USER GUIDELINE FOR COAL BOTTOM ASH and BOILER SLAG IN GREEN INFRASTRUCTURE CONSTRUCTION

by

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USING COAL BOTTOM ASH AND BOILER SLAG IN GREEN INFRASTRUCTURE CONSTRUCTION

INTRODUCTION

This document provides a comprehensive overview of the engineering and construction properties of bottom ash and boiler slag for use in asphalt concrete aggregate, granular base, stabilized base aggregate, and embankment/backfill material. Studies addressing environmental concerns of using bottom ash and boiler slag, both industrial by-products, as construction materials are reviewed. Some case studies are presented to demonstrate successful applications of bottom ash and boiler slag. With the goal of advancing the use of bottom ash and boiler slag in construction application, references to resources and tools are made available.

Coal bottom ash and boiler slag are coarse, granular, incombustible materials that are collected from the bottom of coal burning furnaces. The majority of coal bottom ash and boiler slag are produced at coal-fired electric utility generation stations, with some coming from coal-fired boilers or independent coal-burning electric generation facilities. The type of bottom ash or boiler slag produced depends on the type of coal-burning furnace.

Bottom ash is produced as a result of burning coal in a dry bottom pulverized coal boiler. Unburned material from a dry bottom boiler consists of about 20 percent bottom ash Bottom ash is a porous, glassy, dark gray material with a grain size similar to that of sand or gravelly sand (Steam 1978). Although similar to natural fine aggregate, bottom ash is lighter and more brittle and has a greater resemblance to cement clinker (Rogbeck and Knutz 1996). Bottom ash is collected at the bottom of the combustion chamber in a water-filled hopper and is removed by means of high-pressure water jets and conveyed by sluiceways to a decanting basin for dewatering, stockpiling, and possibly crushing (Steam 1978).

There are two types of wet-bottom boilers that produce boiler slag: slag-tap and cyclone. The slag-tap boiler burns pulverized coal while the cyclone boiler burns crushed coal. Wet-bottom boiler slag is a term that describes the molten condition of the ash being drawn from the bottom of the furnaces. Both boiler types have a solid base with an orifice that can be opened to permit molten ash to flow into a hopper below. The hopper in wet-bottom furnaces contains quenching water. When the molten slag comes in contact with the quenching water, the ash fractures instantly, crystallizes, and forms pellets. High-pressure water jets wash the boiler slag from the hopper into a sluiceway which then conveys the ash to collection basins for dewatering, possible crushing or screening, and stockpiling (Moulton 1973). The resulting boiler slag, often referred to as "black beauty", is a coarse, angular, glassy, black material. When pulverized coal is burned in a slag-tap furnace, as much as 50 percent of the ash is retained in the furnace as boiler slag. In a cyclone furnace, which burns crushed coal, 70 to 85 percent of the ash is retained as boiler slag (NETL 2006).

The American Coal Ash Association (ACAA) (ACAA 2007) estimates that during 2006, the U.S. utility industry generated 16.9 million metric tons (18.6 million tons) of bottom ash and 1.8 million metric tons (2.0 million tons) of boiler slag. Just over 45 percent of all bottom ash produced is used, mainly in transportation applications such as structural fill, road base material, and as snow and ice control products. Bottom ash is also used as aggregate in lightweight concrete masonry units (ASTM C331-05 2005) and raw feed material for the production of Portland cement(ACAA 2007, Cheriaf et. al. 1999, Canpolat et. al. 2004).

Nearly 84 percent of all boiler slag generated annually in the U.S. is utilized (ACAA 2007). More than 85% of the boiler slag is used as blasting grit and roofing shingle granules. Boiler slag is also used in transportation applications including structural fills, mineral filler, and snow and ice control (ACAA 2007). Boiler slag has been used as aggregate in asphalt paving and as a road base and subbase. Much of the boiler slag currently produced is from cyclone boilers, which are falling out of favor due to high NO_X emissions. As older cyclone boilers are retired, the amount of available boiler slag will decrease. For example, 2.57 million tons of boiler slag were produced in 1996 (NETL 2006) compared to 2.03 million in 2006 (ACAA 2007).

The utilization of bottom ash and/or boiler slag in construction projects can save energy, reduce the need to mine virgin materials, and reduce costs for both producers and end users. Project managers are able to enhance green sustainable construction by reducing their carbon footprint.

GENERAL BOTTOM ASH/BOILER SLAG PROPERTIES

Physical Properties

Bottom ashes have angular particles with very porous surface textures. The ash particles range in size from a fine gravel to a fine sand with very low percentages of silt-clay sized particles. Bottom ash is predominantly sand-sized, 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. The largest bottom ash particle sizes typically range from 19 mm (3/4 in) to 38.1 mm (1½ in). Bottom ash is usually a well-graded material although variations in particle size distribution may be encountered in ash from the same power plant.

Boiler slag has a smooth surface texture unless gases are trapped in the slag when quenched, which produces a vesicular or porous particle. Boiler slag from the burning of lignite or subbituminous coal tends to be more porous than from burning eastern bituminous coals (Majizadeh et al. 1979). Boiler slag is essentially a coarse to medium sand with 90 to 100 percent passing a 4.75 mm (No. 4) sieve and 5 percent or less passing a 0.075 mm (No. 200) sieve (Moulton 1973).

The specific gravity of the dry bottom ash is a function of chemical composition, with higher carbon content resulting in lower specific gravity. Bottom ash with a low specific gravity has a porous or vesicular texture, a characteristic "popcorn particle" that readily degrade under loading or compaction (Lovell et al. 1991). Table 1 lists physical properties of bottom ash and boiler slag.

Table 1. Typical physical properties of bottom ash and boiler slag.

Property	Bottom Ash	Boiler Slag	Source	Test Method
Specific Gravity	2.1 -2.7	2.3 - 2.9	Majizadeh (1979)	ASTM D854-06
Dry Unit Weight	7.07 - 15.72 kN/m^3 (45 - 100 lb/ft^3)	7.43 - 14.15 kN/m^3 (60 - 90 lb/ft^3)	Majizadeh (1979)	
Plasticity	None	None	Majizadeh (1979)	ASTM D4318-05 AASHTO T 090
Absorption	0.8 - 2.0%	0.3 - 1.1%	Moulton (1973)	ASTM C128-07a

Mechanical Properties

Typical mechanical properties of bottom ash and boiler slag are listed in Table 2 including: compaction characteristics, durability, shear strength, bearing strength, resilient modulus, and hydraulic conductivity.

Table 2. Typical mechanical properties of bottom ash and boiler slag.

Property	Bottom Ash	Boiler Slag	Source	Test Method	Considerations
Maximum Dry Density kN/m^3 (lb/ft^3)	11.79 - 15.72 (75 - 100)	12.89 - 16.04 (82 - 102)	Lovell et al. (1991), Tanyu et al. (2004)	AASHTO T 085 ASTM D2216-05	Compaction curves of bottom ash generally have a flat shape, indicating insensitivity to water content. (Rogbeck and Knutz 1978, Tanyu et al. 2005).
Optimum Moisture Content, %	Usually <20 12 - 24 range	8 - 20	Lovell et al. (1991), Tanyu et al. (2004)		
Los Angeles Abrasion Loss %	30 - 50	24 - 48	Moulton (1973), Huang (1990)	ASTM C535	Boiler slag exhibits less abrasion loss and soundness loss than bottom ash because of the glassy surface texture and lower porosity (Moulton et al. 1973).
Sodium Sulfate Soundness Loss %	1.5 - 10	1 - 9	Moulton (1973), Huang (1990)	AASHTO T 104 ASTM C88	Coal pyrites or soluble sulfate in bottom ash or boiler slag may account for sodium sulfate soundness loss values.
Internal Friction Angle (drained)	38 - 42° 32 - 45° (<9.5 mm size)	38 - 42° 36 - 46° (<9.5 mm size)	Majizadeh et al. (1979)	ASTM D4767-04 ASTM D 3080	
California Bearing Ratio (CBR) %	21 - 110	40 - 70	Rogbeck and Knutz (1996), Tanyu et al. (2005)	ASTM D1883-05	California Bearing Ratio values are comparable to those of high-quality gravel base materials.
Resilient Modulus (M_R) regression coefficients	K_1 = 5 - 12 MPa K_2 = 0.52		Tanyu et al. (2005), Edil et al. 2002	AASHTO T-294-94	
Hydraulic Conductivity cm/sec	1 - 10^{-3}	10^{-1} - 10^{-3}	Prakash and Sridharan (2006), Siddiki et al. (2004)	ASTM D2434-68 ASTM D5084-03 AASHTO T 215	Bottom ash or boiler slag are not typically susceptible to either liquefaction or frost heave.

Mineralogical and Chemical Properties
The chemical composition of bottom ash and boiler slag particles is controlled by the source of the coal and not by the type of furnace. Coal ash is composed primarily of silica (SiO_2), ferric oxide (Fe_2O_3), and alumina (Al_2O_3), with smaller quantities of calcium oxide (CaO), potassium oxide (K_2O), sodium oxide (Na_2O), magnesium oxide (MgO), titanium oxide (TiO_2), phosphorous pentoxide (P_2O_5), and sulfur trioxide (SO_3). In bituminous coal ash, the three major components (SiO_2, Fe_2O_3, and Al_2O_3) account for about 90 percent of the total components, whereas lignite and subbituminous coal ashes have relatively high percentages of CaO, MgO, and SO_3 (Kim et al. 2005). Sulfate is usually very low (less than 1.0 percent), unless pyrites are present in bottom ash or boiler slag. The chemical composition of some bottom ash provides unique pozzolanic properties that, as with cementitious materials, can result in a favorable time-dependent increase in strength (Kumar and Vaddu 2004).

Environmental Considerations
Air quality during any highway construction involving bottom ash and boiler slag should be taken into consideration (Rogbeck and Knutz 1996). Material handling precautions should be utilized to protect workers and the public from dusting during delivery and construction (EPA 2005).

Bottom ash is typically used in bulk, unencapsulated applications such as in embankments, structural fills, and unbound or stabilized granular bases and subbases . Therefore, the dilution, fixation, and adsorption of trace elements that would occur if bottom ash were mixed with native soils is not expected (Edil et al. 2002). Concentrations of trace elements from the leachate collected from bottom ash test sections have been shown to be higher than those collected from control sections as well as those collected from fly ash test sections (Edil et al. 2006). The possibility of groundwater contamination by trace elements that are commonly associated with coal combustion by-products is a concern. Unencapsulated bottom ash or boiler slag use requires good management to ensure the environment is not impacted negatively. In particular, areas with sandy soils possessing high hydraulic conductivities and areas near shallow groundwater or drinking aquifers should be given careful consideration. An evaluation of groundwater conditions, applicable state test procedures, water quality standards, and proper construction are all necessary considerations in ensuring a safe final product (EPA 2005).

Leaching of metals and during construction are still environmental issues associated with using bottom ash or boiler slag in encapsulated applications, such as asphalt pavement. Bottom ash and boiler slag consist of the same chemical components as fly ash; therefore there exists the potential to leach trace elements. Because bottom ash and boiler slag have larger particles and less surface area per unit volume, the potential to leach trace elements is reduced. Additionally, since coal combustion products mixed in asphalt pavement is considered an encapsulated application, the potential to leach elements is further reduced. A leachate study conducted on test strips of asphalt concrete with bottom ash demonstrated that trace elements were observed, but that there was no evidence that the use of coal ash in asphalt pavements was the source (Churchill and Amirkhanian 1999).

Leachate studies conducted according to methods outlined in Table 3 would provide valuable information in gauging the environmental suitability of coal bottom ash and boiler slag.

Aside from laboratory testing, lysimeter monitoring can provide field information on trace element release and leachate flow. A lysimeter is a device that collects water from overlying materials that can be tested for soluble constituents that were dissolved during rainwater percolation through the material.

A laboratory batch water leach test, column leach test, and below subbase lysimeter study evaluated leachate from bottom ash. Leachates were analyzed for concentrations of cadmium (Cd), chromium (Cr), selenium (Se), and silver (Ag) and compared to groundwater quality standards for Wisconsin. Peak concentrations in the lysimeters below 60 cm of bottom ash were all above peak concentrations found from the laboratory water leach test and were above the peak concentrations from the laboratory column leach test for Cd, Se, and Ag. Peak Cd and Se concentrations in the leachate from the field lysimeters exceeded the Wisconsin groundwater standard. However, with application of dilution factors to account for the reduction in concentration expected between the bottom of the pavement structure and the groundwater table, concentrations would not exceed the groundwater quality standards if the bottom ash layer is at least 1 m above the groundwater table (Sauer et al. 2005).

Due to salt content and low pH, bottom ash and boiler slag may be corrosive. When using bottom ash or boiler slag in an embankment, backfill, subbase, or even in a base course, the ash may come in contact with metal structures and cause corrosion. Therefore, evaluation of the corrosive nature of the bottom ash or boiler slag being used should be investigated.

Corrosivity indicator tests normally used to evaluate bottom ash or boiler slag are pH, electrical resistivity, soluble chloride content, and soluble sulfate content. Materials are judged to be noncorrosive if the pH exceeds 5.5, the electrical resistivity is greater than 1500 ohm-centimeters, the soluble chloride content is less than 200 parts per million (ppm), or the soluble sulfate content is less than 1000 parts per million (ppm) (Ke and Lovell 1992).

Table 3. Extraction conditions for different standard leaching tests (Bin-Shafique et al. 2002).

Test Procedure	**Method**	**Purpose**	**Leaching Medium**	**Liquid-Solid Ratio**	**Particle Size**	**Time of Extraction**
Water Leach Test	ASTM D3987-06	To provide a rapid means of obtaining an aqueous extract	Deionized water	20:1	Particulate or monolith as received	18 hr
TCLP	EPA SW-846 Method 1311	To compare toxicity data with regulatory level. RCRA requirement.<	Acetate buffer*	20:1	< 9.5 mm	18 hr
Extraction Procedure Toxicity (EP Tox)	EPA SW-846 Method 1310	To evaluate leachate concentrations. RCRA requirement.	0.04 M acetic acid (pH = 5.0)	16:1	< 9.5 mm	24 hr
Multiple Extraction Procedure	EPA SW-846 Method 1320	To evaluate waste leaching under acid condition	Same as EP Toxicity, then at pH = 3.0	20:1	< 9.5 mm	24 hr extraction per stage
Synthetic Precipitation Leaching Procedure (SPSL)	EPA SW-846 Method 1312	For waste exposed to acid rain	DI water, pH adjusted to 4.2 to 5	20:1	< 9.5 mm	18 hr

* Either an acetate buffered solution with pH = 5 or acetic acid with pH = 3.0

Modeling

Models currently used to simulate leaching from pavement systems and potential impacts to groundwater include STUWMPP (Friend et al. 2004), IMPACT (Hess et al. 2000), HYDRUS-2D (Simunek et al. 1999, Bin-Shafique et al. 2002, Apul et al. 2005), WiscLEACH (Li et al. 2006), and IWEM (EPA 2002). Among these models STUWMPP, IMPACT, WiscLEACH and IWEM are in the public domain. STUWMPP employs dilution–attenuation factors obtained from the seasonal soil compartment (SESOIL) model to relate leaching concentrations from soils and byproducts to concentrations in underlying groundwater. IMPACT was specifically developed to assess environmental impacts from highway construction. Two dimensional flow and solute transport are simulated by solving the advection dispersion reaction equation using the finite difference method (Li et al. 2006).

WiscLEACH combines three analytical solutions to the advection-dispersion-reaction equation to assess impacts to groundwater caused by leaching of trace elements from CCPs used in highway subgrade, subbase and base layers. WiscLEACH employs a user friendly interface and readily available input data along with an analytical solution to produce conservative estimates of groundwater impact (Li et al. 2006).

The U.S. EPA's Industrial Waste Management Evaluation Model (IWEM), although developed to evaluate impacts from landfills and stock piles, can help in determining whether ash leachate will negatively affect groundwater. IWEM inputs include site geology/hydrogeology, initial leachate concentration, metal parameters, and regional climate data. Given a length of time, the program will produce a leachate concentration at a control point (such as a pump or drinking well) that is a known distance from the source. In addition, Monte Carlo simulations can provide worst-case scenarios for situations where a parameter is unknown or unclear. In comparing IWEM to field lysimeter information, IWEM over predicted the leachate concentrations and could be considered conservative. Overall, however, IWEM performed satisfactorily in predicting groundwater and solute flow at points downstream from a source (Melton et al. 2006).

A source for information on assessing risk and protecting groundwater is the EPA's "Guide for Industrial Waste Management" which can be found at:
http://www.epa.gov/industrialwaste/guide.asp

Due to the variability in bottom ash and boiler slag composition between coal plants, industry-wide generalizations about the environmental impact of bottom ash and boiler slag cannot be made. Also, because of the variety of leachate testing methods and the variety of standards and regulations to compare these test results to, state regulations should be identified and followed when determining the environmental suitability of bottom ash or boiler slag from a particular source.

State Environmental Regulations

The U.S. Environmental Protection Agency (EPA) has delegated responsibility to the states to ensure that coal combustion by-products are properly used. Each state, therefore, should have specifications and environmental regulations.

The state regulations database contains summary information on current regulations in each state and contact information for individuals with regulatory responsibility. The U.S. Federal Highway Administration (FHWA) maintains a searchable library for all highway specifications across the country that can be accessed at http://fhwapap04.fhwa.dot.gov/nhswp/index.jsp .

DESIGN CONSIDERATIONS AND GUIDELINES

Asphalt Concrete Aggregate

Bottom ash and boiler slag have been used as fine aggregates in asphalt paving mixtures since the early 1970's. The American Coal Ash Association reported that, 40,800 metric tons (45,000 tons) of boiler slag and over 17,2000 metric tons (19,000 tons) of bottom ash were used in asphalt paving during 2006 (ACAA 2007).

Both bottom ash and boiler slag have been used as fine aggregate substitute in hot mix asphalt wearing surfaces and base courses, and in emulsified asphalt cold mix wearing surfaces and base courses. Bottom ash has been used as aggregates in hot mix asphalt (HMA) base courses, in emulsified asphalt cold mixes, and in shoulder construction. Bottom ash produced in dry bottom boilers is usually sufficiently well-graded to meet gradation requirements for asphalt concrete. However, bottom ash particles are less durable than conventional aggregates. Consequently, bottom ash is better suited for use in base course and shoulder mixtures or in cold mix applications, as opposed to wearing surface mixtures, although field and laboratory research has shown that hot mix asphalt with up to 15 percent bottom ash had comparable performance to control mixes (Ksaibati and Sayiri 2006).

The most extensive use of bottom ash in bituminous paving has been in West Virginia, where, during the 1970's and 1980's, bottom ash was cold mixed with 6 to 7 percent by weight of emulsified asphalt and used in the paving of secondary roads where durability concerns are reduced. Similar paving has also been done in eastern Ohio (Root and Williams 1976). To improve the characteristics of a cold mix containing bottom ash, boiler slag can be included.

Recent studies have indicated that bottom ash may possess desirable engineering properties and will not degrade HMA performance properties when used to replace a portion of the fine aggregate in an asphalt mix (Ksaibati and Sayiri 2006). No more than 30 percent of bottom ash as aggregate replacement is recommended, mixes with 50 percent or more of bottom ash in asphalt pavements were found to have unacceptable stabilities (Moulton et al 1973). In a study where 15 percent bottom ash replaced aggregate, HMA mixes prepared with bottom ash did not show any significant degradation in performance properties when compared to control mixes. The use of bottom ash as 15 percent replacement of aggregate in HMA mixes maintained desirable strength properties, low temperature properties, and rutting properties. However, the addition of bottom ash required an increase in asphalt content (Ksaibati and Conner 2004).

Boiler slag has been used in the same applications as bottom ash and also as wearing surfaces, emulsified asphalt cold mix bases or surfaces, and asphalt surface treatments or seal coats. Boiler slag produced in wet bottom boilers is uniformly sized, and consists of hard, durable, glassy particles. Boiler slag is typically blended with other fine aggregates to meet gradation requirements of asphalt concrete, due to the hard, durable particles and resistance to surface wear boiler slag is used more frequently in asphalt paving than bottom ash. Boiler slag enhances HMA wearing surfaces, because boiler slag has a dust-free surface, which increases adhesion and anti-stripping characteristics with asphalt. Boiler slag has also been used successfully as a seal-coat aggregate for bituminous surface treatments to enhance skid resistance (NETL 2006).

Boiler slag was first used in asphalt paving in Hammond, Indiana, where, on an experimental basis, bottom slag was blended with conventional aggregate to solve a problem of aggregate polishing. The success of that project and several other demonstration projects in Indiana led to the acceptance and use of boiler slag in Indiana and several other states, including Ohio, Michigan, Missouri, and West Virginia. Boiler slag has also been used as an aggregate in HMA paving in a number of cities such as Cincinnati and Columbus, Ohio, as well as in Tampa, Florida (Cockrell et al. 1970).

Asphalt Concrete Design Considerations:
Properties of bottom ash and boiler slag that are of particular interest when used in asphalt concrete are shown in Table 4.

Screening of oversized particles and blending with other aggregates will typically be required to use bottom ash and boiler slag in paving applications. Boiler slag is typically poorly-graded and bottom ash is typically a well-graded sand-sized material. The recommended percentage of boiler slag should be less than 50 percent to maintain paving mixture stability (Usmen and Anderson 1976). Oversize or agglomerated popcorn particles may be present in some bottom ash sources and should be removed by screening the material with a 19 mm (¾ in) or 12.7 mm (½ in) screen.

Marshall stability and flow values decrease as the percentage of boiler slag increases for a given compactive effort. Mixes blended with rounded siliceous aggregates, such as uncrushed river sand, result in lower quality mixtures than blends containing crushed stone, which possess more desirable angularity and surface texture. Blending crushed stone aggregates with boiler slag is recommended because boiler slags lack microtexture that increases the aggregate-asphalt bond and to provide skid resistance (Özkan et al. 2007).

Optimum skid resistance using boiler slag is achieved in open graded sand mixes where boiler slag is the top-sized aggregate. However, such mixes should limit the percentage of boiler slag in the mix and avoid low filler content. Boiler slag does not appear to be as helpful in terms of skid resistance in coarse graded mixtures, especially if the coarse aggregate is polish susceptible (Usman and Anderson 1976).

The laboratory effort and method of compaction effects pavement properties of mixes containing boiler slag. Kneading compaction improves the stability and flow characteristics compared to Marshall drop hammer compaction. Obtaining adequate compaction is essential with boiler slag mixtures. Optimum compaction is produced by blending boiler slag with well-graded, angular, rough-textured aggregate and limiting the percentage of boiler slag to 50 percent. Porous boiler slag can be used in greater percentages, but excessively porous slag are weak and can crush (Anderson et al. 1976). In addition, porous boiler slag may absorb more asphalt than typical boiler slag, thereby requiring a higher percentage of asphalt cement.

Pyrites that may be present in the bottom ash should also be removed prior to use. Pyrites (iron sulfide) are volumetrically unstable, expansive, and produce a reddish stain when exposed to water over an extended time period. Consequently, no more than 30 percent of the aggregate in an asphalt pavement mix should be replaced with bottom ash (Ksaibati and Sayiri 2006).Technologies exist for processing bottom ash that can provide a cost-effective method to remove impurities (e.g. removal by electromagnets or media separation) so that bottom ash meets product quality targets (Groppo and Robl 2003). Commingling the rejected pyrite with bottom ash is a practice at some power plants. Material handling operations should be modified to keep pyrite and bottom ash-boiler slag separate (Huang 1990).

Bottom ash and/or boiler slag used to produce HMA need to be dried before blending with asphalt cement. Excessive moisture in the aggregates will reduce the production rate of paving material due to the additional drying time required. Both bottom ash and boiler slag are easy to dewater, particularly boiler slag, which consists of glassy particles. Ponded ash, which is usually a mixture of fly ash and bottom ash or boiler slag, should be stockpiled and allowed to drain to a surface dry condition. When used in a cold mix application, bottom ash should be at least surface dry so that moisture does not interfere with the coating of the ash particles by the emulsified asphalt. Boiler slag should also be in a surface dry condition when used as a seal coat aggregate.

Boiler slag has a black color that does not fade. This attribute aids in the melting of snow from the road surface (Kerkhoff 1968). Additionally, boiler slag provides better coverage per mile than limestone chips and the rich black color is an excellent contrast to road strip colors.

The comparatively high optimum asphalt content of mixtures using bottom ash as the only aggregate can be reduced by combining bottom ash with conventional aggregates. Research has shown that sulfur modified bottom ash mixes containing 50 to 100 percent bottom ash aggregate replacement can be achieved with 7.5 percent or less asphalt (Estakhri and Saylak 2000).

Although the asphalt contents of mixes containing bottom ash will be greater than the asphalt contents of conventional asphalt paving mixes, the total weight of asphalt cement used should not be significantly greater because of the low unit weight of the bottom ash. Bottom ash mixes are also likely to have relatively high air void contents. The high air voids are attributable to the rough surface texture of bottom ash particles

Conventional AASHTO pavement structural design methods are appropriate for asphalt pavements incorporating bottom ash or boiler slag (AASHTO 1993).

Similarly, pavement thickness design procedures for cold mix overlays containing bottom ash or boiler slag are the same procedures used for cold mix overlays using conventional aggregates. Modified structural numbers (SN) for cold mix overlays containing bottom ash and/or boiler slag are the same as conventional cold mix overlays.

The same methods and equipment used for mixing, placing, and compacting conventional pavements are applicable for asphalt pavements containing bottom ash or boiler slag. In hot mix applications, bottom ash or boiler slag are typically blended with other aggregates using conventional equipment. Dry bottom ash used in cold mix applications may not require blending and can be prepared by mixing with emulsified asphalt at a central pugmill mixing plant. Cold mix asphalt containing bottom ash or boiler slag can be prepared in advanced and stockpiled for 10 or more days (Moulton et al. 1973).

Cold mixes containing bottom ash can be placed with a paver, spreader box, or can be end dumped and leveled with a grader. Laydown characteristics of dry bottom ash cold mixes placed with either a spreader box or a conventional paving machine are the same as conventional mixes. Spreader box lifts of up to 200 mm (8 in) uncompacted mix can be placed. Lifts greater than 200 mm (8 in) in loose thickness may be difficult to compact (Moulton et al 1973). Adequate compaction is usually achieved with several passes of a pneumatic roller followed by a steel-wheeled roller (Moulton et al. 1973).

Bottom ash and boiler slag possess unique physical and engineering properties that are different from conventional pavement materials; therefore, standard test methods may reject bottom ash or boiler slags that would provide acceptable performance. New or modified test methods are needed to characterize bottom ash and boiler slag properties that influence pavement performance. Improved characterization is needed for both abrasion loss and particle size degradation that may occur during compaction.

Table 4. Design parameters for bottom ash and boiler slag in asphalt concrete applications.

Property	Bottom Ash	Boiler Slag	Source	Test Method	Considerations
Water Absorption %	0.3-6.1		Moulton (1973), Özkan et al. (2007)		The porous nature of bottom ash particles increases absorption of asphalt binder relative to conventional fine aggregate, potentially making it less economical for asphalt aggregate (Ramme and Tharaniyil 2004)
Specific Gravity	1.6 -3.4	2.3 - 2.9	Majizadeh (1979), Huang (1990), Ksaibati and Sayiri (2006)	ASTM D854-06	Bottom ash with high iron can have high specific gravity. Increased porous and popcorn particles decrease specific gravity
Los Angeles Abrasion Loss %	30 - 50	24 - 48	Moulton (1973), Huang (1990)	ASTM C535	Results fall within the specifications of a maximum 50 percent loss by abrasion.
Sodium Sulfate Soundness Loss %	1.5 - 10	1 - 9	Moulton (1973), Huang (1990)	AASHTO T 104 ASTM C88	Soundness values are generally found to be within ASTM C88(19) weight loss specifications of not more than 15 percent after five cycles.

Granular Base
Coal bottom ash and boiler slag have been used as a granular base material in road and parking lot construction. Bottom ash and boiler slag are used as fine aggregates in this application. Bottom ash has been successfully used as granular base since the early 1970's. The American Coal Ash Association reported that 740,000 metric tons (815,000 tons) of bottom ash were used as road base or subbase materials in 2006 (ACAA 2007). The road base or subbase category used by the American Coal Ash Association includes the use of coal bottom ash as an unbound base or in stabilized subbase or stabilized base material. Bottom ash is being studied and used as a granular base in both public (Edil et al. 2002, Tanyu et al. 2003, Tanyu et al. 2005, Seals et al. 1972) and private projects, although private use is not well documented in the literature.

Granular Base Design Considerations:
Some of the engineering properties of bottom ash and boiler slag that are of particular interest in granular base applications are summarized in Table 5.

Bottom ash and boiler slag are considered fine aggregates in a granular base. To improve grain size distribution characteristics of bottom ash or boiler slag, a conventional aggregate or a slag aggregate may be blended with the ash.

Degradation Under Compaction is quantified by calculating the mean size of a material before and after compaction and expressing the index of crushing as the percent reduction between the two mean sizes. The higher the index, the easier a material crushes. The index of crushing for coal bottom ash from a pulverized coal boiler was found to be roughly twice that of conventional aggregates, whereas the index of crushing for boiler slag is essentially the same as that of conventional aggregates. The index of crushing for bottom ash from a stoker-fired boiler was found to be about three times greater than the index of crushing for bottom ash from a pulverized coal boiler (Lovell et al. 1991).

Bottom ash is typically free-draining, reducing the influence of moisture content on compaction characteristics (ASTM E2277-03 2003). Short-term (< 2 days) stockpiling of bottom ash may be required to reduce moisture content. Reclaimed ponded ash may require longer-term stockpiling (~2 weeks) to reduce moisture content. The moisture content of bottom ash should be high enough to prevent dusting during material handling.

Bottom ash may meet granular base specifications without processing (Edil et al. 2002, Moulton et al. 1973). However, the ash may require screening, washing, or blending with conventional aggregate to meet specifications. Oversize or agglomerated popcorn particles may be present in some bottom ash sources and should be removed by screening. Because boiler slag is a poorly-graded material, screening is typically not needed, but blending with conventional aggregate may be required.

Deleterious materials, such as soluble sulfates or coal pyrites, should be removed from bottom ash, boiler slag, or pond ash before use as a granular base. Pyrites should be removed from the coal prior to burning and handled separately from the ash. The pyrites should not be commingled with the ash stream. Although an added cost, processing techniques do exist to remove pyrites from bottom ash.

When the same thickness is used, bottom ash exhibits less load distribution characteristics and would be more flexible than conventional aggregates (Ramme and Tharaniyil 2004), even though bottom ash falls in the categories of "good subbases" and "good gravel bases" on the basis of CBR values (Huang 1990).

Bottom ash or boiler slag used as a granular base may potentially corrode metal structures (AASHTO 1993). Parameters of interest that are related to corrosivity are pH, electrical resistivity, soluble chlorides, and soluble sulfates. A study of 11 bottom ash or boiler slag samples from Indiana indicated that seven of the samples were considered corrosive, principally because of low electrical resistivity (AASHTO 1993), although pH measurements may exhibit high alkalinity indicating low corrosion potential (Kim and Prezzi 2007). Therefore, bottom ash, boiler slag, and ponded ash should be investigated for corrosivity with multiple methods if there is a potential that the ash will come in contact with metal.

The physical properties of coal bottom ash, boiler slag, and ponded ash will vary depending on the type, source, and fineness of the parent fuel, as well as the operating conditions of the power plant (Özkan et al. 2007); therefore, material specific testing is recommended.

Pavement design that includes bottom ash, boiler slag, or ponded ash as an unbound or granular base or subbase material can follow AASHTO methods provided in Guide for Design of Pavement Structures (AASHTO 1993). The AASHTO method accounts for the predicted loading (the predicted number of 80 kN equivalent single axle loads), required reliability (degree of certainty that a design will function properly during the design life), serviceable life (ability to maintain quality during the pavement life), the pavement structure (characterized by the structural number), and subgrade support (related to the resilient modulus of the subgrade) (AASHTO 1993).

A layer coefficient value of 0.10 can be used for the design of flexible pavement systems in which bottom ash, boiler slag, or reclaimed ponded ash are used to construct an unbound or granular base or subbase. A coefficient of 0.10 for bottom ash and/or boiler slag recognizes that bottom ash and/or boiler slag are not structurally equivalent to crushed stone, which is typically given a larger coefficient of 0.15.

Bottom ash used at approximately 1.5 times the thickness of conventional aggregates achieves a comparable stress level in the underlying subgrade. For equivalent deformation, the thickness of bottom ash should be two times the thickness of conventional aggregates to maintain similar deflection at the surface of the base course layer (Ramme and Tharaniyil 2004).

Both bottom ash and boiler slag can be handled and stored using the same methods and equipment that are used for conventional aggregates. Additionally, laboratory and case studies show that with proper design and construction, compacted bottom ash provides adequate support as a working platform or subbase material (Edil et al . 2002, Tanyu et al. 2004). Design charts for selecting the equivalent thickness of compacted bottom ash for working platforms are provided in Tanyu et al. (2004). A methodology for including the structural contribution of working platforms made from bottom ash or other alternative material is presented in Tanyu et al. (2003).

Bottom ash and boiler slag can be dumped and spread with a motor grader or bulldozer or for more accurate grade control, these materials can be placed with a spreader box or paving machine. Bottom ash and boiler slag should be compacted at, or slightly above, optimum moisture content as determined by standard Proctor compaction procedures (ACAA 2007). Bottom ash loses stability at low moisture contents; therefore, high moisture contents should be maintained to allow construction equipment to operate. The addition of up to 30 percent fines in the form of fly ash may remedy the loss of stability upon drying (Moulton 1973). Compaction of bottom ash and boiler slag bases and subbases can be accomplished by static steel-wheeled rollers, pneumatic rollers, or vibratory compaction equipment.

After compaction, a bottom ash granular base layer should be protected. A prime coat of asphalt emulsion can be applied to the base material to prevent moisture evaporation, stabilize the surface, and provide a bond between the base layer and an asphalt or Portland cement concrete wearing surface. An asphalt binder, wearing surface, or concrete pavement should be constructed within a reasonable time after sealing a granular base layer to minimize traffic loads on the base layer.

Table 5. Design parameters for bottom ash and boiler slag in granular base applications.

Property	Bottom Ash	Boiler Slag	Source	Test Method	Considerations
Maximum Dry Density kN/m^3 (lb/ft^3)	11.79 - 15.72 (75 - 100)	12.89 - 16.04 (82 - 102)	Lovell et al. (1991), Tanyu et al. (2004)	AASHTO T 085 ASTM D2216-05	Compaction curves exhibit maximum dry density at either an air-dried condition or a flushed or wet condition (Lovell et al. 1991). Flushed conditions can be maintained in the field, producing a maximum dry density (Huang 1990).
Optimum Moisture Content, %	Usually <20 12 - 24 range	8 - 20	Lovell et al. (1991), Tanyu et al. (2004)		
Specific Gravity	1.9 -3.4	2.3 - 2.9	Majizadeh (1979), Moulton (1973), Lovell et al. (1991)	ASTM D854-06	Bottom ash with relatively low apparent specific gravity is often indicative of the presence of porous particles trapping gases that affect the test results. Bottom ash with relatively high specific gravity may indicate high iron content.
Dry Unit Weight	7.07 - 15.72 kN/m^3 (45 - 100 lb/ft^3)	7.43 - 14.15 kN/m^3 (60 - 90 lb/ft^3)	Majizadeh (1979)		
Internal Friction Angle (drained)	38 - 42° 32 - 45° (<9.5 mm size)	38 - 42° 36 - 46° (<9.5 mm size)	Majizadeh et al. (1979), Moulton (1973)	ASTM D4767-04 ASTM D 3080	
California Bearing Ratio (CBR) %	21 - 110	40 - 70	Rogbeck and Knutz (1996), Tanyu et al. (2005)	ASTM D1883-05	CBR of bottom ash compacted at high moisture contents are higher than CBR of bottom ash compacted at low moisture contents, indicating that compacting at high moisture contents is advantageous.
Resilient Modulus (M_R) regression coefficients	K_1 = 5 - 12 MPa K_2 = 0.52		Tanyu et al. (2005), Edil et al. 2002	AASHTO T-294-94	
Hydraulic Conductivity cm/sec	1 - 10^{-3}	10^{-1} - 10^{-3}	Prakash and Sridharan (2006), Siddiki et al. (2004)	ASTM D2434-68 ASTM D5084-03 AASHTO T 215	Bottom ash is well draining material and is non-susceptible to frost heave.

Stabilized Base Aggregate
In 2006, the American Coal Ash Association reported that over 740,000 metric tons (815,000 tons) of bottom ash were used as road base or subbase materials (ACAA 2007). The road base or subbase category used by the American Coal Ash Association includes the use of coal bottom ash as an unbound base, stabilized subbase, or stabilized base material.

Bottom ash or boiler slag can be used as the fine aggregate fraction or as the entire aggregate in Portland cement or pozzolan-stabilized base and subbase mixtures. Bottom ash and, in particular, boiler slag have been used as aggregate in stabilized base or subbase applications since the 1950's. Most installations have not been well documented, but there is no indication of unsatisfactory performance.

Stabilized base or subbase mixtures contain a blend of aggregates and cementitious materials that bind the aggregates to increase bearing strength. Cementitious properties have been found in both coal bottom ash and boiler slag which make them attractive options for stabilized base.

Case studies report that fly ash stabilized base courses may contain 65 percent bottom ash or boiler slag by weight, while Portland cement mixes may contain up to 95 percent bottom ash or boiler slag. The remaining percentage of a pozzolan stabilized base mix is fly ash, lime, or Portland cement.

Stabilized Granular Base Design Considerations:
Engineering properties of bottom ash and boiler slag that are of particular interest in stabilized granular base applications are summarized in Table 6.

Bottom ash is generally a more well-graded aggregate than boiler slag, which is normally more uniformly graded between the No. 4 (4.75 mm) and No. 40 (0.42 mm) sieves. Pond ash may be a blend of bottom ash and fly ash, and will vary in gradation, depending on the proximity to the discharge pipe in a lagoon. Bottom ash may contain some agglomerations or popcorn-like particles. These agglomerations should either be reduced in size by clinker grinders at the power plant or removed by scalping or screening at the 12.7 mm (½ in) or 19 mm (¾ in) screen.

Bottom ash may meet gradation specifications for stabilized base or may require blending with other coal combustion products or natural aggregates to meet specifications. Boiler slag, being poorly-graded, will require blending to meet gradation specifications. Well-graded aggregates normally require less activator or reagent than poorly graded aggregates in order to produce a well-compacted stabilized base.

Deleterious materials in bottom ash or boiler slag, especially coal pyrites, should be removed prior to use as an aggregate. Low pH values in bottom ash are often used as an indicator for the presence of sulfates. Technologies exist for processing bottom ash that can provide a cost-effective method to remove impurities (i.e. unburnt coal and pyrite) so that bottom ash meets product quality targets (Groppo and Robl 2003).

For pozzolan-stabilized base (PSB) mixtures made with bottom ash or boiler slag and containing coal fly ash (along with lime, Portland cement, or kiln dust as an activator), the initial step in determining mix design proportions is to find the optimum fines content. This is done by progressively increasing the percentage of fines and determining the compacted density of each blend. Each blend of aggregate and fines is compacted into a Proctor mold using standard compaction procedures. Fly ash percentages ranging from 25 to 45 percent by dry weight of the total blend are suggested for the initial trial mixes. The optimum fines content selected by this procedure should be 2 percent higher than the fines content at the maximum dry density. The optimum moisture content must then be determined for this mix design.

Once the design fly ash percentage and optimum moisture content have been determined, the ratio of activator to fly ash must be determined. Using a series of trial mixtures, final mix proportions are selected on the basis of the results of both strength and durability testing according to procedures outlined in ASTM C593.

For cement-stabilized bottom ash and boiler slag mixtures, the only mix design consideration is the percentage of Portland cement. Trial mixes between 5 and 12 percent Portland cement are needed to properly stabilize bottom ash or boiler slag for use as a roller-compacted base course. The results of ASTM C593 compressive strength and durability testing should be the basis for selection of the final mix.

The compacted unit weight of bottom ash or boiler slag mixes is lower than the compacted unit weight of stabilized base mixtures containing conventional aggregates. Consequently, a cement content of 10 percent by weight for a base course mix containing bottom ash or boiler slag may be equivalent to 7 percent by weight cement content for a similar mix containing a natural aggregate.

The trial mixture with the lowest percentage of cement (or activator plus fly ash in PSB mixtures) that satisfies both the compressive strength and the durability criteria is considered the most economical mixture. To ensure an adequate factor of safety for field placement, stabilized base or subbase mixture used in the field should have an activator content that is at least 0.5 percent higher (1.0 percent higher if using kiln dust) than that of the most economical mixture (ACAA 1991).

Designing pavement structures that include stabilized base layers with bottom ash or boiler slag aggregate should follow AASHTO pavement design methods provided in the Guide for Design of Pavement Structures (AASHTO 1993), or the Guide for the Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (NCHRP 1-37A 2004). The AASHTO methods account for the predicted loading (the number of 80 kN equivalent single axle loads), required reliability (degree of certainty that a design will function properly during the design life), serviceable life (ability to maintain quality during the pavement life), the pavement structure (characterized by the structural number), and subgrade support (related to the resilient modulus of the subgrade) (AASHTO 1993).

A hierarchical approach in the mechanistic-empirical design method allows for varying levels of material characterization depending on project criteria. Mechanistic material properties such as dynamic modulus, resilient modulus, and Poisson’s ratio are employed to evaluate pavement performance. The levels in the hierarchical system can directly measure strength characteristics (level 1), can use correlations to develop strength characteristics (level 2), or can use typical material property default values (level 3). Both asphalt stabilized base materials and chemically or cement stabilized base materials are included in the mechanistic-empirical design method under different material categories.

When a Portland cement concrete roadway surface is to be designed with a stabilized base or subbase, the AASHTO structural design method for rigid pavements can be used (AASHTO 1993).

Both bottom ash and boiler slag can be handled and stored using methods and equipment that are used for conventional aggregates.

The blending or mixing of bottom ash or boiler slag in stabilized base mixtures can be done in a mixing plant or in place. Plant mixing provides control over the quantities of materials batched, resulting in a uniform mixture. Mix proportions from in-place mixing are not as accurate as mix proportions from plant mixing, although in-place mixing of mixes containing bottom ash or boiler slag produce satisfactory stabilized base material.

Stabilized base materials should not be placed in layers that are less than 100 mm (4 in) or greater than 200 to 225 mm (8 to 9 in) in compacted thickness. Stabilized base material should be spread in loose layers that are approximately 50 mm (2 in) thicker than the compacted thickness. The top surface of an underlying layer should be scarified prior to placing the next layer. For granular or coarse graded mixtures, steel-wheeled vibratory rollers are used. For fine-grained mixtures, a vibratory sheepsfoot roller, followed by a pneumatic roller, provide quality stabilized base compaction (ACAA 1991).

To develop the design strength of a stabilized base mixture, the material should be well-compacted at the optimum moisture content. To avoid drying, plant-mixed materials should be delivered to the job site as soon as possible and should be compacted within a reasonable time after placement.

Compaction of fly ash stabilized bottom ash or boiler slag mixtures should be completed as quickly as possible after placement. The stabilized material can lose strength capacity if the fly ash hydrates in an uncompacted state. The pozzolanic reaction between Class F fly ash and lime is a relatively slow reaction, and a maximum delay of 4-hours should be followed whereas a maximum delay of 2-hours is recommended for Class C fly ash (White et al. 2005, Little et al. 2000). To slow the reaction, a commercial retarder, such as gypsum or borax, can be added at the mixing plant in low percentages (approximately 1 percent by weight) without adversely affecting the strength development of the stabilized base material (ACAA 1991).

After placement and compaction, the stabilized base material should be properly cured to protect against drying and to assist in the development of in-place strength. An asphalt emulsion seal coat should be applied within 24 hours after placement. The same practice is applicable if a Portland cement concrete or asphalt pavement is constructed above the stabilized base or subbase material. Paving over the stabilized base is recommended within 7 days after the base has been installed. Unless an asphalt binder and/or surface course has been placed over the stabilized material, vehicles should not drive over the stabilized base until an in-place compressive strength of at least 2400 kPa (350 lb/in^2) has been achieved (ACAA 1991).

Stabilized base materials containing bottom ash or boiler slag that are subjected to freezing and thawing conditions should develop a level of in-place strength prior to the first freeze-thaw cycle. For northern states, many state transportation agencies have established construction cutoff dates for stabilized base materials. These cutoff dates range from September 15 to October 15, depending on the state, or the location within a particular state (AASHTO 1993).

Stabilized base materials, especially those in which Portland cement is used as the activator, are subject to cracking. The cracks are typically shrinkage related and are not the result of structural weakness or defects in the stabilized base material. The cracks also not related to the type of aggregate used in the mix. Shrinkage cracks will reflect through the overlying asphalt pavement and should be sealed at the pavement surface to prevent water intrusion and subsequent damage due to freezing and thawing.

An approach to controlling or minimizing reflective cracking associated with shrinkage cracks in stabilized base materials is to saw cut transverse joints in the asphalt surface that extend into the stabilized base material to a depth of 75 to 100 mm (3 to 4 in). Joint spacing of 9 m (30 ft) have been suggested (ACAA 1991). Joints should be sealed with a material such as hot poured asphaltic joint sealant.

Table 6. Design parameters for bottom ash and boiler slag in stabilized granular base applications.

Property	Bottom Ash	Boiler Slag	Source	Test Method	Considerations
Specific Gravity	1.9 -3.4	2.3 - 2.9	Majizadeh (1979), Moulton (1973), Lovell et al. (1991)	ASTM D854-06	Bottom ash with relatively low apparent specific gravity is often indicative of the presence of porous particles trapping gases that affect the test results. Bottom ash with relatively high specific gravity may indicate high iron content.
Dry Unit Weight	7.07 - 15.72 kN/m^3 (45 - 100 lb/ft^3)	7.43 - 14.15 kN/m^3 (60 - 90 lb/ft^3)	Majizadeh (1979)		
Los Angeles Abrasion Loss %	30 - 50	24 - 48	Moulton (1973), Huang (1990)	ASTM C535	Results fall within the specifications of a maximum 50 percent loss by abrasion.
Sodium Sulfate Soundness Loss %	1.5 - 10	1 - 9	Moulton (1973), Huang (1990)	AASHTO T 104 ASTM C88	Soundness values are generally found to be within ASTM C88(19) weight loss specifications of not more than 15 percent after five cycles.

Embankment or Backfill Material
According to the American Coal Ash Association approximately 3.63 million metric tons (4.0 million tons) of bottom ash were utilized in structural fill and embankment applications in 2006 (ACAA 2007). Structural fill and embankment material is the largest use of bottom ash in the U.S. While specifications for bottom ash and boiler slag reuse depend on the application, there are material characteristics that must be met when using bottom ash or boiler slag in embankments or as a structural fill.

Bottom ash and ponded ash have been used as structural fill materials for the construction of highway embankments and/or the backfilling of abutments, retaining walls, or trenches. These materials may also be used as pipe bedding in lieu of sand or pea gravel.

Bottom ash and boiler slag have been successfully used as embankment or structural fill material both nationally and internationally. Bottom ash from WE Energies of Wisconsin was successfully used as a backfill material in Racine, Wisconsin (Ramme and Tharaniyil 2004) as well as fill for a freeway spur in Milwaukee, Wisconsin and other projects (WTIC 1999). Indiana DoT has used bottom ash in numerous transportation applications including as an embankment material (Siddiki et al 2004).

Approximately 1 million metric tons (1.1 million tons) of coal combustion products (mixtures of fly ash, bottom ash, boiler slag, and fluidized bed combustion ash) were used to raise embankments on an ash pond in Rihand, India (Asokan et al. 2005). Coal combustion products including bottom ash have also been used in India for widening existing bridge approaches or building embankments for overpass bridges in Delhi . Bottom ash has been used as a light weight fill over soft soils in Sweden due to the low unit weight of bottom ash (Rogbeck and Knutz 1996).

Embankment/Backfill Design Considerations:
Mechanical characteristics of bottom ash that are important when bottom ash is used as an embankment or fill material are summarized in Table 6:

Dry bottom ash can sustain particle degradation during compaction (Kim et al 2005). Crushing of the bottom ash particles during compaction contributes to an increase in the maximum dry unit weight. Compaction characteristics of mixtures of fly ash and bottom ash have more well-graded size distributions, which allows the fly and bottom ash particles to pack more closely, resulting in an increase in the maximum dry unit weight of the mixture (Kim et al. 2005).

Bottom ash is a well-graded material with particles ranging in size from fine gravel to fine sand with low percentages of silt-clay sized particles. Bottom ash is predominantly sand-sized, usually with 50 to 90 percent passing the No. 4 sieve (4.75 mm) and 0 to 10 percent passing the No. 200 sieve (0.075 mm). Top particle size for bottom ash is typically between 19 mm (¾ in) to 38.1 mm ($1^{-½}$ in).

Granular materials with angular particles are typically more compressible than those with well-rounded particles because the sharp edges of the angular particles tend to be break during compression as well as shear. Although some bottom ash particles are porous and weak, for low stress levels, the compressibility of bottom ash is comparable to that of sand placed at the same relative density (Seals et al. 1972). Coal ash consolidates rapidly; therefore compressibility typically is not a design concern (ASTM E2277-03 2003).

Both bottom ash and boiler slag can be handled and stored using the same methods and equipment that are used for conventional aggregates.

Prior to placement, a site should undergo preparations consistent with preparation requirements for soil fill materials. Construction equipment needed to properly place and compact bottom ash or boiler slag in an embankment or structural backfill includes a bulldozer for spreading the material, a compactor, either a vibrating or pneumatic tired roller, a water truck to provide water for compaction and to control dusting, and a motor grader where final grade control is critical.

Bottom ash and boiler slag is typically dumped and spread with a bulldozer or motor grader in lifts no thicker than 0.3 m (12 in.) when loose. Bottom ash and boiler slag should be compacted at, or slightly above, optimum moisture content as determined by standard Proctor compaction procedures (ACAA 2007). Bottom ash loses stability at low moisture contents; therefore, high moisture contents should be maintained to allow construction equipment to operate. The addition of up to 30 percent fines in the form of fly ash may remedy the loss of stability upon drying (Moulton 1973).

Compaction of bottom ash and boiler slag can be accomplished by static steel-wheeled rollers, pneumatic rollers, or vibratory compaction equipment. For each project, the type of compactor, the moisture content of the bottom ash or boiler slag at placement, the lift thickness, and the number of passes of the compaction equipment should be evaluated using a test strip.

Quality control programs for bottom ash or boiler slag embankments or structural backfills are similar to such programs for conventional earthwork projects. These programs typically include visual observations of lift thickness, number of compactor passes per lift, and behavior of fly ash under the weight of the compaction equipment, supplemented by laboratory and field testing to confirm that the compacted material has been constructed in accordance with design specifications. More information on performance specifications and procedures and method specifications and procedures can be found in ASTM E2277.

Table 7. Design parameters for bottom ash and boiler slag in structural fill/backfill applications.

Property	Bottom Ash	Boiler Slag	Source	Test Method	Considerations
Maximum Dry Density kN/m^3 (lb/ft^3)	11.79 - 15.72 (75 - 100)	12.89 - 16.04 (82 - 102)	Lovell et al. (1991), Tanyu et al. (2004)	AASHTO T 085 ASTM D2216-05	Compaction curves exhibit maximum dry density at either an air-dried condition or a flushed or wet condition (Lovell et al. 1991). Flushed conditions can be maintained in the field, producing a maximum dry density (Huang 1990).
Optimum Moisture Content, %	Usually <20 12 - 24 range	8 - 20	Lovell et al. (1991), Tanyu et al. (2004)		
Internal Friction Angle (drained)	38 - 42° 32 - 45° (<9.5 mm size)	38 - 42° 36 - 46° (<9.5 mm size)	Majizadeh et al. (1979), Moulton (1973)	ASTM D4767-04 ASTM D 3080	
	K_2 = 0.52				
Hydraulic Conductivity cm/sec	1 - 10^{-3}	10^{-1} - 10^{-3}	Prakash and Sridharan (2006), Siddiki et al. (2004)	ASTM D2434-68 ASTM D5084-03 AASHTO T 215	Bottom ash is well draining material and is non-susceptible to frost heave.

END USER RESOURCES
Several resources are available to end users interested in incorporating bottom ash and boiler slag into construction applications and include the following:

American Coal Ash Association (ACAA)
15200 E. Girard Ave., Ste. 3050
Aurora, Colorado 80014-3955
http://www.acaa-usa.org/

Coal Combustion Products Partnership (C2P2)
Office of Solid Waste (5305P)
1200 Pennsylvania Avenue, NW
Washington, DC 20460
http://www.epa.gov/epaoswer/osw/conserve/c2p2/index.asp

Electric Power Research Institute (EPRI)
3412 Hillview Road
Palo Alto, California 94304
http://my.epri.com

Edison Electric Institute (EEI)
1701 Pennsylvania Avenue, N.W.
Washington, D.C. 20004-2696
http://www.eei.org/

Green Highways Partnership
http://www.greenhighwayspartnership.org/

AASHTO Center for Environmental Excellence
444 North Capitol Street, NW Suite 249
Washington, D.C., 20001
202-624-5800
http://environment.transportation.org/

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ASTM C593-06 standard specification for fly ash and other pozzolans for use with lime for soil stabilization. In: Annual book of ASTM standards. ASTM; West Conshohocken, Pennsylvania: 2006.

ASTM C88-05 standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate. In: Annual book of ASTM standards. ASTM; West Conshohocken, Pennsylvania: 2005.

ASTM E2277-03 standard guide for design and construction of coal ash structural fills. In: Annual book of ASTM standards. American Society for Testing and Materials; West Conshohocken, Pennsylvania: 2003.

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