USER GUIDELINE FOR FLUE GAS DESULFURIZATION MATERIAL IN GREEN INFRASTRUCTURE CONSTRUCTION

by

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USING FLUE GAS DESULFURIZATION MATERIAL IN GREEN INFRASTRUCTURE CONSTRUCTION

INTRODUCTION

This document provides a comprehensive overview of the engineering and construction properties of flue gas desulfurization (FGD) material use in stabilized base and flowable fill. Studies addressing environmental concerns of using FGD material, an industrial by-product, as construction materials are reviewed. Some case studies are presented to demonstrate successful applications of FGD material. With the goal of advancing the use of FGD material in construction application, references to resources and tools are made available.

In 2006, FGD scrubber systems at coal-fired power plants generated approximately 27.4 million metric tons (30.2 million tons) of material, or 24.2 percent of all coal combustion products (ACAA 2007). Due to an expected increase in scrubbing applications, the amount of FGD produced is expected to grow during the next few decades (Bigham et al. 2005).

Approximately 30 percent of the FGD material produced in 2006 was beneficially used (ACAA 2007). Fixated or stabilized calcium sulfite FGD scrubber material has been used as an embankment and road base material. FGD products have also been used in place of gypsum, as feed material for the production of Portland cement. In addition, FGD material has been used in flowable fill in mine reclamation and in aerated concrete blocks. Currently, wallboard production represents the largest single market for FGD scrubber material (ACAA 2007).

For FGD scrubber sludge to be a useable construction material, the sludge must first be dewatered and then stabilized or fixated. Fixated FGD scrubber material is generated, dewatered, and stabilized at coal-burning power plants that require scrubbing of flue gas to reduce sulfur dioxide emissions. Plants that require scrubbing typically burn either medium- or high-sulfur coal.

The majority of coal-fired power plants that are equipped with FGD scrubber systems, dewater and stabilize FGD scrubber sludge for beneficial use or landfilling. Dewatering and stabilization is typically done by the utility company, while loading, transporting, and placement of stabilized or fixated FGD scrubber material is typically done by an ash management contractor. Stabilized or fixated FGD scrubber material can be obtained from either a power plant having FGD scrubbers or an ash management contractor. Most coal-burning electric utility companies employ an ash management specialist whose responsibility is to monitor ash generation, quality, use, or disposal, and to interface with ash marketers. To identify an FGD material source, contact the local utility company or visit the American Coal Ash Association's web site at http://www.acaa-usa.org/.

GENERAL FGD MATERIAL PROPERTIES

Physical Properties

Fixated or stabilized calcium sulfite FGD sludge can have a solids content from 55 to 80 percent, depending on the amount of added fly ash. The resultant fixated FGD sludge product is a damp, gray, silty, compactable material capable of developing sufficient compressive strength to support construction equipment (Smith 1985).

Dewatered and fixated calcium sulfite FGD scrubber material can be used for transportation applications, while the calcium sulfate FGD scrubber material is frequently used for wallboard or as a cement additive, although calcium sulfate FGD scrubber material can also be used in transportation applications.

The calcium sulfite material (unoxidized) tends to be finer with a higher specific gravity than the calcium sulfate material (oxidized). The specific gravity of both calcium sulfite and sulfate is less than natural soil, which is approximately 2.7. Calcium sulfite rich FGD material can be expected to have a specific gravity of approximately 2.57, where calcium sulfate rich FGD material is expected to have a lower specific gravity of approximately 2.36 (Smith 1992).

The degree to which wet FGD scrubber material is treated (i.e. dewatered, stabilized, and fixated) influences the physical properties. Table 1 shows the physical characteristics of typical calcium sulfite FGD scrubber material in a dewatered, physically stabilized, and fixated condition. Basic physical properties include solids content, moisture content, and wet and dry unit weight (Patton 1983). Dewatered calcium sulfite FGD sludges are a soft filter cake with a solids content typically in the range of 40 to 65 percent. Calcium sulfate FGD sludges can be dewatered more easily than sulfite sludges and may achieve solids contents as high as 70 to 75 percent (Smith 1993).

Table 1. Physical characteristics of typical calcium sulfite FGD scrubber material.

Physical Property	Dewatered	Stabilized	Fixated	Source
Solids Content (%)	40 - 65	55 - 80	60 - 80	Smith (1992), Patton (1983)
Wet Unit Weight (kN/m^3) (lb/ft^3)	14.9 - 15.7 (95 - 100)	14.1 - 17.3 (90 - 110)	14.1 - 18.1 (90 - 115)	
Dry Unit Weight (kN/m^3) (lb/ft^3)	9.4 - 10.2 (60 - 65)	9.4 - 13.3 (60 - 85)	12.6 - 15.7 (80 - 100)	
Specific Gravity	2.4			

Dewatered and unstabilized calcium sulfite FGD scrubber sludge consists of fine silt-clay sized particles with approximately 50 percent finer than 0.045 mm (No. 325 sieve).

For most dry FGD systems, the FGD by-product is a fine material of uniform consistency with between 56 and 90 percent of the particles having a diameter smaller than 0.025 mm (Kost et al. 2005). Grain size uniformity coefficients are in the range of 1.8 to 2.4, representing a uniform particle size. The specific surface area, ranging from 1.28 to 9.49 m^2 g^{-1}, indicates a nonporous material (Kost et al. 2005). Swell tests conducted according to Method A of ASTM D4546 on dry FGD samples showed a high degree of variability in swelling, in the range of 0 to 60 percent. Swelling observed over time indicates two distinct swelling episodes. The first episode occurs immediately after the introduction of water and produces a 0 to 14 percent volume change. The second episode typically begins 10 to 50 days after the introduction of water and accounts for the remaining swell (Bigham et al. 2005).

Mechanical Properties

Mechanical properties of FGD material are shown in Table 2. The expected range of these mechanical properties is presented for dewatered, stabilized, and fixated calcium sulfite FGD scrubber material.

Table 2. Mechanical properties of calcium sulfite FGD scrubber material.

Mechanical Property	Dewatered	Stabilized	Fixated	Source	Test Method
Internal Friction Angle	20°	35° – 45°	35° – 45°	Smith (1985), Smith (1992), Prusinski et al. (1995), Smith (1991), Solem-Tishmack et al. (1995)	ASTM D4767-04 ASTM D 3080
28-Day Unconfined Compressive Strength (kPa) (psi)	- -	170 – 340 (25 – 50)	340 – 1380 (50 – 200)		
90-Day Unconfined Compressive Strength (kPa) (psi)	- -	- -	980 – 4600 (142 – 667)		
Hydraulic conductivity (cm/sec)	10^{-4} to 10^{-5}	10^{-6} to 10^{-7}	10^{-6} to 10^{-8}		ASTM D2434-68 ASTM D5084-03 AASHTO T 215
Maximum Dry Density kN/m^3 (lb/ft^3)		10.4-12.4 (66-79)			AASHTO T 085 ASTM D2216-05
Optimum Moisture Content, %		27-37			

Resilient modulus tests conducted on mixtures of FGD gypsum stabilized with 6 and 8 percent Type II cement, at a bulk stress of 590 kPa (86 psi), had a resilient modulus of 3,800,000 kPa (550,000 psi) for 6 percent Type II cement and 12,000,000 kPa (1,750,000 psi) for 8 percent Type II cement (Taha 1993). Comparing these results against typical base materials, on the basis of the resilient modulus data, stabilized FGD gypsum blends should perform as well as any other conventional base materials (Taha 1993).

Mineralogical and Chemical Properties

Chemically, FGD material is dominated by Ca, S, Al, Fe, and Si and accompanied by minor elements (i.e., As, Co, Cu, Mo, Ni, P, Se, and Sr). Unlike fly ashes or bottom ashes, neither the parent coal nor the boiler conditions have a significant effect on the physical or chemical properties of the FGD byproducts. Instead, the characteristics of the FGD byproducts are strongly controlled by the type of reagent used, the operating temperature, pressure, and degree of oxidation within the scrubbing unit and the amount of water used to distribute the reagent through the flue gas (NETL 2003). Tables 3 and 4 outline the major and minor element concentrations in typical dry FGD products.

Table 3. Range of average concentration of major elements in dry FGD material (g/kg) (Kost et al. 2005).

Ca	S	Al	K	Si	Mg	Fe
122 - 312	41 - 126	13 - 74	1 - 9	25 - 139	6 - 92	2 - 110

Table 4. Range of average concentration of minor elements in dry FGD material (mg/kg) (Kost et al. 2005).

As	44.1 - 186	**Mo**	8.6 - 25.5
B	145 - 418	**Ni**	29.0 - 80.6
Be	1.6 - 15.1	**P**	220 - 601
Cd	1.7 - 4.9	**Pb**	11.3 - 59.2
Co	8.9 - 45.6	**Se**	3.6 - 15.2
Cr	16.9 - 76.6	**Sr**	308 - 565
Cu	30.8 - 251	**V**	20.1 - 122
Li	11.4 - 84.7	**Zn**	108 - 208
Mn	127 - 207		

Lime and limestone are used as a reagent in 90 percent of FGD systems in the United States (EPRI 1999). Table 5 lists the major components of FGD scrubber material prior to fixation for different sorbent materials and natural or forced oxidation processes (Smith 1992). Except for FGD material subjected to forced oxidation, sludges from the scrubbing of bituminous coals are generally sulfite-rich, whereas forced oxidation sludges, and sludges generated from scrubbing of subbituminous and lignite coals, are sulfate-rich. Fly ash is a principal constituent of FGD scrubber material only if the scrubber serves as a particulate control device in addition to SO_2 removal or if separately collected fly ash is mixed with the sludge (Smith 1992).

As shown in Table 5, the use of limestone as a sorbent with bituminous coals results in significantly lower percentages of calcium sulfite and higher percentages of calcium sulfate and calcium carbonate ($CaCO_3$) than the use of lime as a sorbent with bituminous coals.

Table 5. Major components of FGD scrubber material from different coal types and scrubbing processes (percent by weight).

Type of Process	Type of Coal	Sulfur Content	$CaSO_3$	$CaSO_4$	$CaCO_3$	Fly Ash
Lime (Natural Oxidation)	Bituminous	2.9 - 4.0	50 - 94	2 - 6	0 - 3	4 - 41
Lime (Forced Oxidation)	Bituminous	2.0 - 3.0	0 - 3	52 - 65	2 - 5	30 - 40
Limestone (Natural Oxidation)	Bituminous	2.9	19 - 23	15 - 32	4 - 42	20 - 43
Limestone (Natural Oxidation)	Subbituminous	0.5 - 1.0	0 - 20	10 - 30	20 - 40	20 - 60
Dual Alkali (Ca-Na) (Natural Oxidation)	Bituminous	1.0 - 4.0	65 - 90	5 - 25	2 - 10	0
Fly Ash (Class C) (Natural Oxidation)	Lignite	0.6	0 - 5	5 - 20	0	40 - 70

The primary mineral phases of fixated FGD include hannebachite ($CaSO_3 \times 0.5\ H_2O$), mullite ($Al_6Si_2O_{13}$), quartz (SiO_2), hematite (Fe_2O_3), magnetite (Fe_3O_4), glass, and ettringite [$Ca_6Al_2(SO_4)_3(OH)_{12} \times 26H_2O$] (Laperche and Bigham 2002).

Environmental Considerations

One of the main limitations of present leach test methods is that these methods do not consider the material application. For example, use of coal combustion products in Wisconsin is regulated by Ch. NR 538 of the Wisconsin Administrative Code. This regulation requires water leaching tests (WLT) of material in bulk form, but does not consider mixtures, such as FGD material in flowable fill. In addition, WTL does not necessarily model leachate produced in the field. The WLT indicates the potential for trace element release from bulk coal combustion products, but does not evaluate how a leachate will impact groundwater (Bin-Shafique et al. 2002).

Five widely used standard leaching tests are outlined in Table 6.

Table 6. 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

Leachate studies on dry FGD material show pH typically exceeds 11.0, and some sources can exceed the Resource Conservation and Recovery Act limit of 12.5 for toxic waste, although this high leachate pH is expected to decrease over time (Kost et al. 2005, Cheng et al. 2007). Total dissolved solids mainly consist of Ca, SO_4^{2-}, and SO_3^{2-} and can exceed secondary drinking water standards for total dissolved solids (500 mg L^{-1}) and sulfate (250 mg L^{-1}) (Kost et al. 2005). Trace element concentrations in FGD leachate are generally low (Kost et al. 2005).

One study investigated the potential of replacing clay with FGD in low permeability liners. This study used a lime-enriched, fixated FGD material on a full-scale design and evaluated the leaching potential over a 5½-year period. Maximum concentrations of elements measured during this time met all Ohio nontoxic criteria, and generally met all national primary and secondary drinking water standards. In addition, retention of As, B, Cr, Cu, and Zn was observed and likely due to constituent sorption to mineral components in the FGD material (Cheng et al. 2007).

The results of extraction procedure toxicity leachate tests indicate that fresh or stabilized FGD gypsum will meet EPA Leachate Standards (Taha 1993).

The use of FGD material in stabilized base material applications requires good management and care to ensure that the FGD material does not result in a negative impact on the environment. 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 and FHWA 2005).

State Regulations and Specifications

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, has individual specifications and environmental regulations.

A site maintained by the U.S. Federal Highway Administration (FHWA) contains a searchable library for all highway specifications across the country. This can be found at: http://fhwapap04.fhwa.dot.gov/nhswp/index.jsp

Modeling

Models currently used to simulate leaching from pavement systems and potential impacts to groundwater include STUWMPP (Friend et al. 2004), IMPACT (Hesse et al. 2000), HYDRUS-2D (Simunket 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 coal combustion products 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.

DESIGN CONSIDERATIONS AND GUIDELINES

Stabilized Base

Fixated or stabilized flue gas desulfurization (FGD) scrubber material can be used as a stabilized base or subbase material in the same manner as lime-fly ash or cement-stabilized base materials. Fixated FGD scrubber material may be used in an "as produced" condition, provided the material meets specifications, or the FGD scrubber material can be modified with additional reagents such as Portland cement, lime, fly ash, etc. to improve characteristics. Properly designed fixated FGD scrubber material has comparable strength development and durability characteristics to that of conventional stabilized base materials.

According to a 2005 coal combustion product use survey, 12 states have specifications for soil stabilization, which includes stabilized base and subbase materials (Dockter and Jagiella 2005). FGD scrubber material has been employed as a component in stabilized base and subbase material since the 1970's. Typically dewatered FGD material is combined with fly ash or cement, lime, and aggregate, which is often coal bottom ash. The FGD base mixture is placed and compacted to thicknesses between 150 to 300 mm (6 to 12 in) and then overlaid with a wearing surface. With proper construction, FGD material used in stabilized base applications has performed successfully. Stabilized or fixated FGD scrubber material is used for road base construction has been successfully implemented in Florida, Pennsylvania, Ohio, and Texas (Smith 1989, Smith 1985, Amaya et al. 1997, Prusinski eta l. 1995).

Stabilized base Design Considerations:

FGD scrubber material properties of interest when using FGD material in stabilized bases and subbases are shown in Table 7.

Material from dry FGD systems is handled in a similar manner as fly ash. Dry FGD material may need moisture content conditioning (to approximately 10 percent) prior to transportation to reduce dusting (Berland et al. 2003). Wet FGD material requires dewatering and fixation, which typically occur at the power plant, before transport and use in stabilized base material.

The calcium sulfite scrubber material from wet FGD systems is generally of toothpaste-like consistency (from 25 to 50 percent solids) after dewatering. Dewatering is usually accomplished by belt filter presses or centrifuges. Centrifuges are normally able to dewater the sludge to a higher solids content than filter presses.

Dewatered FGD material must be stabilized or fixated by the addition of dry reagents (quicklime and Class F fly ash, Class C fly ash, or Portland cement) before being use in stabilized base compositions. The fixated wet FGD sludge should have a solids content of at least 65 percent prior to compaction. The material can then be placed and compacted as a base material or blended with additional reagent, natural aggregate, or bottom ash to meet strength and durability requirements.

For most dry FGD systems, the FGD by-product is a fine material of uniform consistency with between 56 and 90 percent of the particles having a diameter smaller than 0.025 mm (Kost et al. 2005). Grain size uniformity coefficients for dry FGD material are in the range of 1.8 to 2.4, which represent a uniform particle size. The particle size distribution and uniformity indicates that dry FGD material can be classified as a silt-sized material (Berland et al. 2003, Kost et al. 2005).

Dewatered and unstabilized calcium sulfite FGD material consists of fine silt-clay sized particles with approximately 50 percent finer than 0.045 mm (No. 325 sieve). Calcium sulfate FGD material is more course and is classified as a silt with sand. At temperatures above 100 c, calcium sulfate particles have been observed to degrade; therefore, oven drying FGD calcium sulfate can affect the particle size distribution (Taha and Saylak 1992). Particle size information for wet FGD material (both calcium sulfite and sulfate) is given in Table 8 (Smith 1992).

Table 8. Typical physical properties of wet FGD scrubber material (Smith 1992).

Property	Calcium Sulfite (Unoxidized)	Calcium Sulfate (Oxidized)
Particle Sizing	%	%
Sand Size	1.3	16.5
Silt Size	90.2	81.3
Clay Size	8.5	2.2

Dry FGD material is collected in a particle control device as a dry product and typically needs to be water conditioned (to approximately 10 percent) to reduce dusting during transport (Berland et al. 2003). Dewatered calcium sulfate FGD scrubber material is typically stabilized or fixated before transport and use as a stabilized road base material. Prior to dewatering, the calcium sulfate slurry has a moisture content of approximately 60 percent. After dewatering, the moisture content is reduced to roughly 35 percent. Following stabilization or fixation, the FGD scrubber material has a moisture content of approximately 15 percent (Smith 1992).

When stabilized or fixated FGD scrubber sludge is used for road base construction, the unconfined compressive strength can be adjusted to meet specifications by adjusting the amount of reagent in a blend. The flexural strength of stabilized FGD sludge road base materials is normally in the 690 to 1720 kPa (100 to 250 lb/in^2) range (Smith 1991). To achieve these strength ranges, fixation reagents such as Portland cement, lime, or fly ash are typically required.

Durability testing of fixated FGD scrubber material may involve either freeze-thaw or wet-dry testing. Freeze-thaw testing should be performed in accordance with ASTM D560. Wet-dry testing should be performed in accordance with ASTM D559. A freeze-thaw study on stabilized calcium sulfite FGD material stabilized with fly ash and lime showed a relationship between higher sample water contents and decrease in strength with freeze-thaw cycling (Chen et al. 1997). Increased cure time prior to first freeze improved freeze-thaw durability and a resistance to water infiltration. This study recommends a minimum of 60 days curing time be allowed before freezing temperatures are expected when using FGD material (Chen et al. 1997).

Base and subbase mix design for FGD scrubber sludge involves blending fixated FGD sludge with one or more stabilization reagents (lime, fly ash, or Portland cement). The stabilized mix design may also include coal bottom ash or aggregate. 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 ASTM C593 procedures.

A minimum unconfined compressive strength of 2800 kPa (400 lb/in^2) is recommended after ambient curing for between 14 and 28 days. If Portland cement is used as the stabilization reagent, some states require 4500 kPa (650 lb/in^2) unconfined compressive strength after curing for 7 days.

Mixes containing fixated FGD scrubber material should be tested for moisture-density relationships and molded as close as possible to optimum moisture content and maximum dry density. If bottom ash is used as an aggregate, the ratio of FGD scrubber sludge to bottom ash is often in the 1.5:1 to 1:1 range. The addition of bottom ash has been shown to enhance the strength development of stabilized base mixes.

When using Portland cement as a stabilization reagent, type II (sulfate resistant) cement should be used. When a pozzolanic fly ash and quicklime are used to stabilize the FGD scrubber material, adequate strength can usually be achieved by the addition of up to 7 to 8 percent cement by weight of dry solids, or by adding more quicklime If a self-cementing fly ash is used as the FGD material fixation reagent, then adding a lower percentage of cement (possibly 3 to 4 percent) or the addition of more fly ash may be needed to achieve the required strength.

Designing pavement structures that include stabilized base or subbase layers that include FGD material typically 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 2004).

Pavement design employing a structural number accounts for the relative strength of the constructed materials. The total structural support from the surface course, base course, and any subbase course equals the required structural number. Layer thicknesses are calculated using layer coefficients that define the structural support. The layer coefficients can be obtained from the relationship provided by AASHTO based on CBR or MR (AASHTO 1993).

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).

Construction procedures for stabilized base and subbase mixtures in which fixated FGD scrubber material is used are the same as conventional pozzolanic stabilized bases and subbases.

Fixated FGD scrubber material is typically stockpiled on a concrete pad at the power plant to allow for initial set of the material, typically less than a few days. The material can then be blended with additional reagent (such as lime or Portland cement), blended with bottom ash, boiler slag, or other aggregate, or transported and placed at a job site in the fixated condition.

Plant mixing of FGD material for stabilized bases is recommended because of the greater control over the quantities of materials batched, which results in a more uniform mixture. Mixing in place of dewatered FGD scrubber material is not recommended because of the toothpaste-like consistency.

Fixated FGD scrubber base materials should be placed in layers that result in a compacted thickness between 10 and 22 cm (4 and 9 in). These materials should be spread in loose layers that are approximately 5 cm (2 in) thicker than the desired compacted thickness. The top surface of an underlying layer should be scarified prior to placing the next layer. Smooth drum, steel wheeled vibratory rollers are most frequently used for compaction, although satisfactory compaction results have also been obtained using smooth drum, steel wheeled static rollers. The smooth drum roller also seals the surface of the road base to minimize adverse impacts from rainfall (Smith 1989).

After placement and compaction, fixated FGD scrubber base material should be properly cured to protect against drying and assist in the development of in-place strength. An asphalt emulsion seal coat can be applied to the top surface of the stabilized base or subbase material. For most types of stabilized base materials, seal coat is applied within 24 hours after placement. Placement of asphalt paving over 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 base material, vehicles should not be permitted to drive on the stabilized base until an in-place compressive strength of at least 2400 kPa (350 lb/in^2) is achieved (ACAA 1991).

Stabilized base materials containing fixated FGD scrubber material that are subjected to freezing and thawing conditions must be able to develop a certain level of cementing action and in-place strength prior to the first freeze-thaw cycle. For northern states, many state transportation agencies have established construction cut-off dates for stabilized base materials. These cutoff dates ordinarily range from September 15 to October 15, depending on the state, or the location within a particular state, as well as the ability of the stabilized base mixture to develop a minimum desired compressive strength within a specified time period (ACAA 1991). A laboratory study on calcium sulfite FGD material recommends a minimum of 60 days curing time between compaction of the FGD material and the first freeze (Chen et al. 1997).

Stabilized base mixtures using self-cementing fly ash as an activator should be placed and compacted as soon as possible after mixing. Delays in placement and compaction of self-cementing fly ash mixes may significantly decrease the strength of the compacted stabilized base material (Thornton and Parker 1980).

Stabilized FGD base layers constructed with fly ash are less likely to produce reflection cracking in overlying pavement as is sometimes the case with Portland cement stabilized base layers. This is most likely due to a less stiff bond. Approaches for controlling or minimizing the potential effects of reflective cracking associated with stabilized base layers have been recommended by the ACAA (ACAA 1991).

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 7. Properties of calcium sulfite FGD scrubber material useful in stabilized base design.

Mechanical Property	Dewatered	Stabilized	Fixated	Source	Test Method	Considerations
28-Day Unconfined Compressive Strength (kPa) (psi)	- -	170 – 340 (25 – 50)	340 – 1380 (50 – 200)			
90-Day Unconfined Compressive Strength (kPa) (psi)	- -	- -	980 – 4600 (142 – 667)			
Hydraulic conductivity (cm/sec)	10^{-4} to 10^{-5}	10^{-6} to 10^{-7}	10^{-6} to 10^{-8}		ASTM D2434-68 ASTM D5084-03 AASHTO T 215	Compacted stabilized FGD material demonstrated a decrease in hydraulic conductivity with an increase in curing time (Butalia and Wolfe 1999).
Maximum Dry Density kN/m^3 (lb/ft^3)		10.4-12.4 (66-79)			AASHTO T 085 ASTM D2216-05	Higher proportions of fly ash yield a higher maximum density (Butalia and Wolfe 1999).
Optimum Moisture Content, %		27-37				
Wet Unit Weight (kN/m^3) (lb/ft^3)	14.9 - 15.7 (95 - 100)	14.1 - 17.3 (90 - 110)	14.1 - 18.1 (90 - 115)			
Dry Unit Weight (kN/m^3) (lb/ft^3)	9.4 - 10.2 (60 - 65)	9.4 - 10.2 (60 - 85)	12.6 - 15.7 (80 - 100)			

Flowable Fill

Flowable fill is a slurry mixture consisting of sand or other fine aggregate material and a cementitious binder that is normally used as substitute for a compacted earth backfill. FGD material (both wet and dry) is being researched as a replacement for fly ash in flowable fill material. However, published research and case studies on this subject are limited. As such, the use of FGD for this application is not well documented, and any use of FGD as a flowable fill should be considered somewhat experimental. Publication of such uses and laboratory research would aid in the understanding of FGD's performance as a flowable fill.

The cementitious reactions that occur with FGD material are well-suited for flowable fill applications (NETL 2003, Butalia et al. 2004). Low unit weight and sufficient shear strength make FGD flowable fill a suitable alternative to commonly used compacted earth backfills (Butalia et al. 2001, Butalia et al. 2004). Research conducted at Ohio State University (OSU) investigated the use of FGD material in flowable fill, the results of these studies make up the majority of this user guideline.

A wet and dry FGD flowable fill testing program conducted at Ohio State University investigated unconfined compressive strength (UCS), flowability, unit weight, penetration resistance, and FGD flowable fill mix design. The tests were conducted on a wet fixated scrubber sludge and dry FGD generated with a lime sorbent (Butalia et al. 2004, Butalia et al. 2001).

Typical flowable fill mixtures include filler material, cementitious material, and can contain mineral admixtures. Filler material usually consists of fine aggregate such as sand, but some flowable fill mixes may contain equal portions of coarse and fine aggregates (Smith 1991).

Flowable Fill Design Considerations:

Engineering properties of FGD flowable fill mixes of interest are summarized in Table 9. Unfortunately many properties needed to design flowable fill mixtures have not yet been investigated and published in the literature.

Flowability is a measure of how well a mixture will flow when being placed. As the amount of water in an FGD flowable fill mix increases, flowability increases but unconfined compressive strength is shown to decrease. The addition of fine aggregate may improve flowability at lower water contents and not adversely affect strength or set time. Flowability can vary from stiff to fluid depending on the project requirements.

Flowability of FGD mixtures can be measured using a standard concrete slump cone, a flow cone, or a modified flow test using an open ended 75 mm (3 in) diameter by 150 mm (6 in) high cylinder (ASTM C143 2005, ASTM C939 2002, Balsamo 1987) . Flowability ranges associated with the standard concrete slump cone (ASTM C143) generally vary from 150 to 200 mm (6 to 8 in).

For placement of flowable fill, a flowability range tested in accordance to ASTM of 180 to 210 mm (7 to 8 in) is recommended. The results of flowability tests on wet FGD scrubber mixes were between 150 and 300 mm (6 to 12 in) (Butalia et al. 2004).

Long term penetration resistance characteristics of FGD material used as a flowable fill are comparable to conventional cement-based flowable fill. Short term penetration resistance characteristics of dry FGD material and water mixes showed penetration resistance values measured with ASTM D6024 less than 689 kPa (100 psi) after 24 hours and less than 1375 kPa (200 psi) after 144 hours (6 days) (Butalia et al. 2001). Early penetration resistance can be increased with the addition of cement, lime, or admixture. In general, larger proportions of cement, lime, or admixture in the FGD flowable fill mixes cause flowable fill to harden faster, although higher longer term strength should be expected (Butalia et al. 2001).

Flowable fill mixtures traditionally are proportioned by trial and error. Most specifications for flowable fill provide quantities of constituents that produce an acceptable product, although some specifications are performance-based (usually based on a maximum compressive strength) and leave the proportioning up to the material supplier. ACI provides guidance for the proportioning of flowable fill mixtures (ACI Committee 229 1999).

Mix designs for FGD flowable fill can be as simple as FGD and water or can contain cement, lime, and/or admixtures in varying amounts to achieve desired properties. Dry FGD and water mixes, at water contents between 65 and 77 percent, showed acceptable flowability and long term strength for flowable fill, but short term penetration resistance may be too low for some construction projects. Mixes containing dry FGD material, water, cement and/or lime (6 to 10 percent), and admixtures (1.3 to 5.9 percent) showed excellent flowability and long term strength along with achieving a penetration resistance of 2750 kPa (400 psi) in one to two days (Lee et al. 1999).

Wet fixated FGD scrubber sludge, with a fly ash to filter cake ratio of 1.25:1 with an additional 5 percent lime, were used in flowable fill mix designs. The wet fixated FGD flowable fill mix designs were at a water content of 82.5 to 84 percent, and had additional cement or lime added at 6 percent of the dry unit weight of the FGD material. Although these mixes had good flowability, the short term (24 hr) penetration resistance for the 6 percent lime mix may be too low for some applications and the 6 percent cement mix developed too much long term strength for excavatable flowable fill (Butalia et al. 2004). Therefore, wet fixated FGD mixes may require admixtures to reduce initial set time and a reduction in cement to reduce long term strength. Long term strength, even beyond 28 days, may need to be investigated if future excavation is a required.

Research is needed on FGD flowable fill with respect to: stability (friction angle), bearing capacity (CBR), corrosivity, resilient modulus, modulus of subgrade reaction, lateral pressure development, bleeding and shrinkage, and hydraulic conductivity. In addition, research is needed in the interaction between admixture, cement, and the properties of FGD flowable fill.

Table 9. Properties of calcium sulfite FGD scrubber material useful in stabilized base design.

Mechanical Property	**Dewatered**	**Stabilized**	**Fixated**	**Source**	**Test Method**	**Considerations**
28-Day Unconfined Compressive Strength (kPa) (psi)	- -	170 – 340 (25 – 50)	340 – 1380 (50 – 200)			
90-Day Unconfined Compressive Strength (kPa) (psi)	- -	- -	980 – 4600 (142 – 667)			
Hydraulic conductivity (cm/sec)	10^{-4} to 10^{-5}	10^{-6} to 10^{-7}	10^{-6} to 10^{-8}		ASTM D2434-68 ASTM D5084-03 AASHTO T 215	Compacted stabilized FGD material demonstrated a decrease in hydraulic conductivity with an increase in curing time (Butalia and Wolfe 1999).
Wet Unit Weight (kN/m^3) (lb/ft^3)	14.9 - 15.7 (95 - 100)	14.1 - 17.3 (90 - 110)	14.1 - 18.1 (90 - 115)			
Dry Unit Weight (kN/m^3) (lb/ft^3)	9.4 - 10.2 (60 - 65)	9.4 - 10.2 (60 - 85)	12.6 - 15.7 (80 - 100)			

Embankments

FGD material can be used for embankment construction and reconstruction of failed slopes (Butalia and Wolfe 2000). As an embankment or fill material, stabilized FGD material is used as a substitute for natural soils. Stabilized compacted FGD material have a high shear strength to unit weight ratio, hence embankments constructed of these materials have higher slope stability factors, steeper permissible slopes, and result in reduced settlement of underlying soils as compared to fills with natural soils (Butalia and Wolfe 2000).

In Pennsylvania in 1989 FGD material reclaimed from a landfill was used in conjunction with fly ash in an embankment project. Other than fly ash, no additional reagents were needed to develop adequate strength for the embankment construction (Brendel and Glogowski 1989). In 1996, Ohio State Route 83 was repaired by constructing a high-strength FGD wall through the failure plane of a rotational slide to prevent further slippage of a highway embankment. The FGD material used in this application developed sufficient strength and was easy to install (Payette et al. 1997).

END USER RESOURCES

Several resources are available to end users interested in incorporating FGD material into construction applications. Additional information on coal ash production and use in the United States can be obtained from:

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 C939-02 standard test method for flow of grout for preplaced-aggregate concrete (flow cone method. In: Annual book of ASTM standards. American Society for Testing and Materials; West Conshohocken, Pennsylvania: 2002.

ASTM D4546-03 standard test methods for one-dimensional swell or settlement potential of cohesive soils. In: Annual book of ASTM standards. ASTM; West Conshohocken, Pennsylvania: 2003.

ASTM D559-03 standard test methods for wetting and drying compacted soil-cement mixtures. In: Annual book of ASTM standards. ASTM; West Conshohocken, Pennsylvania: 2003.

ASTM D560-03 standard test methods for freezing and thawing compacted soil-cement mixtures. In: Annual book of ASTM standards. ASTM; West Conshohocken, Pennsylvania: 2003.

ASTM D6024-02 standard test method for ball drop on controlled low strength material (CLSM) to determine suitability for load application. In: Annual book of ASTM standards. American Society for Testing and Materials; West Conshohocken, Pennsylvania: 2002.

ASTM D6103-04 standard test method for flow consistency of controlled low strength material (CLSM). In: Annual book of ASTM standards. ASTM; West Conshohocken, Pennsylvania: 2007.

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