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Standard Guide for
Design and Construction of Coal Ash Structural Fills[1]

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1. Scope

1.1 This guide covers procedures for the design and construction of engineered structural fills using coal fly ash, bottom ash, or ponded ash.

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

1.3 This guide applies only to fly ash and bottom ash produced primarily by the combustion of coal.

1.4 The testing, engineering, and construction practices for coal ash fills are similar to generally accepted practices for natural soil fills. Coal ash structural fills should be designed using generally accepted engineering practices.

1.5 Laws and regulations governing the use of coal ash vary by state. The user of this guide has the responsibility to determine and comply with applicable requirements.

1.6 The values stated in inch-pound units are to be regarded as the standard. The SI units given in parentheses are for information only.

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

2. Referenced Documents

2.1 *ASTM Standards:*

C 150 Specification for Portland Cement[2]

C 188 Test Method for Density of Hydraulic Cement[2]

C 311 Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete[3]

C 595/C 595M Specification for Blended Hydraulic Cements[2]

D 75 Practice for Sampling Aggregates[4]

D 420 Guide to Site Characterization for Engineering, Design, and Construction Purposes[5]

D 422 Test Method for Particle-Size Analysis of Soils[5]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[5]

D 698 Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft^3(600 kN-m/m^3))[5]

D 854 Test Method for Specific Gravity of Soils[5]

D 1195 Test Method for Repetitive Static Plate Load Tests of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements[5]

D 1196 Test Method for Nonrepetitive Static Plate Load Tests of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements[5]

D 1452 Practice for Soil Investigation and Sampling by Auger Borings[5]

D 1556 Test Method for Density and Unit Weight of Soil In Place by the Sand-Cone Method[5]

D 1557 Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56 000 ft-lbf/ft^3(2700 kN-m/m^3))[5]

D 1586 Test Method for Penetration Test and Split-Barrel Sampling of Soils[5]

D 1883 Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils[5]

D 2166 Test Method for Unconfined Compressive Strength of Cohesive Soil[5]

D 2167 Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method[5]

D 2216 Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock[5]

D 2435 Test Method for One-Dimensional Consolidation Properties of Soils[5]

D 2850 Test Method for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression[5]

D 2922 Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth)[5]

D 3080 Test Method for Direct Shear Test of Soils Under

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

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

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

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

Consolidated Drained Conditions[5]

D 3550 Practice for Ring-Lined Barrel Sampling of Soils[5]

D 3877 Test Methods for One-Dimensional Expansion, Shrinkage, and Uplift Pressure of Soil-Lime Mixtures[5]

D 4253 Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table[5]

D 4254 Test Method for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density[5]

D 4429 Test Method for Bearing Ratio of Soils in Place[5]

D 4643 Test Method for Determination of Water (Moisture) Content of Soil by the Microwave Oven Method[5]

D 4959 Test Method for Determination of Water (Moisture) Content of Soil by Direct Heating Method[6]

D 4972 Test Method for pH of Soils[6]

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

D 5239 Practice for Characterizing Fly Ash for Use in Soil Stabilization[6]

E 1527 Practice for Environmental Site Assessments: Phase I Environmental Site Assessment Process[7]

E 1528 Practice for Environmental Site Assessments: Trans-action Screen Process[7]

E 1609 Guide for the Development and Implementation of a Pollution Prevention Program[7]

E 2201 Terminology for Coal Combustion Products[7]

G 51 Test Method for pH of Soil for Use in Corrosion Testing[8]

G 57 Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method[8]

2.2 *AASHTO Standards:*[9]

T 288 Determining Minimum Laboratory Soil Resistivity

T 289 Determining pH of Soil for Use in Corrosion Testing

T 290 Determining Water Soluble Sulfate Ion Content in Soil

T 291 Determining Water Soluble Chloride Ion Content in Soil

3. Terminology

3.1 *Definitions*—For definitions related to Coal Combustion Products, see Terminology E 2201. For definitions related to geotechnical properties see Terminology D 653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *internal erosion*—piping; the progressive removal of soil particles from a mass by percolating water, leading to the development of channels.

4. Significance and Use

4.1 *General*:

4.1.1 Coal ashes are suitable materials for the construction of engineered, structural fills. Coal ashes may be used as: structural fill for building sites and foundations; embankments for highways and railroads, dikes, levees; and in any other application requiring a compacted fill material. Their low unit weight, relatively high shear strength, ease of handling, and compaction all make coal ashes useful as fill material. Coal ashes may be a cost-effective fill material in many areas because they are available in bulk quantities, conserve natural resources, and reduce the expenditures required for the purchase, permits, and operation of a soil borrow pit. Coal ash often can be delivered at near optimum moisture content.

4.1.2 This guide describes the unique design and construction considerations that may apply to structural fills constructed of coal ash. The requirements for specific structural fills may vary due to local site conditions or the intended use of the structural fill, or both.

4.2 *Regulatory Framework*:

4.2.1 *Federal*—The U.S. Environmental Protection Agency (USEPA) has completed a study of coal combustion by-products for the U.S. Congress and has issued a formal regulatory determination **(1, 2)**.[10] USEPA "encourages the utilization of coal combustion by-products and supports State efforts to promote utilization in an environmentally beneficial manner" **(3)**. USEPA subsequently ruled that national regulation of most beneficial uses of coal ash, including structural fills, is not warranted **(4)**.

4.2.2 *State and Local*—Laws and regulations regarding the use of coal ash vary by state and locality.

4.3 *Economic Benefits*—Coal ash can be a cost-effective fill material. In many areas, it is available in bulk quantities at a reasonable cost. Use of coal ash conserves natural resources and reduces the expenditures for the purchase, permits, and operation of a soil borrow pit.

5. Engineering Properties and Behavior

5.1 *General*—Fly ash and bottom ash exhibit distinct engineering properties and behavior as described below. The engineering properties and behavior of ponded ash may be similar to fly ash or bottom ash, depending on the ratio of each in the ponded ash.

5.2 *Unit Weight*—Many coal ashes have relatively low unit weights. The low unit weight of these materials can be advantageous for some structural fill applications. The lighter weight material will reduce the load on weak layers or zones of soft foundation soils such as poorly consolidated or landslide-prone soils. Additionally, the low unit weight of these materials will reduce transportation costs since less tonnage of material is hauled to fill a given volume.

5.3 *Strength*:

5.3.1 *Shear Strength*—For non-self-cementing fly ash and bottom ash, shear strength is derived primarily from internal friction. Typical values for angles of internal friction for non-self-cementing fly ash are higher than many natural fine-grained soils. These ashes are non-cohesive and although the ash may appear cohesive in a partially saturated state, this effect is completely lost when the material is either completely dried or saturated.

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

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

[8] *Annual Book of ASTM Standards*, Vol 03.02.

[9] Interim Specifications for Transportation Materials and Methods of Sampling and Testing, Part II, AASHTO, 444 North Capitol St., N.W., Suite 225, Washington, DC 20001.

[10] The boldface numbers in parentheses refer to the list of references at the end of this standard.

5.3.1.1 Due to its angular shape, the shear strength of bottom ash is typically greater than fly ash and is similar to the shear strength of natural materials of similar gradation. However, friable bottom ash may exhibit lower shear strength than natural materials of similar gradation.

5.3.2 *Compressive Strength*—Self-cementing fly ash experiences a cementing action that increases with time. Because the hydration of dry self-cementing fly ash commences immediately upon exposure to water, higher compressive strengths will be attained when the fly ash is placed and compacted immediately following addition of water. If too much time lapses, the fly ash particles can become cemented in a loose state, reducing the compacted density and strength.

5.4 *Consolidation Characteristics*—Structural fills constructed of fly ash typically exhibit small amounts of time-dependent, post-construction consolidation. This is because excess pore water pressures dissipate relatively rapidly, and thus, most of the embankment settlement or deformation occurs due to elastic deformation of the material, rather than by classical consolidation. Most deformation due to the mass of the fill or structure thereon generally occurs during construction.

5.4.1 Bottom ash is usually a free-draining material that can be compacted into a relatively dense, incompressible mass. For these reasons structural fills constructed of bottom ash also typically exhibit small amounts of time-dependent, post-construction consolidation or deformation, with most deformation occurring during construction.

5.4.2 Self-cementing fly ash typically exhibits minimal post-construction consolidation or deformation due to cementing and solidification of the fly ash.

5.4.3 Some self-cementing fly ash may swell with time. Section 6.3.8 provides guidance on evaluating the swelling potential of self-cementing fly ash.

5.5 *Permeability*—The permeability of non-self-cementing fly ash is similar to values observed for natural silty soils.

5.5.1 Self-cementing fly ash is relatively impermeable, with permeability values similar to natural clays.

5.5.2 Bottom ash is typically as permeable as granular soils of similar gradation.

5.6 *Liquefaction and Frost Heave*—Fine-grained, non-cohesive materials such as fly ash are susceptible to liquefaction and frost heave when saturated. For this reason, fly ash fills are designed to be well drained or are located in areas where they are not subject to saturation or infiltration by surface or ground water. Self-cementing fly ash is not susceptible to liquefaction.

5.6.1 Bottom ash is not typically susceptible to either liquefaction or frost heave. However, some of the finer bottom ash materials may behave quite similarly to fly ash and would require the same consideration for design as fly ash fills.

6. Testing Procedure

6.1 *General*—Testing requirements are determined based on site conditions, knowledge of the coal ash, intended use of the fill, and local requirements.

6.2 *Sampling*—Practice D 75 or Test Method C 311 as appropriate, and Guide D 420 with sample extraction conducted in accordance with Practice D 1452, Test Method D 1586, or Practice D 3550, as appropriate.

6.3 *Physical and Engineering Characteristics*:

6.3.1 *Grain-Size Distribution*—Test Method D 422. For fly ash, a substantial portion of the material will be finer than the No. 200 sieve and hydrometer analyses will also be required. Use distilled water in the hydrometer test with a deflocculating agent added to prevent fly ash from forming flocs. Self-cementing fly ash[es] may require use of alcohol or other nonreactive solution in place of the standard solution used. Fly ash often has a relatively uniform particle size and precautions against overloading sieves are warranted. Specimen loss through dusting can also be a problem. Specific gravity may vary with particle size. Specific gravity values used in hydrometer analyses should be appropriate to the portion of the sample being tested.

6.3.2 *Specific Gravity*—Test Method D 854. For some fly ash, a significant portion of the particles may have a density less than water and float. Agitation of the slurry may be needed to keep the particles in suspension so that the average specific gravity can be obtained. Alternately for this ash and self-cementing fly ash, Test Method C 188, which uses kerosene as the fluid, may be used.

6.3.3 *Water Content*—Test Method D 2216. For self-cementing fly ash consider lowering the drying temperature to 140°F (60°C) to avoid driving off the water of hydration.

6.3.4 *Compaction*:

6.3.4.1 *Fly Ash*—Test Method D 698 or D 1557. For dry self-cementing fly ash, the time interval between wetting and compaction in the laboratory should be similar to that anticipated during construction to account for the influence of the rate of hydration on compaction characteristics.

6.3.4.2 *Bottom Ash*—Test Methods D 4253 and D 4254 may be used for the determination of maximum and minimum density of coarse-grained bottom ashes that do not exhibit a moisture-density relationship.

6.3.5 *Strength*:

6.3.5.1 *Shear Strength*—Test Method D 3080. This test is preferred because it models the drained conditions that typically exist in a structural fill constructed of coal ash. The method is modified in that the shear box is not to be filled with water.

6.3.5.2 *Compressive Strength of Non-Self-Cementing Fly Ash*—Test Method D 2850. Compact specimens to the unit weights and water contents required by the project compaction requirements.

6.3.5.3 *Compressive Strength of Self-Cementing Fly Ash*—Test Method D 2166. The unconfined compressive strength at various ages is used to evaluate short-term and long-term strength development.

6.3.6 *Hydraulic Conductivity*—Test Method D 5084. Hydraulic conductivity is used to estimate the quantity of infiltration for designing underdrains.

6.3.7 *Compressibility*—Test Method D 2435. Samples should be prepared at the degree of compaction specified for construction and at the optimum water content determined by the compaction test. This is because fly ash tends to lose surface stability in the field when compacted at water contents greater than the optimum for compaction. Coal ash consolidates rapidly, therefore compressibility typically is not a design concern. Because of the non-cohesive nature of some coal ashes, extra care in sample handling is needed.

6.3.8 *Swelling*—Test Methods D 3877, for self-cementing fly ash. Reactions producing the expansive properties may not commence for a period of more than 30 days after initial ash hydration. The test procedures must address this delayed reaction. The procedure should be modified to extend the wetting and drying cycles to a frequency determined by a qualified design engineer.

6.4 *Chemical Characteristics*—Chemical analyses are routinely conducted by many coal ash producers and are communicated to users of this material by means of a Material Safety Data Sheet (MSDS) or some similar communication. For the structural fill designer these results provide information on characteristics that may need to be considered in design, particularly with regard to assessing chemical interaction between fill and other materials or structures. Tests for soluble species may also be required by local regulatory agencies.

6.4.1 *Chemical Composition*—Test Methods C 311 is often used to determine the major chemical constituents.

6.4.2 *pH*—Test Method D 4972 or Practice D 5239. The pH of the coal ash may vary with age, water content, and other conditions.

6.4.3 *Resistivity*—Test Method G 57, a field test, is used to measure coal ash resistivity as an indicator of possible corrosion potential for embedded metals. An alternate laboratory procedure is AASHTO Interim Method of Test T 288. Likely field water contents should be considered in assessing test conditions and results. Field water contents in drained coal ash fills are likely to be close to the optimum water content for compaction. AASHTO Interim Methods of Test T 289, T 290, and T 291 provide measurements of the pH, water-soluble sulfate ion content and water-soluble chloride ion content of the coal ash that are useful in evaluating corrosion potential. Test Method G 51 is also used to determine the pH of soil for use in corrosion testing.

6.4.4 *Sulfate*—Sulfate content as determined from the coal ash chemical analysis by Test Method C 311, or other method is used in a preliminary assessment of the potential for sulfate attack on concrete. As with corrosivity, likely field water conditions and variations in concentrations with time should be considered.

7. Design Considerations

7.1 *General*—The design process and procedures are similar to those normally followed for cohesionless natural soil materials. Cohesion developed by self-cementing fly ash can also be considered in the design of fill slopes and determination of bearing capacity. Refs **(5-9)** provide additional information regarding laboratory testing, design, and construction procedures.

7.1.1 The ultimate end use of the site can present special design considerations. For example, fly ash is not an appropriate medium for septic systems. A thicker soil cover may be appropriate depending on the planned end use of the site. Deed restrictions may be warranted in some instances.

7.2 *Site Characterization*:

7.2.1 *General*—The siting and design of a coal ash structural fill requires the same characterization of site conditions that is typically required of earthwork construction projects of similar size. The geologic and hydrologic conditions at the site must be understood to determine design parameters for the structural fill. In addition, consideration of environmental resources at or near the site is required to avoid or minimize negative environmental consequences. Practices E 1527 and E 1528 may be applied whenever a real estate transaction is involved.

7.2.2 *Geologic and Hydrologic Investigation*—A subsurface investigation may involve a review of available information about the site, a site reconnaissance by a geologist or engineer, and extraction of soil and rock samples for classification and testing, depending on the size and intended use of the structural fill. Guide D 420 provides guidance for conducting subsurface investigations.

7.2.3 *Environmental Resources*—Many sensitive environmental resources such as wetlands, floodplains, rare and endangered species, and cultural resource areas are afforded protection by Federal, state, and local regulations and ordinances. Appropriate action should be taken to comply with the requirements of the regulatory agency having jurisdiction at the structural fill site.

7.3 *Site Preparation and Internal Drainage*—Some structural fills constructed of non-self-cementing fly ash must be well drained because of the sensitivity of the material to the flow of water (that is, piping). Problems such as slope stability, liquefaction, and frost heave that may result from saturation of the fly ash are thus avoided. When necessary, a drainage blanket can be used to provide internal drainage and serve as a capillary barrier. Coal ash should be placed in areas where it is not subject to saturation by surface or ground water to avoid this concern.

7.3.1 *Site Preparation*—Site preparation involves grading and drainage improvements required prior to placement of coal ash. Surface drainage is diverted and controlled. Erosion and sedimentation controls are installed. If needed, wet areas are allowed to drain and dry. Unsuitable materials such as vegetation and topsoil are removed and the subgrade is prepared. Provisions to stockpile any soil needed for final cover are included.

7.3.2 *Site Drainage*—Provisions for positive site drainage are essential if the structural fill is to be reliably maintained in an unsaturated condition. Drainage of seeps and springs encountered during construction should be provided for in design of a site drainage system. A series of perforated pipe drains or aggregate-filled trenches are commonly used for this purpose. These systems are flexible and can be expanded in areal extent as needed to accommodate conditions encountered during construction. Adequate filter protection of drains to ensure long-term, maintenance-free performance should be included. Any provisions needed to control site ground-water levels through collection and drainage should be included in the design.

7.3.3 *Drainage Blanket*—For non-self-cementing fly ash, a drainage blanket of free-draining material may be used. The drainage blanket also serves as a barrier to capillary saturation.

Bottom ash often has a suitable particle size range to serve as a drainage blanket. Sand, gravel, or other aggregate can also be used depending upon the gradation of these materials. Adequate filter protection such as a geotextile between the fill and drainage blanket must be considered and included to ensure satisfactory long-term performance. The drainage blanket should be designed so that the outlets will remain freely drained. Including outlet pipes with rodent screens is one method that is often satisfactory.

7.4 *Surface Cover and Drainage*—Provisions must be made for controlling erosion of coal ash fills. Due to its fine-grained, non-cohesive nature, non-self-cementing fly ash is readily eroded. Unprotected, compacted coal ash is erodible when exposed to surface runoff or high winds. Erosion control is normally accomplished by controlling surface run-on and run-off and by establishing permanent cover with compacted stone, pavement, or soil and vegetation.

7.4.1 *Cover*—Effective cover to control erosion can be either pavement or soil depending upon the final use of the surface. Surface configuration should include provisions for controlled, positive drainage of surface runoff. Minimum slopes to prevent ponding both on surfaces and in drainage ways of approximately 1 to 3 % are desirable so that settlement and minor surface variations can be accommodated.

7.4.2 *Soil Thickness/Vegetation*—The required thickness of soil cover varies and will depend upon site use, climate, and the type of vegetation to be established. The most important consideration is to control wind and water erosion of the surface. On sites where erosion potential is small, 6 in. (150 mm) of cover may provide protection, but 1 ft is probably a practical minimum thickness in most cases. Where erosion potential is greater, or deeper rooted vegetation is planned, greater thicknesses may be warranted. In some cases fly ash/soil blends are used as part of the cover to reduce the need for soil borrow. In these applications, testing of the blend to determine its suitability as a growing medium should be conducted.

7.4.3 *Surface Drainage*—Positive surface drainage is needed to prevent ponding that can lead to erosion problems. Suitable channel linings designed to accommodate storm flows without damage are needed. Slopes on surface areas and in drainage channels should be sufficient to prevent ponding and avoid long-term maintenance problems.

7.5 *Structural Performance*—In order to perform satisfactorily, any fill material must support its own mass, that of the loads to be placed on it, and have acceptable settlement. Each of these aspects is analyzed as part of the design process.

7.5.1 *Slope Stability*—Embankment slopes should be stable and able to stand without slumping or sliding. Stability analyses should consider static, dynamic and seismic loadings, and seepage forces, as appropriate. Desired factors of safety typically range from 1.2 (seismic and dynamic) to 1.5 (static). Stability of exterior slopes, foundation soils and embankment combined, and cover soils should be analyzed.

7.5.2 *Bearing Capacity*—The ability of the fill to support structures bearing on or within the fill can be calculated by conventional procedures used for natural soils.

7.5.2.1 *Footings*—Ultimate bearing capacity analysis is appropriate for footings bearing on compacted coal ash structural fills. The analysis is simplified by the drained, non-cohesive nature of the fill (except for self-cementing fly ash). The relatively low unit weight of coal ash as compared to natural soils should be considered in the analyses. Footings that are wider than the thickness of the fill below the footing or that are located near the edge of slopes are cases that may require special consideration.

7.5.2.2 *Slabs and Pavements*—The ability of the fill to support slabs and pavements to be located on the fill surface can be assessed by standard pavement design procedures and by determining the modulus of subgrade reaction by Test Methods D 1195 or D 1196, or bearing ratio by Test Methods D 1883 or D 4429, as appropriate.

7.5.3 *Settlement*—As with any fill material, settlement due to consolidation and compression of the fill and the underlying materials should be considered in design. Settlement may adversely affect project performance if not considered in design. Conventional methods of analysis used with natural soils are appropriate.

7.5.4 *Lateral Earth Pressure*—Conventional methods of analysis of lateral earth pressure can be used for coal ash considering that the material is cohesionless (except for self-cementing fly ash) and has a lower unit weight than many natural soils. For structures that are fixed and unable to yield, earth pressure at rest coefficients of 0.5 are typically used in estimating loads. For most yielding retaining walls, active earth pressures are determined by Rankine's method. Coulomb's method is generally used for walls over 20 ft (6.1 m) in height.

7.6 *Compaction*—Proper and uniform compaction (including control of molding water content) of coal ash placed in the structural fill increases the strength of the material, reduces the compressibility, and produces a relatively uniform structural fill. Coal ash is readily spread and compacted by conventional construction equipment; vibratory compactors operated at or near resonant frequency are particularly effective.

7.6.1 *Fly Ash*—Because it is fine-grained, fly ash exhibits compaction behavior under static compaction similar to natural soils in that compaction is sensitive to molding water content. Most fly ash has a well-defined compaction relationship, that is, for a given static compactive energy, there exists an optimum water content at which compaction of the fly ash will achieve the maximum dry unit weight. Attempting to compact fly ash above the optimum water content results in displacement of the fly ash and limited densification is attained. Using static compaction, the compaction of fly ash with water contents below the optimum water content requires more compactive effort to achieve desired results. However, the compaction of fly ash is not especially sensitive to variations in water content when using vibratory compactors operated at the resonant frequency. Thus, fly ash that is several percent below the optimum water content can be readily compacted using vibratory compactors operated at the resonant frequency. Compaction characteristics of dry self-cementing ash changes rapidly with time after exposure to water. This property is a result of the rapid rate of hydration that produces a cementitious reaction. A reduction in maximum density of more than

30 pounds per cubic foot can occur and must be addressed by the design and compaction procedures.

7.6.2 *Bottom Ash*—Bottom ash is typically free-draining, therefore, unless saturated, the moisture content of this material has little influence on its compaction characteristics. Simply wetting the bottom ash sufficiently to prevent bulking will promote adequate compaction.

7.6.3 *Placement of Coal Ash*—Coal ash should be placed in loose layers of uniform thickness. Each layer should be compacted to the required density because strength is derived from internal friction and this value is dependent on the relative compaction/unit weight of the coal ash. A maximum layer thickness is usually specified to ensure that the required density is achieved through the full depth of the layer. Control of layer thickness is not as important for self-cementing fly ash because additional strength is derived from the cementitious products formed during the hydration process.

7.6.4 *Degree of Compaction*:

7.6.4.1 *Fly Ash*—A typical requirement is that the fill be compacted to a minimum of 95 to 100 % of the maximum dry unit weight, in accordance with Test Method D 698, or 90 to 95 % of the maximum dry unit weight in accordance with Test Methods D 1557. Similar requirements are usually applied for the subgrade. Either method is acceptable. However, the desired performance of the site in terms of safe slopes and adequate performance of foundations, structures, roadways, and so forth, will dictate the degree of compaction needed.

7.6.4.2 *Bottom Ash*—Granular bottom ash is typically compacted to 70 % relative density, in accordance with Test Method D 4254.

7.6.5 *Compaction Specifications*—Compaction specifications may dictate either the construction method to be used or the performance standard to be attained.

7.6.5.1 *Method Specifications*—Method specifications specify the type of compaction equipment, the fill material placement methods, and the number of equipment passes to be used in compaction. Method specifications are based on the results of field compaction tests on trial test strips. The test strips are normally conducted at the construction site using the equipment proposed for use and materials or sources that will supply fill material for the project. Method specifications have the advantage of providing continuous quality control by monitoring the ongoing construction activities. If the material source changes or the material itself changes during construction, then the field testing should be repeated on the new material. Method specifications may also be useful for situations where variations in material properties make determination of the appropriate compaction curve difficult.

7.6.5.2 *Performance Specifications*:

(1) Fly Ash—The compaction criteria are typically expressed as a percentage of the maximum dry unit weight, in accordance with Test Method D 698 or D 1557 and at molding water contents that do not exceed the optimum water content plus a given percentage and that prevent dusting during placement and compaction. When using static-type compaction, an allowable range of water contents is also usually specified so that the material will be in the range where the required unit weight can be readily achieved. Fly ash has a tendency to be displaced under the mass of the compactor when placed above the optimum water content. Specifications requiring placement over a range of water content less than the optimum water content will control this phenomenon. Experience has shown that vibratory compactors operating at the resonant frequency can achieve the required degree of compaction in a minimum of passes over a wide range of water contents, but not excessively wet, of the optimum water content.

(2) Bottom Ash—Performance specifications for bottom ash typically specify the compaction criteria as a percentage of the relative density in accordance with Test Method D 4254, and may require use of vibratory compaction equipment.

7.6.6 *Dust Control*—Dusting does not occur during placement and compaction of coal ash when the molding water content of the coal ash is sufficient to achieve the desired degree of compaction. Coal ash surfaces exposed to the sun and wind can dry out and become susceptible to dusting. Dusting can be controlled by wetting the coal ash, applying a dust suppressant, constructing wind screens or by placing the final soil cover.

7.7 *Protection of Embedded Materials*—When materials are to be embedded in the structural fill, it is prudent during design to assess whether any deleterious reactions are likely to occur. Specifically, the potential for corrosion of pipes, conduits, and other metal structures should be evaluated. Concrete structures such as culverts, footings, and retaining walls should be evaluated for sulfate attack.

7.7.1 *Corrosion Protection*—Low resistivity is commonly used as an indicator of the corrosion potential of soil or aggregates. Field tests with coal ash have shown that additional contributing factors are high or low pH, high soluble sulfate and soluble chlorides, and partially saturated field moisture conditions. It is appropriate to check all of these factors and consider the lifetime and sensitivity of the embedded material. Appropriate test methods are described in 6.4.3. The standards used by the local state transportation agency for evaluating corrosion potential of soil fill may be used as a reference. The criteria in Refs **(10, 11)** may also be applied in lieu of state requirements.

7.7.2 *Sulfate Attack on Concrete*—Sulfate attack on concrete in coal ash fills has received attention because of the sulfate content in some coal ash. The sulfate exposure is considered severe when the water soluble sulfate in soil (or ash) exceeds 0.20 % by weight, or when sulfate in water exceeds 1500 ppm. As with corrosion, other factors such as moisture will be contributing factors. Also as with corrosion, there is a need to assess sensitivity and lifetime of the structure, and the difficulty of replacement or repair. If sulfate exposure is a concern, the use of blended or sulfate-resistant cements such as those described in Specifications C 595/C 595M and C 150, or application of polymer or bituminous coatings may provide protection.

7.8 *Radionuclides*—As with other structural fill materials, certain radioactive elements are known to occur naturally in coal ash. The model standards and techniques for controlling radon in accordance with Ref **(12)** are recommended for new building construction, where needed.

8. Construction

8.1 *General*—Construction procedures for coal ash structural fills are similar to conventional earthwork operations. Routine methods employed with soil fills to control dusting, erosion, and sedimentation are similarly required.

8.2 *Weather Restrictions*—Construction should be suspended during severe weather conditions. Operations may proceed during moderately wet periods by reducing the amount of water added at the plant or job site to compensate for precipitation. Dry coal ash can also be disked into excessively wet coal ash to reduce the water content to an acceptable level. Because fly ash obtained directly from silos or hoppers dissipates heat slowly, it may be placed during cold weather. If frost penetrates the surface a few inches, it can be removed from the surface or recompacted upon thawing and drying.

8.2.1 *Dust Control*—Dust control measures routinely used on earthwork projects are effective in minimizing airborne particulate at coal ash fill sites. Typical controls include avoiding hauling on completed ash surfaces, use of wind breaks, moisture-conditioning of the coal ash, wetting or covering of exposed coal ash surfaces, chemically treating coal ash surfaces and paving, wetting, and covering of high-traffic haul roads with coarse materials.

8.2.2 *Erosion Control*—Coal ash typically does not require additional sedimentation and erosion control measures beyond those normally employed for soil fills in accordance with state and local requirements.

8.3 *Source and Delivery*—Coal ash is typically supplied from sources containing little or no extraneous or deleterious material. Non-self-cementing fly ash and bottom ash are usually hauled in covered dump trucks with tightly sealed tailgates. These coal ashes may be conditioned with water at the plant, if necessary. Self-cementing fly ash is hauled in pneumatic tank trucks and conditioned with water at the project site or may be partially conditioned and hauled in covered dump trucks to the project site. Care should be taken to not overfill the trucks so that spillage does not occur. Adequate measures must be taken to ensure proper water content when using fly ash or bottom ash that has been stored in landfills, ponds, and lagoons. Trucks should be spray-cleaned with water at the plant to reduce spillage and dust during transport. Provisions should be made for cleaning of public roads in the event spillage does occur.

8.4 *On-Site Storage*—Limit on-site storage of coal ash to the minimum quantity required to maintain the construction schedule. For stockpiles, provide sedimentation and erosion controls in accordance with state and local requirements. Self-cementing fly ash that is not partially conditioned should be stored dry in pneumatic tank trucks or in suitably protected storage silos. Precautions normally taken for bulk storage of cement and lime may be required.

8.5 *Site Preparation*—The base of the fill should be stripped of vegetation and organic soils. The subgrade should be compacted to the desired dry unit weight and underdrains installed, when required.

8.6 *Placement and Compaction*—Place coal ash in uniform layers not exceeding the thickness specified. The coal ash must be spread uniformly; otherwise, the compaction equipment will ride on uneven hard spots in the fill, resulting in softer areas between the high spots. Tracking the coal ash with a dozer or truck prior to compaction will facilitate compaction to the required density. Typically, a coal ash fill is compacted with a vibratory or pneumatic-tired roller. Fill should not be placed on saturated or frozen material. If water must be added to obtain optimum water content condition, allow adequate time for the entire lift to equilibrate, yet compact before the surface dries out. Water should be sprayed uniformly.

8.6.1 Most coal ashes can be placed and compacted in a manner very similar to soil and aggregate fill materials. In fact, most coal ashes exhibit very little cohesion and are not as sensitive to variations in moisture content as natural soils.

8.6.1.1 Fly ash is typically placed and compacted in a manner similar to non-cohesive fine-grained soils. Smooth drum vibratory rollers and pneumatic-tired rollers typically compact fly ash most effectively. Although not always, fly ash typically exhibits a measurable moisture-density relationship that can be utilized for compaction quality control. It should be noted that fly ash that exhibits self-cementing properties must be compacted soon after the addition of water.

8.6.1.2 Bottom ash is generally placed and compacted in a manner similar to non-cohesive coarse-grained soils or fine aggregate. Smooth drum vibratory rollers and pneumatic-tired rollers typically are most effective for the compaction of these materials. Bottom ash may or may not exhibit consistent moisture-density relationships.

8.7 *Cover*—Structural fill slopes should be covered with soil and revegetated as soon as practicable following the fill placement operations. Top surfaces should also be covered promptly to reduce infiltration of precipitation and runoff into the fill and to minimize surface erosion.

8.8 *Quality Control*—Quality control programs for coal ash structural fills are similar to quality control programs for earthwork projects. These programs typically include visual observation of coal ash placement operations, supplemented with laboratory and field testing to confirm that the structural fill is constructed as designed. The testing requirements will vary depending on whether a method specification or performance specification is used.

8.8.1 Visual observations are typically made to verify lift thickness, the number of passes of the compactor on each lift, and the behavior of the coal ash under the weight of the compaction equipment. Laboratory compaction tests (Test Methods D 698, D 1557, D 4253 and D 4254) are performed to establish baseline data needed to control compaction in the field. Field unit weight and water content tests are conducted regularly on compacted lifts to verify that the required degree of compaction is achieved. Test Methods D 1556, D 2167, or D 2922 may be used to determine the field unit weight. Test Methods D 2216, D 4643, or D 4959 may be used to estimate the water content.

8.8.2 It is prudent to maintain daily job logs documenting site conditions, weather, and work activities. Water content and unit weight tests should be taken as specified by the design engineer and whenever visual observations indicate the desired degree of compaction is possibly not being achieved. As a guide in performance specifications, one test for every 1000 to 2000 cubic yards of fill is suggested.

9. Keywords

9.1 bottom ash; coal ash; embankment; fly ash; pollution prevention; resource conservation; structural fill; utilization

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