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Beneficial Use of Industrial By-Products

Identification and Review of Material Specifications, Performance Standards, and Technical Guidance

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Section 1
Introduction

Millions of tons of industrial by-products are generated each year in the United States, and significant percentages of these by-products have desirable properties that make them suitable for a variety of beneficial use applications. While more and more of these industrial by-products are being beneficially used, a significant portion continues to be landfilled as solid waste. Because many of the by-products pose little threat to the environment, disposal at a landfill might be viewed as the discarding of a commodity, and it forces the consumption of additional natural resources.

The National Council for Air and Stream Improvement, Inc. (NCASI), and the United States Environmental Protection Agency (USEPA) Region 5, organized an initiative to foster the beneficial use of industrial by-products. As part of this initiative, NCASI and the USEPA hosted the Midwest Industrial By-Products Beneficial Use Summit in August 2002, which brought together personnel from state regulatory agencies, representatives from industries, and technical experts. Informed by the discussion at the summit, NCASI funded a study through a USEPA grant to identify and summarize existing performance standards, material specifications, and technical guidance (collectively "standards") for the beneficial use of industrial by-products. This document is a summary of the results of that study.

The following four industries were targeted in the literature search:

- Cement
- Foundry
- Pulp and paper
- Utility (coal-fired power plants)

The by-products from the four target industries were identified, along with the more significant or probable beneficial use options for each by-product. Where available, existing standards for each beneficial use option were noted and summarized.

Other industries also have by-products with beneficial use options; however, limited funding necessitates focusing only on the four industries listed above. This document is intended to be a living document, in that new standards, or existing standards for industrial by-products from other industries, can be added to the document in the future. The intention is that this document will educate state regulatory personnel, industry representatives, and others regarding beneficial use options for industrial by-products and the standards that affect beneficial use.

Section 2
The Cement Industry

The cement industry produced 98 million tons of Portland and masonry cement in the U.S. in 2001. The United States is third in the world in cement production, and world output was about 1.9 billion tons. In 2001, 115 plants in 37 states were producing Portland cement. The top seven cement-producing states were Texas, California, Pennsylvania, Michigan, Missouri, Alabama, and Florida, in descending order (van Oss, 2001). In 2000, these plants employed about 221,000 people (U.S. Census Bureau, 2002).

The use of pozzolanic (cementitious) materials in construction dates back to before the birth of Christ. The Egyptians used gypsum and lime mortars in the pyramids. The Greeks also used lime mortars in construction. The Romans used lime as a cementitious material in the construction of the Appian Way, the Coliseum, and the Pantheon in Rome. Pliny reported a mortar mixture of 1 part lime to 4 parts sand. Vitruvius reported a 2 parts pozzolana to 1 part lime mixture. (http://matse1.mse.uiuc.edu/~tw/concrete/hist.html, 2003).

In 1824, Joseph Aspdin patented the cement mixture he produced in his kitchen. The stone mason/inventor heated a mixture of finely ground limestone and clay and then ground the mixture into a powder and added water to produce a hydraulic cement that hardened. Aspdin named the product Portland cement because it reminded him of stone quarried on the Isle of Portland off the British coast (www.portcement.org/cb/concretebasics_history.asp, 2003).

The cement industry produces Portland cement (cement), a fundamental ingredient in concrete. Concrete is a mixture of cement (10-15%), fine aggregate (22-30%), coarse aggregate (38-45%), water (15-20%), and air (5-8%). Concrete is used in a variety of construction applications, such as architecture, pipes, pavement, and masonry, and is considered an integral component in today's infrastructure (http://www.portcement.org/index.asp, 2003). Cement is a manufactured ingredient that, when mixed with water, will hydrate. This chemical reaction solidifies and strengthens the concrete.

Cement is composed of calcium, silicon, aluminum, and iron and is manufactured from a mixture of limestone, clay, sand, and iron ore, which have been proportioned, ground, and mixed together. Cement plants will use either a dry or a wet process as the next step. In the wet process, water is added to the dry mixture to produce a slurry. In the dry process, on the other hand, no water is added to the mixture. The slurry or dry mixture is then fed to a kiln and heated to temperatures between 2,600°F and 3,000°F. These temperatures promote a series of chemical reactions that fuse the materials and create cement clinker pellets (clinker). The clinker is cooled and ground to a fine powder and combined with gypsum to regulate the setting time of the cement. This fine powder is Portland cement (http://www.portcement.org/index.asp, 2003).

The cement industry has a limited number of by-products that result from the manufacturing process. The most voluminous by-product generated is cement kiln dust (CKD).

2.1 Cement Kiln Dust

CKD is the finely divided dry alkaline particulate matter carried from a cement kiln by the exhaust gas, and captured by the kiln's air pollution control system. CKD is composed of mixtures of calcined and uncalcined feed materials, fine cement clinker, fuel combustion by-products, and alkali compounds. The specific chemical and physical characteristics of the CKD depend, in part, on the kiln process, the method used to collect the CKD, as well as the composition of the raw material used as feed in the production of the Portland cement (USDOT, 1998). In general, however, the composition of CKD is similar to that of cement and consists of calcium carbonate, calcite, silicate, potassium sulfate, calcium sulfate, aluminum oxide, iron oxide, potassium chloride, magnesium oxide, sodium sulfate, and potassium fluoride.

An estimated 14.2 million tons of CKD are generated in the United States each year. Approximately 64 percent is used within the cement plant as feed material for the kiln; however, because only limited amounts of potassium and sodium are acceptable in cement, the remaining 36 percent cannot be reused within the plant. Of the 36 percent of CKD that remains, only 6 percent is currently used in beneficial use applications, thereby leaving 4.3 million tons of CKD to be stockpiled or disposed in landfills (USDOT, 1998).

CKD is generally nonhazardous and has a relatively low potential for leaching heavy metals. Trace constituents in CKD include cadmium, lead, selenium, and radionuclides; and these constituents are generally found at concentrations of less than 0.05 percent by weight. However, since these constituents are potentially toxic, and since the composition of CKD can vary between cement plants, it is important to assess the mobility and leachability of these trace constituents in the CKD one is proposing to beneficially use (USDOT, 1998).

2.1.1 Beneficial Uses

CKD has a chemical composition similar to that of cement; therefore, the primary value of CKD is its cementitious properties. Its alkalinity and particle size also provide value for a variety of beneficial use options. Some of the potential beneficial uses of CKD that take advantage of its cementitious, alkaline, and physical properties are as follows:

- **Waste solidification/Soil stabilization** - Waste stabilization is currently one of the most common beneficial uses for CKD. Some wastes can be physically unstable and chemically hazardous. The adsorptive capacity and cementitious properties of CKD allow it to reduce the moisture content and increase the bearing capacity of the waste, respectively; while its alkalinity allows CKD to neutralize waste, immobilize hazardous constituents, and control residual odor (Bhatty, 1995). CKD is a cost-effective alternative to other conventional waste treatment materials like lime and cement (University of Maine, 2002). The Turner Fairbanks Highway Research Center indicates in its User Guidelines for Granular Base that CKD has been used as a stabilizing and solidifying agent for environmental remediation (USDOT, 1998). Wastes from coal mine effluent (Haynes and Kramer, 1982) and industrial wastewater, to sewage and oil sludges (Morgan et al., 1984), have been stabilized using CKD.

  CKD is also used to stabilize soft or wet soil that is unsuitable for engineering purposes. CKD can be used to improve the properties of this soil *in situ*, and as an activator in pozzolanic stabilized base mixtures. The adsorptive capacity and cementitious properties of CKD allow it to reduce the moisture content and increase the bearing capacity of the soft soil (USDOT, 1998). A study conducted on test sections of road in Illinois indicated that CKD can be used successfully in place of lime or Portland cement for roadway base stabilization (Lin and Zhang, 1992). CKD not only effectively improves soil strength, but also reduces construction time and costs. When lime is used as a stabilizing agent, the soil must be remixed and compacted 48 hours after the lime is first applied (Miller and Zaman, 2000). On the other hand, when CKD is used as a stabilizing agent, the mixing and compacting of CKD are completed when it is initially applied or within 24 hours. The Turner Fairbanks Highway Research Center User Guide for Stabilized Base, a 1992 survey of state transportation agencies, indicates that at least 22 states have made use of pozzolan-stabilized base (USDOT, 1998). CKD can be mixed with soil to modify plastic limits or moisture content to provide the desired stabilized properties.

- **Replacement for Portland cement in concrete block manufacturing** - The physical characteristics of CKD are similar to those of cement. CKD and cement are solid materials with fine particulate form. Both of these products have pozzolanic properties and exhibit a similar color of various shades of gray. Therefore, it is appropriate to replace a fraction of Portland cement with CKD in numerous applications. The use of CKD as a component of concrete blocks has been demonstrated. Testing results associated with replacing 10 percent of the cement with CKD in the manufacturing process of concrete blocks indicate a significant increase in the compressive strength of the units at 28 days.

- **Replacement for Portland cement in redi-mix concrete** - Because the physical characteristics of CKD are similar to those of cement—solid material with fine particulate form, with pozzolanic properties—replacing a fraction of Portland cement with CKD in numerous redi-mix applications is appropriate.

- **Hydraulic barrier in a landfill liner/cover** - Landfill liner and covers must maintain a low permeability to contain leachate and prevent infiltration of water, respectively. Clay has generally been used to provide these low-permeability layers in landfill liners and covers; however, the cementitious properties of CKD make it a possible substitute for clay. Laboratory and field studies have shown that CKD can be compacted at an optimum moisture content to achieve permeabilities between 10^{-5} and 10^{-9} centimeters per second (cm/s), which may be suitable for many landfill applications (Todres, 1992; Johns et al., 1995; and Schmidt et al., 1999). Further work to evaluate this beneficial use is under way at several sites.

- **Land application as agricultural soil amendment** - Optimizing soil chemistry is a critical process in agriculture. Liming agents are frequently used to neutralize acidic soil. Because of its alkalinity, CKD can be, and has been, successfully used as a liming agent in acidic soil (http://agguide.agronomy.psu.edu/pdf.htm, 2003). The Clemson University Department of Crop and Soil states that the reasons for using aglime are to neutralize the acidity of soil and to add calcium and magnesium to the soil. Aglime does this; however, since carbonates are not very soluble in water, limestone must be ground very finely and mixed with the soil to be effective at neutralizing the acidity of soil. Because CKD contains higher percentages of oxides and hydroxides than of carbonates, and because it is very fine, it is more reactive than ground limestone.

  CKD is being used in some Canadian Provinces to help maintain soil fertility. The high concentrations of calcium carbonate restore the soil's pH, acidified by fertilizers, while providing nutrients in the form of potassium and sulfur (Risdale, 1994). Furthermore, in its guidelines, the Turner Fairbanks Highway Research Center discusses a significant potential market for the use of CKD as a soil conditioner for agricultural purposes (USDOT, 1998).

- **Flowable fill** - Flowable fill or controlled low-strength material (CLSM) is a mixture of coal fly ash, water, sand, and Portland cement that flows like a liquid, sets up as a solid, and is self-leveling (ACAA, 2003a). The American Concrete Institute (ACI) defines flowable fill as "… a cementitious material that is in a flowable state at the time of placement and has a specified compressive strength of 1,200 psi or less at 28 days." Flowable fill has been used as backfill in trenches, abutments, and retaining walls, and as fill for abandoned pipelines and utility vaults (USDOT, 1998). The cementitious properties of CKD make it a viable and inexpensive substitute for all or a portion of Portland cement in flowable fill mixtures.

- **Mineral filler in asphalt paving** - Of all of the paving material used in the United States, asphalt is the most popular, and the most prevalent type of asphalt paving material is hot-mixed asphalt (HMA). HMA is made by coating dried coarse and fine aggregates with hot asphalt cement, which acts as a binder. CKD has been used successfully to replace a portion of the mineral filler used in HMA. Current specifications for mineral filler in HMA (AASHTO M17) call for material passing the No. 50 sieve to be between 95 and 100 percent. Typically, the maximum particle size of CKD is about 0.3 mm (No. 50 Sieve), which conforms to the mineral filler top-size requirements. In addition to its desirable physical properties, the cementitious properties of CKD have been shown to increase the stability and stiffening of HMA (USDOT, 1998).

– **Sorbent to remove sulfur dioxide from cement kiln flue gas** - Flue gas generated from the fuel used to heat cement kilns can contain sulfur dioxide (SO_2), nitrogen oxides (NO_x), hydrogen chloride (HCl), and volatile organic compounds (VOCs), all of which present environmental hazards and are therefore subject to USEPA regulations. When coal is the fuel source, the flue gas will generally exceed emission standards for sulfur dioxide. In order to meet USEPA emission standards, scrubbers must be used to remove the sulfur dioxide. Demonstration projects have shown that CKD can be used as the sole reagent in removing sulfur dioxide from the flue gas, at efficiencies of 90 to 95 percent (USDOE, 2001).

At one location, a full-scale demonstration project was funded by the U.S. Department of Energy, National Energy Technology Laboratory (2001). The project achieved the following results:

- SO_2 removal efficiency averaged 94.6 percent.
- NO_x removal efficiency averaged 25 percent during the last several months and 18.8 percent for the entire operating period.
- 250 tons/day of CKD were used, reducing the raw feedstock requirement by 10 percent and eliminating solid waste disposal costs.
- Pilot testing conducted at USEPA laboratories showed 98 percent HCl removal.

The process involved making effective contact between flue gas and a potassium-rich slurry composed of CKD. Flue gas passed through the slurry as it moved over a special sieve tray. The slurry was then recycled as feedstock. The waste heat was used to concentrate and crystallize the potassium sulfate (K_2SO_4) by-product. The outputs to the process were recyclable CKD, potassium-based fertilizer, scrubber exhaust gas, and distilled water.

This technology is applicable in a number of other areas, including coal-fired power plants, municipal solid waste incinerators, and the pulp and paper industry. Facilities with wet scrubbing systems are potential users of CKD as a substitute for limestone, with the potential for additional benefits, and lower costs.

In a second full-scale demonstration project, a 30-day trial was conducted at a electric power-generating plant utilizing 2,500 tons of CKD as the sorbent. The CKD provided slightly better SO_2 capture at a lower slurry flow rate and a lower slurry density. The plant was able to reduce the number of spray bars as a result of the increased reactivity.

- **Mine reclamation** - Because the physical characteristics of CKD are similar to those of Portland cement, CKD can be used as a grout mixture to fill abandoned mine shafts. When mixed with water, it can be pumped in slurry form into abandoned underground shafts, where it will hydrate and set up like Portland cement mortar or grout.

2.1.2 Standards

A general American Society for Testing and Materials (ASTM) standard (ASTM 5050-96) was identified for CKD that itemizes possible beneficial use options for CKD. In addition, a Federal Aviation Administration (FAA) specification for CKD-treated subgrade was also identified. A number of technical guidance documents for beneficial use of CKD published by the United States Department of Transportation (USDOT) and the Portland Cement Association were also identified. The standards, specifications, and guidance documents identified for the beneficial use of CKD are summarized in Table 1.

2.2 Alternative Raw Materials for Cement Production

2.2.1 Production Needs for Alternative Feed Stocks

Cement producers use by-products from other industries as raw materials to make new Portland cement. Industrial by-products commonly used are fly ash, foundry sand, baghouse dust, refractories, causticizing residue, scrap tires, and mine tailings. Additional information on the use of alternative materials can be found in subsequent sections of this document under the specific industrial by-product used as a feed stock.

2.2.2 Standards

Although no technical standards were found for the use of industrial by-products as alternative feed stocks, as these uses grow, more data will likely become available.

2.3 Industry Efforts to Foster Increased Use of By-Products

The cement industry is working to increase the beneficial use of its by-products in several ways. Individual cement companies have attempted at the plant level to use as much CKD as possible in their processes and to seek out and follow up on potential beneficial uses outside of the plant. Because the cost of transporting materials has a tremendous impact on the benefit of potential uses, corporate efforts within companies are also closely linked to the locations at which the by-product is generated, to maximize the potential for the economic viability of the use.

In addition, the Portland Cement Association (PCA) is actively working to promote beneficial uses of CKD through its ongoing research efforts and continuous improvement program. Under the continuous improvement program, the PCA is considering the establishment of a numeric goal for which to strive in the reduction of the amount of CKD that needs to be disposed. The PCA's data indicate that the amount of CKD sent to long-term management units in 1990 was 6 percent of the total annual clinker production and that, in 2000, that amount had been reduced to 3 percent. The industry is looking for ways in which to reduce this amount even further.

Table 1
CKD Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Soil Stabilization/Waste Solidification	
FHWA-RD-97-148. **User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 8, Kiln Dusts and Stabilized Base**. U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	This guideline covers the use of CKD as the activator in pozzolanic-stabilized base mixtures. The guideline lists the relevant AASHTO and ASTM standards to follow for the mix design of the stabilized base. In addition, the guideline also discusses the performance record, the material processing requirements, the engineering properties, and the construction procedures.
ACE-1370. **Item P-157 Cement Kiln Dust (CKD) Treated Subgrade: Regional Modification to AC 150/5370-10A**. Federal Aviation Administration, Airports Division FAA Central Region. April, 2001.	This specification is a template or master specification to use when specifying CKD as a subgrade stabilizer. The specification includes the materials, the composition, the weather limitations, the equipment, the construction methods, and the method of measurement. In addition, the specification references the relevant ASTM and AASHTO standards required in the design.
RP343. **Use of Cement Kiln Dust in Stabilizing Clay Soils.** Portland Cement Association. 1996.	This guideline discusses the use of CKD in the stabilization of clay soil. The guideline details the mechanisms of stabilization, the characteristics of CKD, and the results of studies on CKD as a pozzolanic or ion exchange stabilization agent in clays. It provides a basis for the selection of the appropriate CKD as well as for the conclusions and recommendations.
IS525. **Suggested Specification for Solidification/Stabilization of Waste**. Portland Cement Association. 1999**.**	This specification covers the use of CKD as a solidification or stabilizing agent for waste. The specification includes a discussion on the performance requirements and testing, the contractor qualifications, the equipment, the binding reagents, the field operation, and quality control.
RP332. **Cement-Based Solidification/Stabilization of Lead-Contaminated Soil at a Utah Highway Construction Site**. Portland Cement Association. 1997.	This guideline is a reprint from *The Journal of Environmental Cleanup Costs, Technologies & Techniques*. The article describes the use of CKD in soil stabilization at a specific Superfund site in Utah. The article includes detailed information on the design and construction aspects of the use.
Landfill Liner (Permeability and Compaction)	
RD 106. **Cement Kiln Dust: Field Compaction and Resulting Permeability**. Portland Cement Association. 1992.	This guideline provides specific details on the field compaction, density, moisture, and permeability testing of CKD. In addition, the guideline also presents the results of a field study that analyzed the permeability of CKD with respect to the degree of compaction.

Table 1 (*continued*)
CKD Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Landfill Liner (Permeability and Compaction) (*continued*)	
RD 103. **Cement Kiln Dust Management: Permeability**. Portland Cement Association. 1992.	This guideline discusses approaches for obtaining compaction of CKD and for testing the permeability of the compacted CKD in the field. In addition, the guideline also provides laboratory results on the effects of compaction on the permeability of CKD.
Mineral Filler in Asphalt Paving	
FHWA-RD-97-148. **User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 8, Kiln Dusts and Asphalt Concrete**. U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	This guideline covers the use of CKD as a mineral filler in hot-mixed asphalt. The guideline references AASHTO M17, the specification for mineral filler in bituminous paving mixtures, and provides data to show that CKD meets the specification. In addition, the guideline discusses the performance record, the engineering properties, the design considerations, and the recommended construction procedures. The document also briefly covers the use of CKD as asphalt concrete aggregate, asphalt cement modifier, stabilized base, and flowable fill.
General	
ASTM D 5050-96 (2002). **Standard Guide for Commercial Use of Lime Kiln Dusts and Portland Cement Kiln Dust.** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 11.04.	This brief standard provides a list of applications and appropriate test procedures to establish selected uses for CKD, including structural, stabilization, fixation, solidification, pH control, flocculation, and agricultural purposes.

Section 3
Foundry Industry

The foundry industry produces metal castings that are found in over 90 percent of all manufactured goods and equipment. Metal castings are an integral component of other manufacturing sectors, such as motor vehicles, agricultural equipment, construction machinery, mining machinery, oil field equipment, valves and fittings, pumps and compressors, railroad equipment, metalworking machinery, etc.

A casting is a metal part formed by pouring molten metal into a sand mold or metal die. The mold or die is composed of two halves that, when mated, form a cavity into which the molten metal is poured. The mold or die form the external surface of the casting. If an internal cavity is required in the casting, a sand core is placed inside the mold cavity. After the metal solidifies, the mold is broken, the cores are removed, and the casting is readied for finishing operations. The sand is then remolded and used over and over again until it no longer possesses the properties necessary to produce quality castings.

The foundry industry is made up of approximately 2,620 individual foundries employing more than 220,000 people nationwide. Nearly 80 percent of the foundries are small and have fewer than 100 employees. In 2001, the industry produced nearly $27 billion worth of finished castings, even though they operated at 76 percent of actual capacity (AFS, 2002).

The top 10 foundry-producing states, based on a 2001 survey of total casting shipments, are as follows:

Ohio	15%	Michigan	6.3%
Alabama	12.5%	Pennsylvania	5.8%
Wisconsin	11.5%	California	3.6%
Indiana	11.5%	Virginia	3.0%
Illinois	6.7%	Texas	2.9%

Foundries pour a number of different metal alloys, which can be classified into two basic categories, ferrous and nonferrous. Ferrous metals include grey iron, ductile iron, malleable iron, and steel. Nonferrous alloys include aluminum, brass, bronze, zinc, magnesium, titanium, nickel, cobalt, and tin. In 2003, ferrous foundries are projected to produce 77.7 percent of the total tonnage of castings, while nonferrous foundries are projected to produce the remaining 22.3 percent (AFS, 2002).

The foundry industry, itself, is one of the world's first recyclers. For centuries, foundries have been making new metal objects by remelting old ones. In fact, the oldest casting still in existence is that of a copper frog made in Mesopotamia, dating back to 3,200 B.C. Old and discarded products, such as appliances, sewer grates, cans, automobiles, and water meters, are used as raw materials by the foundry industry to produce new castings. An estimated 15 to 20 million tons of scrap metal that would otherwise be sent to overcrowded landfills are being remade into new castings each year (AFS, 1999).

As with most industries, the foundry industry generates its own by-products. Typical by-product streams from the foundry industry include foundry sand, foundry slag, baghouse dust, and furnace and ladle refractory. Of these major by-product streams, foundry sand and slag are the two most often beneficially used.

3.1 Foundry Sand

Foundry sand is, by far, the largest waste stream generated by the foundry industry. For most foundries, sand accounts for 55 to 90 percent of the total waste stream for a facility. Foundries typically recycle their mold and core sand at least 8 to 10 times within the process before they are forced to remove some sand to maintain proper grain size (AFS, 1999). The foundry industry estimates that they use and reuse about 100 million tons of sand annually (AFS, 1999). Approximately 6 million tons can no longer be reused within the process and become available for beneficial use or disposal. Of this amount, less than 1 million tons are estimated to actually be beneficially used on an annual basis. The remainder of the sand must be land-disposed since no viable beneficial use options are available.

Two major types of foundry sand are used in the molding process, green sand and chemically bonded sand. Green sand, which makes up the largest percentage of the two, is generally made up of silica sand (80–85%); bentonite clay (8–10%); sea coal (3.5–6%), which is a ground bituminous coal; and water (3–4%). Other minor ingredients (flour, rice hulls, starches, cereals, etc.) may be added to absorb moisture, improve the fluidity of the sand, or stiffen the sand, based on the production needs of the individual foundry. The term "green sand" is somewhat misleading in that it is actually black; however, the term is used to describe the green strength (or molding) characteristic of the sand.

The other type of molding sand is broadly termed chemically bonded sand. As the name implies, chemically bonded sand is made by mixing silica sand with a chemical binder (1–3%) to form a mold or core. A catalyst initiates the reaction that cures the chemical resin and hardens the sand core or mold. Oil, shell core, shell mold, hot box, warm box, cold box, and no-bake (or air-set) are just some of the chemically bonded sands. The most common chemical binders include phenolic-urethanes, epoxy, furfural alcohol, and sodium silicate.

The vast majority of foundry sand is nonhazardous and has a relatively low leaching potential for heavy metals and organics. The USEPA estimates that about 2 percent of the foundry sand generated in the United States exceeds the hazardous waste characteristic for toxicity (USEPA, 1998). Foundry sand generated by foundries that pour leaded brass or bronze alloys has the highest potential for exhibiting the toxicity characteristic.

3.1.1 Beneficial Uses

Because foundry sand is made up of mostly natural sand materials, its properties are similar to the properties of natural or manufactured sand. Thus, it can normally be used as a replacement for sand. Some of the potential beneficial uses for foundry sand are as follows:

- **Structural fill** - Probably the most popular beneficial use for foundry sand is associated with structural fill, embankments, or pipe bedding. Foundry sand is typically classified as SP, SM, or SP-SM under the Unified Soil Classification System (USCS). Using the American Association of State Highway and Transportation Officials' (AASHTO's) classification system, foundry sand would be classified as A3, A-2, or A-2-4. Many contractors have found that working with foundry sand is similar to working with conventional construction materials. It is typically compacted in 6- to 12-inch lifts and should be compacted as close to optimum moisture content as possible (within 1-2%) (FIRST, 2002).
- **Road base/subbase** - Road base material is typically made of a mixture of crushed rock and enough fine material to hold the rock in place and provide for good compaction. To meet specifications for road base material, foundry sand would typically have to be blended with another aggregate to achieve the proper gradation (FIRST, 2002).
- **Fine aggregate in asphalt paving** - Asphalt concrete is the most popular paving material used in the United States. It is estimated that over 94 percent of all pavements in the U.S. are covered with asphalt. The most prevalent type of asphalt paving material is hot-mixed asphalt (HMA). HMA is made by coating dried coarse and fine aggregates with hot asphalt cement, which acts as a binder. Foundry sand has been used successfully to replace a portion of the fine aggregate used in HMA. Studies have shown that foundry sand can be used to replace between 8 percent and 25 percent of the fine aggregate content. Current specifications for fine aggregate in HMA (AASHTO M29) call for limits on material passing the 200 sieve to be between 5 and 10 percent. Typical foundry sand has higher percentages of fines and would

require screening prior to blending or would require that it be used in a limited fashion to achieve the required grain size (FIRST, 2002) (Hughes, 2002a and 2002b).

- **Aggregate for flowable fill (CLSM)** - Flowable fill or controlled low-strength material (CLSM) consists of sand, water, cement, and sometimes fly ash. The consistency of the mixture when delivered to a site is very fluid to aid in placement. The major benefit of CLSM is that it is an in-place product that, although equivalent to a high-quality compacted soil, it does not require expensive compaction efforts (equipment and labor). The American Concrete Institute (ACI) defines flowable fill as, "… a cementitious material that is in a flowable state at the time of placement and has a specified compressive strength of 1,200 psi or less at 28 days." Flowable fill has been used as backfill for bridge structures and embankments; as bedding for slabs and pipes; and as fill for caissons, piles, abandoned storage tank excavations, sinkholes, shafts, and tunnels. Almost all foundry sand can be used in flowable fill mixtures. The ACI (229R) found that foundry sand with up to 20 percent fines produced acceptable flowable fill mixtures (FIRST, 2002) (http://www.rmrc.unh.edu, 2003).

- **Fine aggregate for concrete** - Portland cement concrete is a mixture of approximately 25 percent fine aggregate, 45 percent coarse aggregate, 20 percent cement, and 10 percent water. Foundry sand can be used beneficially in concrete production as a replacement for fine aggregate. Fine aggregate consists of either natural sand or crushed stone with particle diameters of less than ⅜ inch. Typically, foundry sand is too fine to be used as a complete substitute for natural materials. In order to meet the specification for fine aggregate (ASTM C33), foundry sand is typically blended with coarser sand to achieve the desired grain-size distribution. Other aspects of foundry sand that might limit its use as a substitute for fine aggregate include clay content and organic content. These can interfere with the hydration of the cement and ultimately its strength. Foundry sand that has very few fines has been substituted for natural fine aggregates in a laboratory study. The results showed that the resulting concrete had similar compressive strengths, tensile strengths, and modulus of elasticity values as concrete made with natural materials. However, foundry sand that had not been processed to remove fines was used to replace 33 percent of the natural fine aggregate in concrete. The resulting compressive strengths were between 2,600 and 4,000 psi. Concrete mixtures with these strength levels would not be suitable for use in structural applications, and would be more suitable for buried applications like sewer pipe and below-grade concrete (FIRST, 2002).

- **Raw material for cement manufacturing** - Portland cement reacts chemically with water when hydrating, which causes it to set and to harden. When it is mixed with fine and coarse aggregate, concrete is formed. Portland cement has two specifications: ASTM C150 and ASTM C1157. Portland cement is manufactured by mixing sources of calcium oxide, silica, alumina, and iron oxide in the proper proportions in a kiln. These ingredients are found in natural rock, such as shale, dolomite, and limestone. Foundry sand can be a substitute for natural silica in Portland cement. In order for foundry sand to be used as a silica source, it must have a silica content equal to, or in excess of, 80 percent; it must be a low-alkali material; and it must have a uniform particle size. Most foundry sand would meet these criteria. However, most cement plants need extremely large quantities of these materials. Further, most cement plants have been sited close to natural sources of these materials, which makes it difficult for foundry sand to be economically competitive (FIRST, 2002).

- **Soil blending/Manufactured topsoil/Potting soil/Compost** - Foundry sand can be used as an ingredient in manufactured topsoil. The combination of its uniformity, consistency, and black color (in the case of green sand) makes it an ideal component. Foundry sand has also been used as a component in compost. It reduces the formation of clumps and prevents the mixture from compacting. This allows air to circulate through the mixture to stimulate decomposition. In Ohio, some nurseries are blending foundry sand with other soil and compost to produce a potting mix for ornamentals. Concerns about the application of foundry sand in soil mixes that will be used on food chain crops have precluded the widespread application of this beneficial use. However, research is currently under way with the U.S. Department of Agriculture's Agricultural Research Service to evaluate the risks associated with foundry sand–manufactured soil and to design specifications for the most advantageous mixtures.
- **Fine aggregate for concrete block** - Foundry sand has been used as a source of fine aggregate in the production of concrete block. The ultimate use, shape, and size of the product governs the type and gradation of the aggregate required in the concrete mixture. Concrete block manufactured with a 50 percent substitution of foundry sand for fine aggregate has achieved compressive strengths of between 50 and 2,500 psi.
- **Alternative daily cover** - Foundry sand has been used quite successfully as an alternative cover material to the traditional 6 inches of daily soil cover required by states for active faces of a landfill. This is especially useful when a landfill operation does not have an abundant supply of on-site cover soil.
- **Hydraulic barrier in landfill final cover** - Foundry sand (green sand) with a clay content in excess of 6 percent, a liquid limit of greater than 20, and a plasticity index of greater than 3 has been shown to exhibit a low permeability. Studies have shown that foundry sand possessing these characteristics can be used for final cover at landfills.

- **Rock wool** - Rock wool fibers are commonly used to reinforce other materials, such as building material insulation, and are similar to fiber glass. Rock wool is produced by combining blast furnace slag with silica or alumina in a cupola and then converting the molten material into fibers. Foundry sand has proved to be an effective source of silica in rock wool. In order for the foundry sand to be used, it must first be pretreated and formed into briquettes.

3.1.2 Standards

No material specifications developed on a national level for the use of foundry sand were identified. What currently exists in the literature are a number of technical guidance documents and a few material specifications developed by various Transportation Departments on a state level. A summary of the existing standards, specifications, and guidance for the use of foundry sand is presented in Table 2.

3.2 Foundry Slag

Foundry slag is generated during the melting process in foundry operations. The slag is a fairly complex mass that is relatively inert. It is composed of metal oxides (produced as a result of the oxidation of the metal during the melting process), melted refractory, sand from recycled scrap castings, coke ash, and other materials. Slag may be conditioned by fluxes or flocculants to facilitate removal from the furnace.

The physical form of the slag largely depends on the method of collection. Slag that is quenched in water will typically form gravel-sized particles. Slag that is removed from the furnace and poured into sand molds or “pigs” will typically resemble boulder-sized masses. Slag generated from pouring ladles used to transfer the molten metal to the mold is typically raked from the ladle onto the pouring floor. This type of slag is generally in the shape of a flat piece of metal and/or small rock-sized chunks.

3.2.1 Beneficial Uses

Foundry slag has been beneficially used in a number of applications. The most significant factor that determines whether or not foundry slag is suitable for use is the particle size. Most of the foundry slag that has been used has either been generated as part of a wet quenching collection system, or if collected dry, has undergone some particle size reduction. Although many foundries have suitable beneficial uses for their slag, published information or research on the use of foundry slag is limited. Some of the potential beneficial uses for foundry slag are as follows:

- **Coarse aggregate for concrete** - Little has been written about the use of foundry slag as a substitute for coarse aggregate in concrete mixtures. In 1994, the University of

Wisconsin - Milwaukee's Center for By-Products Utilization conducted a research project involving the use of air-cooled foundry slag as a partial replacement for native coarse aggregate in concrete. They compared reference concrete mixes made with native coarse aggregate to mixes that used 50 percent and 100 percent substitution of foundry slag for native coarse aggregate. The research found comparable 28-day compressive strengths between concrete mixtures using native coarse aggregate and those using foundry slag as coarse aggregate. However, the concrete mix that used a 100 percent substitution of foundry slag for coarse aggregate had a modulus of elasticity that was slightly higher than the reference concrete mixture (Naik, et al., 1994) (Tesch and Loeffler, 2001).

- **Coarse aggregate for asphalt** - Just as foundry slag has been used as a substitute for native coarse aggregate in concrete mixtures, it has also been used in asphalt mixtures. Here again, the slag is usually crushed to achieve the desired particle size. In general, the slag is crushed so that it will pass the ¾ -inch sieve. In addition to the larger aggregate, the desired mix will also contain about 7 to 8 percent fines that pass the 200 sieve (Lenahan, 2003).

- **Coarse aggregate for highway subbase** - Historically, foundries have used their slag as a substitute for coarse aggregate in road construction projects in and around the foundry for a number of years. In many cases, it has been used as the single source of material for gravel road construction. In other instances, it is used for roadbed, base course, or subbase material.

  Slag that has been water quenched tends to have a lowered wear resistance and soundness. For most subbase applications in which these two properties are critical, air-cooled, as opposed to water-quenched, slag is used. Most often, air-cooled slag is crushed to a ¾-inch particle size or less in order to meet most state coarse aggregate specifications. Once properly sized, these by-products can serve as suitable substitutes for native coarse aggregate in this application.

  At the present time, the Transportation Research Board is sponsoring a research effort conducted by the University of Wisconsin to evaluate the effectiveness of using foundry slag as a subbase material to help stabilize soft subgrade. The sections of roadway in which foundry slag was used as a means of providing soft ground stabilization provided a degree of stabilization equivalent to that of the traditional method of using rock aggregate (Tesch and Loeffler, 2001).

- **Raw material for cement manufacturing -** Portland cement is manufactured by mixing sources of calcium oxide, silica, alumina, and iron oxide in the proper proportions in a kiln. These ingredients are found in natural rock, such as shale, dolomite, and limestone. Foundry slag can be a substitute for calcium oxide, alumina, and iron in Portland cement. One of the issues that typically limits the use of foundry slag as a raw material in the manufacture of Portland cement is that it often is not available in quantities large enough to make it economically competitive with other natural materials. However, when native materials do not contain the necessary ingredients to manufacture Portland cement, alternatives such as foundry slag become more attractive.

3.2.2 Standards

No material specifications developed on a national level for the use of foundry slag were identified. What currently exists in the literature is a material specification developed by the Texas Department of Transportation. A summary of the existing standards, specifications, and guidance for the use of foundry sand is presented in Table 3.

3.3 Foundry Baghouse Dust

In order to control particulate emissions from foundry operations, foundries use conventional wet scrubbers and dry baghouse collection systems. Typical foundry operations that require some form of air pollution control for particulate emissions are melting, pouring, cooling, shakeout, and grinding and finishing. The nature of the dust collected is a function of the foundry operation that generates the dust. For example, the dust collected over the melting operation tends to be high in metals content. Dust collected over pouring, and cooling and shakeout operations tends to be high in silica content. Dust from grinding and finishing operations tends to be a combination of silica and metals.

3.3.1 Beneficial Uses

Most foundries dispose of the residuals collected in these devices as solid waste. However, more recently, foundries have been looking for ways to beneficially use these materials. Currently, there are two potential beneficial uses for dust collected in dry baghouses, as follows:

- **Raw material for cement manufacturing** - Dust that has a significant silica content (i.e., that collected over the sand system and that collected over grinding and finishing operations) may be suitable for use as a silica substitute in the manufacture of Portland cement.
- **Filler for plastic extrusion** - A research effort is under way to evaluate the feasibility of using foundry baghouse dust as filler material in the manufacturing of extruded plastic parts. The advantage of the foundry dust is that it is very dense and allows the extruded part to have significant weight. In addition, the research has shown that both virgin and recycled plastics can be used to make the dust/plastic composite material. The composite, depending on the plastic binder, may be stronger than concrete, may have excellent vibration and sound deadening

properties, and may be competitive from a cost perspective, with incumbent materials. Resource Recovery Corporation of West Michigan (RRC) is using foundry baghouse dust to produce prototype plastic extrusion counter weights for use in office furniture (Lenahan, 2003).

3.3.2 Standards

No material specifications have been developed on any level for use of foundry baghouse dust.

3.4 Foundry Furnace and Ladle Refractory

Furnaces used to melt metal as part of the casting process must be lined with refractory materials. Ladles used to transfer the molten metal from the melting furnace to the pouring station are also lined with refractory materials. Typical refractory materials used by the foundry industry are made of alumina, carbon, silica, fireclay, magnesia, dolomite, and calcium oxide. As part of normal operations, foundries must replace the linings of their furnaces and ladles in order to maintain the refractive properties of the material. The refractory brick and castable refractory materials removed from the ladles and furnaces in the foundry industry represent a by-product that can potentially be put to some beneficial use.

3.4.1 Beneficial Uses

Currently, most used refractory materials generated by the foundry industry are managed as solid wastes. Two of the primary reasons why these by-products are not beneficially used are because of the large particle size and the variable particle size generated during the removal process. Furnace refractory materials can be as large as small boulders and as fine as dust. Grinding of the used refractory material to a more useable particle size can enhance its capability to be beneficially used.

Used refractory materials generally possess the same environmental risks that are posed by the raw materials themselves. Refractory materials that contain significant quantities of chromium have been known to leach high levels of the metal. However, most refractory materials are fairly inert and pose limited risk when reused. Foundries that pour leaded brass and bronze alloys have sometimes experienced high levels of lead in the refractory materials removed from their furnaces and ladles. However, used refractories from ferrous and aluminum foundries have not shown similar characteristics for obvious reasons.

– **Raw material for cement manufacturing** - Refractory brick that is high in silica or alumina may be suitable for use in Portland cement manufacturing. These materials can be substituted for native materials that may not be available in the proper quantities. Typically, used foundry refractory material will have to be ground to achieve a particle size that is suitable for the cement kiln that will be using the material.

3.4.2 Standards

No material specifications have been developed on any level for the use of foundry furnace refractory or ladle refractory.

3.5 Industry Efforts to Foster Increased Use of By-Products

Most of the efforts to foster increased use of foundry by-products have been undertaken by the American Foundry Society (AFS) and by the Foundry Industry Recycling Starts Today (FIRST) group. The AFS has sponsored a number of research efforts to properly characterize by-products generated by the foundry industry and to determine how they behave in the environment. This effort led to additional research into the feasibility of using these by-products in a number of applications.

More recently, the FIRST group has been leading the industry efforts to encourage the use of foundry by-products. Currently, the FIRST group is involved in three research efforts that it believe will lead to the development of national specifications for the use of foundry by-products. The first project, which is being conducted by the University of Wisconsin, involves the development of specifications for the use of foundry sand in asphalt concrete pavement. The second project, which is being conducted by Penn State University, involves the development of specifications for the use of foundry sand in controlled low-strength material (CLSM) or flowable fill. The third project, which is being conducted by the U.S. Department of Agriculture's Agricultural Research Service, involves the evaluation of the use of foundry sand in the manufacture of topsoil and horticultural soil.

Table 2
Foundry Sand Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Structural Fill	
2002 Construction and Material Specifications, Section 703.11, **Structural Backfill for 603 Bedding and Backfill.** Ohio Department of Transportation, Division of Construction Management, Office of Construction Administration. Columbus, Ohio. 2002.	This Ohio DOT specification covers the use of structural backfill for pipe culvert, sewer, and drain bedding and for backfill for highway construction projects. The specification specifically refers to the use of foundry sand for this purpose as long as it also meets the requirements of the Ohio Environmental Protection Agency (OEPA), Division of Surface Water Policy 400.007 (Beneficial Use of Non-Toxic Bottom Ash, Fly Ash, and Spent Foundry Sand and Other Exempt Waste).
Fine Aggregate in Asphalt Paving	
FHWA-RD-97-148. **User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 7, Foundry Sand and Asphalt Concrete.** U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	The purpose of this guideline is to assist those who have an interest in using or increasing their understanding of the types of by-product materials that can be used in pavement construction applications. The specific chapter reference provides guidelines for the substitution of foundry sand for natural sand (fine aggregate) in asphalt concrete. The guidelines suggest that foundry sand can be used as a substitute for natural sand in asphalt concrete. Hot-mixed asphalt pavements for which foundry sand has been substituted for natural sand at levels higher than 15 percent have been susceptible to moisture damage owing to the hydrophilic nature of the foundry sand (primarily silica). This has resulted in the stripping of the asphalt cement coating and the accelerated deterioration of the pavement.
Flowable Fill	
FHWA-RD-97-148. **User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 7, Foundry Sand and Flowable Fill.** U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	The purpose of this guideline is to assist those who have an interest in using or increasing their understanding of the types of by-product materials that can be used in pavement construction applications. The specific chapter reference provides guidelines for the substitution of foundry sand for natural sand (fine aggregate) in flowable fill. The guidelines suggest that foundry sand can be substituted for natural sand in flowable fill. However, if a jurisdiction requires that the fine aggregate conform to ASTM C33 for flowable fill, the foundry sand will have to be blended with natural sand or other suitable material to achieve the proper gradation.

Table 2 (*continued*)
Foundry Sand Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
229R-99: **Controlled Low-Strength Materials.** Technical Document, American Concrete Institute, Committee 229, Controlled Low-Strength Materials, Farmington Hills, Michigan. 1999.	This technical document provides information on the properties of controlled low-strength materials (CLSM) or flowable fill.
Fine Aggregate for Portland Cement Concrete	
INDOT Highway Specifications, Section 904.02(a), **Fine Aggregates For Portland Cement Concrete.** Indiana Department of Transportation, Indianapolis, Indiana. 1999.	According to this specification, "Natural sand which has been used as foundry sand…" can be used in precast concrete units or precast concrete pipe. The specification requires that the foundry sand comply with Indiana Department of Environmental Management Class III or Class IV requirements.
Alternative Daily Cover at a Landfill	
ASTM D6523-00. **Standard Guide for Evaluation and Selection of Alternative Daily Covers (ADCs) for Sanitary Landfills.** American Society for Testing and Materials. April 2000.	This standard provides a general set of guidelines to assist end users in assessing different options for ADCs at sanitary landfills. The standard provides key performance information on broad classifications of ADCs, and foundry sand is included as a subcategory. The suitability and acceptability of ADCs are dependent on climate, operating conditions, and regulatory requirements; therefore, specific performance information must be evaluated on a case-by-case basis.

Table 3
Foundry Slag Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Asphalt Concrete	
Special Specification 3157 - **Cold-processed - Recycled Paving Material (RPM) for Use as a Base Course.** Texas Department of Transportation. Austin, Texas. 1993.	This Texas Department of Transportation specification covers the construction of cold-processed recycled paving material (RPM). According to this specification, foundry slag, along with other nonhazardous recycled materials may be substituted for naturally occurring gravel or crushed stone for use as coarse aggregate in the construction of cold-processed RPM. The only restriction on the use of foundry slag as coarse aggregate is that it be nonhazardous and that it meet gradation requirements.

Section 4
The Pulp and Paper Industry

The U.S. pulp and paper industry produces roughly 30 percent of the world's paper and is made up of approximately 600 pulp and paper mills located in 40 states. These facilities are large manufacturing sites, with nearly 70 percent employing more than 100 people. In 2000, the industry employed 182,000 people nationwide and produced $79 billion in pulp and paper products. Pulp and paper mills are located near their raw material source or their customers, causing the facilities to be located mainly in the Southeast, Northwest, Northeast, and North Central regions of the United States (USEPA, 2002).

Pulp and paper mills process wood fiber or secondary fiber (recycled paper) to make pulp and paper. Paper may be sent to converting facilities to manufacture specialized products, such as cartons, corrugated boxes, writing paper, and sanitary paper. This report focuses on the major by-products created by the pulp and paper mills, and not by the converting operations.

Pulping is the process of separating wood chips or recycled paper into individual fibers by either chemical, semichemical, or mechanical methods, with chemical processes being the most common for wood chips. Chemical pulping degrades wood by dissolving the lignin holding the cellulose fibers together. Chemical recovery is a crucial component of the chemical pulping process: it recovers process chemicals for reuse, which has both economic and environmental benefits. This chemical recovery system associated with the kraft pulping process produces by-products collectively termed causticizing materials.

Paper mills are engaged in manufacturing paper using pulp from wood and from recycled paper as the sources of fiber. Paper is made by mixing the fibrous material with water, and spreading the wet mixture onto a moving screen. Water is removed by gravity, vacuum pressure, and heat.

Water is recycled in pulp and paper mills to conserve energy and raw materials; however, some must be discarded to minimize problems such as corrosion or scaling. Excess process water is either treated on-site by the facility or by a municipal wastewater treatment plant. On-site treatment often consists of clarification (primary) and biological (secondary) treatment to remove suspended solids and soluble organic materials. The solid materials are separated from the treated water and are typically dewatered to a cake-like consistency utilizing belt presses or screw presses.

Energy is required to manufacture both pulp and paper. This energy can be provided by public utilities or generated on-site by the use of recovery boilers, power boilers, and turbines. Recovery boilers burn liquid called spent liquor, which is generated during the chemical pulping process. Power boilers typically burn coal, natural gas, wood, oil, and mixed solid fuels (*e.g.*, coal, wood residues, process residues, tires, etc.). Proportions of fuels used in this industry's power boilers have changed over the last few decades, with a decrease in the use of fossil fuels and an increase in the use of wood and process residues (USEPA, 2002).

The pulp and paper industry generates several by-products in its manufacturing processes. The most significant by-products are residuals from wastewater treatment, ashes from the power boilers, and causticizing materials generated from chemical recovery associated with kraft pulping. Wastewater treatment plant (WTP) residuals are composed of wood fibers, minerals and microbial biomass remaining after wastewater treatment. Boiler ash is composed of the noncombustible materials that remain after the burning of coal, wood, and other mixed fuel sources. For purposes of this report, the ashes will be divided into three categories: (1) coal ash, (2) wood ash, and (3) mixed fuel ash. Causticizing materials are composed of lime mud, lime slaker grits, and green liquor dregs. The above materials normally do not meet the definition of a RCRA hazardous waste (NCASI, 1990).

4.1 Wastewater Treatment Plant (WTP) Residuals

Wastewater treatment plant residuals constitute the largest solid waste stream generated by the pulp and paper industry. In 1995, the pulp and paper industry generated 5.8 million dry tons of WTP residuals, 2.8 million dry tons (49 percent) of which were managed in beneficial use applications, with the balance being disposed in a landfill (NCASI, 1999a). In terms of beneficial use, 26 percent of the WTP residuals were burned for energy production, 12 percent were land-applied, 5.5 percent were reused or recycled in the paper-making process, and 5.5 percent were used in other applications.

Wastewater treatment plant residuals are composed of the solid materials, traditionally called "sludge," which are collected in the process of treating wastewater prior to its release to the environment. The solids content of the WTP residuals ranges from 20 to 60 percent, depending in part upon the dewatering method applied, and generally has a near-neutral pH. These WTP residuals consist predominantly of primary and/or secondary solids derived from primary and/or secondary treatment, respectively. Primary residuals customarily are composed of wood fibers and an inorganic fraction (consisting of clay, calcium carbonate, titanium dioxide, and other material used in pulp and paper production) collected during the separation of solids from the raw wastewater in primary treatment. Secondary residuals mainly consist of the microbial biomass collected by clarification following biological treatment. Secondary residuals also contain a small fraction of inorganic constituents, including macro-nutrients (nitrogen, phosphorus, and potassium) and micro-nutrients (iron, zinc, and other metals). Facilities often combine primary and secondary solids before dewatering, because secondary solids are difficult to dewater alone (NCASI, 1993).

Wastewater treatment plant residuals are generally low in potential environmental contaminants (Vance, 2000). Potential environmental hazards are associated with trace constituents (dioxins and metals). It should be noted, however, that recent trends away from chlorine bleaching have greatly reduced the presence of dioxins. Although concentrations of metals and organics of potential concern are generally quite low, it is important to assess the mobility and leachability of these trace constituents in the WTP residual one is proposing to beneficially use (Vance, 2000).

4.1.1 Beneficial Uses

Beneficial uses of WTP residuals are based upon the chemical composition and physical characteristics of the residuals. The value of their chemical composition lies with the high fiber or high mineral content of primary WTP residuals, and the high organic content and macro-nutrients and micro-nutrients in secondary WTP residuals. Physical characteristics, such as low hydraulic conductivity and large absorption capacity, also bring value to many beneficial use applications. Some of the potential beneficial uses that take advantage of the chemical and physical composition of WTP residuals are as follows:

- **Soil amendment** - Optimizing soil chemistry is a critical process in sustaining agricultural and forested lands. The chemical composition of WTP residuals makes them excellent candidates for land application to supply organic matter and nutrients in agricultural and forested soil. Secondary WTP residuals generally have carbon to nitrogen ratios ranging from about 5:1 to 20:1, thus making the residuals a significant source of nitrogen. Secondary residuals also can be a good source of phosphorus. The organic matter in primary WTP residuals can improve the water- and nutrient-holding capacity of sandy soils, and the aeration and permeability of clayey soils. Also, both primary and secondary WTP treatment residuals can provide a significant source of other macro- and micro-nutrients (Camberato et. al., 1997). In addition to providing nutrients and organic matter to soil, some WTP residuals high in mineral content have been successfully applied as liming agents to raise the pH of acidic soil (Matysik and Gilmore, 2001).
- **Compost** - WTP residuals are also used as feedstock to compost. Composting is a process that converts organic residues into humus-like soil amendments. Large-scale compositing of WTP residuals is typically accomplished aerobically under controlled conditions. The compost produced has the potential to be applied in horticultural, agricultural, land reclamation, landscaping, and individual consumer

application to sustain soil nitrogen reserves and to improve the structural properties of soil (NCASI, 1993 and Champagne, 2002).

- **Alternative daily cover** - WTP residuals are successfully used as an alternative cover material to the traditional 6 inches of daily soil cover used for active faces of a landfill. An alternative daily cover can also help control blowing litter, animals, and insects at the landfill. Depending upon physical characteristics, some WTP residuals may require modification for consistency and workability before use as daily cover material.

- **Hydraulic barriers** - WTP residuals can achieve hydraulic conductivities on the order of 10^{-7} cm/s, and have been successfully used to construct the hydraulic barrier in landfill cover systems. Consolidation decreases the hydraulic conductivity and increases the shear strength; thus, the properties of hydraulic barriers constructed from WTP residuals improve with time (Quiroz and Zimmie, 1998). It should be noted that WTP residuals have distinctly different qualities (high water content, high organics content, and low shear strength) as compared to clay, which is traditionally used as the hydraulic barrier; therefore, special design considerations must be made when using WTP residuals. For example, minimum hydraulic conductivity has been shown to occur approximately 50 percent wet of the optimum moisture content (Moo-Young and Zimmie, 1996), and there generally is no reason to field adjust the moisture content.

- **Absorbent/Animal bedding** - Primary WTP residuals have the capacity to absorb large amounts of liquid. This desirable characteristic has been exploited by the animal bedding/litter and industrial sorbent industries (NCASI, 1993). WTP residuals have been successfully used as the base raw material in many industrial sorbent and animal bedding products, which are available on the market today. Two examples of companies that use WTP residuals in their absorbent products are International Absorbents, Inc., and Complete Spill Solutions.

- **Lightweight/Glass aggregate** - The mineral constituents of WTP residuals, commonly referred to as the ash content, can be converted to aggregate material through a heat fusing process. In the production of lightweight aggregate, the WTP residuals are typically mixed with fly ash and pelletized. The pellets are placed in a rotary kiln and heated. Once cooled, the resulting product is a lightweight aggregate that typically meets ASTM standards, and which can be used in concrete masonry, landscaping, and geotechnical applications. In the production of glass aggregate, the mineral constituents of the WTP residuals are melted by high temperatures and tapped off. The molten liquid is then cooled rapidly in a water quenching system, and the resulting product is glass aggregate. The glass aggregate can be used in floor tiles, abrasives, roofing shingles, asphalt and chip seal aggregates, and decorative landscaping. In the production of both lightweight aggregate and glass aggregate, the heat fusing process destroys any dioxins, furans, and other organics and encapsulates heavy metal constituents, such that the leached extracts of the resulting aggregates pass drinking water standards (NCASI, 1995).

- **Admixture in Portland cement concrete** - WTP residuals can be added as an admixture to concrete to serve as a source of wood fiber. Wood fibers have been shown to increase the durability and pumpability, while reducing shrink-related cracking in concrete (NCASI, 1993). The addition of residuals also may provide greater freeze-thaw cracking resistance and greater salt-scaling resistance than plain concrete (Naik et al., 2002). However, care must be taken to not reduce compressive strength, and a higher dose of high-range water-reducing admixture may be needed to avoid a high water demand in the concrete.
- **Raw material in cement manufacturing** - Those WTP residuals with a high inorganic content can serve as feedstock in the production of cement. The basic raw materials required to make cement include limestone, clay, sand, and iron ore, which provide calcium, silicon, aluminum, and iron. WTP residuals high in inorganics can contain significant quantities of these base materials (NCASI, 1993).
- **Building board** - Pulp extrusion is a process for converting WTP residuals into both structural and nonstructural solid panel and profile products. The WTP residuals require the addition of a water-soluble polymer to alter rheological properties, such that a homogeneous pulp paste can be formed and extruded. Following extrusion, the residuals are consolidated by press drying. The resulting physical and mechanical properties of the building board are dependent upon the type of fiber used as the feed material; however, the mechanical properties of building board manufactured from WTP residuals have been shown to be similar to the mechanical properties of traditional wet-process hardboard (Scott et al., 2000). Residuals from a deinking mill in the Netherlands have been used to manufacture commercial building board (Christiansen, 1998); however, the board-making facility has closed.
- **Other** - WTP residuals have also been used successfully as agricultural chemical carriers, in roofing tar or felt paper, as a fuel pellet ingredient, and to produce manufactured soil.

4.1.2 Standards

No material specifications developed on a national level for the use of WTP residuals were identified. However, specifications have been developed which consider general requirements for many of the beneficial use end products identified for WTP residuals. In addition, general guidelines were identified for the use of WTP residuals in soil amendments and hydraulic barriers. A summary of the standards, specifications, and guidance documents that were identified for the use of WTP residual is presented in

Table 4. Table 4 also lists the names of some companies that use WTP residuals in beneficial use applications.

4.2 Coal-fired Boiler Ash

Coal-fired boiler ash (coal ash) is composed of the noncombustible materials that remain after the incineration of coal during energy generation activities. Coal ash comprises about 15 percent of the 2.8 million tons of ash produced by the pulp and paper industry each year (NCASI, 1999a). Please refer to Section 5 (Utility Industry) for further discussion on the composition, uses, and standards for coal fly ash and coal bottom ash/boiler slag.

4.3 Wood-fired Boiler Ash

Wood-fired boiler ash (wood ash) comprises about 22 percent of the 2.8 million tons of ash that are produced by the energy generation activities in the pulp and paper industry each year. Of the total ash generated, 28 percent (0.8 million tons) is used in a beneficial use application, thus leaving approximately 2.0 million tons of ash to be disposed in a landfill or lagoon (NCASI, 1999a).

Wood ash is composed primarily of the noncombustible materials that remain after the incineration of wood and/or bark during energy generation activities. Wood ash is composed mainly of oxides and carbonates of potassium and calcium, but it also contains significant amounts of phosphorus, magnesium, iron, aluminum, and other micronutrients (NCASI, 1999b). Compared to coal ash, wood ash typically is higher in calcium and potassium and lower in aluminum and iron. Wood ash can also have a high level of unburned carbon, in some cases as high as 25 percent or more measured as loss-on-ignition (LOI) (Thacker, 2001).

Wood ash is generally low in potential environmental contaminants. Potentially hazardous constituents include trace metals such as arsenic, cadmium, and selenium; however, wood ash generally has more consistent and lower metals concentrations as compared to coal ash (Vance, 2000). Research has generally shown that these constituents do not leach into groundwater in land applications and do not leach from products that contain ash. However, because these trace constituents are potentially toxic and the composition of the ash can vary, it is important to assess the mobility and leachability of these trace constituents in the ash one is proposing to use, prior to considering its beneficial use (ACAA, 2003b).

4.3.1 Beneficial Uses

The primary value of wood ash is in its chemical composition. Beneficial use applications that take advantage of the chemical properties are as follows:

- **Soil amendment** - This is currently one of the most common beneficial use applications for wood ash. Optimizing soil chemistry is a critical process in agriculture. Wood ash neutralizes the pH of acidic soil in a manner similar to the use of agricultural lime and serves as a nutrient source (fertilizer) to agricultural soil (Alberta Environment, 2002). The small particle size of wood ash may promote a more rapid change in the pH of the soil as compared to traditional agricultural lime. Wood ash has also been successfully applied as a forest soil amendment. Wood ash has been proven to raise the pH of acidic soil and serves as a nutrient source to promote the growth of trees (Matysik and Gilmore, 2001).
- **Compost** - Composting is a process that converts organic matter into useful soil amendments. Wood ash has proved to be a useful additive to compost, in that it provides color enhancement and odor control to the compost, while consuming less space than bark and similar materials (NCASI, 1993).
- **Soil waste stabilization** - Wood ash is an effective agent for the chemical and/or mechanical stabilization of soil. Soil stabilization is the alteration of soil properties to improve its chemical or engineering performance. Wood ash is used to neutralize acidic soil to prevent the leaching of contaminants, and to bind contaminants within the soil. Wood ash is also used in the same manner to stabilize waste materials, such as sludges when managed in land disposal units. The wood ash neutralizes the acidic waste material to prevent leaching of contaminants and to bind contaminants within the waste (NCASI, 1993).
- **Other** - Many of the beneficial use options listed under fly ash and bottom ash/boiler slag for coal-fired combustion in Section 5 are also viable options for wood ash. However, less research and data are available in the literature for these beneficial use applications with respect to wood ash. Please refer to the coal-fired combustion products for a more formal description of these options as they apply to coal fly ash and coal bottom ash. Modifications to the wood ash may be required before it can be used in many of these applications, in order to account for the compositional differences between the coal and wood ashes.

4.3.2 Standards

National standards were not identified for any beneficial use options for wood ash. However, standards prepared for Alberta and Quebec Canada were identified, which specified the use of wood as a soil amendment. Two additional guidelines for the use of wood ash as a soil amendment were also identified. These standards and guidelines are summarized in Table 5.

4.4 Mixed Fuel Source Boiler Ash (WTP Residual, Coal, and/or Wood)

Mixed fuel source ash is the most common ash produced by the pulp and paper industry, accounting for 63 percent of the 2.8 million tons of ash produced each year. Mixed fuel ash is managed similarly to wood ash and coal ash. As a whole, 72 percent of the boiler ash produced by the pulp and paper industry is disposed in a landfill or lagoon, and 28 percent (or 2 million tons) is employed in beneficial use applications (NCASI, 1999a).

Mixed fuel source ash is composed of the noncombustible materials derived from the incineration of mixtures in varying proportions of wood, coal, WTP residuals, and/or other materials during energy generation activities. The composition of mixed-fuel ash may be more variable from facility to facility, since the relative proportion of the different fuels is variable.

4.4.1 Beneficial Uses

Many of the beneficial use options identified in Subsection 5.1 (coal fly ash), Subsection 5.2 (coal bottom ash), and Subsection 4.1 (wood ash) are viable options for mixed fuel ash. However, the variable proportion of the fuels used in mixed fuel energy generation causes the composition and engineering properties of the resulting ash to vary. Mixed fuel source ash is beneficially used; however, little literature is available that describes these use options. The beneficial uses for mixed fuel ash will be generally stated here to be similar to those of coal and wood ashes. The specific use option for each mixed fuel ash will highly depend upon the relative proportions of the fuels. Please refer to Section 5 and Subsection 4.1 for discussions of coal and wood ash, respectively.

4.4.2 Standards

Please refer to Section 5 and Subsection 4.1 for lists of standards related to coal and wood ash, respectively.

4.5 Causticizing Materials

The causticizing materials (green liquor dregs, lime slaker grits, and lime mud) are generated in the chemical recovery process, which recovers inorganic process chemicals used in the kraft pulping process. Approximately 1.7 million dry tons of these causticizing materials are produced each year. The lime slaker grits, the green liquor dregs, and the lime mud account for 15, 30, and 55 percent of the total weight, respectively. Of the 1.7 million tons of causticizing material produced, approximately 1.4 million tons (or 81 percent) are disposed in a landfill each year, with the balance (300,000 tons) used in beneficial use applications (Thacker, 2001).

Green liquor dregs are composed of nonreactive and insoluble materials remaining after inorganic process chemicals (smelt) from the recovery furnace are mixed with water. The dregs are removed by gravity clarification. Green liquor dregs consist of carbonaceous material, along with compounds of calcium, sodium, magnesium, and sulfur. They typically contain 45 to 55 percent solids (Thacker, 2001).

Lime mud (calcium carbonate and water) is burned in a lime kiln to regenerate the material to lime (calcium oxide). It normally is not a by-product; however, excess lime mud can be generated in those facilities with limited lime kiln capacity and during periods of kiln downtime. Lime mud is composed primarily of calcium carbonate, but may also contain unreacted calcium hydroxide, unslaked calcium oxide, magnesium, and sodium. The solids content of lime mud is generally between 70 and 80 percent (Thacker, 2001).

Lime slaker grits are produced when lime is mixed with green liquor. They are composed of overburned and/or underburned lime that is produced in the lime kiln. The grits also contain sodium, magnesium, and aluminum salt, and the solids content ranges from to 70 to 80 percent (Thacker, 2001).

Collectively, the causticizing materials can be characterized as having a pH above 11, and as containing varying proportions of calcium, aluminum, iron, sodium, potassium, sulfur, magnesium, and chlorine (Thacker, 2001). Calcium is a predominant component.

Causticizing residuals generally do not exhibit a significant environmental hazard. Causticizing materials have low concentrations of heavy metals, and generally exhibit neither RCRA corrosivity characteristics, nor toxicity characteristics. As with other industrial by-products, the toxicity and leachability of trace constituents in the causticizing residuals one is proposing for beneficial use should be assessed prior to its application (NCASI, 1999b).

4.5.1 Beneficial Uses

Beneficial use methods for causticizing residuals tend to take advantage of the calcium content and/or alkalinity of these materials. The potential beneficial uses that take advantage of the chemical composition of causticizing residuals are as follows:

- **Soil amendment** - Land application is the most commonly practiced beneficial use for causticizing materials, with lime mud being the material that is most commonly used as a soil amendment. The residuals serve as liming agents, replacing agricultural limestone as a means of raising soil pH to a range that enhances crop production (Camberato, et al., 1997). Causticizing residuals tend to neutralize soil more rapidly than agricultural limestone because they generally consist of smaller particles. Causticizing materials have also been successfully applied as a forest soil amendment. They have been shown to raise the pH of acidic soil and promote the growth of trees seedlings (Camberato et. al., 2000).

- **Alternative daily cover** - Lime slaker grits have been successfully used as an alternative cover material to the traditional 6 inches of daily soil cover used for active faces of a landfill. The use of grits as an alternative daily cover helps to control blowing litter, animals, and insects at the landfill.
- **Raw material in cement manufacturing** - Causticizing materials are utilized as feedstocks in the production of cement. The basic raw materials required to make cement are calcium, silicon, aluminum, and iron. Causticizing materials have high percentages of calcium, aluminum, and iron, and if properly washed (as is the norm), they generally are low in constituents that can negatively impact the production and quality of cement, such as sulfur and sodium.
- **Soil stabilization** - Soil stabilization is the alteration of soil properties to improve the chemical or engineering performance of the soil. Lime slaker grits have generally been used in this application. Lime slaker grits, when mixed with sand and compacted in lifts, have been shown to handle heavy-truck traffic better than typical soil surfaces. Lime slaker grits has also been shown to be effective as a dust suppressant on unpaved roads. While the dust from the grit/sand roads is finer than that produced from native soil roads, the grit has a better liquid-holding capacity, which improves efficiency for dust suppression techniques (NCASI, 1993)
- **Fine aggregate in asphalt paving** - Lime mud, lime slaker grits, and green liquor dregs have been used successfully as a substitute for fine aggregate in HMA (described in Subsection 3.1.1).
- **Other** - Causticizing materials have also been used in surface mine reclamation, for feedstock in compost, as an admixture to hydraulic barrier material, as a settling aid in wastewater treatment, for pH adjustment of process water, and as an ingredient in manufactured soil.

4.5.2 Standards

Very little information was available for the beneficial use of causticizing materials. One standard from Quebec, Canada, for the use of causticizing materials as agricultural liming agents was identified; however, no other standards, specifications, or guidelines that were specific to causticizing materials were identified. One general standard for alternative daily cover was also identified. The two standards are summarized in Table 6.

4.6 Industry Efforts to Foster Increased Use of By-Products

One of the leaders in promoting the beneficial use of by-products of the pulp and paper industry is the National Council for Air and Stream Improvement (NCASI) (http://www.ncasi.org/). NCASI has been an environmental resource for the forest products industry since 1943. Today, NCASI serves as an environmental resource for the forest products industry in its broadest definition, addressing a wide range of issues of importance to this industry, including the promotion of the beneficial use of the industry's by-products.

In an effort to promote beneficial use applications among its members, NCASI publishes technical reports and bulletins that address the potential beneficial use applications of pulp and paper industry by-products. In addition, NCASI has recently worked with the USEPA Region 5 in sponsoring the Midwest Industrial By-Products Beneficial Use Summit that brought together regulators and industry representatives, to better understand the beneficial use of industrial by-products. NCASI's website is www.ncasi.org.

In addition to NCASI, the Technical Association of the Pulp and Paper Industry (TAPPI) provides resources to the pulp and paper industry relating to beneficial use of pulp and paper by-products. Founded in 1915, TAPPI is the leading technical association for the worldwide pulp, paper, and converting industries providing information, education, and knowledge-sharing opportunities. TAPPI's Environmental Division actively supports beneficial use through its Residuals Management Committee. Active information exchange, and training and education are promoted at its annual meeting held in the spring each year. In addition, TAPPI hosts an active discussion board and "Ask the Experts," which are electronic forums that allow those interested in beneficial use alternatives to network with each other and industry experts. TAPPI's Web site is www.tappi.org.

Table 4
Paper Industry Wastewater Treatment By-Products Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Soil Amendment[(1)]	
Planning Guide and State Regulation Summary for Land Application of Mill By-Product Solids. NCASI Technical Bulletin 863. National Council for Air and Stream Improvement. May 2003.	This guideline describes practical steps for establishing a successful land application program for wastewater treatment plant residuals, boiler ash, and other alkaline by-product solids. The guideline discusses regulatory considerations, methods for evaluating feasibility, state contacts and permitting, research results, and environmental management and compliance issues.
Utilizing Paper Mill By-Products as Forest Soil Amendments: Forest Responses, Recommendations, and Industry Case Studies. NCASI Technical Bulletin 798. National Council for Air and Stream Improvement. February 2000.	This guideline reviews the characteristics and forest land applications of wastewater treatment residuals and boiler ash, provides a review of successful land application programs and regulatory considerations, and provides recommendations for using these by-products successfully as forest soil amendments, while minimizing the potential for adverse effects on the environment.
Compost	
AASHTO MP 10-03. **Standard Specification for Compost for Erosion/Sediment Control (Compost Blankets).** American Association of State Highway and Transportation Officials.	This specification covers compost produced from various organic by-products (including industrial residuals and biosolids), for use as a surface mulch for erosion/sediment control on sloped areas.
Alternative Daily Cover at a Landfill	
ASTM D6523-00. **Standard Guide for Evaluation and Selection of Alternative Daily Covers (ADCs) for Sanitary Landfills.** American Society for Testing and Materials. April 2000.	This standard provides a general set of guidelines to assist end users in assessing different options for ADCs at sanitary landfills. The standard provides key performance information on broad classifications of ADCs, and wastewater treatment plant residuals are included as a subcategory. The suitability and acceptability of ADCs are dependent on climate, operating conditions, and regulatory requirements; therefore, specific performance information must be evaluated on a case-by-case basis.
Hydraulic Barrier Layers	
Laboratory Hydraulic Conductivity Testing Protocols for Paper Mill Residuals Used for Hydraulic Barrier Layers. NCASI Technical Bulletin 848. Nelson, M. and C. Benson. June 2002.	This guideline provides research-defined protocols for the determination of hydraulic conductivity of wastewater treatment plant residuals for use as hydraulic barriers in landfill covers. The guideline includes a draft of an ASTM standard guide, which is currently being balloted by ASTM through Subcommittee D18.04.

Table 4 (*continued*)
Paper Industry Wastewater Treatment By-Products Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Hydraulic Barrier Layers (*continued*)	
EPA/600/R-93/182. **Quality Assurance and Quality Control for Waste Containment Facilities.** Daniel, D. and R. Koerner. September 1993.	This technical guideline provides guidance for developing construction quality assurance procedures for solid waste landfills. The guideline contains a section on hydraulic barriers, which includes discussions on liner requirements, compaction requirements, construction variables that affect hydraulic barriers, and preprocessing and placement techniques. The guideline is not specific to wastewater treatment residuals, but the quality assurance procedures apply generally to all types of barrier materials.
A Field Study of the Use of Paper Industry Sludges in Landfill Cover Systems: Final Report. NCASI Technical Bulletin 750. National Council for Air and Stream Improvement. November 1997.	This guideline provides the research results of field-scale landfill covers that were constructed to compare the field performance of paper industry WTP residuals and clay hydraulic barriers. The results showed that WTP residuals had hydraulic conductivities comparable to those of clay and underwent no deterioration.
BioMix®	BioMix® is trademarked by Allied Waste Industries and is a blend of soil and Short Paper Fiber®. The end product is a manufactured soil with a hydraulic conductivity of between 10^{-7} and 10^{-9} cm/s. The standards for selection of the wastewater treatment plant residuals and production of BioMix® are confidential.
Industrial Sorbents/Animal Bedding	
ASTM F726-99. **Standard Test Method for Sorbent Performance of Adsorbents.** American Society of Testing and Materials. February 1999.	This standard covers a test method that describes the performance of adsorbents in removing nonemulsified oils and other floating immiscible liquids from the surface of water. The standard provides definitions, testing procedures, and adsorbent classifications.
International Absorbents, Inc.	International Absorbents, Inc., creates trademarked animal bedding and industrial absorption products from pristine wastewater treatment residuals. International Absorbents' specifications and standards for selection and production are confidential.
Complete Spill Solutions (formerly Cellutech, Inc.)	Complete Spill Solutions creates trademarked industrial absorption products from wastewater treatment residuals. Its specifications and standards for selection and production are confidential.

Table 4 (*continued*)
Paper Industry Wastewater Treatment By-Products Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Lightweight/Glass Aggregate	
ASTM C 331-03. **Standard Specification for Lightweight Aggregates for Concrete Masonry Units.** American Society for Testing and Materials. May 2003.	This specification covers lightweight aggregates intended for use in concrete masonry units, when a prime consideration is to reduce the density of the unit. The specification provides the general physical requirements for lightweight aggregates, the test methods, and an aggregate grading guide for concrete masonry units. The specification is not specific to WTP residuals.
ASTM C 330-03. **Standard Specification for Lightweight Aggregates for Structural Concrete.** American Society for Testing and Materials. May 2003.	This specification covers lightweight aggregates intended for use in structural concrete in which a prime consideration is to reduce the density while maintaining the compressive strength of the concrete. The specification provides the general physical requirements and the test methods for lightweight aggregates. The specification is not specific to WTP residuals.
Lightweight/Glass Aggregate (*continued*)	
Minergy Corporation	Minergy Corporation has a patented technology for creating glass aggregate from WTP residuals. Minergy Corporation's standards and specifications for selection and production are confidential.

Note:
(1) Most states require materials promoted or sold as liming agents or fertilizer to be registered with the state agricultural department. In general, the materials are required to meet a defined set of specifications (e.g., calcium carbonate equivalence) to be considered liming agents.

Table 5
Wood Ash Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Soil Amendment[1]	
Standards and Guidelines for the Use of Wood Ash as a Liming Material for Agricultural Soils. IBSN: 0-7785-2280-6. Alberta Environment, Science and Standards Branch. July 2002.	These (Canadian) standards and guidelines apply to wood ash recovered from energy generation systems. The standards and guidelines provide general information on wood ash, regulatory requirements for generators, and recommended practices for land managers.
Product from Residue: Standard Setting for Alkaline Mill Residues in Quebec. Tappi Proceedings, 1998 International Environmental Conference and Exhibit. pp. 779-783.	This standard for Quebec, Canada, covers various alkaline residues, including wood ash, for use as agricultural liming agents. The standard provides the performance requirements and includes the quality requirements for metals and specific organic contaminants.
Recommended Practices for Using Wood Ash as an Agricultural Soil Amendment. Bulletin 1147. The University of Georgia, College of Agricultural and Environmental Sciences. September 2002.	This guideline covers a procedure for applying wood ash as a lime substitute on agricultural lands. The guideline provides general information on the methods to be used by wood ash producers and dealers, the tests to be performed on the wood ash, and the application practices for landowners.
Planning Guide and State Regulation Summary for Land Application of Mill By-Product Solids. NCASI Technical Bulletin 863. National Council for Air and Stream Improvement. May 2003.	This guideline describes practical steps for establishing a successful land application program for wastewater treatment plant residuals, boiler ash, and other alkaline by-product solids. The guideline discusses regulatory considerations, methods for evaluating feasibility, state contacts and permitting, research results, and environmental management and compliance issues.
Utilizing Paper Mill By-Products as Forest Soil Amendments: Forest Responses, Recommendations, and Industry Case Studies. NCASI Technical Bulletin 795. National Council for Air and Stream Improvement. February 2000.	This guideline reviews the characteristics and forest land applications of wastewater treatment residuals and boiler ash, provides a review of successful land application programs and regulatory considerations, and provides recommendations for using these by-products successfully as forest soil amendments, while minimizing the potential for adverse effects on the environment.

Note:
(1) Most states require materials promoted or sold as liming agents or fertilizer to be registered with the state agricultural department. In general, the materials are required to meet a defined set of specifications (e.g., calcium carbonate equivalence) to be considered liming agents.

Table 6
Causticizing By-Products Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Soil Amendment[1]	
Planning Guide and State Regulation Summary for Land Application of Mill By-Product Solids. NCASI Technical Bulletin 863. National Council for Air and Stream Improvement. May 2003.	This guideline describes practical steps for establishing a successful land application program for wastewater treatment plant residuals, boiler ash, and other alkaline by-product solids. The guideline discusses regulatory considerations, methods for evaluating feasibility, state contacts and permitting, research results, and environmental management and compliance issues.
Product from Residue: Standard Setting for Alkaline Mill Residues in Quebec. Tappi Proceedings, 1998 International Environmental Conference and Exhibit. pp. 779-783.	This standard for Quebec, Canada, covers various alkaline residues, including lime mud, green liquor dregs, and slaker grits for use as agricultural liming agents. The standard provides performance requirements and includes quality requirements for metals and specific organic contaminants.
Alternative Daily Cover at a Landfill	
ASTM D6523-00. **Standard Guide for Evaluation and Selection of Alternative Daily Covers (ADCs) for Sanitary Landfills.** American Society for Testing and Materials. April 2000.	This standard provides a general set of guidelines to assist end users in assessing different options for ADCs at sanitary landfills. The standard provides key performance information on the broad classifications of ADCs. The suitability and acceptability of ADCs are dependent on the climate, the operating conditions, and the regulatory requirements; therefore, specific performance information must be evaluated on a case-by-case basis.

Note:
(1) Most states require materials promoted or sold as liming agents or fertilizer to be registered with the state agricultural department. In general, the materials are required to meet a defined set of specifications (e.g., calcium carbonate equivalence) to be considered liming agents.

Section 5
The Utility Industry
(Coal Combustion Products)

Over half of the electricity produced in the United States is generated by the combustion of coal. The current energy policy in the U.S. focuses on supply-side solutions to future energy needs, provided by up to 400 gigawatts (GWs) of new generating capacity by 2020 (EPRI, 2003). The combustion of coal is projected to continue to provide over half of the nation's electrical energy needs during this time frame. In response to this growth in electricity demand, the demand for coal continues to increase. The total coal production in the U.S., now at 1,100 million tons per year, is expected to increase by 5.9 percent over the next 5 years.

The majority of coal combustion products (CCPs) are produced at coal-fired electric generating stations, although CCPs are also produced by many smaller industrial or institutional coal-fired boilers. The amount and types of CCPs produced at an electric generating station will depend on the type of boiler, the source of coal, and the type of emission controls installed. The electric utility industry uses three types of coal-fired boilers to generate electricity: (1) dry-bottom boilers, (2) wet-bottom boilers, and (3) cyclone furnaces. When coal is burned in a coal-fired boiler, it leaves behind ash—some of which is removed from the bottom of the furnace (bottom ash and boiler slag), and some of which is carried upward by the hot combustion gases of the furnace, and removed by collection devices (fly ash) (EPRI, 2003). In addition, a significant number of power plants burning medium- or high-sulfur coal have installed flue gas desulfurization (FGD) equipment used to remove sodium oxide (SO_x) from the combustion gases. FGD systems typically employ lime or limestone as a reactive agent to remove SO_x, and the process produces the by-product termed FGD material.

In a dry-bottom boiler, about 80 percent of the unburned material or ash is entrained in the combustion gases and is captured as fly ash. The remaining 20 percent of the ash is dry-bottom ash collected in water-filled hoppers at the bottom of the furnace. In wet-bottom and cyclone boilers, the bottom ash is kept in a molten state and tapped off as liquid into an ash hopper to form boiler slag. In wet-bottom furnaces, as much as 50 percent of the ash is retained as boiler slag, with the remaining 50 percent being captured as fly ash. In a cyclone furnace, some 70 to 80 percent of the ash is retained as boiler slag, with the rest being captured as fly ash (USDOT, 1998).

All coal contains a variety of noncombustible minerals, which consist primarily of silica, alumina, and iron, with smaller percentages of calcium, magnesium, sulfates, and other compounds (USDOT, 1998). The amount and the types of noncombustible minerals are based on the coal source. These noncombustible minerals remain as by-products after coal is burned, and are collectively termed coal ash. Coal ash is regulated as a solid waste under Subtitle D of the Resource Recovery and Conservation Act (RCRA). Coal ash has a relatively low leaching potential for heavy metals. Trace constituents in coal ash include arsenic, cadmium, selenium, and radionuclides. Research has generally shown that these constituents do not leach into groundwater in land applications and do not leach from products that contain coal ash. However, because these trace constituents are potentially toxic and the composition of coal ash can vary, assessing the mobility and leachability of these trace constituents in the coal ash one is proposing to use is important, prior to considering its beneficial use (ACAA, 2003b).

The use of ash as a building material is not new. More than 2,000 years ago—long before the invention of Portland cement—the Romans used volcanic ash to construct magnificent structures that are still standing today, such as the Pantheon (ACAA, 2003d). Modern interest in using coal fly ash as a cementitious product began in post-war Europe. By the 1950s and 1960s, power plants were collecting their fly ash and creating a number of beneficial uses.

In 2001, approximately 37 million tons of coal combustion products were beneficially used in the United States based on information provided by the American Coal Ash Association (ACAA, 2003a). This represents approximately 31 percent of the almost 118 million tons produced in 2001. But 81 million tons are still being disposed in landfills. America's power plants are investing in equipment and programs to collect, store, and deliver by-products to the markets that need them. The future use of CCPs will be affected by the ability of the industry to overcome negative perceptions, as well as the potential consequences of future environmental rules on the quality and usability of these products.

5.1 Fly Ash

Fly ash is the most significant product generated by the combustion of coal, with over 68 million tons being produced in 2001 (ACAA, 2003a). Approximately 32 percent of the fly ash that is produced is reused in beneficial use applications, leaving approximately 44 million tons to be disposed in landfills or lagoons.

Fly ash is composed of the fine-grained, powdery particulate material that remains suspended in the exhaust gas during the combustion of coal. The ash is collected by electrostatic precipitators, or other methods, through the stacks of a plant. The physical and chemical characteristics of fly ash vary among the combustion methods, coal properties, and particle shape of the fly ash. Fly ash is typically finer than Portland cement and lime. Fly ash consists of silt-sized particles that are generally spherical, typically ranging in size between 10 and 100 microns (ACAA, 2003a).

Fly ash consists primarily of oxides of silicon, aluminum, iron, and calcium. Magnesium, potassium, sodium, titanium, and sulfur are also present to a lesser degree (ACAA, 2003a). Fly ash is divided into two categories based on chemical composition: Class C and Class F. Class C fly ash is derived from subbituminous and lignite coal and contains more than 20 percent calcium oxide (CaO) and 1 to 3 percent free lime. Class C fly ash is considered self-cementing. Class F fly ash is derived from bituminous and anthracite coal and contains less than 10 percent CaO and no free lime (USDOT, 1998). Class F fly ash is not self-cementing.

5.1.1 Beneficial Uses

Currently, the primary value of fly ash is its cementitious properties. In addition to the cementitious properties, the unique spherical shape, particle size distribution, and alkalinity of fly ash provide value for a variety of beneficial use options. Some of the potential beneficial uses for fly ash that take advantage of its cementitious, alkaline, and physical properties are as follows:

- **Mineral admixture in Portland cement concrete** - Fly ash has been successfully used as a mineral admixture in concrete for over 60 years (USDOT, 1998), and this is currently the most common beneficial use application for fly ash (ACAA, 2003a). As a mineral admixture, fly ash functions in addition to, or as replacement for, a portion of Portland cement in the concrete mixture. Its use as a mineral admixture takes advantage of the cementitious properties of the ash. Portland cement contains approximately 65 percent free lime, some of which becomes free and available during hydration. When fly ash is present with the free lime, it reacts and provides additional cementitious material to the concrete, thus improving many of the properties of the concrete. The introduction of fly ash decreases the cost, improves the workability, decreases the water demand, reduces the heat of hydration, increases the ultimate strength, reduces the permeability, and improves the durability of the concrete.
- **Grout** - Fly ash has been used successfully as an ingredient in grout to fill voids under a pavement slab without raising the slab (subsealing), or to raise and support concrete pavements at specified grade tolerances (ACAA, 2003a). Subsealing grout must be able to flow and fill very small voids, and have adequate strength to support the pavement slab. The spherical particle shape and cementing properties of fly ash provide these required characteristics. The difference between grout and flowable fill (defined below) is in the unconfined compressive strength of grout. Subsealing grout typically exceeds the strength limit of flowable fill (8,300 kPa) at 28 days, which is necessary for the intended purpose of the grout.

- **Mineral filler in asphalt paving** - Fly ash has been used successfully to replace a portion of the mineral filler used in hot-mixed asphalt (HMA). Current specifications for mineral filler in HMA (AASHTO M17) call for material passing the No. 200 sieve to be between 70 and 100 percent. Most fly ash falls within a size range of between 60 and 90 percent passing the No. 200 sieve. In addition, fly ash generally can also meet the organic impurity and plasticity requirements for mineral filler specification (USDOT, 1998). Fly ash provides some additional benefits to HMA, which include reducing the potential for stripping owing to its hydrophobic and alkaline properties and providing a lower cost alternative to other mineral fillers (ACAA, 2003a).
- **Flowable fill** - Flowable fill is a mixture of coal fly ash, water, sand, and Portland cement that flows like a liquid, sets up as a solid, and is self-leveling (ACAA, 2003a). Flowable fill has been used to backfill trenches, abutments, and retaining walls, and to fill abandoned pipelines and utility vaults (USDOT, 1998). There are two types of flowable fill mixes: those high in fly ash content and those low in fly ash content. The flowable character of these mixtures derives from the spherical and irregular particle shape and size of fly ash. Virtually any fly ash can be used in flowable fill mixtures. In mixes high in fly ash content, self-cementing fly ash (Class C) is used and can replace up to 100 percent of the Portland cement content. In mixtures of low fly ash content, Class F (low calcium oxide content) fly ash is generally used, and the cementitious properties of the mixture are dependent upon the Portland cement content. Fly ash is a critical component in these mixtures, as it provides the flowable character of the fill (ACAA, 2003).
- **Structural fill** - Fly ash can be used as a structural fill to construct fills and embankments. This is currently the second most common beneficial use application for fly ash. When fly ash is constructed in lifts and compacted at an optimum moisture content, it becomes capable of supporting roads and structures (ACAA, 2003a). Because the addition of moisture is necessary for the construction of the structural fills, Class F fly ash is generally used. The self-cementing properties of Class C fly ash would pose a handling problem and a potential inability to achieve the required degree of compaction for the fills (USDOT, 1998).
- **Waste solidification/Soil stabilization** - Fly ash is an effective agent for the chemical and/or mechanical stabilization of soil and waste. Waste solidification/Soil stabilization is the alteration of waste or soil properties to improve the chemical or engineering performance of the waste or soil. Class C fly ash is generally used in waste solidification/soil stabilization for its self-cementing properties; however, Class F fly ash is also used when liming agents are to be added to the soil. The primary reason fly ash is used for this purpose is to improve the compressive and shear strength of the waste or soil. In addition, fly ash is also used to control the shrink and swell of plastic soil, and to reduce the water content of wet soil. It

controls the shrink/swell of soil by cementing soil grains together, thus restricting soil particle movement. Class C fly ash reduces the water in soil, through chemical reactions (Class C fly ash contains tricalcium aluminate, which is highly reactive with water), and through simple dilution (ACAA, 2003a). In addition to affecting the physical properties of a waste or soil, fly ash is used to neutralize acidic soil to prevent the leaching of contaminants, and to bind contaminants within the waste or soil.

- **Soil amendment** - Optimizing soil chemistry is a critical process in agriculture. Liming agents are frequently used to neutralize acidic soil. Because Class C fly ash is composed of over 20 percent lime, it can be, and has been, successfully used as a liming agent in acidic soil (http://agguide.agronomy.psu.edu/pdf.htm, 2003).

5.1.2 Standards

Numerous ASTM standards were identified for the use of fly ash in Portland cement concrete, for soil and waste stabilization, fill material, and surface mine reclamation. In addition, specifications from AASHTO and the American Concrete Institute (ACI) were also identified for the use of fly ash in hot-mixed asphalt and flowable fill. Technical guidelines for the use of coal ash in Portland cement, as mineral filler in hot-mixed asphalt, as fill material, and in flowable fill were also identified. The standards, specifications, and guidelines that were identified for fly ash are summarized in Table 7.

5.2 Bottom Ash/Boiler Slag

Approximately 18.8 million tons of bottom ash and 2.5 million tons of boiler slag were produced in 2001 (ACAA, 2003a). Approximately 30 percent of the bottom ash that was produced and approximately 72 percent of the boiler slag that was produced is used in beneficial use applications. Consequently, 13 million tons of bottom ash and 0.7 million tons of boiler slag were placed either in landfills or in lagoons.

Bottom ash is the coarse-grained, granular, sand-like material that falls to the bottom of a dry-bottom boiler during the combustion of pulverized coal. Bottom ash is predominantly sand-sized particles, usually with 50 to 90 percent passing a 4.75 mm (No. 4) sieve, and 0 to 10 percent passing a 0.075 mm (No. 200) sieve (USDOT, 1998).

Boiler slag is vitrified bottom ash. It has the same origin as bottom ash, but is a different end product as a result of the type of coal-burning furnace used. Bottom ash is generated from a dry-bottom boiler, whereas boiler slag is generated from a wet-bottom boiler. When the latter boiler is used, the material that would be bottom ash is kept in a molten state and tapped off as a liquid. The wet-bottom boiler contains quenching water to cool the molten liquid. In this type of furnace, the molten liquid is cooled rapidly, and thus the end product is a coarse, hard, angular, and glassy material (USDOT, 1998). Boiler slag is essentially a course to medium sand, predominately single sized and within a range of 5 to 0.5 mm (No. 4 to No. 40 sieve size).

5.2.1 Beneficial Uses

The primary value of bottom ash and boiler slag is the particle size of these materials. The durability of boiler slag is an additional value. The beneficial use applications that take advantage of the particle size of bottom ash and boiler slag and the durability of the slag are as follows:

- **Fine aggregate in asphalt paving** - Both bottom ash and boiler slag have been used successfully as a substitute for fine aggregate in HMA (described in Subsection 2.1.1). Current specifications for fine aggregate in HMA (ASTM D1073) call for 100 percent of the material to pass the 9.5 mm sieve. Boiler slag generally meets this size requirement without requiring additional screening; whereas, bottom ash frequently requires screening of oversized material to satisfy this definition of a fine aggregate. Boiler slag consists of hard and durable particles, and is thus used more frequently as fine aggregate in HMA than is bottom ash (USDOT, 1998).
- **Granular base** - Both bottom ash and boiler slag have been used as the unbound aggregate or granular base in pavement construction. The bottom ash and boiler slag must meet the conventional material specifications for gradation, soundness, and abrasion loss for the granular base to be used in this application. If the gradation requirement cannot be met, the ash or slag can be mixed with other aggregates (USDOT, 1998).
- **Soil stabilization/Waste solidification** - Bottom ash and boiler slag have been used successfully for soil stabilization as either the fine aggregate fraction or as the entire aggregate fraction in Portland cement or pozzolan-stabilized base or subbase mixtures. When gradation requirements are specified for a subbase mixture, the bottom ash or boiler slag may need to be blended with other aggregates (USDOT, 1998). These materials have also been used successfully in waste stabilization applications. The bottom ash and boiler slag can be applied to solidify the wastes and/or to chemically fixate inorganic constituents.
- **Structural fill** - Bottom ash and boiler slag can be used as structural fill material. When these materials are constructed in lifts and compacted at an optimum moisture content, they become capable of supporting roads and structures. The specific engineering properties of bottom ash and boiler slag may vary greatly; therefore, it is recommended that the ash and slag always be evaluated for its specific fill application requirements.

- **Snow and ice control** - Both bottom ash and boiler slag have been used as an anti-skid material on icy roads (Alliant, 2003).
- **Other** - Bottom ash and boiler slag have been used in surface mine reclamation, and boiler slag has also been used as blasting grit and as roofing shingle granules (Alliant, 2003).

5.2.2 Standards

ASTM standards for the use of bottom ash and boiler slag in structural fills, waste solidification/stabilization, and surface mine reclamation were identified. In addition, several technical guidelines were also identified for the use of these by-products as fine aggregate in asphalt, granular base, structural fill, and stabilized base. These standards and guidelines are summarized in Table 8.

5.3 Flue Gas Desulfurization (FGD) Material

The use of FGD material has significantly grown in recent years, and is expected to grow even more. In 2001, approximately 28 million tons of FGD material were produced (ACAA, 2003c). Approximately 27 percent of the material was reused in beneficial use applications in 2001, up from only 6.7 percent in 1996. However, in 2001, almost 21 million tons of FGD material were placed either in landfills or in holding ponds.

FGD material is the wet solid residue generated from the treatment of emissions at coal-fired power plants. The burning of pulverized coal produces sulfur dioxide (SO_2) emissions that, without treatment, would exceed USEPA air emission standards. The best available technology for treating SO_2 emissions is with wet scrubber FGD systems. These systems are designed to introduce an alkali sorbent in a spray form into the exhaust gas of the coal-fired boiler. The alkali reacts with the SO_2 gas and is collected in a liquid form as calcium sulfite or calcium sulfate slurry. The calcium sulfite or sulfate is allowed to settle and is separated from the water, and the resulting material is collectively termed FGD material. The proportion of the calcium sulfite or sulfate in the FGD material is a function of the FGD process used by a plant (USDOT, 1998).

When dewatered, calcium sulfite FGD material becomes a soft filter cake with a solids content typically in the 40 to 65 percent range (USDOT, 1998). Calcium sulfate FGD material can be dewatered much more easily and may have a solids content of up to 70 to 75 percent after dewatering. FGD material is primarily made up of silt-sized particles.

5.3.1 Beneficial Uses

The primary value of FGD material is its chemical composition. FGD material that has a higher calcium sulfate content has a variety of beneficial use applications in the construction and agricultural industry. Some of the beneficial use applications that take advantage of the chemical composition of FGD material include the following:

- **Wallboard** - This is the most common beneficial use application for FGD material that is rich in calcium sulfate. Wallboard is traditionally made from naturally occurring gypsum, which is a hydrated form of calcium sulfate. FGD that is rich in calcium sulfate can be used to replace the gypsum in wallboard, thus reducing the demand to mine natural gypsum. This is an especially popular alternative along the eastern seaboard, where gypsum is scarce and the use of FGD scrubbers is relatively common (EPRI, 1999).
- **Soil stabilization/Waste solidification** - FGD material has been used successfully as stabilized base and subbase material in highway construction projects and as a solidifying and stabilizing agent with inorganic wastes. In soil stabilization applications, fixated FGD material is produced in a compactable condition and can be used in the same manner as other lime, fly ash, or cement-stabilized base materials. The FGD material can be used as is, if testing shows that it can meet the required compressive strength and durability. If the FGD material cannot meet these requirements on its own, then a fixating reagent (Portland cement, lime, fly ash, etc.) must be added to the material to increase its strength and durability (USDOT, 1998). In waste stabilization applications, FGD material chemically fixates inorganic waste constituents, and its high pH stabilizes the waste.
- **Admixture in Portland cement concrete** - FGD that is rich in calcium sulfate is added to Portland cement in order to retard the setting of concrete. This allows wet concrete that is transported in ready-mix trucks to be transported greater distances while remaining workable. To be used in this application, the FGD material must not contain significant quantities of calcium chloride, which can accelerate the setting of the concrete and promote corrosion of the reinforcement bars (EPRI, 1999).
- **Soil amendment** - Optimizing soil chemistry is a critical process in agriculture. Liming agents are frequently used to neutralize acidic soil. Because FGD material has a high pH, it can be, and has been, successfully used as a liming agent in acidic soil. In addition, FGD material has a high permeability, thus making it an excellent soil conditioner, and it provides a good source of sulfur and calcium to specific crops (legumes, potatoes, and cotton). FGD has also been shown to provide beneficial trace elements to the soil and to enhance root nodule growth (EPRI, 1999).
- **Structural fill** - FGD material can be used as a structural fill when it has been fixated to produce a soil-like material. When the fixated FGD material is

constructed in lifts and compacted at an optimum moisture content, it becomes capable of supporting roads and structures. The specific engineering properties of FGD material vary greatly; therefore, it is recommended that the material always be evaluated for its specific fill application requirements (EPRI, 1999).

– **Mine reclamation** - Flowable fill that contains FGD material is used in reclaiming coal mines that are no longer in use. This flowable fill reduces acid mine drainage and fills voids, which helps to prevent subsidence of the ground above the mine. The fill is injected into areas where leaching can occur. The fill eliminates the possibility of air and/or oxygenated water from reaching acid mine drainage-forming materials. In addition, the alkaline nature of the FGD material can help to neutralize any acids that do form (EPRI, 1999).

5.3.2 Standards

ASTM standards for the use of FGD material in waste solidification/stabilization, structural fills, and surface mine reclamation applications were identified. In addition, one technical guideline for the use of FGD material in stabilized bases was identified. These standards and guidelines are summarized in Table 9.

5.4 Industry Efforts to Foster the Increased Use of Coal Combustion Products

The coal combustion industry has an extensive history in fostering the use of coal combustion products (CCPs). One of the primary organizations leading these efforts is the American Coal Ash Association (ACAA), a not-for-profit 501(c)(6) organization that promotes the beneficial use of CCPs for its members (http://www.acaa-usa.org/who.htm). The mission of the American Coal Ash Association (ACAA) is to advance the management and use of CCPs in ways that are technically sound, commercially competitive, and environmentally safe. ACAA and its members work to gain the recognition and acceptance of specifiers, designers, contractors, legislators, regulators, and others for CCPs on par with competing engineering and manufactured materials. To accomplish its mission, ACAA sponsors educational workshops and meetings on topics related to CCP management and use and provides training to CCP managers and interested parties. ACAA also publishes technical reports, pamphlets, and documents that describe CCP utilization and applications. ACAA holds an international symposium biannually, at which more than 100 technical papers are presented by authors from around the world. Proceedings of these symposia are published through a cooperative agreement with the Electric Power Research Institute. This international cooperation has strengthened the awareness of the value and variety of uses for CCPs.

In 2003, the Coal Combustion Products Partnership (C^2P^2) was established to promote the beneficial use of CCPs and the environmental benefits that result from their use (http://www.epa.gov/epaoswer/osw/conserve/c2p2). The C^2P^2 is a joint agency-industry effort among the USEPA, the ACAA, the Utility Solid Waste Activities Group (USWAG), the Department of Energy, and the CCP generators and marketers. The C^2P^2 initiative includes three primary activities: (1) a challenge program promoting and recognizing participants, (2) barrier-breaking activities, and (3) the development of CCP utilization workshops.

Table 7
Fly Ash Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Mineral Admixture in Portland Cement Concrete	
ASTM C 311-02. **"Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete."** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 04.02.	This standard covers procedures for sampling and testing fly ash for use in Portland cement concrete. The standard provides a list of chemical and physical analyses required for characterizing fly ash.
ASTM C 618-02. **"Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete."** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 04.02.	This specification covers the use of coal fly ash in concrete where cementitious action is desired. The specification offers a classification system for fly ash based on chemical and physical requirements.
AASHTO M 295-00. **"Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete."** American Association of State Highway and Transportation Officials. 22nd Edition. 2002.	This specification covers the use of coal fly ash in concrete where cementitious action is desired. The specification offers a classification system for fly ash based on chemical and physical requirements. This standard is synonymous with ASTM C 618-02.
FHWA-RD-97-148. **User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 5, Coal Fly Ash and Portland Cement Concrete.** U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	This document covers the use of fly ash as a mineral admixture in Portland cement concrete. The document references relevant ASTM standards and provides data to show how fly ash meets these standards. In addition, the document discusses the performance record, the engineering properties, the design considerations, and the recommended construction procedures.
ACI 232.2R. **Use of Fly Ash in Concrete.** American Concrete Institute. ACI Committee 315.	This document reviews the origin and properties of fly ash, the effect fly ash has on the properties of Portland cement concrete, and the proper selection and use of fly ash in the production of Portland cement concrete.
FHWA-1F-03-019. **Fly Ash Facts for Highway Engineers: Chapter 3, Fly Ash in Portland Cement Concrete.** American Coal Ash Association. June 2003.	This document covers the use of fly ash as a mineral admixture to Portland cement concrete. The document discusses the benefits to using fly ash, the mix design and specification requirements, the properties of fly ash and how fly ash meets the design requirements, and construction practices.

Table 7 ***(continued)***
Fly Ash Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Mineral Admixture in Portland Cement Concrete ***(continued)***	
Fast-Track Concrete Pavements. Technical Bulletin 004P. American Concrete Pavement Association. 1994.	This guideline covers the use of fly ash in fast-track concrete mixtures. The guideline mainly provides a procedure for designing fast-track concrete; however, one section specifically addresses the use of fly ash in fast-track concrete and provides some general design specifications for the fly ash.
Grout	
ASTM C593-95. **Standard Specification for Fly Ash and Other Pozzolans for Use with Lime.** American Society for Testing and Materials. February 1995.	This specification covers the use of fly ash with lime in plastic mortars, nonplastic mixtures, and other mixtures that affect lime pozzolanic reactions. The specification covers terminology, physical properties, and test methods.
FHWA-1F-03-019. **Fly Ash Facts for Highway Engineers: Chapter 9, Fly Ash Grouts for Pavement Subsealing.** American Coal Ash Association. June 2003.	This document covers the use of fly ash as a grout for sealing voids beneath pavement slab sections. The document covers mix design and specification requirements, and construction practices.
Slab Stabilization Guidelines for Concrete Pavements. Technical Bulletin 018P. American Concrete Pavement Association. 1994.	This guideline covers the use of fly ash grout as a slab stabilization material. The guideline provides testing procedures and selection criteria for the fly ash that will be used to make the pozzolan-cement grout.
Mineral Filler in Asphalt Paving	
AASHTO M 17-83. **Standard Specification for Mineral Filler for Bituminous Paving Mixtures.** American Association of State Highway and Transportation Officials. 14th Edition. 1986.	This specification covers mineral filler added as a separate ingredient for use in asphalt paving mixtures. The specification provides a general description of the mineral filler and lists its physical requirements. The standard is not specific to fly ash.
FHWA-RD-97-148. **User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 5, Coal Fly Ash and Asphalt Concrete.** U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	This document covers the use of fly ash as a mineral filler in hot-mixed asphalt. The document references AASHTO M17, the specification for mineral filler in bituminous paving mixtures, and provides data to show that fly ash meets the specification. In addition, the document discusses the performance record, the engineering properties, the design considerations, and the recommended construction procedures.
FHWA-1F-03-019. **Fly Ash Facts for Highway Engineers: Chapter 8, Fly Ash in Asphalt Pavements.** American Coal Ash Association. June 2003.	This document covers the use of fly ash as a mineral filler in hot-mixed asphalt. The document provides the mix design and specification requirements for the hot-mixed asphalt, in reference to AASHTO M17.

Table 7 *(continued)*
Fly Ash Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Flowable Fill	
ASTM 595.03. **Standard Specification for Blended Hydraulic Cements.** American Society for Testing and Materials, *Annual Book of ASTM Standards*. Volume 04.01.	This specification covers five classes of hydraulic cements for both general and specific applications. The specification prescribes the ingredients and proportions, along with some select performance requirements.
Flowable Fill (*continued*)	
ACI 229R-99. **Controlled Low-Strength Materials.** American Concrete Institute: ACI Committee 229. April 1999.	This guideline provides information on the application, the material properties, the mix design, and the recommended construction procedures for flowable fill. The guideline covers the use of fly ash in flowable fill within the mix design subsection.
FHWA-RD-97-148. **User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 5, Coal Fly Ash and Flowable Fill.** U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	This document covers the use of fly ash in the production of flowable fill (controlled low-strength material). The document references relevant ASTM standards. In addition, the document discusses the performance record, the material processing requirements, the engineering properties, the design considerations, and the recommended construction procedures.
FHWA-1F-03-019. **Fly Ash Facts for Highway Engineers: Chapter 5, Fly Ash in Flowable Fill.** American Coal Ash Association. June 2003.	This document covers the use of fly ash as an ingredient in flowable fill. The document provides the mix design and specification requirements for mixes with both high and low fly ash content.
Structural Fill	
ASTM E 1266-88. **Standard Practice for Processing Mixtures of Lime, Fly Ash, and Heavy Metal Waste in Structural Fills and Other Construction Applications.** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 11.04.	This standard provides descriptions and references of test methods and commercial practices relating to the processing of fly ash in construction applications. The standard provides a discussion on the properties of fly ash as applicable to fill material, the applications pertaining to waste solidification, the laboratory procedures for developing design mixtures, and the recommended construction procedures.
ASTM E 1861-97. **Standard Guide for Use of Coal Combustion By-Products in Structural Fills.** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 11.04.	This standard covers the use of coal combustion products in engineered structural fills. The standard provides the design and construction procedures and the required tests for the coal combustion products.

Table 7 (*continued*)
Fly Ash Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Structural Fill (*continued*)	
FHWA-RD-97-148. **User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 5, Coal Fly Ash. Embankment, or Fill**. U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	This document covers the use of fly ash as structural fill or embankment material. The document references numerous case studies that have used fly ash as structural fill in the United States. In addition, the document discusses the material processing requirements, the engineering properties, the design considerations, and the recommended construction procedures.
FHWA-1F-03-019. **Fly Ash Facts for Highway Engineers: Chapter 6, Fly Ash in Structural Fills/Embankments.** American Coal Ash Association. June 2003.	This document covers the use of fly ash as a structural fill and embankment material. The document covers the design and specification requirements, and the construction practices. These documents and specifications are generally similar to those for engineered soil fills.
Technical Advisory T 5080.9. **Use of Coal Ash in Embankments and Bases.** U.S. Department of Transportation, Federal Highway Administration. May 1988.	This guideline covers the use of coal ash as an embankment material. The guideline discusses environmental concerns, design considerations, and construction considerations.
Waste Solidification/Soil Stabilization	
ASTM E 2060-00. **Standard Guide for Use of Coal Combustion By-Products for Waste Stabilization.** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 11.04.	This guideline covers the methods for selecting and applying coal combustion products for use in chemical stabilization of trace elements in waste and wastewater. The standard provides the test methods for characterization, a framework for selecting a coal combustion product, and the test methods for assessing stabilization of the waste.
ASTM D 5239-98. **Standard Practice for Characterizing Fly Ash for Use in Soil Stabilization.** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 04.08.	This standard covers procedures for characterizing fly ash to be used in soil stabilization. The standard lists representative test methods for determining the chemical, physical, and cementitious properties of fly ash. In addition, the standard provides a guideline that explains the significance of the properties in soil stabilization.
FHWA-RD-97-148. **User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 5, Coal Fly Ash and Stabilized Base.** U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	This document covers the use of fly ash as a component of stabilized base and subbase mixtures. The document references relevant ASTM standards and provides data to show how fly ash meets these standards. In addition, the document discusses the performance record, the material processing requirements, the engineering properties, the design considerations, and the recommended construction procedures.

Table 7 (*continued*)
Fly Ash Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Waste Solidification/Soil Stabilization (*continued*)	
FHWA-1F-03-019. **Fly Ash Facts for Highway Engineers: Chapter 7, Fly Ash in Soil Improvement.** American Coal Ash Association. June 2003.	This document covers the use of fly ash as an additive to improve the engineering performance of soil. The document provides design requirements to improve the strength of soil, to control the shrink and swell of soil, and to reduce water content.
FHWA-1F-03-019. **Fly Ash Facts for Highway Engineers: Chapter 4, Fly Ash in Stabilized Base Course.** American Coal Ash Association. June 2003.	This document covers the use of fly ash as an ingredient in stabilized base course mixtures for highway construction. The document provides the mix design and specification requirements, the testing procedures, and the construction practices.
Coal Fly Ash in Pozzolanic Stabilized Mixtures for Flexible Pavement Systems (Flexible Pavement Manual). American Coal Ash Association.	This document covers the use of fly ash as an ingredient in stabilized base course mixtures for highway construction. The document covers the material selection criteria, mix design, AASHTO's pavement thickness design criteria, and the pavement construction specifications and design requirements.
Fly Ash for Soil Improvement. Geotechnical Special Publication No. 36. American Society of Civil Engineers. 1993.	This guideline includes eight technical papers that address the use of fly ash in general and specific case studies for soil stabilization applications.
Soil Amendment[(1)]	
AASHTO MP 10-03. **Standard Specification for Compost for Erosion/Sediment Control (Compost Blankets).** American Association of State Highway and Transportation Officials.	This specification covers compost produced from a variety of feedstocks, including industrial residuals, for use as a surface mulch for erosion/sediment control on sloped areas. The specification provides reference to standard test methods and field applications.
General	
ASTM D 5759-95. **Standard Guide for Characterization of Coal Fly Ash and Clean Coal Combustion Fly Ash for Potential Uses.** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 11.04.	This standard provides recommended test procedures for the characterization and evaluation of fly ash. In addition, the standard provides a guideline to select potential end uses of the fly ash based on the results of the recommended physical and chemical tests.

Table 7 (*continued*)
Fly Ash Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Other	
ASTM E 2243-02. **Standard Guide for Use of Coal Combustion By-Products in for Surface Mine Reclamation.** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 11.04.	This standard covers the use of coal combustion products for surface coal mine reclamation applications. The standard provides guidance to identify the coal combustion products with the appropriate engineering properties and environmental performance for recontouring applications.
DOT Specifications[2]	
IL DOT Art 1010.01. Section 1010. **Fly Ash.** Illinois Department of Transportation Specifications.	This specification covers the use of fly as an admixture in Portland cement concrete and mineral filler in asphalt. The specification references AASHTO M 295 as a guide to follow for design and construction.
DOT Specifications[1] (*continued*)	
Review of PennDOT Publication 408 for the Use of Recycled Co-Product Materials. Commonwealth of Pennsylvania Department of Transportation. April 1999.	This guideline provides a summary of the current uses and relevant specifications for fly ash in PennDOT–related projects. The guideline also provides lists of potential uses for fly ash and the steps required for the PennDOT to formalize specifications for these potential uses.

Note:

(1) Most states require materials sold as liming agents to be registered with the state agricultural department. In general, liming agents are required to meet a defined set of specifications (e.g., calcium carbonate equivalence).

(2) Numerous state DOTs have construction specifications that reference the use of fly ash for various applications, including embankment fill, flowable fill, subbase, and Portland cement; however, a complete listing of state DOT specifications was not included for brevity. States that have such specifications include Iowa, Maine, Maryland, Minnesota, Mississippi, Montana, North Carolina, New York, Tennessee, Texas, and Wisconsin.

Table 8
Bottom Ash/Boiler Slag Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Fine Aggregate in Asphalt Paving	
FHWA-RD-97-148. ***User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 4, Coal Bottom Ash/Boiler Slag and* Asphalt Concrete.** U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	This document covers the use of bottom ash and boiler slag as aggregate in asphalt mixtures. The document covers the gradation requirement for aggregate and the relevant ASTM standards that the aggregate must meet. In addition, the document discusses the performance record, the engineering properties, the design considerations, and the recommended construction procedures.
Granular Base	
FHWA-RD-97-148. ***User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 4, Coal Bottom Ash/Boiler Slag and* Granular Base.** U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	This document covers the use of bottom ash and boiler slag as a granular base material for road and highway construction projects. The document references numerous case studies that have used bottom ash and/or boiler slag as granular base in the United States. In addition, the document discusses the material processing requirements, the engineering properties, the design considerations, and the recommended construction procedures.
Waste Solidification/Soil Stabilization	
ASTM E 2060-00. **"Standard Guide for Use of Coal Combustion By-Products for Waste Stabilization."** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 11.04.	This guideline covers the methods for selecting and applying coal combustion products for use in chemical stabilization of trace elements in waste and wastewater. The standard provides test methods for characterization, a framework for selecting a coal combustion product, and the test methods for assessing stabilization of the waste.
FHWA-RD-97-148. ***User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 4, Coal Bottom Ash/Boiler Slag and* Stabilized Base.** U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	This document covers the use of bottom ash and boiler slag as either the fine aggregate fraction or the entire aggregate fraction in Portland cement concrete. The document references numerous case studies that have used bottom ash and/or boiler slag as aggregate in concrete in the United States. In addition, the document discusses the material processing requirements, the engineering properties, the design considerations, and the recommended construction procedures.

Table 8 (*continued*)
Bottom Ash/Boiler Slag Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Structural Fill	
ASTM E 1861-97. **"Standard Guide for Use of Coal Combustion By-Products in Structural Fills."** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 11.04.	This standard covers the use of coal combustion products in engineered structural fills. The standard provides the design and construction procedures and the required tests for the coal combustion products.
Technical Advisory T 5080.9. **Use of Coal Ash in Embankments and Bases.** U.S. Department of Transportation, Federal Highway Administration. May 1988.	This guideline covers the use of coal ash as an embankment material. The guideline discusses environmental concerns, design considerations, and construction considerations.
Other	
ASTM E 2243-02. **"Standard Guide for Use of Coal Combustion By-Products in for Surface Mine Reclamation."** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 11.04.	This standard covers the use of coal combustion products for surface coal mine reclamation applications. The standard provides guidance to identify the coal combustion products with the appropriate engineering properties and environmental performance for recontouring applications.

Table 9
FGD Material Standards/Specifications/Guidelines

STANDARD/SPECIFICATION/GUIDELINE	DESCRIPTION
Soil Stabilization/Waste Solidification	
ASTM E 2060-00. **"Standard Guide for Use of Coal Combustion By-Products for Waste Stabilization."** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 11.04.	This guideline covers the methods for selecting and applying coal combustion products for use in the chemical stabilization of trace elements in waste and wastewater. The standard provides the test methods for characterization, a framework for selecting a coal combustion product, and the test methods for assessing stabilization of the waste.
FHWA-RD-97-148. ***User Guidelines for Waste and By-Product Materials in Pavement Construction: Chapter 6, FGD Scrubber Material and*** **Stabilized Base.** U.S. Department of Transportation Federal Highway Administration: Turner-Fairbanks Highway Research Center. April 1998.	This document covers the use of FGD material as a stabilized base or subbase material. The document refers to the relevant ASTM standard regarding the mix design for stabilized base. In addition, the document discusses the performance record, the material processing requirements, the engineering properties, the design considerations, and the recommended construction procedures.
Structural Fill	
ASTM E 1861-97. **"Standard Guide for Use of Coal Combustion By-Products in Structural Fills."** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 11.04.	This standard covers the use of coal combustion products in engineered structural fills. The standard provides the design and construction procedures and the required tests for the coal combustion products.
Mine Reclamation	
ASTM E 2243-02. **"Standard Guide for Use of Coal Combustion By-Products in for Surface Mine Reclamation."** American Society for Testing and Materials, *Annual Book of ASTM Standards:* Volume 11.04.	This standard covers the use of coal combustion products for surface coal mine reclamation applications. The standard provides guidance to identify the coal combustion products with the appropriate engineering properties and environmental performance for recontouring applications.

Section 6
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