. These materials are the best general candidates for use in this chemical fixation process. Lower-calcium CCPs may also be effective with addition of a calcium source that maintains the pH above 11.5. Ettringite forms as a result of hydration of many high-calcium CCPs, so adequate water must be available for the reaction to occur. The mineral and amorphous phases of CCPs contribute soluble elements required for ettringite formation, and the ettringite formation rate can vary based on the mineral and amorphous phase compositions.

4.3 *Environmental Considerations*:

4.3.1 *Regulatory Framework*:

4.3.1.1 *Federal*—EPA has completed a study of four high-volume CCPs (fly ash, bottom ash, boiler slag, and FGD material) for the U.S. Congress and has issued a formal regulatory determination **(3, 4)**. EPA "encourages the utilization of coal combustion by-products and supports state efforts to promote utilization in an environmentally beneficial manner" **(5)**. In a 1994 Report to Congress, the U.S. Department of Energy (DOE) also encouraged the utilization of CCPs and indicated that DOE will work with federal agencies and state and local governments to increase CCP utilization **(6)**. There is currently no regulatory program at the federal level that addresses the utilization of CCPs. The wastes or wastewater requiring stabilization may fall under federal jurisdiction, so the final stabilized material may need to be evaluated and disposed of according to federal regulations. Potentially applicable federal regulations may include the Resource Conservation and Recovery Act (RCRA), Hazardous Solid Waste Act (HSWA), Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), and Superfund Amendment and Reauthorization Act (SARA). A brief description of these regulations is included in the EPA document, entitled *Stabilization/Solidification of CERCLA and RCRA Wastes: Physical Tests, Chemical Testing Procedures, Technology Screening, and Field Activities* **(2)** and have been summarized by ACAA **(7)**. The EPA document states "stabilization/solidification is a proven technology for the treatment of hazardous wastes and hazardous waste sites." According to EPA **(2)**, stabilization/solidification is the BDAT for the disposal of some metals since they cannot be destroyed by other means. Provisions in federal laws list requirements that land disposal of hazardous wastes is only acceptable if these wastes are treated with the BDAT or with technology that meets or exceeds the treatment level of BDAT. Wastes that contain free liquids are prohibited from land disposal by federal RCRA regulations or by equivalent state regulations, or both. The chemical binding of free liquids brought about by solidification allows wastes that fail the EPA Paint Filter Test (EPA Method 9095-SW846) **(8)** to be land-disposed after successful S/S treatment.

4.3.1.2 A summary of coal fly ash utilization in waste stabilization/solidification, including a discussion of environmental/regulatory issues, demonstrations, and commercial applications, has been prepared **(7)**.

4.3.1.3 *State*—Most states do not have specific regulations addressing the use of CCPs, and requests for CCP use are handled on a case-by-case basis or under generic state recycling laws or regulations. Some states have adopted laws and regulations or issued policies and/or guidance regarding CCP use, but CCP use varies widely within these states **(9)**. Waste or wastewater requiring stabilization and the final stabilized material may also be regulated by individual states, so these regulations need to be identified and followed. Many states are authorized to manage the hazardous waste management programs within their state. RCRA and HSWA statutes allowed the states to become authorized by EPA. It is therefore extremely likely that S/S-treated waste will be regulated by a state.

5. CCP Characterization

5.1 *General*—Characterization of the CCP(s) under consideration for use as a stabilizing agent is needed to determine bulk chemical and mineralogical composition to form ettringite when hydrated and that sufficient alkalinity is available to maintain a high pH.

5.2 *Sampling and Handling*—Sampling CCPs for testing purposes should conform to Practice D 75 or Test Method C 311 as appropriate. Proper laboratory protocols for handling fine material should be followed.

5.3 *Chemical Composition*—Test Method C 311 is often used to determine the major chemical constituents of CCP samples. The most critical constituents requiring quantitation are calcium, aluminum, and sulfur.

5.4 *pH*—Test Method D 4972 or Practice D 5239 may be used to determine CCP pH. In assessing the test results, consideration should be given to the possibility that the pH of the CCP may differ with age, water content, and other conditions. EPA Method SW-9045 **(10)** is also applicable.

5.5 *Buffer Capacity*—The buffer capacity of the CCP is important in maintaining the high pH that generally is a requirement for the stabilization mechanisms of interest when CCPs are used as stabilization agents. The CCP must have enough buffer capacity to maintain the pH of the stabilized waste in the appropriate range so the waste remains stable over time and under environmental stresses. Test Method C 400 can be applied to evaluate the buffer capacity of the CCP. Determine the basicity factor for the CCP as noted in Test Method B of Test Method C 400.

5.6 *Swelling*—Test Method D 3877 can be used to determine the swelling potential of self-hardening (high-calcium) CCPs and FGD material. The reactions producing the expansive properties generally do not commence for a period of more than 30 days after initial CCP hydration. The test procedure must address this delayed reaction. The procedure should be modified to extend the wetting and drying cycle to 60 days. Expansive reactions, including the formation of ettringite, may have an impact on the permeability of the stabilized waste. Following completion of hydration at 60 days, the mineral composition should be determined.

5.7 *Mineral Composition (Optional)*—XRD is used to determine the mineral content of CCPs. Fly ash, bottom ash, and boiler slag contain significant amorphous phases that cannot be identified through the use of XRD techniques. Many ASC by-products have a higher calcium content compared to that of CCPs. XRD evaluation can be performed on the hydrated CCP collected from the swelling test, summarized in 5.6, to determine whether or not the CCP tested forms hydrated minerals.

6. Selection of CCP for Waste Stabilization

6.1 *General*—Many CCPs have the potential to stabilize inorganic trace elements; however, those with the highest potential are finely powdered materials, including fly ash, spent dry scrubber sorbents, and certain ASC by-products. Specifically, CCPs that are known to undergo hydration reactions that result in the formation of certain minerals, including ettringite, carbonate minerals, and insoluble sulfates, have high potential to be useful as stabilizing agents for many trace elements that are not organically associated. A CCP exhibiting high pH also offers advantages in the stabilization of trace elements.

6.2 *Chemical Properties*—The chemical properties of CCPs used in waste stabilization applications may include a wide range of chemical compositions, pHs, buffering capacities, and reactivities.

6.2.1 *Chemical Composition*—CCPs of differing chemical composition can offer advantages for solidification/stabilization applications. Most coal fly ashes are pozzolanic; however, certain subbituminous and lignite coal ashes may contain higher amounts of calcium oxide and exhibit greater cementitious properties. Cementitious CCPs offer additional advantages in solidification/stabilization applications; the potential formation of monolithic structures of CCP-waste combinations without addition of cement or other additives; appropriate chemical components that allow the formation of ettringite for stabilization of oxyanions (such as oxyanions of arsenic, boron, chromium, molybdenum, selenium, and vanadium), which is accomplished by substituting these oxyanionic species for $SO_4^{=}$ in the ettringite structure; and high pH, which facilitates ettringite formation and precipitation of low-solubility metal carbonates. The presence of sulfate in CCPs being considered for solidification/stabilization applications can offer advantages in reducing the mobility of barium through barium sulfate formation. The presence of iron and/or manganese species can enhance the formation of low-solubility metal oxyhydroxides.

6.2.2 *pH*—It is recommended that the pH of the CCP be determined using methods noted in 5.4. CCPs exhibiting high pH (>8) offer advantages in numerous solidification/stabilization mechanisms.

6.2.3 *Hydrated Mineral Formation*—The CCP selected should be hydrated using the procedure to determine swelling potential listed in 5.6. Thirty (30) days is recommended as the minimum hydration time; however, 60 days may provide more reliable results because ettringite formation is a slow reaction. As noted in 5.7, XRD is the best analytical tool to determine the presence of hydration products.

6.2.4 *Buffer Capacity*—The buffer capacity of the CCP should be determined as noted in 5.5. As an example of the use of the calculated basicity factor, to ensure that the CCP has the capability to neutralize significant acid while maintaining the pH above 11.5 for ettringite stability, a BF >0.1 would be appropriate. The limit for the BF of the CCP should be evaluated on the basis of the expected mechanism of solidification/stabilization, the candidate waste, and/or the site conditions expected for the stabilized material (see 7.5.2).

6.3 *Final CCP Selection*—One or more CCP(s) can be selected for the laboratory-scale demonstration of the stabilization process using the criteria listed in this section. CCPs meeting the specified criteria should be subjected to the laboratory-scale demonstration using the candidate waste as noted in Section 8.

7. Waste Characterization and Stabilized Material Testing

7.1 *General*—Specific characteristics of the waste or wastewater requiring stabilization must be determined. The concentrations of the elements expected to participate in the chemical fixation reactions are required to determine the quantity of stabilization agent or CCP to use. The pH and buffer capacity of the waste must be known. All waste characterization tests and procedures must be performed on representative samples of the specific waste to be treated. The final stabilized material form must also be evaluated for specific parameters to verify that the stabilization process has been effective.

7.2 *Physical Tests for Wastes*—Physical testing of the waste prior to treatment provides information on treatability, transport, storage, and mixing considerations. Physical testing of the stabilized material form provides information on the relative success of the stabilization process.

7.2.1 *Particle-Size Analysis*—The results of particle-size analysis provide information on the relative proportions of gravel, sand, silts, and clay-sized particles within the waste, uniformity, concavity, average grain size, and maximum and minimum particle sizes and can be determined using Test Method D 422.

7.2.2 *Atterberg Limits*—The Atterberg Limits are a series of tests originally developed to determine the characteristics of clays used in ceramics. The recommended test procedure is Test Method D 4318, which is used to determine the liquid limit (the moisture content at which the material flows as a viscous liquid), plastic limit (the moisture content at the boundary between the plastic and brittle states), and plasticity index (the difference between the liquid and plastic limits).

7.2.3 *Moisture Content*—The moisture content of the waste can be determined using Test Method D 2216, which will indicate the amount of free water in the waste (waters of hydration are not included as part of the moisture content). Water may not be the only liquid phase in a waste requiring stabilization, so care must be taken to remove other liquids or otherwise account for them in determining the moisture content.

7.2.4 *Density*—The bulk density of a material is the ratio of the total weight of the material to the total volume and is frequently used to convert weight to volume for materials-handling calculations. Several methods are appropriate for determining the bulk density of the waste prior to stabilization. These include laboratory Test Methods D 2937 and D 1556 and an in situ measurement, Test Method D 2922.

7.2.5 *Suspended Solids*—In the case of stabilizing oxyanionic species in a wastewater or liquid waste, it is recommended to determine the suspended solids in the wastewater using Method 2540D as detailed in the Standard Methods for Examination of Water and Waste Water **(11)**. A liquid waste is defined as having less than 1 % suspended solids. Suspended solids can be removed from liquid waste or wastewater by filtering.

7.2.6 *Paint Filter Liquids Test*—The regulatory test (Title 40 of the Code of Federal Regulations [40 CFR] Sections 264.314 and 265.314) **(8)** is used to determine if a waste contains free liquids. For wastes treated by S/S to address free liquids, the EPA generally requires attainment of 50 psi unconfined compressive strength in the treated waste. This is to demonstrate that the free liquids were bound chemically rather than merely sorbed.

7.3 *Physical Tests for Stabilized Materials*—The physical nature of the waste may or may not change on application of the CCP for chemical stabilization depending on the CCP selected, the character of the waste, and the stabilization process used. Solidification is not a criterion for stabilization of oxyanionic species through ettringite formation, but solidification generally reduces the permeability of the stabilized waste, which offers the advantages of limiting contact with air and water (or other gases and liquids). If solidification is desirable, it must be factored into the selection criteria for the CCP.

7.3.1 *Compaction Testing*—The moisture-density relationship can be determined on the stabilized waste using Test Method D 558. This test determines the moisture content that allows maximum compaction, which provides maximum density of the stabilized waste. It is cautioned here that the moisture content must be adequate to provide the waters of hydration needed for the ettringite formation reaction to occur and that the ettringite formation is slow and can require 30 days or longer to complete. Moisture-density relationships developed in the laboratory must take this into account.

7.3.2 *Density*—The bulk density of the stabilized material can be determined as noted in 7.2.4 if the stabilized material is not solidified. If the stabilized material is solidified, a sufficiently cured cube or cylinder of the stabilized material can be weighed and measured. The volume of the cube or cylinder can be determined, and the density can then be calculated **(12)**.

7.3.3 *Permeability Testing*—The permeability of the stabilized material is important in estimating the quantity and flow of water through that material under saturated conditions. Recommended test procedures are Test Method D 5084 and EPA Method 9100-SW846 **(12)**.

7.3.4 *Strength Testing*—Optional strength tests may be performed depending on the requirements of the site and final stabilized material. Several types of strength tests are listed here and can be used as appropriate to the site and final stabilized material.

7.3.4.1 Unconfined compressive strength can be determined using Test Methods D 2166 or D 1633. Results of unconfined compressive strength provide information on the ability of the stabilized waste to support overburden, the optimum water:additive ratios and curing times for setting reactions, and the changes in strength from waste to stabilized material.

7.3.4.2 EPA generally requires attainment of 50 psi unconfined compressive strength for a treated waste that originally contained free liquids.

7.3.4.3 Flexural strength testing provides a means to assess the tensile strength of the solidified mass under flexural loading conditions and can be determined by using Test Method D 1635.

7.3.4.4 Cone index is determined to indicate stability and bearing capacity. The appropriate test method is Test Method D 3441.

7.3.5 *Durability Testing*—Durability testing is performed to evaluate the resistance of a stabilized material to external environmental stresses such as freezing and thawing or wet-and-dry cycles. The tests noted require molded samples of the stabilized material form, which may be appropriate depending on the consistency and texture of the stabilized material.

7.3.5.1 Freeze-thaw testing can be accomplished using Test Method D 4842 as appropriate for the specific site or stabilized material, or both.

7.3.5.2 Wet-dry cycle testing of the stabilized material can be performed using Test Method D 4843.

7.3.5.3 *Paint Filter Liquids Test*—The regulatory test (Title 40 of the Code of Federal Regulations [40 CFR] Sections 264.314 and 265.314) **(8)** used to determine if a waste contains free liquids. For wastes treated by S/S to address free liquids, the EPA generally requires attainment of 50 psi unconfined compressive strength in the treated waste. This is to demonstrate that the free liquids were bound chemically rather than merely sorbed.

7.4 *Chemical Characterization of Wastes*—Wastes to be stabilized require chemical characterization. The primary chemical characterization must include determination of bulk chemical composition and pH. The major constituents of the waste must be quantitated, and any species requiring stabilization must be quantitated.

7.4.1 *Chemical Composition*—Major oxide content of the waste can be determined according to Test Method C 114. Additional total elemental analysis can be determined according to EPA SW-846 **(13)**.

7.4.2 *pH*—Methods noted in 5.4 are applicable to determining the pH of the waste.

7.5 *Chemical Characterization of Stabilized Materials*—The primary chemical characterization required for stabilized materials is leaching/extraction tests.

7.5.1 *Leaching Tests*—Numerous leaching tests have been developed to evaluate the leaching behavior of wastes and stabilized materials. Commonly applied leaching tests are listed and referenced in Table 1, but the selection of the test procedure(s), leachate test parameters, and interpretation of leachate test results must be guided by the appropriate regulatory authority.

7.5.2 *Buffer Capacity*—The buffer capacity of the stabilized material can be evaluated by use of the ASTM procedure noted in 5.5.

8. Laboratory-Scale Demonstration of Stabilization

8.1 *General*—Laboratory-scale development and demonstration of the stabilization technology are recommended prior to field application of any stabilization agent. Laboratory-scale demonstrations must be performed with representative samples of the waste requiring stabilization and the selected CCP(s).

TABLE 1 Leaching Methods Applicable to Stabilized Materials

Test Method	Leaching Solution	Liquid:Solid Ratio	Leaching Duration
TCLP **(14)**	Acetic acid/acetate buffer	20:1	18 h
EP Tox **(13)**	Acetic acid	16:1	24 h
California WET (Waste Extraction Test) **(15)**	Sodium citrate	10:1	48 h
MEP **(16)**	Multiple solutions (acetic acid, sulfuric acid, and nitric acid)	20:1	24 h/ extraction
MWEP **(17)**	Distilled/deionized water or other for specific silt	10:1	18 h/ extraction
ASTM D 3987	Distilled/deionized water	20:1	24 h
SGLP **(18)**/LTL **(18)**	Synthetic groundwater dictated by site or distilled/deionized water	20:1	18 h/30, 60, 90 days
SPLP **(19)**	Sulfuric acid	20:1	18 h

8.1.1 *Waste: CCP Ratios*—Using the results of physical and chemical characterization techniques recommended for the wastes, a range of waste:CCP ratios should be identified and tested for process variables and stabilized material testing.

8.1.2 *Mixing Requirements*—Laboratory-scale mixing techniques that approximate the anticipated full-scale stabilization process must be used to mix the waste and CCP to produce the initial stabilized material.

8.1.3 *Curing*—The initial stabilized material sample(s) must be cured prior to evaluation. A cure time of 30 days is recommended as the minimum time prior to evaluation of the stabilized material. It is recommended that additional cure times of 60 days and 90 days also be used for additional samples to determine a qualitative rate of stabilization reactions.

8.1.4 *Swelling*—Determine the amount of swelling, if any, on all cured samples using appropriate methods as noted in 5.7. Solidified masses should be examined for cracking that may result from swelling.

8.1.5 *Leachability*—Using the prescribed leaching test(s), evaluate the leaching potential on cured samples relative to appropriate regulatory requirements.

8.1.6 *Mineralogy*—If warranted, XRD may be used to verify the presence of hydration minerals such as ettringite in cured samples.

8.1.7 *Stabilized Material Stability*—Determine the physical stability or integrity of the stabilized material using tests indicated in 6.3.5.

9. Field Application of CCPs as a Waste Stabilization Agent

9.1 *General*—Waste stabilization can be accomplished by several processes for full-scale projects. Selection of the best process requires consideration of the physical and chemical properties of the waste or wastewater. Common processes are drum processing, plant processing, and in situ processing. CCPs have commonly been used in plant processing and in situ processing **(20-22)**.

9.1.1 *Environmental Issues*—Site variables must be taken into account when evaluating the stabilization technology and process. These variables include proximity to water table, surface waters, and soil permeability.

9.1.2 *Process Requirements*—Equipment needs, equipment access, and dry storage for the CCP must all be considered prior to field application.

9.1.3 *Economic Considerations*—Costs and availability of the CCP, labor costs, and other factors relating to the process, site preparation, or landfilling must be part of the decision to proceed with the stabilization process.

REFERENCES

(**1**) Hassett, D.J., Pflughoeft-Hassett, D.F., McCarthy, G.J. "Ettringite Formation in Coal Ash as a Mechanism for Stabilization of Hazardous Trace Elements," *In Proceedings of the Ninth International Ash Use Symposium—Volume 2: Stabilization and Aquatic Uses*, Orlando, FL, Jan. 22-25, 1991, EPRI GS-7162, Project 3176, 1991, pp. 31–1 to 31–17.

(**2**) U.S. Environmental Protection Agency, *Stabilization/Solidification of CERCLA and RCRA Wastes: Physical Tests, Chemical Testing Procedures, Technology Screening, and Field Activities*, EPA/625/6-89/022, May 1989.

(**3**) Report to Congress, *Wastes from the Combustion of Coal by Electric Utility Power Plants*, U.S. Environmental Protection Agency, EPA/530-SW-88-002, Feb. 1988.

(**4**) U.S. Environmental Protection Agency. "Final Regulatory Determination on Four Large-Volume Wastes from the Combustion of Coal by Electric Utility Power Plants," 40 CFR Part 261, Aug. 2, 1993.

(**5**) U.S. Environmental Protection Agency. *Technical Resource Document: Solidification/Stabilization and Its Application to Waste Materials* EPA/530/R-93/012, June 1993.

(**6**) Report to Congress, *Barriers to the Increased Utilization of Coal Combustion/Desulfurization Byproducts by Governmental and Commercial Sectors*, U.S. Department of Energy, Office of Fossil Energy, July 1994.

(**7**) American Coal Ash Association, *Solidification and Stabilization of Wastes Using Coal Fly Ash: Current Status and Direction*, April 1995.

(**8**) U.S. Environmental Protection Agency "Method 9095: Paint Filter Liquid Test," *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods (SW846)*, Vol 1C, 3rd ed. 1990.

(**9**) American Coal Ash Association, *Solid Waste Regulations Governing the Use of Coal Combustion Products (CCPs)*, Aug. 1998.

(**10**) U.S. Environmental Protection Agency, "Method 9045c: Soil and Waste pH," *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods (SW846)*, Vol 1C, 3rd ed. 1990.

(**11**) American Public Health Association; American Water Works Association; and Water Environment Federation. "Method 2540D: Total Suspended Solids Dried at 103°–105°C," *Standard Methods for the Examination of Water and Wastewater*, 19th ed., 1995.

(**12**) U.S. Environmental Protection Agency," Method 9100: Saturated Hydraulic Conductivity, Saturated Leachate Conductivity, and Intrinsic Permeability," *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods (SW846)*, Vol 1C, 3rd ed. 1990.

(**13**) U.S. Environmental Protection Agency, "Method 1310: Extraction Procedure (EP) Toxicity Test Method and Structural Integrity Test," *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods (SW846)*, Vol 1C, 3rd ed. 1990.

(**14**) U.S. Environmental Protection Agency, "Method 1311: Toxicity Characteristic Leaching Procedure (TCLP)," *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods (SW846)*, Vol 1C, 3rd ed. 1990.

(**15**) State of California, "Environmental Health Standards-Hazardous Waste," California Code, Title 22, Section 66261.126: 1991, pp. 669–672.

(**16**) U.S. Environmental Protection Agency, "Method 1320: Multiple Extraction Procedure (MEP)," *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods (SW846)*, Vol 1C, 3rd ed. 1990.

(**17**) U.S. Environmental Protection Agency, "Solid Waste Leaching Procedure Technical Document for Public Comment," Report No. EPA/530-SW-84-924, 1984.

(**18**) Hassett, D.J.; Pflughoeft-Hassett, D.F. "Environmental Assessment of Coal Conversion Solid Residues," In Proceedings of the 10th International Ash Use Symposium - Vol 1: High-Volume Uses/Concrete Applications; Orlando, FL, Jan. 18–21, 1993, EPRI TR-101774, Project 3176, 1993.

(**19**) U.S. Environmental Protection Agency, "Method 1312: Synthetic Precipitation Leaching Procedure (SPLP)," *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods (SW846)*, Vol 1C, 3rd ed. 1990.

(**20**) Pritts, J.W., Neufeld, R.D., and Cobb, J.T., *Stabilization of Heavy Metal Containing Hazardous Wastes with By-Products from Advanced Clean Coal Technology Systems.*

(**21**) Cobb, J.T., Neufeld, R.D., Schreiber, E.M., Clifford, B.V., Pritts, J.W., Beeghley, J.H., and Bender, C.F., *Treatment of Metal-Laden Hazardous Wastes with Advanced Clean Coal Technology By-Products*, topical report, Award No. DE-FC21-94MC31175, August 18, 1994–August 18, 1995.

(**22**) Wilk, C.M., *Stabilization of Heavy Metals with Portland Cement: Research Synopsis*, Portland Cement Association, IS007, 1997.