Guidelines for the Beneficial Use of Advanced SO_2 Control By-Products

TR-108403

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REPORT SUMMARY

This design guide describes the use of the by-products produced from advanced SO_2 control processes as construction materials in high-volume applications such as road base stabilization, structural fills, manufactured aggregates, soil amendments, and concrete applications. The engineering data, major design parameters, standard specifications, and construction procedures in the report should help utility by-product managers and power plant managers incorporate these applications in their by-product management plans.

Background

Advanced technologies to control SO_2 emissions from coal-fired power plants are now approaching full-scale commercial application. These technologies include furnace lime or limestone injection, spray dryers, sodium injection, and atmospheric fluidized-bed (AFBC) technologies. The solid by-products from these technologies are significantly different than conventional coal combustion by-products. Many of these processes reduce SO_2 by use of a sorbent, thus yielding an increased volumes of by-products with different characteristics than conventional coal fly ashes. An understanding of the chemical and leachate composition, physical properties, and engineering properties of these by-products is necessary for sound engineering decisions about their use. With the exception of the sodium sorbent injection by-product, each advanced SO_2 control (ASC) by-product contains calcium, silicon, iron, aluminum, and sulfur compounds that harden when water is added, in many cases developing significant unconfined compressive strengths.

Objectives

To provide guidance on design methods for the use of ASC by-products in a variety of large volume engineering applications.

Approach

The project team summarized literature data and the results of laboratory and full-scale demonstration projects developed under EPRI sponsorship to produce guidelines on the use of ASC by-products in a variety of large volume engineering applications. The report specifically addresses ASC by-products from five technologies: 1) fluidized bed combustion, 2) furnace sorbent injection, 3) spray dryers, 4) sodium sorbent injection, and 5) calcium sorbent injection.

Results

The data obtained during this project showed the advantages of ASC by-products include their cementitious/pozzolanic activity; fine grain size distribution similar to conventional coal fly ash; non-hazardous waste classification according to EPA criteria; and high pH, calcium, and sulfur content, characteristics useful for soil amendment applications. This report provides guidance to the laboratory test protocols, design methods, and construction practices for each of the applications. Special considerations and limitations with respect to each of the by-products are discussed. For example, for road base applications, one of seven applications covered in the guidelines, the methodology includes laboratory testing, trial mix design, measurement of dry density and optimum moisture content after seven days, and further testing of successful mixes after 28 days for unconfined compression strength. Long term expansion data were obtained from only a few demonstrations; these tests should be conducted on candidate materials to confirm dimensional stability of the by-product, especially for road base applications. The road base thickness design can follow the same procedures as for cement and ash stabilized road bases.

EPRI Perspective

Advanced SO_2 control technologies can be used to reduce air emissions at a lower cost for a variety of market conditions. Improvements in plant performance can also be realized through the use of ASC by-products in industrial/institutional applications.

In 1983 EPRI initiated a broad-based effort to promote the use of coal ash in roadways and embankments because this use would consume large amounts of the coal ash produced by utilities. In 1985 under the Advanced SO_2 Waste Management Project (RP2708) this effort was extended to the five ASC by-products covered in this report. This manual supplements the information in other EPRI manuals and demonstration reports (EPRI reports TR-100472 and TR-108402) to assist utilities in the management of their coal combustion by-products.

TR-108403

Interest Categories

Waste and water management

Keywords

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By-products
Flue gas desulfurization

ABSTRACT

The purpose of this study is to provide guidance on design methods for the use of advanced SO_2 control (ASC) by-products in road base stabilization, soil stabilization, sludge stabilization, structural fill, grout, manufactured aggregates, cement production, cement replacement in concrete, and soil amendment. The ASC by-products which were investigated include: fluidized bed combustion (FBC), furnace sorbent injection, spray dryer, sodium sorbent injection, and calcium sorbent injection by-products. For each use, the following are presented: major design parameters, standard specifications and/or outline of design procedures; design concerns specific to ASC by-products; and summaries of published laboratory and field trials.

With the exception of sodium sorbent injection by-product, each by-product contains calcium (Ca), silicon (Si), iron (Fe), aluminum (Al), and sulfur (S) compounds which harden with water. In many cases, the by-products develop significant unconfined compression (UC) strengths with the addition of only water, although in many (but not all) cases, UC strength is greatly increased with small additions of lime or cement. For many by-products and uses, laboratory test results are promising when compared to standard specifications. In general, field trials are too few to provide enough data to develop clear guidelines on ASC by-product use. Occasional long-term laboratory or field trials indicate excessive expansion or strength loss. However, prehydration has been used with some success to reduce expansion, strength loss, and exothermic reactions, especially with FBC by-products.

As soil amendments to improve plant growth, FBC and furnace sorbent injection ash have been successful in studies by several investigators. In this use, expansion is not a concern. Considerations which determine acceptable by-product application rates include fertility of soil by-product mixtures and metal loading rates.

EXECUTIVE SUMMARY

Project Objective

In response to increasingly stringent air quality regulations, new technologies are being developed to control airborne emissions from electric power generating plants. Federal, state, and privately funded programs are working to develop both new systems and retrofit technologies to achieve superior environmental protection at a lower cost for a variety of market conditions. In some cases, not only is environmental conformance achieved but plant performance, in terms of life, capacity, and/or efficiency, is increased. These methods are referred to as advanced SO_2 control (ASC) or clean coal technologies. Many of these techniques reduce SO_2 by use of a sorbent, which results in increased volumes of waste and new waste products. The development of ASC by-product utilization will help to reduce the disposal costs of these materials.

The purpose of this report is to provide guidelines for the beneficial use of ASC by-products. This report specifically considers by-products produced from the following processes:

- Fluidized bed combustion (FBC)
- Furnace sorbent injection (FSI)
- Spray dryer (SD)
- Sodium sorbent injection (SSI)
- Calcium sorbent injection (CSI)

In view of the physical and chemical characteristics of the ASC by-products, it is believed that there are potential uses for ASC by-products in highway construction, mining and soil amendment. The ASC by-products are dry powders and have physical properties similar to those of conventional fly ash. Their chemical properties are somewhat different from conventional fly ash, however, due to the alkaline reagents used for SO_2 emission control. The similar characteristics may allow ASC by-products to be used in lieu of conventional fly ash in similar applications. The chemical differences, however, will require some changes in utilization practices.

Table ES-1 summarizes the utilization options with moderate to high potential, as identified in previous EPRI projects.

Table ES-1
Utilization Options of ASC By-Products

Use Area	FBC Fly Ash	FBC SBM	FSI	SD	SSI	CSI
Road Base Stabilization	✓	✓	✓	✓		✓
Soil Stabilization	✓	✓	✓	✓		✓
Sludge Stabilization	✓	✓	✓	✓		✓
Structural Fill	✓	✓	✓	✓		✓
Grout	✓	✓	✓	✓	✓	✓
Aggregate Production/Replacement		✓	✓	✓		✓
Cement Production/Replacement	✓		✓	✓		✓
Soil Amendment	✓	✓	✓	✓		✓

Advantages of ASC by-products for utilization include:

- Dry particles
- Cementitious / pozzolanic reactivity
- Grain size distribution similar to conventional fly ash
- Non-hazardous
- High pH, calcium, and sulfur (for soil amendment)

Possible disadvantages of some ASC by-products for utilization include:

- Exothermic hydration
- Potential for expansion
- High soluble sodium salt content of sodium sorbent injection by-products
- Potential for corrosion or sulfate attack on concrete
- Long-term performance characteristics are not fully understood
- Excessive sulfur

This report provides guidance to the laboratory test protocols, design methods, and construction practices for each of the applications. Special considerations with respect to using each of the by-products are discussed.

Road Base

ASC by-products have been used in only a few road base demonstration projects. The design procedure is similar to the procedure used to design stabilized fly ash road base, which involves design of the base course mix and determination of the thickness of each layer of the pavement system. An additional consideration with SO_2 by-products is the possibility of long-term expansion.

Initial laboratory tests are performed on by-product samples to provide data on the basic physical, chemical, and engineering behavior of the by-product. After the trial mix is selected, it is necessary to determine the maximum dry density and optimum moisture content of the mixture so that 7-day unconfined compression testing can be performed. If any trial mix fails to achieve the required strength, a new mix must be selected and tested accordingly until a mix satisfies the strength criterion. The trial mix is then tested for 28-day unconfined compression strength. If there is no increase in strength, a new trial mix should be selected and tested until all criteria are met. Long-term expansion should be tested to check dimensional stability of a by-product road base. Road base thickness design can follow the same procedures for cement or fly ash stabilized road base.

Soil Stabilization

Soil stabilization using fly ash, both alone and in conjunction with lime or cement, has increased significantly during the past decade. The ASC by-products, due to physical and chemical similarities to a lime-fly ash mix, have the potential to be used in soil stabilization. Another important composition in ASC by-products is calcium sulfate/sulfite which will react with Al_2O_3 and SiO_2 to form ettringite. The formation of ettringite contributes to the strength development, but may also induce unwanted swelling.

The ASC by-product stabilized soil can be used as subgrade or subbase material. The unconfined compressive strength and durability of material are important criteria for final application. Durability includes the ability to withstand potential damage due to freezing and thawing, and wetting and drying action.

Soil stabilization with ASC by-products has been documented for only a few laboratory and field demonstration projects. These projects indicate which ASC by-products typically increase soil strength, especially when lime is added. The potential for expansion or swelling should be investigated and controlled by testing the by-product:soil mixtures at various proportions, and by exercising appropriate quality controls during construction.

Sludge Stabilization

FBC fly ash and spent bed material, furnace sorbent injection by-product, spray dryer by-product, and calcium sorbent injection by-product have potential for use as stabilizing agents for FGD sludge, industrial waste sludge and hazardous waste sludge.

The by-products generated from ASC technologies have some chemical, physical, and engineering properties which are similar to conventional fly ash. The exact composition of a by-product is determined by the injection process, the coal source, and the type of sorbent. But in general, the primary components include fly ash, unspent sorbent (lime, limestone or dolomite), and reaction products (calcium sulfate/sulfite). The high percentage of fly ash in by-products indicates the potential for pozzolanic activity. The unreacted lime or limestone contributes to the self-hardening characteristics of the by-products.

Hydration of the by-product would result in the reduction in the sludge moisture content and produce a strength gain.

Another important reaction is the formation of ettringite and/or thaumasite from the calcium, aluminum, silica, and sulfur in by-products. The ettringite/thaumasite crystal, which is an expansive structure, has the capability to immobilize the trace elements in sludge by causing them to be trapped to the crystal structure. The formation of ettringite/thaumasite crystal also provides strength.

Depending upon the sludge characteristics, ASC by-products may also be used as drying agents or provide alkalinity for pH adjustment. Blending ASC by-products with sludge may make a more stable and readily used material than sludges stabilized with conventional fly ash.

In general, alkaline of ASC by-products may be useful to stabilize metals in acidic hazardous waste which have reduced solubilities at a higher pH, such as cadmium, iron, manganese, zinc, copper and cobalt.

Structural Fills

In summary, ASC by-products have been used successfully in a limited number of structural fill projects. Laboratory testing indicates that ASC by-products develop significant unconfined compressive strengths. Although unconfined compressive strengths vary with type and source of by-product, as well as with time and curing conditions, for most samples tested both short- (7 day) and long-term unconfined compressive strengths were adequate for typical structural fill designs. Optimum moisture contents of compacted ASC by-products must be determined differently than for soil due to hydration reactions and/or steaming. Of the materials tested, AFBC and FSI by-products generated significant heat during hydration, while spray dryer and calcium sorbent injection by-product did not. Long-term testing or field demonstrations are recommended to assess ultimate strength and dimensional stability. Preconditioning or stockpiling may mitigate problems with exothermic reactions or expansion should they occur.

Grout

In summary, all of the by-products show significant potential for use in grout based on laboratory compression strengths. Both low permeabilities and low leachate concentrations would result in minimal environmental concerns in most grout applications. Potential problems which would limit use of grout include: grouts with high sulfate levels in leachate are not appropriate near concrete structures; grouts with high heat of hydration are not appropriate for mass grouting; grouts which expand after set may damage adjacent materials. Also, long-term durability should be tested. Heat of hydration, expansion, and durability may all be improved for some ASC by-products by prehydration of the material. Laboratory tests should be performed on each proposed mixture to investigate these concerns.

Aggregates

Synthetic aggregate can be produced from ASC by-products. Depending on the chemical composition, ASC by-products may need prehydration. Cement, lime, or conventional fly ash may be added to the mixture to promote strength development.

Production of aggregate includes the formation of pellets, briquettes or large blocks. These may be sintered, cured, and/or crushed. Mechanical agglomeration can be used to form pellets and a briquetting machine used to form briquettes. Moist curing, elevated temperature curing, CO_2 environment curing, or sintering at high temperatures can be employed. After curing, briquettes/blocks are tested for compressive strength and then are crushed to produce aggregates. Aggregates should then be tested in terms of specific gravity, gradation, absorption, abrasion resistance and soundness in accordance with the corresponding ASTM test method.

ASC by-products have been used to produce artificial aggregates in various studies. Some by-product aggregates have shown promising test results. Results were specific to the by-product and production methods used.

Cement Production and Replacement

According to ASTM C 595 specifications for blended cement, and ASTM C 618 specifications for use of fly ash as a mineral admixture in concrete, ASC by-products show low potential for use as a cement replacement in concrete. The physical properties of the by-products may meet the ASTM criteria, but the high sulfate/sulfite content in these by-products typically prohibit by-products use in concrete. However, ASC by-products may prove useful as raw feed in cement production, if used in proportions such that the final cement composition meets ASTM C 150.

Soil Amendment

Based on laboratory chemical testing, many ASC by-products have potential as soil amendments. Laboratory testing must be performed to determine the correct agronomic rates.

The actual degree of benefit from an ASC by-product is expected to be specific to each crop, soil, and application rate, and can be best assessed by a field study. Reclamation would allow ash use at a higher rate of application, but be limited to mine lands.

Efforts should be made to register the by-product under the lime or fertilizer laws of each state. The by-product should be marketed as a low grade lime, by-product, or soil amendment, rather than an agricultural lime substitute (when allowed), so as not to mislead or disappoint farmers.

Due to by-product variability, nutrient and environmental testing should be performed frequently to protect public health, to reduce liability, and so that the by-product would be applied at the proper agronomic rate.

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INTRODUCTION

Project Objective

In response to increasingly stringent air quality regulations, new technologies are being developed to control airborne emissions from electric power generating plants. Federal, state, and privately funded programs are working to develop both new systems and retrofit technologies to achieve superior environmental protection at a lower cost for a variety of market conditions. In some cases, not only is environmental conformance achieved but plant performance, in terms of life, capacity, and/or efficiency, is increased[1]. These methods are referred to as advanced SO_2 control (ASC) or clean coal technologies. Many of these techniques reduce SO_2 by use of a sorbent, which results in increased volumes of waste and new waste products. The development of ASC by-product utilization will help to reduce the disposal costs of these materials.

The purpose of this report is to provide guidelines for the beneficial use of ASC by-products. This report specifically considers by-products produced from the following processes:

- Fluidized bed combustion (FBC)
- Furnace sorbent injection (FSI)
- Spray dryer (SD)
- Sodium sorbent injection (SSI)
- Calcium sorbent injection (CSI)

Previous studies have suggested that the following applications may be technically feasible and have potential market value[2]:

- Road base stabilization
- Soil stabilization
- Sludge stabilization

- Structural fill
- Grout
- Aggregates
- Cement production and replacement
- Soil Amendment

This report provides guidance to the laboratory test protocols, design methods, and construction practices for each of the applications. Special considerations with respect to using each of the by-products are discussed.

The Goal of ASC Technology

The 1970 Clean Air Act and amendments authorized the EPA to establish New Source Performance Standards (NSPS) for fossil-fuel electric generating stations[1]. The NSPS promulgated in 1971 limited emissions to 500 grams of SO_2 per million btu of coal burned. This limit was commonly met by switching to low sulfur (western) coal. An added restriction in 1977 was to decrease allowable SO_2 emissions by 70-90% of potential combustion concentrations for plants built after September 18, 1978.

As a result, 1978 brought a massive deployment of wet scrubbers, the only commercially available SO_2 control technology. Between 1978 and 1989, over 150 plants[3] producing 50,000 MW of power were fitted with flue gas desulfurization (FGD) scrubbers at a cost of $20 billion[4]. The need for immediate compliance resulted in processes that could have been accomplished at a lower cost, had more time and money first been spent on optimizing technology. Although wet scrubbers are effective, typically removing 90% of the sulfur, they are expensive to install and maintain, and are difficult to retrofit on older plants with site and design constraints. Scrubber retrofits in some cases may exceed the original cost of the plant[5].

A major disadvantage of wet FGD scrubbers is that the resulting by-product is a calcium sulfite-based sludge which often has the consistency of toothpaste. FGD sludge absorbs water from the air at approximately the same rate as it evaporates, thus the sludge never dries. Handling and disposing of wet FGD sludge remains an expensive and complex problem, as dewatering and stabilizing the wet FGD sludge are needed for handling and disposal. Large quantities are produced – a wet scrubber for a 500 MW plant produces enough sludge each year to cover a one square mile area 45 cm (one-half foot) deep[5]. Over the life of the plant, a $2x10^6$ square meters, 12 meters (500-acre, 40-foot) deep pond would be needed. Wet scrubbers also require a high water use, about 500-2500 gpm for a 500 MW unit, and reduce a plant's electricity output by 1-2%[1].

The goal of ASC technologies is to provide simpler emission control technologies which are less costly, better integrated with the plant, and in some cases, control both SO_2 and NO_x. ASC and CCT programs have been funded by many organizations, including DOE, EPRI, EPA, TVA, the Department of the Treasury, seven state governments, and privately financed ventures[3]. EPRI has independently sponsored comprehensive investigations of sulfur reducing technologies, including spray dryers, fluidized bed combustion (FBC), furnace sorbent injection, sodium sorbent injection, calcium sorbent injection, and advanced coal cleaning. EPRI test programs and studies have resulted in the publications listed on Table 1-1.

The DOE CCT program, begun in 1986, provides cost sharing for privately initiated projects, combining public and private resources. The DOE committed approximately $5 billion to 46 showcase projects to reduce SO_2 and / or NO_x emissions[6,7]. The selected projects were both new and retrofit technologies, with emphasis on lowest cost technologies and systems to utilize high sulfur coal. EPRI also contributed funds for the DOE CCT programs, mostly for instrumentation, testing and technical assistance.

The 1990 Clean Air Act amendments require power plants to cut SO_2 emissions by one-half and NO_x by 30%, or 10 million tpy below 1980 levels. Under Phase I, 110 MW plants were to comply with these standards by 1995-97. Phases II placed a cap on all plants at 8.9 million tpy SO_2 by the year 2000.

ASC technologies are one of several options for future emissions compliance. The spectrum of compliance options also includes switching, blending and washing coal; additional FGD scrubbers; advanced scrubbers (which are expected to remove 95-99% of SO_2); switching to natural gas; purchasing emission allowances; and retiring older plants[8]. Actual development of ASC technologies will depend on process efficiencies and costs, but is predicted to reach 10 GW capacity by the year 2000.

Utilization of ASC by-products will improve the environmental impact and cost competitiveness of these processes. The combination of stringent emissions regulations, increased volume of by-products, and diminishing land areas available for disposal make ASC by-product utilization an attractive alternative.

Table 1-1
EPRI Studies on ASC By-Products

Title	Report Number	Date
Chemical/Physical Stability of Flue Gas Cleaning Waste	FP-671	Jan. 1979
Full-Scale Scrubber Sludge Characterization Studies	FP-942	Jan. 1979
Coal Mine Disposal of Flue Gas Cleaning Wastes	CS-1376	May 1980
Study of Long-Term Chemical and Physical Properties of Mixtures of Flue Gas Cleaning Wastes	CS-1533	Sept. 1980
Recovery, Utilization and Disposal of Solid By-Projects Generated by Dry Flue Gas Desulfurization Systems: State-of-the-Art and Research Needs	CS-1765	March 1981
Compatibility of Admix and Synthetic Liner Materials with Clean Coal Technology By-Products	GS-72265	March 1981
Landfill Disposal of Limestone Dual Alkali Flue Gas Desulfurization Waste	CS-2259	Sept. 1982
Composition and Leaching of FBC Wastes at the Alliance Test Facility	CS-3715	Nov. 1984
Advanced SO_2 Control Solid-Waste Management Planning Study	CS-4402	Feb. 1986
Management of Solid By-Products from Advanced SO_2 Control Systems	CS-5076	Apr. 1987
Utilization Potential of Advanced SO_2 Control By-Products	CS-5269	June 1987
Calcium Spray Dryer Waste Management: Design Guidelines	CS-5312	Sept. 1987
Sampling and Analytic Protocol for Advanced SO_2 Control By-Products	CS-5625	Feb. 1988
Laboratory Characterization of Advanced SO_2 Control By-Products: Spray Dryer Wastes	CS-5782	May 1988
Laboratory Characterization of Advanced SO_2 Control By-Products: Furnace Sorbent Injection Wastes	CS-5783	May 1988
Advanced SO_2 Control By-Product Utilization: Laboratory Evaluation	CS-6044	Sept. 1988
Atmospheric Fluidized-Bed Combustion Waste Management Design Guidelines	CS-6053	Dec. 1988
Design Guidelines for a Furnace Sorbent Injection Waste Management System	GS-6382	June 1989
Design Guidelines for a Sodium Injection Waste Management System	GS-6486	Sept. 1989
Laboratory Characterization of Advanced SO_2 Control By-Products: Dry In-Duct Injection Wastes Sodium and Calcium In-Duct Injection Wastes	GS-6622	Dec. 1989

Table 1-1
(Continued)

Title	Report Number	Date
Commercialization Potential of AFBC Concrete: Part 2, Mechanistic Basis for Cementing Action	GS-7122	Jan. 1991
Calcium-Based Flue Gas Desulfurization Sludge Disposal Ponds	TR-103914	April 1994
Sodium-Based Flue Gas Desulfurization Sludge Disposal Ponds	TR-103915	April 1994
Revegetation of Flue Gas Desulfurization Sludge Pond Disposal Sites	TR-103312	Dec. 1994
Land Application Uses for Dry Flue Gas Desulfurization By-Products	TR-105264	July 1995
FGD By-Product Disposal Manual	TR-104731	Aug. 1995
Use of FGD Gypsum and Bottom Ash in Roadway and Building Construction	TR-105236	Aug. 1995
Laboratory Characterization of Atmospheric Fluidized-Bed Combustion By-Products	TR-105527	Sept. 1995

ASC Processes

The ASC by-products considered in this study are produced in either the combustion or post-combustion phase of boiler operations, as follows:

- Combustion
  - Fluidized bed combustion
  - Furnace sorbent injection
- Post-combustion
  - Spray dryer
  - Sodium sorbent injection
  - Calcium sorbent injection

An overview of each process follows:

Combustion

Fluidized Bed Combustion. The basic principle of fluidized bed combustion is to burn coal in a bed of crushed limestone sorbent that is fluidized by upward jets of hot air. As the coal burns, sulfur is released. The limestone acts as a chemical reagent to capture the sulfur before it can escape the boiler. The atmospheric fluidized bed combustion (AFBC) process operates at normal atmospheric pressure, while the pressurized fluid bed combustion (PFBC) process operates at 6 to 16 times the normal atmospheric pressure[6]. The AFBC process is depicted on Figure 1-1[9]. The DOE's PFBC utility demonstration project is presented on Figure 1-2[10].

Because the tumbling motion of the coal enhances the burning process, combustion temperatures in the fluidized bed system can be held to around 760 to 870°C (1400 to 1600°F), which is almost half the temperature of a conventional boiler, and below the point at which nitrogen oxides are formed[6]. Fluidized bed combustors can remove 90-95% of SO_2 and 50-70% of NO_x. Thus, fluidized bed combustors can meet both sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emission standards without additional pollution control equipment.

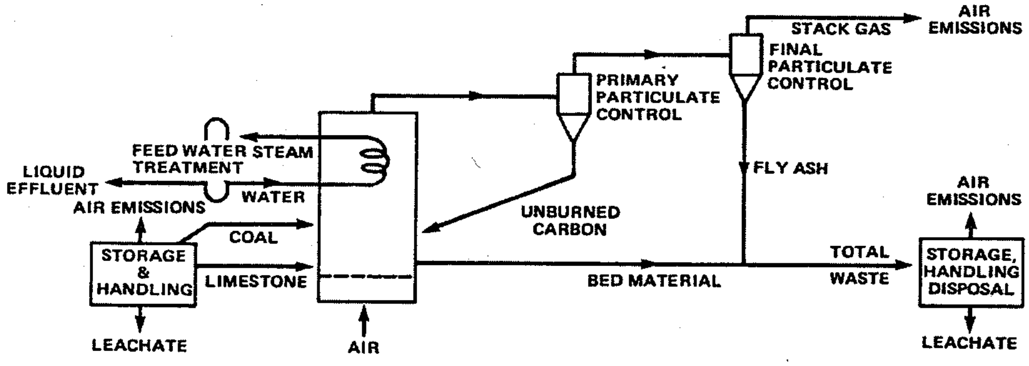

Figure 1-1
Atmospheric Fluidized Bed Combustion Flow Diagram

(SOURCE: Envirosphere Company, *Advanced SO_2 Control Solid-Waste Management Planning Study,* Palo Alto, Calif: Electric Power Research Institute, Feb. 1986, CS-4402.)

Fluidized bed combustion is well established in industrial applications in Europe, and is used in over 70 industrial boilers in the U.S. FBCs offer many advantages when converting older units, including extending plant life and / or increasing capacity, and increasing plant efficiency from 30-35% to 40%[1]. FBC units can be small, providing incremental growth with demand. Also, factory-fabricated units require minimal construction time at the plant[5]. Pressurized fluidized bed systems provide the advantage of a combined cycle which can drive both gas and steam turbines[1].

Fluidized bed boilers can be either bubbling bed systems or circulating bed systems. A bubbling bed combustor is shown in Figure 1-3[6]. In a bubbling bed combustor, burning and desulfurization take place in a shallow limestone bed agitated by air injected at low velocities. The by-product produced from a bubbling bed unit will have a high lime and unburned carbon content due to the lower sorbent utilization and combustion efficiency[2].

Circulating fluidized bed combustion (CFBC) is a newer method of FBC. In a circulating bed combustor, the coal-limestone mix is circulated from a combustion chamber through a cyclone filter and back into the boiler with high velocity air jets. The mix is circulated many times per hour, increasing the residence time and improving combustion efficiency[2]. Due to the improved efficiency, CFBC by-product typically has less free lime.

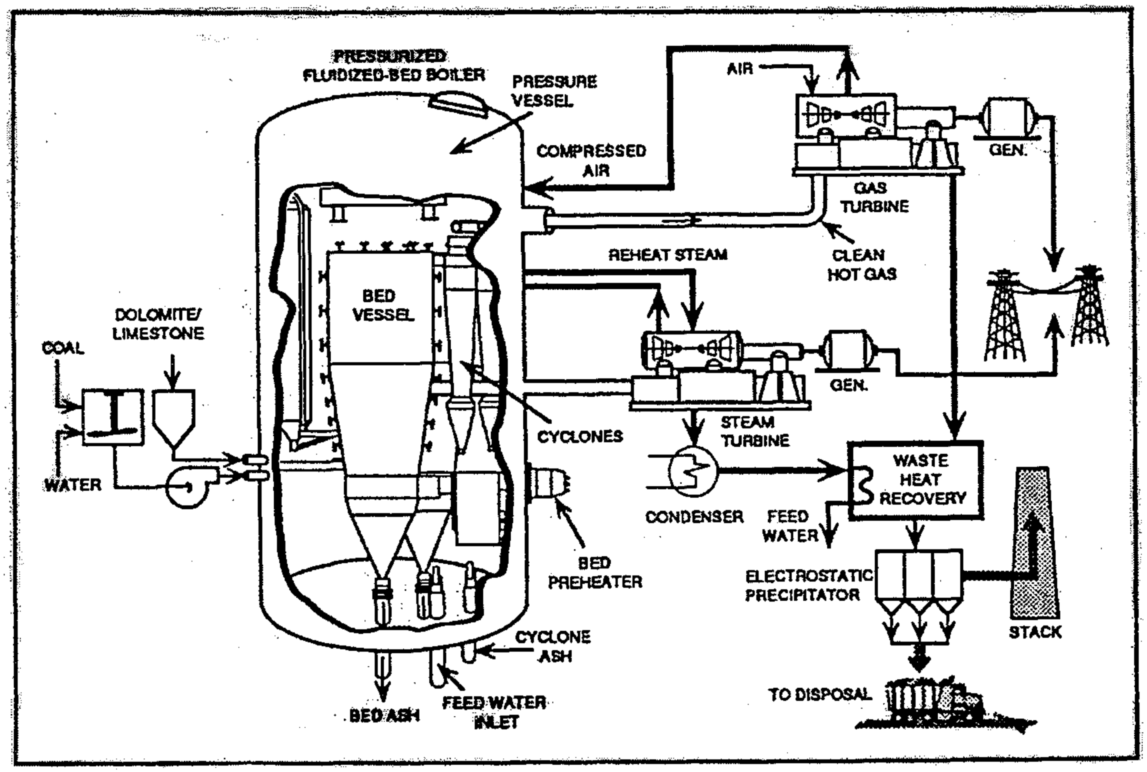

Figure 1-2
Pressurized Fluidized Bed Combustion, Ohio Power Company, New Haven, WV, and Appalachian Power Company, Philip Sporn Plant, Units 3 and 4.

(SOURCE: U.S. Department of Energy. *Clean Coal Technology Demonstration Program.* June 1991.)

Furnace Sorbent Injection. Advances have also been made in other types of coal-burning technologies, again combining high combustion efficiency with SO_2 removal. Furnace sorbent injection (FSI) involves the combustion of coal in the presence of a calcium-based material such as limestone or hydrated lime. Two FSI processes have been developed - the limestone injection multistage burner (LIMB) process and the limestone injection upper furnace process. The LIMB process is depicted on Figure 1-4.

Both FSI processes use limestone or hydrated lime as the sorbent. The sorbent is injected separately rather than pre-mixed with the coal. At high temperatures, the limestone or hydrated lime rapidly release CO_2 or H_2O, respectively, and form a porous microstructure after decomposition. The decomposed lime particles have much greater exposed surface area and become highly reactive. In the furnace of a coal-fired boiler, the lime particles chemically react with SO_2 and oxygen to form solid calcium sulfate. With furnace sorbent injection technology, 50-60% SO_2 removal efficiency can be achieved[2].

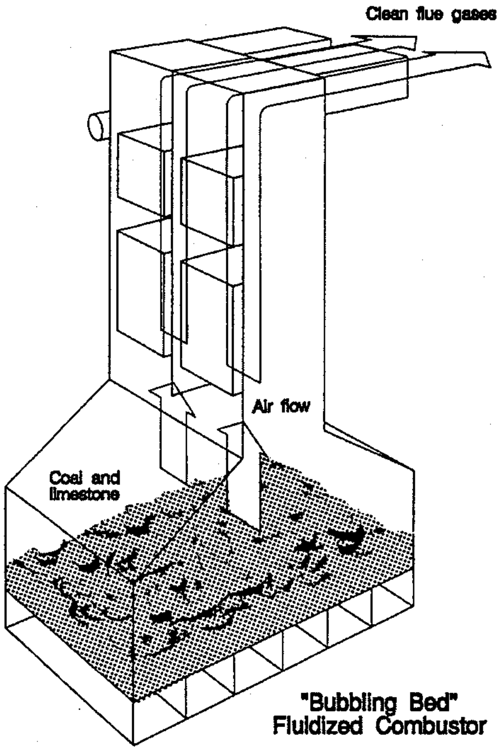

Figure 1-3
Bubbling Bed Fluidized Combustor

(SOURCE: U.S. Department of Energy. *Clean Coal Technology: The New Coal Era.* June 1990. DOE/FE-0193P.)

Post-Combustion

Post-combustion cleaning technologies include spray dryers, sodium sorbent injection, and calcium sorbent injection, which clean SO_2 from the flue gas. The SO_2 removal efficiencies for these processes are as high as 90%[6]. These technologies produce a dry powder, sometimes called “dry FGD.” The major advantage of dry FGD compared to wet FGD is that the by-products can be utilized or disposed without dewatering.

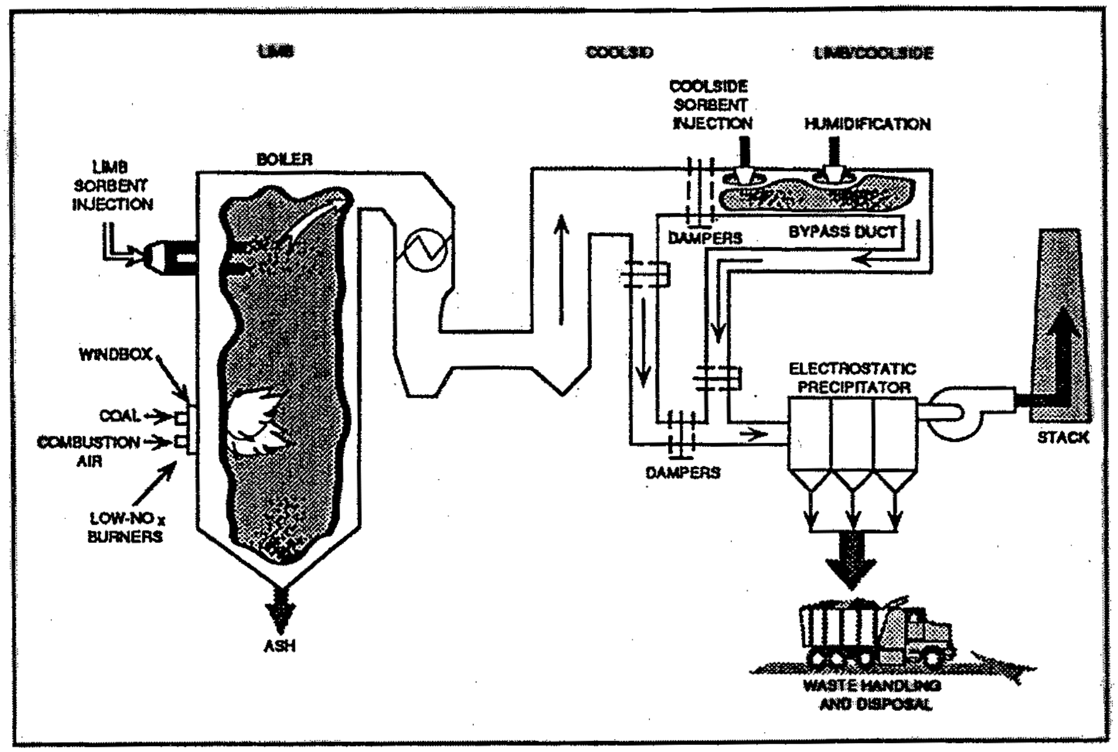

Figure 1-4
Limestone Injection Multistage Burner (LIMB) Process and Coolside Duct Injection of Lime Sorbent.

(SOURCE: U.S. Department of Energy. *Clean Coal Technology Demonstration Program.* June 1991.)

Spray Dryer. Spray dryer (SD) technology works by spraying an atomized hydrated lime (alkali) slurry into the flue gas stream, where it is dried by the hot flue gas. A typical spray dryer system is shown on Figure 1-5[9]. The SO_2 in the flue gas reacts with the alkali in the droplets, then the heat of the flue gas dries the atomized solution to form fine calcium sulfite/sulfate particulates. The by-product particles are collected downstream in an electrostatic precipitator or baghouse, along with fly ash. The spray dryer technology can remove 90% of the sulfur and has been commercially applied to low-sulfur coals[11].

Sodium Sorbent Injection. Sodium sorbent injection (SSI) technology uses sodium-based material for SO_2 removal. The system involves the injection of dry sodium sorbent into the flue gas, as shown on Figure 1-6[9]. Here the sorbent reacts with SO_2 to form fine sodium sulfite/sulfate particulates. The particulates then are collected downstream with the fly ash in an electrostatic precipitator or baghouse. Sodium sorbent injection can remove 70-90% of the sulfur[11].

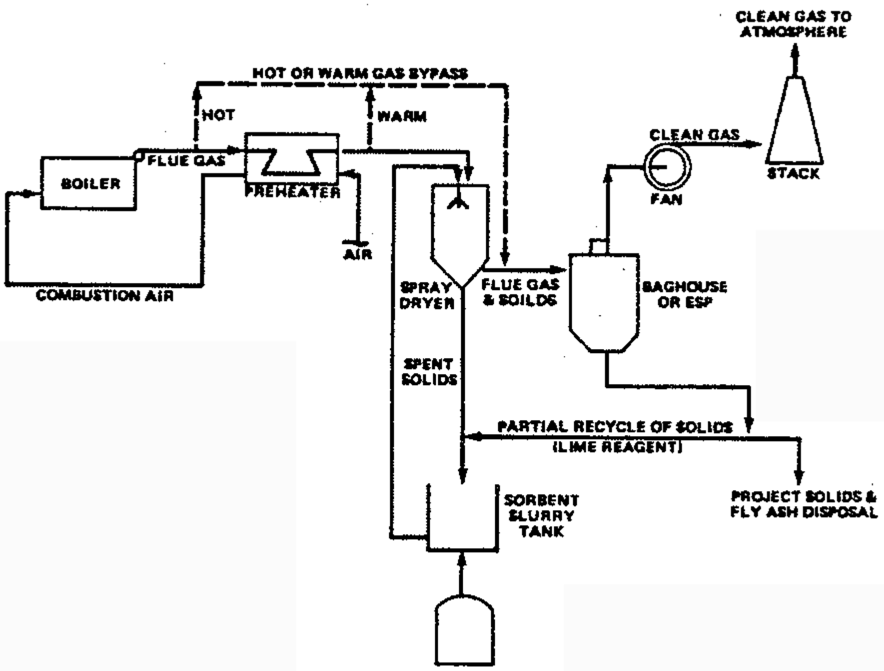

Figure 1-5
Typical Spray Dryer/Particulate Collection Flow Diagram

(SOURCE: Envirosphere Company. *Advanced SO_2 Control Solid-Waste Management Planning Study.* Palo Alto, Calif: Electric Power Research Institute. February 1986.
CS-4402.)

Calcium Sorbent Injection. Calcium sorbent injection (CSI) technology employs the same process as sodium sorbent injection technology. The difference is that lime or hydrated lime sorbent are used for calcium sorbent injection system instead of sodium sorbent for sodium sorbent injection system. Calcium sorbent injection can remove 50% or greater of the sulfur[12]. Unlike sodium sorbent injection, the efficiency of sulfur removal of CSI is more sensitive to the flue gas humidity. Increasing flue gas humidity would benefit the sulfur removal percentage.

Current and Projected Production Rates

The production rate of ASC by-products depends upon the number of plants which use these technologies and the volume of by-product produced per plant. There are dozens of coal-fired electric utility power plants which have operated or are operating ASC processes (Table 1-2). During the first decade of the next century, it is projected that coal will become the world's most utilized fuel[6]. To meet emission regulations, the ASC processes may be widely used, and more ASC by-products are expected.

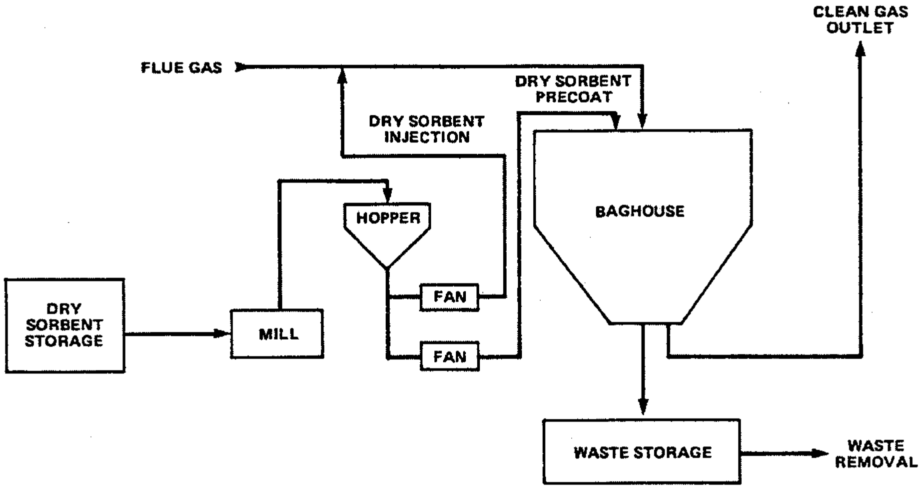

Figure 1-6
Typical Dry Sodium Injection System Schematic

(SOURCE: Envirosphere Company. *Advanced* SO_2 *Control Solid-Waste Management Planning Study.* Palo Alto, Calif: Electric Power Research Institute. February 1986.
CS-4402)

In general, the ASC processes produce increased by-product quantities compared to conventional coal combustion technology, because of the alkali sorbent injection or addition. A 100 MW AFBC boiler unit can be expected to produce approximately 100,000 tons per year (tpy) of by-products. This estimate is based on burning coal containing 12% ash and 3.5% sulfur and a calcium sorbent to sulfur ratio of 1 to 2.5[2]. Using furnace sorbent injection technology, the amount of by-product is expected to be about double the amount of fly ash normally generated from a conventional process burning the same coal[2]. It is estimated that a 500 MW spray dryer system will produce approximately 185,000 tpy of by-product, and a 500 MW sodium sorbent injection system will generate 215,000 tpy of by-products, based on burning coal with 1% sulfur, 10% ash, and expected 70% sulfur removal[2].

ASC By-Products Characterization

The chemical, physical, and engineering characteristics of the ASC by-products must be defined to evaluate their use in highway construction. These characteristics determine how each by-product will react with its environment and with the other mixture components involved in specific utilization options. It is also useful to know how the differences in the ASC processes such as process operating conditions, source and type of coal, type of sorbent, etc., change the by-product characterization.

Table 1-2
Utility Plants Which Have Used ASC Technologies

Fluidized Bed Combustion:

- Shawnee Plant, Tennessee Valley Authority, Paducah, KY
- Tidd Plant (PFBC), AEP Generating Company, Columbus, OH
- Nucla Station (Circulating Bed), Colorado Ute Electric Association, Nucla, CO
- Thames Plant, AES, Connecticut
- Blackdog Plant (Bubbling Bed AFBC), Northern States Power Company, Burnsville, MN
- Reference Plant, Northern States Power Company, Burnsville, MN
- R. M. Heskett Station, Montana-Dakota Utilities Company, Mandan, ND
- Philip Sporn Plant (PFBC), Appalachian Power Company, New Haven, WV
- Texas-New Mexico Power Company (Circulating Bed), Fort Worth, TX
- Iowa State University Power Plant, Ames, IA
- Archer Daniels Midland Power Plant, Cedar Rapids, IA
- Archer Daniels Midland Power Plant, Des Moines, IA

Furnace Sorbent Injection, Including LIMB Units:

- Edgewater Plant, Ohio Edison Company, Lorain, OH
- Whitewater Valley Station, Richmond Power & Light, Richmond, IN
- Lakeside Plant, Springfield City Water, Power & Light, Springfield, IL
- Edwards Plant, Central Power and Light Company, Corpus Christi, TX
- Hennepin Plant, Illinois Power Company, Hennepin, IL
- Ontario Hydro, Ontario, Canada
- Yorktown Station, Virginia Electric and Power Company, Yorktown, VA

Spray Dryer Systems (Lime Sorbent):

- Antelope Valley Station, Basin Electric Power Coop., Beulah, ND
- Arapahoe Station, Public Service Company of Colorado, Denver, CO
- Pryor Station, Grand River Dam Authority, Pryor, OK
- Holcomb Station, Sunflower Electric Coop., Holcomb, KS
- Shiras Station, Marquette Board of Light and Power, Marquette, MI
- Laramie River Station, Basin Electric Power Coop., Wheatland, WY
- Craig Station, Colorado-Ute Electric Association, Craig, CO
- Rawhide Energy Station, Platte River Power Authority, Wellington, CO
- Riverside Plant, Northern States Power Company, Minneapolis, MN
- Springerville, Tucson Electric Power Company, Springerville, AZ
- Generating Plant, United Power Association, Stanton, ND

- Valmy Steam Plant, Sierra Pacific Power Company, Valmy, NV
- Shawnee Plant, Tennessee Valley Authority, Paducah, KY

Sodium Sorbent Injection Systems:

- Arapahoe Station, Public Service Company of Colorado, Denver, CO
- Cameo Station (KVB Test Facility), Public Service Company of Colorado, Palisade, CO
- Ray D. Nixon Station, Colorado Springs Utilities, Fountain, CO
- Nucla Station, Colorado-Ute Electric Association, Nucla, CO
- Four Corners Plant, Arizona Public Service Company, Fruitland, NM
- Coyote Station, Montana-Dakota Utilities Company (Sodium Spray Dryer) Beulah, ND
- Leland Olds Plant, Basin Electric Power Cooperative, Stanton, ND

Calcium Sorbent Injection System:

- Arapahoe Station, Public Service Company of Colorado, Denver, CO

Three methods of by-product characterization are by chemical reactivity, physical characteristics, and leachate chemistry. All of these criteria influence utilization potential and are interrelated. Changes in one property can produce changes in the other properties and furthermore, affect the utilization potential.

Generally, the differences between the properties of ASC by-products and those of conventional fly ash and bottom ash result from the sorbent addition / injection for SO_2 removal. Chemical compounds related to ASC by-products are listed on Table 1-3. Unlike Class F coal ash, SO_2 control by-products contain significant quantities of calcium or sodium oxide (CaO or Na_2O) and calcium or sodium sulfate / sulfite ($CaSO_4$ and Ca SO_3 or Na_2SO_4 and Na_2SO_4). Like many sources of Class C fly ash, these compounds react exothermically (release heat) with the addition of water. Also, the high alkalinity of these by-products produces higher pH leachate than most conventional fly ash. The characteristics of these by-products are presented in Table 1-4. By-product formation reactions are presented in Table 1-5.

The by-products produced from FSI, SD, SSI, or CSI technologies, as well as AFBC fly ash, are dry powders which are collected in an electrostatic precipitator or baghouse. Spent bed material (SBM) and char from AFBC technology are collected by different methods. The main components in ASC by-products are fly ash, calcium (or sodium)-sulfur reaction products, and unreacted sorbent. ASC fly ashes (up to 70% of total by-products) have similar properties to conventional fly ash but are more alkaline, which indicate potential self-hardening or cementing properties. When some ASC by-products contact moisture, rapid hydration releases heat and increases the temperature of the material. If heat of hydration is excessive, cracking, weakening, or even blowouts may occur as the material reacts.

The calcium-sulfur reaction occurs in the combustion boiler during both atmospheric fluidized bed combustion and furnace sorbent injection technologies. Because of the lower combustion temperature, AFBC fly ash typically has a high unburned carbon, irregularly shaped particles, and low pozzolanic reactivity. However, a higher FSI combustion temperature results in spherical, glassy FSI fly ash particles. The calcium-sulfur reaction products produced from both technologies are calcium sulfate. There is little or no calcium sulfite due to the oxidizing atmosphere inside the boiler.

The SO_2 can be removed at the post-combustion (flue gas) stage using either spray dryer, sodium sorbent injection, or calcium sorbent injection technologies. The by-products, which are dry powders, are also called dry FGD. The fly ash content produced from SD, SSI, or CSI technologies is generally higher than that from AFBC and FSI technologies. The physical properties of SD fly ash, SSI fly ash, and CSI fly ash are similar to conventional fly ash, but are extremely fine. Fly ash is coated by and intermixed with calcium (sodium)-sulfur reaction product and is collected together with reaction product and unreacted sorbent. The SD technology produces mainly sulfite components, SSI technology produce mainly sulfate components, and CSI technology produce both sulfite and sulfate components. Unlike other ASC methods, the SSI technology uses a sodium-based material as sorbent. The resulting sodium compound is much more soluble in water than the calcium compound, which may result in elevated sodium concentrations in leachate.

These by-products do not exhibit toxic or hazardous characteristics under current regulatory definitions. Table 1-6 summarizes the characteristics of five ASC by-products. The characteristics of conventional fly ash are also listed for reference.

Table 1-3
Some Chemical Compounds Relevant to ASC By-Product Formation and Utilization

Name	Formula
Alkali	Ca or Na
Anhydrite	$CaO \cdot SO_3$ or $CaSO_4$
Calcite or Calcium Carbonate (limestone)	$CaCO_3$
Calcium Oxide (lime)	CaO
Calcium Sulphate	$CaSO_4$
Calcium Sulphite	$CaSO_3$
Hannebachite	$CaSO_3 \bullet \frac{1}{2}H_2O$
Ettringite	$3CaO \bullet Al_2O_3 \bullet 3CaSO_4 \bullet 32H_2O$ or $Ca_6 Al_2 (SO_4)_3 (OH)_{12} \bullet 26H_2O$
Thaumasite	$2CaO \bullet 2SiO_2 \bullet 2CaCO_3 \bullet 2CaSO_4 \bullet 30H_2O$ or $Ca_6Si_2 (SO_4)_2 (CO_3)_2 (OH)_{12} \bullet 24H_2O$
Gypsum	$CaO \bullet SO_3 \bullet 2H_2O$ or $CaSO_4 \bullet 2H_2O$

Hematite or Iron Oxide	Fe_2O_3
Hydrated (slaked) Lime or Portlandite	$Ca(OH)_2$
Sodium Hydroxide	$NaOH$
Periclase or Magnesium Oxide	MgO
Quartz or Silicon Dioxide	SiO_2
Sodium Sulfate	Na_2SO_4
Sodium Sulfite	Na_2SO_3

Table 1-4
Description of ASC By-Products

Process	Atmospheric Fluidized Bed Combustion [6,13,17,18]	Furnace Sorbent Injection [11,14,17,18]	Spray Dryer [11,15,17,18]	Sodium Sorbent Injection [11,16,18]	Calcium Sorbent Injection [12,18]
Stage	Combustion	Combustion	Post-combustion	Post-combustion	Post-combustion
Reagent Type	Lime	Lime	Lime	Sodium	Lime
Toxicity	Non-toxic and non-hazardous	Non-toxic and non-hazardous	Non-toxic and non-hazardous	The by-product is a non-toxic and non-hazardous material. However, the sodium compounds are much more soluble in water than the calcium compounds in other advanced SO_2 control by-products. The high content of soluble sodium salts in the SSI by-product may restrict utilization opportunities.	Non-toxic and non-hazardous
Particle Description	The primary by-products generated during this process includes AFBC fly ash, spent bed material (SBM), and char (not all units). AFBC fly ash is collected with either a fabric filter or electrostatic precipitator. SBM is withdrawn from the bottom of the boiler, and char is a coarse flue gas residue collected by a cyclone device.	The by-product is a dry powder. The main components of this by-product are fly ash, unreacted limestone or lime, and calcium sulfate. There may also be some calcium sulfite if there is not enough oxygen to completely oxidize the sulfite to sulfate inside the boiler.	The by-product is a combination of spherical, glassy fly ash particles coated by and intermixed with fine crystals of calcium-sulfur reaction by-product. The by-product is a dry powder, which is collected together with fly ash in an electrostatic precipitator or a baghouse.	The major portion of sodium-sulfur reaction product is sodium sulfate (Na_2SO_4) sodium sulfite (Na_2SO_3) is generally the lower percentage. Some calcium is also present in oxide or silicate form and in the fly ash component.	The by-product contains fly ash, unreacted lime or hydrated lime, and sorbent-sulfur reaction products. The primary reaction products are calcium sulfite ($CaSO_3$) and calcium sulfate ($CaSO_4$). The by-product has low bulk density and very high surface area.

Table 1-4 (Continued)

Process	Atmospheric Fluidized Bed Combustion [6,13,17,18]	Furnace Sorbent Injection [11,14,17,18]	Spray Dryer [11,15,17,18]	Sodium Sorbent Injection [11,16,18]	Calcium Sorbent Injection [12,18]
Particle Description (Continued)	Due to the low combustion temperature, AFBC fly ash does not fuse into a glassy matrix. The particles have irregular shapes, lower pozzolanic reactivity, and higher amounts of unburned carbon (loss-on-ignition up to 15%) compared with conventional fly ash. AFBC fly ash is similar in particle size distribution and fineness to conventional fly ash. SBM and char materials are slightly coarser, fine-sand-sized particles with a low density. AFBC by-products (fly ash, SBM and char) consist mainly of calcium sulfate ($CaSO_4$) and calcium oxide (CaO). There is also some unreacted limestone ($CaCO_3$). There is no calcium sulfite due to the oxidizing environment inside the AFBC boiler.	The physical characteristics of furnace sorbent injection by-product are similar to conventional fly ash. The by-product has approximately the same particle size distribution as conventional fly ash. The particle size is strongly dependent on the degree of fineness of the limestone or lime prior to injection. The high combustion temperature results in spherical, glassy FSI fly ash particles. Approximately 40-70% of the by-product is fly ash. The free lime content is 15-30%, which is significantly higher than other advanced SO_2 control by-products. The calcium sulfate/sulfite content is 10-35%. FSI by-product generally has high loss-on-ignition values.	The particles of spray dryer by-products are a little finer than those of conventional fly ash. Fly ash makes up from 40-70% by weight of the total spray dryer by-product. Compared to flyash, spray dryer by-products have a higher heat of hydration, more alkaline leachate, and are self-hardening.	The by-product consists of spherical, glassy fly ash particles coated by and intermixed with sodium sulfite/sulfate and unreacted sorbent. The by-product is collected together with fly ash in a baghouse or electrostatic precipitator. The physical characteristics of the by-product are similar to conventional fly ash, but the particles are extremely fine. Fly ash makes up from 40-70% by weight or the total by-product.	The particle size, specific gravity, permeability, and unconfined compressive strength of calcium sorbent injection by-product is similar to conventional fly ash.

Table 1-5
By-Product Formation Reactions

1. Atmospheric fluidized bed combustion[6, 13, 17, 18]
   - Limestone is added to the combustion chamber, where coal is burned in the limestone bed. The basic calcium-sulfur reactions inside the boiler are:

     $CaCO_3 \rightarrow CaO + CO_2$
     $CaO + SO_2 + ½ O_2 \rightarrow CaSO_4$
   - There is no calcium sulfite due to the oxidizing environment inside the AFBC boiler.
2. Furnace sorbent injection[11, 14, 17, 18]
   - Limestone or hydrated lime is injected into the combustion chamber. The basic calcium-sulfur reaction inside the boiler is:

     $CaCO_3 \rightarrow CaO + CO_2$ or $Ca(OH)_2 \rightarrow CaO + H_2O$
     $CaO + SO_2 \rightarrow CaSO_3$
     $CaSO_3 + ½ O_2 \rightarrow CaSO_4$
3. Spray dryer technology[11, 15, 17, 18]
   - The wet lime slurry is injected into the flue gas stream. The basic calcium-sulfur reaction is:

     $CaO + H_2O \rightarrow Ca(OH)_2$
     $Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O$
     $CaSO_3 + ½ O_2 \rightarrow CaSO_4$
     $CaSO_4 + ½ H_2O \rightarrow CaSO_3 . ½H_2O$
     $CaSO_4 + 2 H_2O \rightarrow CaSO_4 . 2H_2O$
   - The main portion of calcium-sulfur reaction product is calcium sulfite hemihydrate ($CaSO_3 . ½H_2O$), with smaller portion of calcium sulfate.
4. Sodium sorbent injection[11, 16, 18]
   - The dry sodium-based alkali sorbent is injected into the flue gas stream. The sodium-sulfur reaction is:
     $Na_2CO_3 \rightarrow Na_2O + CO_2$
     $Na_2O + SO_2 + NaSO_3$
     $Na_2SO_3 + ½ O_2 \rightarrow Na_2SO_4$
   - The major portion of sodium-sulfur reaction product is sodium sulfate ($Na_2 SO_4$); sodium-sulfite (Na_2SO_3)
5. Calcium sorbent injection[12, 18]
   - Lime or hydrated lime is injected into the flue gas stream. The calcium-sulfur reaction is

     $Ca(OH)_2 + CaO + H_2O$
     $CaO + SO_2 \rightarrow CaSO_3$
     $CaSO_3 + ½ O_2 \rightarrow CaSO_4$
   - The reaction products are primarily calcium sulfate ($CaSO_3$) and calcium sulfate ($CaSO_4$)

Table 1-6
Summary of the Characteristics of ASC By-Products

	Fly Ash	AFBC	FSI	SD	SSI	CSI
Chemical: (%)						
CaO	1-30	4-56	17-44	18-32	4-7	14-41
SiO_2	20-65	2-31	14-38	16-32	25-34	10-30
Al_2O_3	15-30	2-13	7-20	6-23	6-13	4-13
Fe_2O_3	4-20	2-11	6-11	2-8	1-13	1-4
MgO	1-5	0.3-2	0.6-3	0.6-6	0.7-4	0.6-1
K_2O	0.5-3	0.1-1	0.5-2	0.2-0.8	0.4-0.7	0.4-2
Na_2O	0.1-8	0.1-3	0.1-1	0.9-5	6-67	0.3-0.6
SO_3	0.1-8	1-24	1-50	6-22	9-23	11-14
OH	0-8	2-18	6-20	0.5-10	0.2-2	0.5-22
pH	3-12	12-13	11-13	9-13	11-13	9-13
Physical:						
Aerated Bulk Density (kg/m^3)	560-1040	230-1460	530-800	580-960	700-830	380-620
Settled Bulk Density (kg/m^3)	960-1680	590-1600	850-1120	720-1250	850-1170	660-1030
Dry Density (kg/m^3)	1300-1410	1070-1510	1090-1280	1230-1390	1300-1470	1110-1140
Optimum Moisture (%)	10-31	20-60	36-52	16-54	20-29	42-44
Specific Gravity	1.5-3.1	1.8-3.1	2.6-3.1	2.3-2.8	2.2-2.4	2.1-2.2
Particle Size (mm)	0.001-0.4	0.012-0.85	0.018-0.027	0.001-0.07	0.001-0.02	0.009-0.02
Specific Surface Area (m^2/g)	0.2-3.1	1-24	2.8-3.9	1.6-7.5	1.6-2.3	6.8-7.8
Permeability (cm/sec)	10^{-7}-10^{-4-}	10^{-11}-10^{-3}	10^{-9}-10^{-5}	10^{-9}-10^{-6}	10^{-6}-10^{-5}	10^{-7}-10^{-6}
Unconfined Compressive Strength (OMC, 7 days 100% relative humidity, kPa)	340-2030	130-13790	880-3480	280-4690	180-1850	430-560

Utilization

Utilization Reactions

As described in the above sections, the ASC by-products contain significant portions of aluminous and siliceous compounds. Also, the by-products contain high percentages of alkali (calcium or sodium) ions. The chemical species SiO_2, Al_2O_3, Fe_2O_2 and CaO give the ASC by-products self-hardening or cementing characteristics when in contact with water. The hydration reactions are complex, with the major hydration products being cementitious materials. The strength developed is dependent on the quantity of cementitious materials produced. The principal reactions are:

$$\begin{gathered}
CaO + H_2O \rightarrow Ca(OH)_2 \\
xCa(OH)_2 + ySiO_2 + zH_2O \rightarrow xCaO \bullet ySiO, \bullet zH_2O \\
xCa(OH)_2 + yA1_2O_3 + zH_2O \rightarrow xCaO \bullet yAl_2O_3 \bullet zH_2O \\
xCa(OH)_2 + ySiO_2 + zAl_2O_3 + wH_2O \rightarrow xCaO \bullet yAl_2O_2 \bullet zSiO_3 \bullet wH_2O
\end{gathered}$$

As noted from the above reactions, unreacted lime (CaO) from ASC by-products will react with water or moisture to form portlandite ($Ca(OH)_2$). This reaction is exothermic (heat releasing).

Other important components of ASC by-products are the calcium-sulfur reaction products. The calcium sulfate may contribute to early strength gains through the formation of ettringite and thaumasite. Ettringite and thaumasite form through the following hydration reactions[19]:

$$3CaO + Al_2O_3 + 3CaSO_4 + 32H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O \text{ (ettringite)}$$

$$2CaO + 2SiO_2 + 2CaSO_4 + 2CaCO_3 + 30H_2O \rightarrow 2CaO \cdot 2SiO_2 \cdot 2CaSO_4 \cdot 2CaCO_3 \cdot 30\ H_2O \text{ (thaumasite)}$$

The ettringite and thaumasite formations are caused by the reaction of $CaSO_4$ with CaO, Al_2O_3, SiO_2 and water[20]. Two types of ettringite are formed in the hydration of $CaSO_4 \cdot CaO \cdot Al_2O_3$, system[21]. The colloidal ettringite is produced when lime content is higher in the system. This type of ettringite has a water absorption characteristic. The crystals of colloidal ettringite, which are expansive, combine with large amounts of water, leading to a decrease in moisture content. The formation of cementitious crystals also provides strength, however, slow formation and expansion of these crystals may break early cementitious bonds, reducing the overall strength of the material. On the other hand, when the minor amounts of lime are present in the system, needle-shaped ettringite is produced. This type of ettringite has no dimensional changes on hydration and usually gains strength.

ASC by-products pozzolanic reactions are similar to those of other lime-fly ash mixtures. The pozzolanic reactivity of an ASC by-product is dependent on the fly ash percentage and alkali content. The high sulfate/sulfite composition may contribute to the strength, but may also cause expansion. The utilization of ASC by-products in various areas is discussed in Section 2 through Section 9. A brief summary is presented below.

Liability Issues

Liability issues associated with utilization of advanced SO_2 control (ASC) by-products include:

- Exemption from RCRA Subtitle C hazardous waste regulations
- Potential Superfund (CERCLA) liability
- Product liability

Regarding RCRA hazardous waste regulations, “large volume wastes,” which include “fly ash, bottom ash, boiler slag and flue gas emission control wastes” are exempt from RCRA Subtitle C hazardous waste regulations, as of a federal ruling on August 9, 1993. FBC by-products are exempt pending further study, and are scheduled for a final ruling on April 1, 1998. In the interim, FBC ash can be utilized as a non-hazardous waste, except as otherwise determined under state laws.

Non-hazardous solid wastes which are exempt from Subtitle C are regulated under Subtitle D. Subtitle D of RCRA in turn delegates regulation of these non-hazardous industrial wastes to the individual states.

Under the Federal Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (Superfund), flue gas emission control wastes and FBC ash (as well as fly ash, bottom ash and boiler slag) are considered “hazardous substances.” Both the generator and disposer are liable for any environmental damages caused by these wastes. Regarding beneficial uses, this issue is of greatest concern for stabilization/solidification of hazardous wastes, as a utility providing an ASC by-product for hazardous waste stabilization is vulnerable to financial responsibility under CERCLA for clean-up of environmental damage caused by the hazardous waste, unless it can be proven that the ASC by-product did not contribute to the environmental degradation.

The third legal issue of interest regarding ASC by-products is product liability, i.e., a marketed product must perform as advertised.

Utilization Options

In view of the physical and chemical characteristics of the ASC by-products, it is believed that there are potential uses for ASC by-products in highway construction, mining and soil amendment. The ASC by-products are dry powders and have physical properties similar to those of conventional fly ash (see Table 1-6). Their chemical properties are somewhat different from conventional fly ash, however, due to the alkaline reagents used for SO_2 emission control. The similar characteristics may allow ASC by-products to be used in lieu of conventional fly ash in similar applications. The chemical differences, however, will require some changes in utilization practices. The most promising utilization options are:

- Road base stabilization
- Soil stabilization
- Sludge stabilization
- Structural fill
- Grout
- Aggregate
- Cement production and replacement
- Soil Amendment

Table 1-7 summarizes the utilization options with moderate to high potential, as identified in previous EPRI projects.

Table 1-7
Utilization Options of ASC By-Products

Use Area	FBC Fly Ash	FBC SBM	FSI	SD	SSI	CSI
Road Base Stabilization	4	4	4	4		4
Soil Stabilization	4	4	4	4		4
Sludge Stabilization	4	4	4	4		4
Structural Fill	4	4	4	4		4
Grout	4	4	4	4	4	4
Aggregate Production/Replacement		4	4	4		4
Cement Production/Replacement	4		4	4		4

Soil Amendment	4	4	4	4		4

Advantages of ASC by-products for utilization include:

- Dry particles
- Cementitious / pozzolanic reactivity
- Grain size distribution similar to conventional fly ash
- Non-hazardous
- High pH, calcium, and sulfur (for soil amendment)

Disadvantages of ASC by-products for utilization include:

- Exothermic hydration
- Potential for expansion
- High soluble sodium salt content of sodium sorbent injection by-products
- Potential for corrosion or sulfate attack on concrete
- Long-term performance characteristics are not fully understood
- Excessive sulfur

Road Base Stabilization [2,12,18]. The FBC fly ash and spent bed material, furnace sorbent injection by-product, spray dryer by-product, and calcium sorbent injection by-product have potential for use as binder material or aggregate in road base stabilization. The function of ASC by-products as binder material or aggregate is greatly dependent on their chemical compositions and particle size. In order to minimize effects of the heat expansion and promote dimensional stability in base course mixes, preconditioning is needed for those ASC by-products which contain high free lime (CaO). Preconditioning consists of simply wetting the materials and allowing expansion to occur and heat to dissipate prior to utilization. For a stabilized road base, a minimum 7-day unconfined compressive strength of 2760-3450 kPa (400-500 psi) is required. Cement, lime, or fly ash may be added to the mixture to achieve the strength requirement. Strength, freeze-thaw durability, dimensional stability and leachate characteristics are the major criteria for evaluating the use of an ASC in stabilized road base.

Soil Stabilization[2,18]. The FBC fly ash and spent bed material, furnace sorbent injection by-product, spray dryer by-product, and calcium sorbent injection by-product have potential for use as an agent in soil Stabilization. The free lime content and fly ash content are factors for evaluating ASC by-product suitability. Free lime hydration contributes to moisture reduction in the initial stage, while the pozzolanic activity of fly ash contributes to strength development and improves long-term durability of stabilized soils. For stabilizing fine-grained soils, the ASC by-products act as a lime binder; for stabilizing coarse-grained soils, the ASC by-products act as a cement binder. Cement or lime may also be added to the mixture if the free CaO content is insufficient. Due to the sulfate, sulfite, and high CaO contents in ASC by-products, linear expansion and leachate tests are required, in addition to strength and freeze-thaw durability tests.

Sludge Stabilization [2,18]. The FBC fly ash and spent bed material, furnace sorbent injection by-product, spray dryer by-product, and calcium sorbent injection by-product are considered to have potential for use as stabilizing agents for sludge stabilization. Sludge stabilization is similar to soil stabilization, except that sludge has a lower solids content than soil. Therefore, the percentages of ASC by-products used in sludge stabilization is higher than those in soil stabilization. Usually, the ASC percentage is greater than 50% of the sludge content. The physical properties, free lime content, and leachability are potential indicators of ASC by-products suitability. Free lime hydration contributes to a high rapid heat release, which reduces the moisture and increases the density very quickly. Hydration of ASC by-products also forms ettringite and thaumasite crystals, which are expansive. The ettringite and thaumasite immobilize the trace elements in sludge by causing them to adhere to the crystal structure. FGD sludge, municipal sludge, and some industrial and hazardous waste sludges can be stabilized by ASC by-products.

Structural Fill [2,12,18,22,23]. All ASC by-products in this study may have the potential for use as structural fill. The evaluation of ASC by-products as fill material depends on their physical and engineering properties. However, the leachate characteristics and dimensional stability are important factors which affect the suitability of ASC by-products as structural fill material.

Grout [2,18]. The FBC fly ash, furnace sorbent injection by-product, spray dryer by-product, and calcium sorbent injection by-product have potential to be used as grout material. An evaluation of the suitability of ASC by-products as grout material would be based on their chemical characteristics and particle size and distribution. The ASC by-products can be used as binder material, as a fine aggregate, as filler material and for improving flow properties. Depending on the CaO content of ASC by-products and the strength requirement of grout material, it may be necessary to add cement or fly ash. If ASC by-products contain high free CaO, preconditioning would be required to prevent the heat buildup, especially during mass grouting.

Aggregates Production [2,18]. All ASC by-products in this study have the potential to be used for aggregate production. Two types of artificial aggregate, synthetic and lightweight aggregates, have been produced from ASC by-products in laboratory scale tests. Synthetic aggregate was prepared by high pressure compaction and lightweight aggregate was prepared by high temperature kiln-firing. To be used for the production of aggregate, ASC by-products should contain a high cementing ability. Cement or conventional fly ash may need to be added as a binder.

Cement Production and Cement Replacement [2,12,18,22,23]. Some sources of FBC fly ash, furnace sorbent injection by-product, spray dryer by-product, and calcium sorbent injection by-product may be useful in cement production and cement replacement in concrete, although, the sulfate level of most ASC by-products exceeds that allowed by ASTM C 618. The chemical composition of ASC has a significant influence on their utilization potential in these areas. ASC by-product can also be used in the production of "expansive" cement. Cement produced from ASC by-products should be tested according to ASTM C 150 and C 595.

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2

ROAD BASE

Overview

Advanced SO_2 control (ASC) by-products have potential as substitutes for lime or fly ash in road base construction. A possible advantage would be faster strength development and less sensitivity to cold weather during curing. However, the potential for expansion should be explored for each by-product source and mix. Also, a separate hydration step may be required prior to mixing and placement. An ASC by-product road base would be required to fulfill design and performance criteria similar to a cement-stabilized road base. As such, it would provide pavement support, but may not be appropriate where a free-draining base course is required. When used as base course beneath a portland cement concrete pavement, the potential for sulfate attack on concrete should be considered.

State of Practice

At the present time, ASC by-products have been used in only a few experimental road base demonstration projects using AFBC by-product and spray dryer by-product.

Design Procedure

Designing a by-product road base is a complex procedure requiring design of both the base course mix and the thickness of each layer of the pavement system. Numerous mixture combinations, as well as pavement systems, are possible. Mixtures using small percentages of ASC by-products in aggregate-based mixes have been tested which developed adequate strength without excessive expansion. Although mixtures with moderate proportions of by-product would allow the beneficial use of greater quantities of material, test road bases with moderate percentages of AFBC spent bed material (SBM) experienced excessive expansion.

The possibilities of using high proportions of by-product in road base, similar to stabilized fly ash base courses (90% fly ash / 10% cement), will also be outlined, although no documented use or demonstration of this type of base course is known.

Conceptual Design

The design of a by-product base course involves the following:

- Identify the source of by-product to be used
- Determine the type of base course mix - with or without aggregate
- Develop a mix design and characterize the product through laboratory testing
- Develop the pavement design by determining the thickness of the base course and the wear surface
- Determine construction procedures and quality control requirements

The base course should provide satisfactory strength and durability, negligible expansion, be easy to place and be economically competitive with alternative designs.

The design mix should not only indicate the proportions of dry materials, but also include the quantity of water in the mix and a specified compacted density that is required to satisfy strength and/or durability criteria. Several iterations may be required to develop the final pavement design and construction sequence.

There are two methods for using fly ash in road base which will be considered for ASC by-product use. Those methods are:

- By-product: aggregate base mix
- Stabilized by-product without aggregate

By-product: aggregate road base shows promise with ASC by-products based on a few trial studies. Road base without aggregate would utilize much larger volumes of by-product and has been done successfully with fly ash, but this use has not been tested with ASC materials.

Several design procedures for fly ash and AFBC stabilized road base will be presented for use with ASC by-products[1,2,3].

Mix Design/Laboratory Testing

The objective of the mix design procedure is to provide a base course with the required proportions to:

- Provide adequate strength and durability

- Maintain dimensional stability
- Be easy to place and compact
- Be economical

To provide strength, durability, and dimensional stability, the following criteria should be applied to SO_2 control by-product base course:

1. The 7-day unconfined compressive strength of the mix, when cured under moist conditions and at 21 ± 2°C (70 ± 3°F), must be 2760-3100 kPa (400-450 psi) (for cylindrical specimens having a length to diameter ratio of 2:1)[2].
2. The strength of the mix must increase with time[2]. The 28-day unconfined compressive strength should be at least 3790-4140 kPa (550-600 psi).
3. The minimum compressive strength after a 7-day cure and vacuum-saturation (ASTM C 593) shall be 2760 kPa (400 psi) for pavements in regions that have freezing and thawing cycles[2].
4. Expansion requirements are not well established. However, it is suggested that linear expansion be restricted to between 0.1 to 0.5%[3].

Laboratory Testing Program for By-Product Base Course. The generalized laboratory testing procedure for by-product base course is outlined below.

- Step 1 - Select Source. The selection of power plant is determined almost solely by proximity to end-use location.
- Step 2 - Select Representative Samples. Samples are taken to obtain as realistic a representation as possible of the variation in the by-product from that source. Samples should be taken over a period of time. A minimum of three representative samples is recommended.
- Step 3 - Perform Initial Laboratory Testing. A number of initial laboratory tests can be performed to provide data on the basic physical and engineering behavior of the material. The following tests should be performed on each representative sample collected:
  - Loss on Ignition (LOI)
  - CaO - ASTM C 25, Chemical Analysis of Limestone, Quicklime, and Hydrated Lime

- Gradation: For AFBC SBM: ASTM C 136 - Sieve or Screen Analysis of Fine and Coarse Aggregate

  For Other ASC By-Products: ASTM C 311 - Blaine Fineness, Specific Surface

- Step 4 - Test Hydration. The following test is useful for by-products that react exothermically to determine the quantity of water and time needed to fully hydrate a by-product. This test was suggested by Minnick for use with AFBC residue (SBM)[3]. Hydration of this residue generated considerable heat and steam, sometimes with violent or explosive force. FSI by-products have also shown significant heat of hydration. For spray dryer and calcium injection by-products, however, heat of hydration is minima1[4].

  In order to assist the user in determining the appropriate quantity of water to use for a given source of by-product, the following laboratory procedure has been suggested[3].

  - Select a 13.5 kg representative sample of by-product.
  - Select a representative portion of the sample (approximately 0.25 kg) and dry to determine the initial moisture content. Drying should be accomplished at a temperature no greater than 55°C.
  - Split the remaining portion of the sample into five smaller samples of approximately 2.5 kg each.
  - Add different amounts of water to each of the five samples. Since temperature readings must be made immediately, the water should not be added to every sample at the same time. Ten percent water based on the dry weight of the residue should be added to the first sample. The other four samples should have additions of 20, 30, 40, and 50%, respectively.
  - Record the elapsed time and temperature immediately after the water addition and at times of 2, 5, and 10 minutes, and then every 10 minutes until the temperature returns to within 2 degrees of ambient.
  - Determine the moisture contents after the final temperature readings are taken and 24 hours after the water was added.
  - After the 24 hour moisture content sample is taken, add an additional 10% of water and record any temperature rise.
  - Determine the final moisture content after the temperature returns to ambient following the second addition of water.

- The reactivity of the residue can then be quantified by use of the procedure for "slaking reactivity" for quicklime, ASTM Standard C 110, "Test Methods for Physical Testing of Quicklime, Hydrated Lime, and Limestone." In some cases, adjustment of water-residue ratio may be required when using the test procedure.

- Useful information can also be obtained by observing the condition of the residue during the testing procedures. Any hardening of the residue should be noted, as well as physical effects brought on by the addition of water. The residue should be described as dry, moist, or wet in appearance.

> Minnick states: "The time rate of temperature rise is also important.
> A rapid rise in the laboratory will indicate the probability of an explosive reaction in the plant or field. It has been noted at times that with a highly reactive residue the reaction is delayed when hydrating a large mass of material. However, when the reaction does get fully underway, the temperature rise is rapid and violent.
>
> The moisture content determinations that are made during the laboratory procedure provide information on the amount of free water that is available from the residue for compaction of the road base mixture. It is usually necessary to add additional water during the plant mixing cycle in order to bring the moisture content to optimum. The second addition of water in the laboratory procedure provides an indication as to whether hydration was completed by the first addition. If no temperature rise occurs after the second addition, hydration was complete previous to that addition. If a temperature rise does occur, then hydration was incomplete.
>
> The approximate optimum amount of water added for conditioning of the residue is that whereby only a small amount of moisture remains after mixing (such that the residue is lightly damp, but not wet) and hardening of the residue has not, and will not occur. If too much water is added to the residue, and the residue remains wet after mixing, the residue will solidify to a monolithic mass in the stockpile"[3].

Note that while hydrated AFBC residue did not harden in Minnick's testing program, it is possible that other by-products may harden during or after hydration. If hardening is significant, this may prohibit full hydration prior to mixing and compaction of material.

- Step 5 - Select Trial Mixes. The results of the initial laboratory testing can be used to determine the cement content (if any) of the first trial mix for each sample.

A stabilized coarse aggregate base course consists of a fine matrix and coarse aggregate. The fine matrix may include ASC by-product, aggregate passing the No. 4 sieve, fly ash, cement, or lime. Trends of properties with mix proportions using ASC by-product base course have not yet been established. However, for lime-fly ash-aggregate mixtures, higher strength and improved durability are achieved when the coarser aggregate particles “float” in the matrix. This occurs when the matrix material slightly overfills the void spaces between the coarser aggregate particles[2].

For a given aggregate, factors that can be varied in the process of determining satisfactory mixture proportions are: percentage of matrix fines; proportions of the various fine ingredients within the fine matrix; and total moisture content. For most coarse aggregates, the fine matrix can be expected to range from 10 to 20% by dry weight of the total mixture. For sandy aggregates, recommended matrix contents typically range from 15 to 30%. For coal ash by-product aggregates, including bottom ash and boiler slag, the matrix content will typically range from 20 to 40% by dry weight of the total mixture[1].

The selection of good mixture proportions starts with incremental additions of fines to the aggregate to determine the amount of fines needed to reach maximum dry density. Mold one test specimen at each fines content in accordance with ASTM C 593 compaction procedures at the estimated optimum moisture content. Once the optimum fines content is found, add 2% to the amount of fines and prepare test cylinders for strength and durability testing. For most well-graded coarse aggregates, the combined amount of fines blended with the aggregate will be between 10 and 20% of the total weight of the mix. Within the fine matrix, cement/fly ash ratios of 1:3 to 1:4 are typical. Similar ratios and percentages may be considered as a starting point for ASC by-product-aggregate road base mixes.

For mixtures without aggregate, potential base courses could consist of compacted by-products used alone or mixed with lime, cement, or fly ash. Lime or cement will be necessary for most by-products, with the possible exception of AFBC fly ash.

- Step 6 - Perform Moisture-Density Tests on Trial Mixes. Once the initial cement content has been chosen for a trial mix for each representative sample, the moisture-density relationship for each trial mix should be determined in accordance with AASHTO T 134. This is necessary since for most materials the unconfined compressive strength decreases markedly with a decrease in density; therefore, strength testing is done at maximum dry density and optimum moisture content (OMC). It is necessary to establish the moisture-density relationship for each by-product trial mix. Values of maximum dry density and optimum moisture content for a new trial mix should not be extrapolated from previous data.

- Step 7 - Perform 7-Day Unconfined Compression Tests. Unconfined compressive strength tests should be performed on test cylinders from each trial mix. Generally dimensions of the cylinders should be such that the length is twice the diameter. Cylinders should be molded at maximum dry density and optimum moisture content of the trial mix in accordance with AASHTO T 134, and wrapped tightly in plastic bags or coated with paraffin to prevent moisture loss. Cylinders should be moist-cured for 7 days at a constant temperature of 21 ± 2°C (70 ± 3°F). At the end of 7 days, cylinders may be capped in accordance with AASHTO T 231 (the sulfur capping compound is recommended) and broken in accordance with AASHTO T 22. The unconfined compressive strength shall be the average of three test breaks per mix. Strengths after vacuum saturation testing should exceed 2760 kPa (400 psi) for adequate freeze-thaw resistance.
- Step 8 - Select Revised Trial Mixes. If the trial mix for any representative sample fails to produce a 7-day unconfined compressive strength of 2760-3100 kPa (400-450 psi), a second trial mix should be developed having a lesser or greater cement content, depending upon whether the average trial mix strength was greater or less than the specified range. Although trial mixes with 7-day strengths above 3100 kPa (450 psi) have adequate strengths for base/subbase applications, they do not represent the most economical mix. Steps 6 and 7 are repeated using a revised trial mix. The mix revision and testing process continues until a trial mix is developed which satisfies the compressive strength criterion.
- Step 9 - Perform 28 Day Unconfined Compression Tests. The trial mix for each representative sample which satisfies the 7-day strength criterion should be tested to verify the mix's strength gain with time. Unconfined compression tests are performed in the manner as outlined in Step 7. If a trial mix fails to produce a strength gain it is recommended that the by-product be eliminated from consideration as lack of strength gain could have serious consequences on the long-term durability of a construction project. Erratic strengths over time (increase followed by decrease followed by increase) may indicate expansion reactions.

  In areas subject to severe winter temperatures and field conditions, frost heave and durability testing should be performed on a trial mix that satisfies 7- and 28 day strength criteria. Failure of a mix to meet durability criteria will necessitate increasing the cement content until the criteria is met.

  There are two design methods/criteria for long-term strength of a stabilized road base. One design philosophy is that long-term strengths of approximately 5520 kPa (800 psi) prevent reflective cracking of flexible pavements. Alternatively, rigid lime-fly ash-aggregate base courses have been placed with long-term compressive strengths as high as 27590-34480 kPa (4000 to 5000 psi). This type of base course is subject to cracking, but can be controlled by saw cutting joints at predetermined intervals. Control of cracking of high strength base courses is discussed at length in the *ACAA Flexible Pavement Manual*[1] and will be discussed in brief in the subsection, “Construction.”

- Step 10 - Expansion Testing. Long-term expansion should be tested to check dimensional stability of a road base material. Standard ASTM expansion tests are not directly applicable for this situation, so a unique test simulating road base conditions must be devised. One possibility would be to compact the by-product near the OMC following Proctor compaction procedures in a 10 cm (4-inch) diameter clear plastic tube. The clear tube will allow measurement of sample height. Initial sample heights should be measured. Samples should be subject to alternating inundation and draining (wetting-drying), with periodic length measurements for a minimum of 90 days.

Pavement System Design

Following design of the base course mix, the thickness of each layer of the flexible pavement system must be determined. The design procedures for stabilized fly ash pavement, which are described in the *ACAA Flexible Pavement Manual*[1] and *Fly Ash Design Manual for Road and Site Applications, Vol. 1: Dry or Conditioned Placement*[2], can be followed. The procedures and design examples are presented in Appendix A.

Minnick suggests a structural number (SN) of 0.20 to 0.28 for bases composed of AFBC residue, fly ash and aggregate. The lower coefficients are for bases with 7 day compressive strengths of 4140 kPa (600 psi) or less, while the higher range of coefficients are for base strengths greater than 4140 kPa (600 psi).

Construction Details

Materials Handling, Transport and Storage

Material may be conditioned during silo discharge to a predetermined water content to provide prehydration. Conditioned material can be transported in covered dump trucks and should be discharged from the truck directly to the pug mill or batch plant with minimal storage.

Various other handling alternatives are possible, although each would increase project costs. One alternative is pneumatic transport and silo storage followed by hydration in a mix plant. Another alternative may be conditioning to a minimal water content during silo discharge to control dusting, followed by a separate step to complete hydration at the mix plant. This may be necessary for very reactive materials. If conditioned material is stored, it should be protected with water-proof tarpaulins.

Mixing and Placement

Mixing of either by-product aggregate mixes or stabilized by-product without aggregate can be performed in an on-site pugmill or at a remote concrete batch plant. The base course material can then be hauled from the batch plant to the site in open-bed dump trucks. Spreading of the mixed base material can be accomplished by spreader boxes or asphalt pavers. Trials should be run to confirm that the material will feed evenly without segregation. Automatic grade control devices are recommended to achieve a uniform layer thickness when placing. For most ASC by-products compaction may be accomplished by pneumatic, vibratory, and steel wheel rollers. For compaction of an AFBC residue-aggregate mix, a 10-ton vibratory roller is recommended. Compacted layer thickness should not exceed 15 to 20 cm (6 to 8 inches) per lift.

If the finished layer thickness exceeds 15 to 20 cm (6 to 8 inches), the material should be compacted in more than one lift. Before placing a second layer, the surface of the first layer should be scarified to provide suitable bonding between the two surfaces. The minimum layer thickness should be not less than 10 cm (4 inches).

Materials should be mixed, placed, spread, and compacted with minimal time delays to achieve full strength development. Construction should only be carried out under weather conditions acceptable for stabilized road base such as normally required with lime/fly ash or Portland cement aggregate compositions.

Joints

Straight transverse and longitudinal joints should be formed at the end and edges of each day’s construction by cutting back into the completed work to form a true vertical face free of loose or shattered material. All material resulting from the trimming operation should be removed from the area to prevent mixing with fresh base course material. When the bituminous wear surface is constructed for a roadway or parking lot, it should be placed so that the wear surface joints coincide with the base course longitudinal joints.

Saw cutting of roadway pavement joints at regular intervals to control reflective cracking that may occur as a result of shrinkage cracks in the base course is sometimes used.

A recommended approach to control cracking in high-strength stabilized aggregate base is to saw-cut joints on the surface of the base course layer to 7.5 to 10 cm (3 to 4 inches). After placement of asphalt paving, the asphalt paving over the joints can be saw-cut and filled with rubberized asphalt sealant, or a reflective crack can be sealed with hot-poured sealant.

Other

Several other aspects of construction must be considered to produce a properly performing base course. These include seal coats, time delay before traffic loading, and construction cut-off dates. General guidance on these items is as follows:

- If possible, the bituminous wear surface should be constructed immediately after finishing the base course. If this is not feasible, a sealant or curing material should be applied to protect and cure the base course until the bituminous wear surface is constructed, or for a period of seven days or more. At no time should the moisture content of the surface of the base course be allowed to fall below the optimum moisture content.
- Application of the sealant should occur as soon as possible, but no later than 24 hours following compaction. An emulsified asphalt, liquid asphalt cement, or other bituminous curing material can be applied at the rate of 0.1 to 0.2 gallons per square meter.
- A minimum amount of curing is required to ensure attainment of desired cured strengths in the field. The general guideline for defining the construction cutoff date for stabilized base course is that the ambient air temperature should not fall below 10°C (50°F) for the first seven days following completion of the base course[2]. It is suggested that the engineer refer to the construction specification of his respective state highway department for construction cutoff dates for lime-pozzolan-aggregate or soil-cement.
- No traffic should be permitted on the pavement until the bituminous wear surface has been constructed and the base course has been cured for more than seven days.

Quality Control

Each component of the mix should be checked to meet specifications. Equipment should be clean and properly operating.

The following tests can be performed to check consistency of the by-product:

- For exothermic by-products, reactivity of dry material can be checked by adding 20% water, and comparing observed temperature rise to that obtained in the laboratory during mix design.
- For exothermic by-products, completeness of hydration can be verified by mixing and additional 20% water to a hydrated sample. Little or no temperature rise indicates satisfactory hydration.

- CaO should be measured and compared to that determined on mix design material.
- Sieve analysis or Blaine fineness should be performed periodically.
- LOI should be performed periodically.

A test strip must be constructed prior to full-scale construction of the project to verify the adequacy of the proposed compaction criteria, construction procedures, and equipment.

During construction, tests on the base course material are recommended for quality control purposes. The samples for testing should be random and represent the average material placed. Recommended tests include the following:

- Moisture-Density Relationship (AASHTO T 134)
- Moisture Content (ASTM D 2216) (drying temperature not to exceed 60°C)
- Cement Content of Freshly Mixed Soil-Cement (ASTM D 2901) or Lime Content in Lime-Treated Soils (AASHTO T 232)
- In-place Density (AASHTO T 238, AASHTO T 205, or AASHTO T 191)
- Unconfined Compressive Strength: 7- and 28-day (AASHTO T 22)
- Depth of Mixing for Mix-in-Place Methods (visual)

Post-Construction Maintenance/Evaluation

Post-construction evaluation generally concerns cracks and leachate. Surface cracks may be fatigue cracks from traffic loads or reflection cracks from cracking of the base course. Cracks should be repaired to prevent water from entering the base course and accelerating pavement failure. They can be monitored by visual inspections throughout the life of the pavement.

Load-deflection of a pavement can be monitored with Dynaflect or Benkelman beam tests, a falling weight deflectometer or a multi-depth deflectometer.

Environmental Considerations

Minimal leachate generation would be expected from a properly designed by-product pavement base course for the following reasons:

- The wearing surface will be relatively impermeable and limit the amount of infiltration into the base course. In addition, crowning the surface will assist in channeling the water off the road and into the adjacent drainage ditches.

- Proper road design precludes groundwater from coming in contact with the pavement system. Therefore, no source of water should be in contact with the base course from below.

- Drainage ditches should channel runoff away from the pavement, and thus will not provide a source for lateral seepage into the base course.

Case Histories

Several ASC by-product base course projects are summarized below.

Sherburne County Plant Haul Road [5,6]

A test road to demonstrate various uses of a spray dryer by-product was constructed at Northern States Power's Sherburne Plant in Minnesota. The pavement layers consisted of (top to bottom), the pavement, base, subbase, and embankment. In the various test sections, spray dryer by-product was used in asphaltic and Portland cement pavement, subbase, and embankment layers (see Figures 5-14 and 5-15). Construction took place from September 26 through October 10, 1991. No spray dryer by-product was used in the base layer, which consisted of 14 cm (5½ inches) of Class 5 gravel. Additional discussion of this project is presented in Section 5, "Structural Fills."

In three of the test sections, by-product was mixed with granular layers for a subbase beneath the pavement. The subbase consists of a 60 cm (2-foot) layer of a granular mix incorporating 20% by-product. Above the granular subbase layer is a select granular layer incorporating 12% by weight spray-dryer by-product.

The unamended granular material met or exceeded Minnesota Department of Transportation (Mn/DOT) Specifications Section 3149.2A. The subbase data is presented on Table 2-l.

Table 2-1
Subbase Data for Sherburne County Plant Haul Road

Material (% by weight)	Field Option Moisture (%)	Field Density (kg/m^3)	7-Day Compression Strength (kPa)	28-Day Compression Strength (kPa)	Hydraulic Conductivity (cm/sec)
12% Spray Dryer By-Product in Select Granular Subbase	8.9	1830	1780	7610	—
20% Spray Dryer By-Product in Granular Subbase	9.6	1830	3740	11120	$2.8x10^{-9}$

(SOURCE: Radian Corporation, *Year-End Summary Report for EPRI's Demonstration Road at Northern States Power Company's Sherburne County Power Plant in Becker, Minnesota,* Revised Draft, Vol. 1, May 8, 1992.)

Trace element concentrations of all extracts of spray dryer mixtures were far below the limits that would classify these materials as hazardous according to TCLP toxicity. For a mixture consisting of 15% spray dryer by-product and 85% granular (2A) aggregate, elemental concentrations were compared to Minnesota Pollution Control Authority (MPCA) Drinking Water Limits using EPA Method 1312. MPCA proposed drinking water limits were exceeded for only barium, in only one of two duplicate tests.

The road has been in use since construction. Performance has been satisfactory and no maintenance has been required.

EPRI Laboratory Study [4]

A laboratory study was performed as part of EPRI Project 2708 to test AFBC, spray dryer, furnace injection, sodium injection and calcium injection by-products in various applications. A series of tests on stabilized road base were included in these tests. Two mixtures were tested. One mixture consisted of 90% gravel, 7% by-product and 3% lime, the other of 90% gravel and 10% by-product. Test results are presented on Table 2-2. Results vary widely depending on the specific by-product tested. Note that while spray dryer ash HS05 had significantly higher strengths when mixed with lime, lime did not increase the strength of furnace injection OL03. This illustrates both the need for source-specific testing and the fact that significant strengths can be achieved with some ASC by-products.

AFBC Residue Road Base[3]

Minnick studied the development of potential uses of AFBC by-products from 1976 to 1982. Mixing AFBC SBM, sand and Class F fly ash, he developed mixtures which fulfilled the following requirements:

- Compressive strength - 2760 kPa (400 psi) at 7 days
- Durability - 14% weight loss
- Expansion - Restricted between 0.1 to 0 5%.

Laboratory evaluations found that at least 6% AFBC SBM was needed to achieve 2760 kPa (400 psi) at 7 days. At this proportion, durability was excellent (weight losses less than 5% after 9 freeze-thaw cycles). AFBC by-product in excess of 9% , however, resulted in excessive expansion. Strength data for mixtures with less than 10% AFBC by-product are presented on Table 2-3. Dimensional stability data for mixtures using 6%, 10%, and 12% AFBC SBM are presented on Table 2-4.

Minnick recommends complete hydration of the by-product prior to mixing with other components of the road base. To hydrate the by-product, dry AFBC SBM was mixed with water, discharged, and cured outdoors for 10 days. The cured by-product was passed through the mixer to break up agglomerates or lumps.

Compaction of the AFBC SBM mixture road base was best accomplished using a 10-ton vibratory roller with lift thickness not exceeding 15 cm (6 inches). Some pneumatic tired and vibratory walk-behind rollers also produced satisfactory results. For thicker layers, the material should be scarified and placed in multiple lifts.

Minnick recommends moisture contents within 2% of the laboratory optimum moisture content, and dry densities at least 95% of maximum of ASTM C 593.

AFBC Stabilized Road Base[7]

In combination with conventional fly ash, AFBC SBM was used in laboratory and field studies as a stabilizing agent in road base, subbase, and shoulder applications. SBM was first hydrated with 30% water, then allowed to reach equilibrium before blending with other mixture components. Laboratory samples were molded at maximum dry density and optimum moisture content. Significant compressive strength development was observed in the laboratory samples.

Table 2-2
Stabilized Road Base - Laboratory Evaluation of Various ASC By-Products

					Compressive Strength (kPa)[c]					
	By-Product	Optimum Moisture Content (%)			Mixture (with lime)[a]			Mixture (without lime)[b]		
Sample No.	CaO (%)	By-Product	Mixture (with lime)[a]	Mixture (without lime)[b]	Vac-Sat	4-Hr Soak	28 Day	Vac-Sat	4-Hr Soak	28 Day
AFBC:										
TV03 (bed)	45.1	32	NA	8.6	NA	NA	NA	2400	1740	2260
TV05 (ash)	22.6	50	9.0	9.1	6170	6770	10830	5210	5350	7230
SF06 (comp.)	39.1	39	NA	9.6	NA	NA	NA	**	**	370
Spray Dryer:										
LR07	26.9	28	8.7	NA	1150	1460	3390	NA	NA	NA
HS05	20.0	24	7.8	6.4	2080	2400	4900	540	530	1570
Furnace Injection:										
OL03	36.1	42	8.2	8.7	1160	1430	4530	3760	2970	4760
OL08	16.8	38	NA	8.0	NA	NA	NA	2930	3590	2860
Calcium Injection:										
AA10-02	14.0	NA	NA	10.0	NA	NA	NA	190	**	730
Sodium Injection:										
NX04	4.5	20	7.2	NA	1210	1360	4700	NA	NA	NA

Notes:

NA - Not Analyzed
** - Cylinders disintegrated
a - Mixtures consisted on 90% gravel, 7% by-product, and 3% lime
b - Mixtures consisted of 90% gravel and 10% by-product
c - Average of three samples, ASTM C 593

(SOURCE: *Advanced* SO_2 *Control By-Product Utilization: Laboratory Evaluation*, CS-6053, September 1988.)

Table 2-3
Compressive Strength of Road Base Mixes with Less than 10% AFBC Residue

Mix Formula (% by Weight)					
Sand Aggregate	AFB Residue [a]	Pulverized Coal Fly Ash [b]	Dry Density (kg/m^3)	Compressive Strength[d] (kPa) 7 Day	28 Day
69	9	22	1880	5480	14680
69	6	25	1880	4680	7040
69	3	28	1870	2190	3080

[a] Georgetown University bed residue

[b] National Minerals fly ash

[c] Each density is the average of 12 samples

[d] Each strength is the average of 2 samples

Notes:

Test specimens were Proctor size (10 cm diameter x 12 cm high), prepared in accordance with ASTM C 593 and cured at 23°C (73°F). Specimens were soaked for
4 hours prior to testing.

Amounts of residue in excess of 9% were not included due to excessive expansion in such mixtures.

(SOURCE: L. John Minnick, *Development of Potential Uses for the Residue from Fluidized Bed Combustion Processes*, Department of Energy, December 1982.)

In October 1978, approximately 160 tons of experimental road base material containing SBM was placed to a depth of 15 cm (6 inches) on 58 m (190 feet) of a two-lane highway reconstruction of State Route 149 in eastern Ohio. Three different mixtures were used, with AFBC comprising 15 to 30% of the mix. The mix proportions, quantities, and laboratory strength development characteristics of these mixes are listed in Table 2-5. The mixture preparation included premixing the SBM with aggregate and water in a pugmill mixer several weeks before placement. The stockpiled material blends were then mixed with optimum proportions of fly ash and water on the day the products were shipped to the job site. During mixing, an excess of moisture was added to Mix A due to the moisture control device not functioning properly. Several weeks after placement of these base materials, Mix A began showing signs of linear expansion. The reason for the expansion may be insufficient hydration during initial mixing and the excessive moisture in a compacted state, which allowed additional hydration, and accompanying volume changes occurred.

Table 2-4
Dimensional Stability of AFBC Road Base[a]

		Standing in 6 mm Water				Totally Submerged			
		Height		Diameter		Height		Diameter	
Source of Aggregate[b]	Mixture Proportions[c]	7 Day	28 Day	7 Day	28 Day	7 Day	28 Day	7 Day	28 Day
Dilles Bottom	60/12/28	1.82	2.68	1.56	2.19	3.00	5.80	2.60	5.06
	70/10/20	1.14	3.23	1.16	3.11	0.98	3.18	0.78	2.86
	80/06/14	0.79	2.16	0.53	1.92	1.05	2.22	0.60	1.78
Canton	60/12/28	1.76	2.17	1.29	1.97	1.03	1.94	1.06	1.83
	70/10/20	1.15	1.94	0.52	1.21	0.71	1.18	0.55	1.20
	80/06/14	0.95	1.95	0.77	1.76	0.83	1.79	0.87	1.87
Columbus	60/12/28	1.49	2.22	1.25	1.94	1.58	2.46	1.33	2.18
	70/10/20	1.29	2.12	0.95	1.59	1.22	2.33	0.87	1.45
	80/06/14	0.69	1.88	0.52	1.84	0.37	1.10	0.27	0.94

Notes:

[a] Percent change in height and diameter at 28 days of 12 cm high x 10 cm diameter specimens stored at 23 °C (73 °F).

[b] Canton and Dilles Bottom are siliceous gravels; Columbus aggregate is a limestone; AFB residue is from Alliance, Ohio; pulverized coal fly ash s from Ohio Edison Company, Ashtabula, Ohio.

[c] Aggregate / AFB residue / pulverized coal fly ash.

(SOURCE: L. John Minnick, *Development of Potential Uses for the Residue from Fluidized Bed Combustion Processes*, Department of Energy, December 1982.)

Further field tests were conducted during the fall of 1979. SBM materials were preconditioned. The conditioning process involved adding 25% to 32% water to SBM, thoroughly mixing for several minutes, discharging the SBM onto a stockpile, and then recrushing several weeks later. Several larger size test pads were placed in the field. Dimensional stability measurements showed that length changes slow down after 6 to 9 months.

Summary

ASC by-products have been used in only a few road base demonstration projects. The design procedure is similar to the procedure used to design stabilized fly ash road base, which involves design of the base course mix and determination of the thickness of each layer of the pavement system. An additional consideration with SO_2 by-products is the possibility of long-term expansion.

Initial laboratory tests are performed on by-product samples to provide data on the basic physical, chemical, and engineering behavior of the by-product. After the trial mix is selected, it is necessary to determine the maximum dry density and optimum moisture content of the mixture so that 7-day unconfined compression testing can be performed. If any trial mix fails to achieve the required strength, a new mix must be selected and tested accordingly until a mix satisfies the strength criterion. The trial mix is then tested for 28-day unconfined compression strength. If there is no increase in strength, a new trial mix should be selected and tested until all criteria are met. Long-term expansion should be tested to check dimensional stability of a by-product road base. Road base thickness design can follow the same procedures for cement or fly ash stabilized road base.

The construction procedure should consider material handling, transport and storage, mixing and placement, compaction, and finishing. It may be necessary to precondition the by-product in order to control dusting or time of setting for very reactive by-products. Materials should be mixed, placed, spread, and compacted with minimal time delays to achieve full strength development. At the end and edges of each day’s construction, the joints should be formed to control reflective cracking. If the wearing surface is not constructed immediately, a sealant or curing material should be applied to protect and cure the base course. It is desirable to conduct environmental, construction, and performance monitoring at the site.

Table 2-5
Mix Proportions, Laboratory Tests, and Quantities of AFBC SBM Used in Ohio Road Base Demonstration

		Demonstration Statistics		Laboratory Tests			
				Compressive Strength, kPa		Durability[a]	
Mix	**Composition % by Weight**	**Average Length of Section, m**	**Amount Placed tons**	**7 days @ 22.8°C**	**7 days @ 22.8°C**	**Vacuum Saturation,[b] kPa**	**Freeze/ Thaw,[c] % loss**
A	40% aggregate [d] 30% Alliance AFBC residue 30% fly ash	15.24	40	6020	10880	8680	0.41
B	75% aggregate [d] 15% Alliance AFBC residue 10% fly ash	22.86	60	5780	8630	10230	0.60
C	75% aggregate [d] 15% Battelle AFBC residue 10% fly ash	20.1	60	1530	6120	5410	0.62

Notes:

[a] Average of three individual values.

[b] Tested in accordance with ASTM C 593-76a.

[c] Tested in accordance with ASTM Freezing-and-Thawing Tests of Compacted Soil-Cement Mixtures (D 560-57).

[d] Canton gravel meeting ODOT 301 specifications.

(SOURCE: R. J. Collins, *Aggregate-Related Applications for Residues from Fluidized Bed Combustion Boilers*, ASTM Publication Code No. (PCN) 04-774000-08.)

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3

SOIL STABILIZATION

Overview

This section discusses using advanced SO_2 control (ASC) by-products for soil stabilization. ASC by-products are rich in calcium, alumina, silica and iron, similar to the chemical composition of lime/cement-fly ash mixtures. This suggests that these by-products may have value as agents for soil stabilization.

Soil stabilization can be defined as a means of permanently altering soil to increase its strength and bearing capacity, and decrease its water sensitivity and volume change potential[1]. Stabilized soil can be used in the construction of roadways, parking areas, foundations for pavement, embankments, and other structural applications. Soil stabilization can eliminate the need for expensive borrow materials, expedite construction by improving wet or unstable soil, or allow a reduction pavement thicknesses by improving subgrade conditions[2].

Cement and lime are the most effective stabilizers for a wide range of soils. Fly ash has also been used to stabilize soils in recent years. Since many fly ashes are low in CaO content, lime or cement is commonly added. The resulting mixtures have been found to be serviceable as subgrade in highway construction.

There are two types of soil stabilization:

- Physical stabilization
- Chemical stabilization

The primary method of physical stabilization is compaction. However, compaction alone is sometimes not enough to provide soil stability, especially for fine-grained cohesive soils.

Chemical stabilization traditionally uses lime or cement as the stabilizer. Lime-fly ash and cement-fly ash mixtures were developed as stabilizers in the past decade. Class F fly ash requires the addition of cement or lime because it is not self-hardening. Class C fly ash is usually used alone as stabilizer. However, if its free lime content is low, the Class C fly ash may need to be combined with small quantities of lime or cement[2].

Chemical stabilization provides the following benefits:

- Reduction of plasticity characteristics

- Strength development

When the stabilizer is mixed with moist, plastic soils, a hydration reaction occurs in which calcium ions are released. As a result, cation exchange and flocculation-agglomeration occurs which reduces the moisture content and improves the plasticity characteristics of the amended soil.

The long-term strength of stabilized soils may increase due to pozzolanic reactions[3]. In cement-stabilized soil, the hydration of the different cement constituents occurs at different rates, providing cementitious hydration products responsible for the early and long-term strength gains. In lime-stabilized soil, the pozzolanic reaction depends on the cooperative reaction between the lime and the soil. Many soils contain silica, alumina and iron, which will react with lime and develop long-term strength. Usually, cement stabilization is used for coarse-grained soils, such as sands, silty or clayey sands, and gravels; lime stabilization is used for fine-grained soils such as silts or clays[3].

During the past decade, both Class C and Class F fly ashes have been successfully used with or without lime or cement in soil stabilization[2]. Many Class C fly ashes are cementitious and have been used without the addition of lime or cement for stabilizing various types of soil. The hydration of Class C fly ash behaves more like cement than lime because most of the calcium in Class C fly ash is in a combined form with silicate and aluminate with very little in a free oxide form. Therefore, the Class C fly ash is more suited for stabilizing coarse-grained soils.

Class F fly ash is often pozzolanic. Because of its low calcium oxide content, Class F fly ash is used as a stabilizer agent. For stabilizing coarse-grained soils, Class F fly ash is used with cement to improve the strength. In the stabilization of fine-grained soils, Class F fly ash is used with lime to improve the properties of expansive clay and other fine-grained soils. The lime-fly ash mixtures are also used to stabilize arid or semi-arid soils, to raise the pH, and to modify the inherent properties of the soil.

Because of the low cost of fly ash and its excellent pozzolanic properties, there are many cases in which the addition of fly ash to a stabilizer is more advantageous than using only the stabilizer[2]. Depending on the soil type, added fly ash may increase strength and improve durability at a lower cost than lime or cement stabilizer alone. When the fly ash has a high free lime content, soil stabilization can be performed with fly ash alone.

The use of ASC by-products in soil stabilization is similar in many respects to the use of Class C fly ash or lime/cement-fly ash as stabilizers, since the main compositions of

ASC by-products are fly ash, calcium sulfate / sulfite, and unreacted lime. With the exception of sodium sorbent injection by-product, ASC by-products have a high calcium content which may lead to the self-cementing characteristics similar to most of the Class C fly ash. The presence of unreacted lime in the by-products helps the moisture reduction, plasticity modification, and pH adjustment of soils. In addition, the calcium components will react with siliceous and aluminous components in the fly ash to induce a cementing action and develop long term strength gains due to the pozzolanic reaction.

Another important component of ASC by-products is calcium sulfate / sulfite. The presence of sulfate / sulfite may contribute to moderate strength gains in soil stabilization due to the beneficial formation of ettringite. Ettringite formation is created by the reaction of $CaSO_4$ with Al_2O_3, and SiO_2. The contribution of ettringite to the development of strength, particularly in soil with a high moisture content, is mainly for the following reasons: each ettringite crystal combines with a large number of water molecules, causing a significant decrease in moisture content, leading to an increase in the dry density of stabilized soil.

This section presents the details associated with design and construction of stabilized soil using ASC by-products, as well as environmental considerations. The design procedures presented below are directed towards achieving a degree of stabilization acceptable for subgrade materials.

State of Practice

Ohio State University conducted a series of laboratory scale studies and field demonstrations on the engineering properties of soil stabilized with ASC by-products[4-10]. The tests included compressive strength, permeability, swelling potential, compressibility, and leachate. Furnace sorbent injection by-product and spray dryer by-product were used. The laboratory test results showed high strength, low compressibility and low permeability. Swelling potential was found, although it appears that preconditioning or aging ASC by-product prior to use may reduce the effective swell. The concentration of heavy metal contaminants in the leachates were consistently below EPA criteria. Field demonstrations were conducted at an Ohio State University research farm where both PFBC ash and wet FGD sludge were used to stabilize the soil base in cattle feedlots.

Another laboratory scale test was performed by ICF Northwest under an EPRI research program to evaluate the suitability of ASC by-products for soil stabilization[11]. Mixtures of 90% soil, 7% ASC by-product, and 3% lime achieved 28 day compressive strengths between 2760 and 8970 kPa (400 and 1300 psi). Mixtures of 90% soil, 10% ASC by-product, and no lime achieved 28-day compressive strengths between 1170 and 3310 kPa (170 and 480 psi).

A demonstration project using AFBC by-product for a highway subgrade modification was conducted by the University of Kentucky Transportation Center[12]. Two experimental sections of subgrade soils modified with AFBC by-product were constructed in Kentucky. A laboratory study was carried out prior to site construction. The laboratory tests included liquid and plastic limits, specific gravities, particle-size analyses, soil classifications, visual descriptions, moisture contents, moisture-density relations, CBR tests, swell tests, unconfined compressive strength tests, and pH values. About two months after stabilization, non-uniform heave occurred in the asphaltic base course. The pavement was milled and the final surface was placed about nine months after construction. The pavement performed reasonably well over the following 5 years.

Design Procedure

Conceptual Design

Soil stabilization can improve the properties of an unsuitable soil by reducing the moisture content, decreasing the plasticity index, increasing the shear strength, and improving the durability of the soil. Typically, soil is stabilized to serve as subgrade or subbase material in highway construction.

The lime and fly ash compositions of ASC by-product are indicators of potential suitability for soil stabilization. The lime will flocculate clay minerals and reduce soil plasticity. In addition, the lime will react with the siliceous and aluminous compounds in the fly ash to form cementitious materials and develop long-term strength.

At present, there is no standard specification for ASC by-product used as soil stabilization material. However, there are apparent similarities between ASC by-product:soil mixture and lime/cement-fly ash-soil mixtures, which make it reasonable to assume that similar design criteria could be adopted for selecting suitable ASC by-product:soil mixtures.

The basic design criteria for stabilized soils are unconfined compressive strength and durability. Durability refers to a material's ability to resist damage caused by freeze-thaw and wet-dry cycles.

The American Society for Testing and Materials has developed a specification for the use of lime-fly ash-soil mixtures[2]. The specification (ASTM C 593) establishes minimum unconfined compressive strength and durability requirements. The unconfined compressive strength criterion of 2760 kPa (400 psi) in 7 days under accelerated curing conditions has proven to be quite acceptable, except that recommendations have been made for reducing this requirement to as low as 690 kPa (100 psi) for subbase applications[2]. The accelerated curing at 38°C (100°F) produces a 7-day approximation of the 28 day strength of a mixture under ambient conditions when there is not enough time available to run the 28-day test. The specimen-molding and strength-testing procedures of this specification can be used for ASC by-product:soil mixtures, but curing should take place at 21°C (70°F), rather than 38°C (100°F).

ASTM C 593 presents vacuum saturation testing as a measure of freeze-thaw durability. Basically, a sample is subjected to a vacuum for a specified period of time, then it is submerged in water and the vacuum is removed, to quickly saturate the sample as fully as practical. The criterion for the strength at the end of the test has been suggested at 2760 kPa (400 psi). [This criterion allows essentially no loss of compressive strength between the start and the end of the durability test, if the material's compressive strength is initially near the 2760 kPa (400 psi) minimum.] An additional requirement of a maximum 10 percent strength loss due to vacuum-saturation may also be advisable[2].

An important difference between ASC by-product: soil mixtures and lime/cement-fly ash-soil mixtures is the existence of sulfate/sulfite components in the ASC by-products. The sulfate/sulfite components join the chemical reaction and form ettringite, which may increase strength, but may also cause unexpected expansion. The expansion problem has been previously observed when using lime to stabilize high sulfate content soil[2]. This reaction usually occurs slowly and may not become apparent until six months to two years or more after construction. Since the ASC by-products contain high sulfate/sulfite and abundant aluminum contents, dimensional stability should be one of the durability criteria.

The above strength and durability criteria are directed toward soil stabilization with emphasis on its use in highway construction. ASC by-products can also be used for soil modification to improve the characteristics of wet muddy sites to expedite construction. Strength and durability criteria are not normally applied to this use as they are in highway use[2]. An evaluation of the effectiveness of stabilizers can be done simply by monitoring the improvement in the soil characteristics or properties of concern as the amount of stabilizer is varied. Also, when using ASC by-products for any soil modification, the dimensional stability must be checked.

The cost of subgrade modification is offset by increased pavement serviceability, decreased pavement thickness, or savings in construction time.

Specifications for soil stabilization are typically available in the state department of transportation standard specifications. Since the use of ASC by-product for soil stabilization is not a well-established practice, specifications for lime-fly ash or fly ash treatment of soils in-place can be used as guidelines.

Design Input Parameters

The materials, mixture proportions, construction methods and environmental conditions all have an influence on the properties of stabilized soil. Knowledge of these influence factors is basic to an understanding of the behavior of stabilized soil. In order to satisfy the strength and durability criteria of an ASC by-product:soil mixture, five major parameters should be considered:

- The nature of soil
- The type and properties of ASC by-product
- The proportion of ASC by-product to soil
- The moisture-density relationship of ASC by-product:soil mixture
- Curing condition and curing age

The Nature of Soil. Factors are present in soils that prevent uniform reaction with ASC by-product, thereby adversely affecting the strength and durability of stabilized soil. These contributing factors include: type of soil; physical and chemical composition; grain-size distribution; response to water; and workability[3].

The influence of the nature of the soil is indicated by the range of by-product requirements. Clays containing montmorillonite minerals react readily with lime, with the effect of immediate reduction in plasticity and gradual pozzolanic strength development. Clays containing illite, chlorite, vermiculite, or kaolinite may be slightly pozzolanic in themselves. Silty soils with less than 10 or 12 percent clay may be somewhat pozzolanic, depending upon mineral composition[2].

Properties of ASC By-Products. With the exception of sodium injection by-product, all other ASC by-products have potential for use as a soil stabilizer. The lime content, fly ash content, and sulfate/sulfite content are the major factors for evaluating their suitability for use as stabilizers. If there is insufficient lime in the by-product, cement or lime may be added.

The Proportion of ASC By-Product to Soil. In general, for stabilizing granular soils the amount of ASC by-product can be selected on the basis of maximum dry density of the mixture. For stabilizing fine-grained soils there appears to be no optimum amount of stabilizer; the strength of the stabilized soil increases as the total amount of stabilizer is increased[2]. The selection of a total stabilizer percentage is then based on economic considerations. However, as discussed in Section 2, “Road Base,” high compressive strength may result in problems with pavement performance due to reflective cracking. A ten percent mixture of ASC by-product will typically achieve a compressive strength exceeding 690 kPa (100 psi)[11].

The Moisture-Density Relationship of ASC By-Product Soil Mixture. The moisture content at the time of compaction has a strong influence on the properties of stabilized soi1[3]. The influence of moisture is related to its ability to improve workability and to provide adequate water requirements for ASC by-product hydration.

The strength and durability of stabilized soil are also strongly influenced by density[3]. In general, the compressive strength of an ASC by-product:soil mixture increases with increasing density to a point near the maximum dry density.

Experiments have shown that, for most lime/cement-fly ash-soil mixtures, maximum compressive strength is obtained at a moisture content slightly less than the optimum moisture content required for maximum dry density[2]. In the case of soils containing montmorillonite clay, the moisture content required for maximum compressive strength is slightly *greater* than the optimum moisture content for maximum dry density. Generally, however, the difference between the two moisture contents is not great, and since the optimum moisture content for maximum density is more easily determined, the optimum moisture content is usually used in the laboratory testing program for determining mixture design. As excess mix water can result in increased cracking, a moisture content slightly below the optimum moisture content is recommended.

Curing Condition and Curing Age. Strength development of stabilized soil is greatly dependent on curing conditions. As documented, the lime-fly ash-soil mixture develops strength more slowly than cement-fly ash-soil mixture[2]. The rate of strength development of ASC by-product:stabilized soil is dependent upon the source of material. For mixtures with slow strength development, construction is better done during the warm months. Portland cement can also be added to improve the early strength development.

As with any pozzolanic reaction, the cementation of an ASC by-product:soil mixture will proceed more rapidly at higher temperatures. Warmer temperatures may also reactivate the pozzolanic reaction after a period of cold weather. Ultimately, the reaction will proceed until the chemical compounds participating in the reaction are depleted.

Laboratory Testing

Laboratory tests are needed to provide information on the nature of soil, the properties of ASC by-products, the proper mixture proportions and to determine whether any ASC by-product mixture is beneficial. Several tests are listed on Table 3-l. The laboratory test program should include:

- Soil classification
- Chemical analysis of ASC by-product

- Trial mixture selection
- Moisture-density relationship
- Compressive strength
- Freeze-thaw durability
- Dimensional stability

Soil Classification. The soil class determined by the Unified Soil Classification System (USCS) is based on the particle size distribution (ASTM D 422) and liquid and plastic limits (ASTM D 4318). Specific gravity (ASTM D 854) and moisture content (ASTM D 2216) are also recommended to determine general soil properties.

Chemical Analysis of ASC By-Product. ASTM C 311 can be used to determine the chemical composition of ASC by-products, especially the lime content, fly ash percentage, and sulfate/sulfite content.

Trial Mixture Selection. For trial mixtures, the ASC by-product content can be varied from 5 to 15% , with the soil content from 85 to 95%. If cement/lime addition is necessary, there will be three variable components in the mixtures. A suggested approach is to prepare trial mixtures with a fixed soil content and varying ratios of ASC by-product to cement/lime. The trial mixtures are then prepared and tested for strength. From the data, the strength-stabilizer relationship can be established and a range of satisfactory mixtures selected for further testing and economic comparison.

Moisture-Density Relationship. Moisture-density relationship can be is determined in accordance with ASTM D 558; Standard Proctor (ASTM D 698 or AASHTO T 99); or Modified Proctor (ASTM D 1557 or AASHTO T 180). The moisture-density test is performed on untreated soil and trial ASC by-product:soil mixtures. The purpose of this test is to study variation in the optimum water content and maximum dry density of the by-product:soil mixture as the percentage of by-product is increased. The values from the moisture-density test are used to determine the moisture content that will provide adequate compaction in the field.

Table 3-1
Tests for Soil Stabilization with ASC By-Products

ASTM Test No.	Test
C311	Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete
C593	Specification for Fly Ash and Other Pozzolans for Use with Lime
D558	Test Method for Moisture-Density Relations of Soil-Cement Mixtures
D559	Test Method for Wetting and Drying Compacted Soil-Cement Mixtures
D560	Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures
D1633	Test Method for Compressive Strength of Molded Soil-Cement Cylinders
D3668	Test Method for Bearing Ratio of Laboratory Compacted Soil-Lime Mixtures
D3877	Test Methods for One-Dimensional Expansion, Shrinkage and Uplift Pressures of Soil-Lime Mixtures
D4546	Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils
D4609	Guide for Evaluating Effectiveness of Chemicals for Soil Stabilization
D5102	Test Method for Unconfined Compressive Strength of Compacted Soil-Lime Mixtures

(SOURCE: 1996 Annual Book of ASTM Standards, Vols. 04.01, 04.02, 04.08, and 04.09.)

The optimum moisture content is determined by preparing ASC by-product:soil mixtures with varying amounts of water. These mixtures are compacted using a standard ASTM or AASHTO procedures, and the compacted density is determined. Dry densities of the stabilized samples are plotted as a function of moisture content to produce a curve. The moisture content corresponding to the peak of the curve is called the “optimum moisture content,” while the density corresponding to the peak is called the “maximum dry density.” If mixtures are too wet or too dry, it is difficult to achieve proper compaction. Field compaction requirements usually specified as a percent or maximum density and variation from the optimum moisture content, for example: 95% maximum dry density at the optimum moisture content ±1%

Compressive Strength. The unconfined compressive strength is determined in accordance with the methods outlined in ASTM C 593. The unconfined compressive strength is used to establish the most effective percentage of ASC by-product. Samples should be prepared using the moisture content and density requirements determined in the previous step.

Prior to testing, samples should be cured for a 28-day period at 21 ± 2ºC (70 ± 3ºF) and 100% relative humidity[2]. ASTM C 593 specifies curing lime-fly ash-soil mixtures at 38°C (100°F) for 7 days as an approximation of a 28-day cure at 21°C (70°F), and a similar approximation can be made for mixtures containing ASC by-products.

Freeze-Thaw Durability. Freeze-thaw test specimens should be molded and cured in the same manner as compressive strength test specimens. The vacuum saturation method described in ASTM C 593 is recommended for freeze-thaw testing.

Dimensional stability. Since ASC by-products contain sulfate / sulfite, there is a potential for expansion / swelling which would cause the subgrade to become unstable. Linear expansion is determined by measurement of linear change with the curing age. The swelling test can be conducted in accordance with ASTM D 4546.

Detailed Design

Thickness Design. Thickness design methods have not yet been developed specifically for ASC by-product: soil mixtures. In the case where the natural soil is granular, the addition of a by-product would make it possible to consider the stabilized soil as a subbase or base course and thus, to reduce the minimum thickness of the base course to be constructed on the improved subgrade. Where the purpose of stabilization is to improve the subgrade, no reduction of the minimum thickness is recommended. Table 3-2 lists the minimum thicknesses recommended for lime / cement-fly ash-soil and fly ash-soil mixtures. This table may provide guidance for ASC by-product:soil mixtures.

Table 3-2
Recommended Minimum Thickness for Lime/Cement-Fly Ash-Soil and Fly Ash-Soil Mixtures

Application	Recommended Minimum Thickness cm (inches)
Base Course	15 (6)
Subbase Course	10 (4)
Subgrade Modification	10 (4)

(SOURCE: GAI Consultants, Inc. *Fly Ash Design Manual for road and Site Applications, Volume 1: Dry or Conditioned Placement*. April 1992.)

Construction Details

Both mix-in-place methods and stationary plant methods are used in soil stabilization construction[3]. Since most soils are stabilized or modified in-situ, the construction procedures described below are based on the mix-in-place methods. The construction steps involved in soil stabilization and soil modification are similar, differing only in minor detail. Soil stabilization requires more thorough processing and job control than soil modification. Quality control of stabilized soil begins with quality control of the raw materials. It is then necessary to control the proportions of ASC by-product and soil; and finally, the mixing, compacting, surfacing and curing operations. Basic construction steps include:

- Determination of the soil condition
- Scarification and pulverization
- ASC by-product spreading
- Mixing
- Compaction
- Finishing
- Curing
- Surfacing

Determination of the Condition of the Soil

The field moisture content and density of the soil should be determined and compared to design conditions and construction requirements.

Scarification and Pulverization

The soil should be scarified to the specified depth and width of stabilization and then partially pulverized.

ASC By-Product Spreading

ASC by-product should be uniformly spread at the specified rate. Dry by-product may be a dusting problem. Placement of dry material from a pneumatic tanker truck can be performed using a “spray” bar across the back of the truck, with a cloth shroud to minimize dusting. Dry material should not be spread under windy conditions.

If lime/cement is included in the design, the lime/cement and ASC by-product may be spread separately or be preblended. Preblended stabilizer is also stored and placed dry. When the lime content in ASC by-product is low, it may be conditioned first. Conditioned ASC by-product can be dumped from trucks and spread with a grader or a spreader box.

Mixing

ASC by-product and soil must be thoroughly blended. Mixing-in-place is done with heavy-duty rotary mixers or similar equipment. During this step, water is often added to raise the moisture of ASC by-product:soil mixture to optimum moisture content. The optimum moisture content from the laboratory moisture-density relationship test is used as a basis for the determination of water requirement. The percentage of water required is the difference between the optimum moisture content and the moisture content of the raw soil plus ASC by-product.

The moisture content at the time of compaction is one of the most significant criteria for compaction control. Therefore, field moisture contents must be determined frequently.

The uniformity of mixing of ASC by-product, soil and water can be determined by visual inspection of a uniform color to the full depth and width of mixing.

Compaction

At the completion of mixing, the ASC by-product:soil mixtures should be immediately compacted to the specified density. Field in-place density tests must be performed to confirm that the required density is being achieved.

ASC by-product:soil mixtures involving coarse-grained soils can be compacted with vibratory rollers. ASC by-product:soil mixtures incorporating cohesive soils are best compacted with pneumatic-tired or sheepsfoot rollers[2].

Compaction of some stabilized soils may result in the formation of horizontal shear planes, resulting in a thin, platey structure in the upper part of the compacted layer. These compaction planes should be removed by light scarification with a spike-toothed harrow, weeder, or nail drag, and the loosened material then moistened and recompacted with a pneumatic-tired roller[2].

Finishing

The finishing operations control the nature of the surface and may have influence on other performance characteristics of the stabilized base. The best procedure depends on the equipment and the soil characteristics. Inspection should be aimed at obtaining a smooth, dense, moist surface that is free of cracks, ridges and compaction planes.

Curing

The compacted ASC by-product:soil mixture should be cured prior to loading in order to achieve the maximum strength gain. The period of curing should be based on a comparison of laboratory test results to design requirements. Either type of curing may be used: 1) moist curing, which involves maintaining the surface in a moist condition by light sprinkling and rolling when necessary, or 2) membrane curing, which consists of sealing the compacted layer with a bituminous prime coat.

Surfacing

Road bases and subgrades stabilized with ASC by-products should be surfaced with a wearing course determined by traffic and serviceability requirements. The types of surfacing can range from bituminous binder and seal coat to plant mix asphaltic concrete. A double bituminous surface treatment, usually 1.9-cm (¾ -inch) thick, is common for light duty roads. In areas of higher traffic volumes, wearing surfaces should be increased in thickness. Plant-mix asphaltic concrete 3.8-7.6 cm (1½ to 3 inches) in thickness is often used[2]. In areas where the pavement is subjected to freeze-thaw cycles, thicker surfacings can reduce the number of freeze-thaw cycles to which a stabilized soil base or subbase will be subjected.

Environmental Considerations

During construction, attention to problems such as dust control, noise, traffic and similar factors are the same as for any similar roadway construction project. Provisions should be made to prevent dusting during delivery and placement of the by-product, such as special enclosed trucks with bottom unloading facilities.

Case Histories

Laboratory Testing and Field Demonstrations, Ohio State University[4-10]

A laboratory program was designed to characterize the engineering properties of a silty clay stabilized using spray dryer and furnace sorbent injection by-products. Tests were conducted to evaluate compressive strength, permeability, swelling potential, compressibility, and leachate composition. These tests were performed on compacted samples of by-product:soil mixtures at the optimum moisture content.

The ASC by-products substantially improved the strength and stiffness of the soil. The strength of the stabilized soil was dependent on the relative proportions of soil to by-product in the mixture. All stabilized soil mixtures developed strength of at least 690 kPa (100 psi) by 28 days. The coefficient of permeability of stabilized soil varied from 4.3×10^{-5} to 9.1×10^{-10} cm / set. Generally, the permeability of stabilized soil decreased with time due to the chemical reaction occurring within the mixture. The swelling potential was determined according to ASTM D 4546. Every sample showed an increase in volume over time. Volume change was due to the formation of ettringite. Ettringite was found in swelled samples using x-ray diffraction techniques. Consolidation test results (ASTM D 2435) showed low compressibility of stabilized soil.

The concentrations of heavy metals in the leachate were quite low compared to EPA standards for drinking water.

In 1993, Ohio State University conducted field demonstration projects using PFBC ash and wet FGD sludge to stabilize a soil base located at the University research farm. The soil had high water and organic material contents resulting in very low strength. Stabilization was accomplished by blending PFBC ash into the top 20 cm of field soil and compacting the mixture. A layer of PFBC ash was then placed as wearing surface. All the field placement and compaction activities were performed using standard farm equipment. Wet FGD sludge, fly ash, and lime were used in two additional projects. The PFBC-soil mixture has performed satisfactorily. Monitoring of the long-term performance, for example the effects of freeze-thaw cycles, will continue.

ICF Northwest Inc. Laboratory Testing [11]

In this test program, the by-products from AFBC, spray dryer, furnace injection, calcium injection, and sodium injection were mixed with A-7 clay soil, with and without additional lime. Soil had a liquid limit of 28.5 and a plastic limit of 24. The mixtures consisted of a) 90% soil, 7% by-product, and 3% lime; b) 90% soil and 10% by-product; and c) control mixture of 90% soil, 7% conventional fly ash, and 3% lime. The compressive strengths were determined. Table 3-3 lists the results of strength testing.

Compressive strengths at 28 days ranged from 1190 to 3300 kPa (173 to 478 psi) for the mixtures without lime and from 4340 to 8920 kPa (630 to 1293 psi) for the mixtures with lime. All of the ASC by-product mixtures with lime achieved higher strength than the control mixture (lime and fly ash).

Table 3-3
Soil Stabilization - Laboratory Evaluation of Various ASC By-Products

	28-Day Compressive Strength, kPa	
ASC By-Product	**Mixture with Lime**	**Mixture without Lime**
AFBC (bed)	NA	2660
(ash)	8920	2970
Spray Dryer	4340	2830
Furnace Injection	7540	3300
Calcium Injection	NA	1190
Sodium Injection	6630	NA
Fly Ash	4120	NA

(SOURCE: ICF Northwest. *Advanced SO_2 Control By-Product Utilization, Laboratory Evaluation*. September 1988.)

University of Kentucky Demonstration Project [12]

AFBC by-product was used to modify two highway soil subgrade sections in Kentucky. In a preliminary laboratory study, the following tests were performed: liquid and plastic limits, specific gravities, particle-size analysis, soil classifications, visual descriptions, moisture con-tents, moisture-density relationships, bearing ratio tests, swell tests, unconfined compression, and pH. The optimum percentage of AFBC by-product was 5% , based on both unconfined compressive strength and pH tests. Two percent were added for use in the field, resulting in a mixture containing 7% AFBC by-product. The unconfined compressive strengths of the remolded specimen with 5% AFBC by-product were about four times greater than the strengths of untreated (unsoaked) remolded specimens.

Field soil stabilization was begun in May 1987. Two sections of subgrade soils, of about 2 miles in total length, were modified. The original pavement consisted of 22 cm (8.5 inches) of asphaltic concrete and 43 cm (17 inches) of dense graded aggregate base. With 30 cm (12 inches) of AFBC by-product:soil subgrade, the thickness of base coarse was reduced from 43 cm to 13 cm (17 inches to 5 inches). Both modified sections included 7% AFBC by-product, but in the second section construction procedures were altered based on difficulties encountered when constructing the first section.

Swell occurred about two months after stabilization. Therefore, both laboratory and field studies on treated soil swell characteristics were conducted. Laboratory swell tests lasted up to 186 days until primary swell was completed. Vertical swell magnitudes as large as 26% were obtained. In the field, primary swell of 9 cm (3.5 inches) occurred within about 9 months after mixing. In August 1988, the AFBC by-product treatment pavement sections were milled to remove portions of the heaved asphaltic surfaces and the final asphaltic surface course was placed. Secondary swell measured was about 0.5 cm (0.2 inches) over a period of about 5 years. Projections of the total secondary swell is about 1.3 cm (0.5 inch) over a period of approximately 26.5 years. The AFBC by-product modified subgrades and pavements performed well for 5 years following the initial swelling.

Summary

Soil stabilization using fly ash, both alone and in conjunction with lime or cement, has increased significantly during the past decade. The ASC by-products, due to physical and chemical similarities to a lime-fly ash mix, have the potential to be used in soil stabilization. Another important composition in ASC by-products is calcium sulfate/sulfite which will react with Al_2O_3, and SiO_2 to form ettringite. The formation of ettringite contributes to the strength development, but may also induce unwanted swelling.

The ASC by-product stabilized soil can be used as subgrade or subbase material. The unconfined compressive strength and durability of material are important criteria for final application. Durability includes the ability to withstand potential damage due to freezing and thawing, and wetting and drying action. The factors considered in the design of ASC by-product soil mixture are:

- Soil classification
- The type and properties of ASC by-product
- The ASC by-product:soil mixture proportions
- The moisture-density relationship of ASC by-product:soil mixture
- Curing conditions and curing age

A laboratory testing program is needed to develop the mix design. The extent of this testing program is dependent upon the size and economics of the project. The laboratory test includes :

- Soil classification
- Chemical analysis of ASC by-product

- Trial mixture selection
- Moisture - density relationship
- Compressive strength
- Freeze-thaw durability
- Dimension stability

Soil stabilization projects typically involve mix-in-place methods. Basic construction steps include:

- Determination of the condition of the soil
- Scarification and pulverization
- ASC by-product spreading
- Mixing
- Compacting
- Finishing
- Curing
- Surfacing

Soil stabilization with ASC by-products has been documented for only a few laboratory and field demonstration projects. These projects indicate which ASC by-products typically increase soil strength, especially when lime is added. The potential for expansion or swelling should be investigated and controlled by testing the by-product:soil mixtures at various proportions, and by exercising appropriate quality controls during construction.

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4

SLUDGE STABILIZATION

Overview

This section describes the use of advanced SO_2 control (ASC) by-products for sludge stabilization. FBC fly ash and spent bed material, furnace sorbent injection by-product, spray dryer by-product, and calcium sorbent injection by-product have potential for use as stabilizing agents for FGD sludge, industrial waste sludge and hazardous waste sludge[1,2]. Liability issues related to sludge or waste stabilization are presented in Section 1.

FGD sludge is produced when coal combustion power plants use various flue gas desulfurization (FGD) processes to reduce sulfur oxide emissions. In FGD processes, lime or limestone slurries are used for scrubbing the exhaust gases. Therefore, FGD sludge consists mainly of different combinations of calcium and sulfur. Two types of FGD sludge, unoxidized FGD sludge and oxidized FGD sludge, are produced. Oxidized FGD sludge is primarily calcium sulfate dihydrate which does not require stabilization. It is a marketable by-product and is often sold for use in wallboard. Unoxidized FGD sludge is largely calcium sulfite hemihydrate. It has less potential for direct reuse. Disposal of FGD sulfite sludge may require stabilization, which is often achieved by using fly ash or fly ash together with lime.

Land disposal of hazardous and non-hazardous industrial waste sludges usually requires some form of stabilization or solidification. Stabilization converts a sludge to a more stable form, and solidification produces a stabilized sludge with high structural strength and low permeability. At present, various combinations of fly ash with cement or lime are used as inorganic binder materials for industrial waste sludges.

The selection of a stabilizing agent depends on the characteristics of the sludge and cost. For FGD sludge and non-hazardous waste sludge, fly ash or fly ash together with lime are frequently used as stabilizing agents. In this case, the silica and aluminum in fly ash react with calcium in lime to form a low-strength solid. Lime may also raise the pH value of the sludge. For hazardous waste sludge, fly ash together with lime or cement can be used as stabilizing agents.

The by-products generated from ASC technologies have some chemical, physical, and engineering properties which are similar to conventional fly ash. The exact composition of a by-product is determined by the injection process, the coal source, and the type of sorbent. But in general, the primary components include fly ash, unspent sorbent (lime, limestone or dolomite), and reaction products (calcium sulfate/sulfite). The high percentage of fly ash in by-products indicates the potential for pozzolanic activity. The unreacted lime or limestone contributes to the self-hardening characteristics of the by-products.

Hydration of the by-product would result in the reduction in the sludge moisture content and produce a strength gain.

Another important reaction is the formation of ettringite and/or thaumasite from the calcium, aluminum, silica, and sulfur in by-products. The ettringite/thaumasite crystal, which is an expansive structure, has the capability to immobilize the trace elements in sludge by causing them to be trapped to the crystal structure. The formation of ettringite/thaumasite crystal also provides strength.

ASC by-products usually have a high lime content, thus, they can be expected to be highly alkaline. The high alkalinity of by-products may result in a reduction in the mobility of many heavy metals[3]. The properties of ASC by-products may provide the necessary chemical and mineralogical environment to promote the chemical stabilization of waste materials. Therefore, ASC by-products may have the potential to chemically stabilize hazardous waste sludge.

Depending upon the sludge characteristics, ASC by-products may also be used as drying agents or provide alkalinity for pH adjustment. Blending ASC by-products with sludge may make a more stable and readily used material than sludges stabilized with conventional fly ash.

Sludge stabilization is similar to soil and road base stabilization in many respects. However, since most sludges generally have a high moisture content and low solids content, the percentage of ASC by-products used in sludge stabilization is considerably higher than that used in soil or road base stabilization.

State of Practice

Several laboratory scale projects have investigated the use of ASC by-products for sludge stabilization. One project performed by ICF Northwest[1, 2] and funded by EPRI evaluated the ability of by-products to stabilize FGD sludge and municipal sludge. The results indicated that sludge stabilization with ASC by-products is technologically feasible.

Another laboratory test performed by the University of North Dakota concluded that ettringite was formed from ASC by-product hydration and had the ability to chemically stabilize trace elements present in hazardous waste[4]. The formation of ettringite depends on the available calcium, aluminum, and sulfur and requires a high pH (more than 11.0).

Western Research Institute, sponsored by EPRI and the U.S. Department of Energy, conducted a laboratory study to evaluate the ability of by-products to stabilize hazardous organic and inorganic wastes[3]. Two sources of AFBC by-product and two sources of spray dryer by-product were mixed with four selected hazardous wastes. The leachates were analyzed for hazardous constituents using the toxicity characteristic leaching procedure (TCLP). The study concluded that the four by-products can be used to stabilize hazardous materials containing cadmium. However, the spray dryer by-products were not effective in stabilizing chromium.

In general, alkaline of ASC by-products may be useful to stabilize metals in acidic hazardous waste which have reduced solubilities at a higher pH, such as cadmium, iron, manganese, zinc, copper and cobalt.

Design Procedure

Conceptual Design

Sludge stabilization is similar to soil stabilization in many respects. As with soil stabilization, the ASC by-product is a principal component of the stabilization agent, therefore, the properties of the by-product are important factors for its stabilization potential. The chemical nature of the by-product, its capacity to stabilize sludge, and its potential impact on the environment are the key design considerations. The basic criteria that determines whether or not a by-product can successfully stabilize sludge are its chemical composition and grain size distribution.

As discussed in Section 1, the ASC by-products contain unreacted lime or limestone and calcium sulfate/sulfite, in addition to the oxides of aluminum, silicon, and iron observed in conventional fly ash. When a by-product is mixed with sludge, the lime reacts with the moisture from the sludge. Some by-products give off considerable heat from hydration. Both lime and calcium sulfate create a high water demand, which dries the sludge more quickly. In addition, upon aging or curing, the three major components in by-products, fly ash (SiO_2, Al_2O_3), free lime (CaO), and calcium sulfate ($CaSO_4$), may combine with water to form ettringite and/or thaumasite. The crystals of ettringite and thaumasite combine with large amounts of water leading to a decrease in moisture content.

Since sludge has a lower solids content than soil, the percentage of by-product used in sludge stabilization is higher than in soil stabilization. Substantial quantities of by-product are simply added to increase the solids content. The amount of added by-product can be greater than 50% of the total (wet) weight of the sludge.

The addition of a by-product increases the volume of materials in two ways. By-product addition increases the solids content by simply increasing the amount of dry material.

The increase in volume with the by-product addition is also caused by the formation of an expansive compound, ettringite. The ettringite mineral phase has the ability to substitute various oxyanions, such as arsenic, boron, selenium, chromium, and sulfite into its structure in place of SO_4. Therefore, ettringite formation indicates that by-products may have the potential to chemically stabilize hazardous waste sludge.

When stabilizing hazardous waste sludge, toxic compounds may be stabilized by a number of chemical processes. The lime in by-products reacts with water in the sludge, raising the pH. Some heavy metals are subsequently immobilized in the highly alkaline environment. Many inorganic constituents can be stabilized by alkaline materials as precipitates of carbonates, hydroxides, sulfates, silicates, or any number of complex solid phases. Additionally, many inorganics may be adsorbed by metal oxide phases present in the by-products. The behavior of hazardous organics may be controlled by sorption reactions.

If a stabilized sludge site is expected to be developed, strength is a major design parameter. The U.S. EPA has proposed a minimum allowable unconfined compressive strength of 345 kPa (50 psi) as a measure of adequate bonding[5]. Laboratory tests should be conducted to determine the blends of by-product and sludge that produce the desired strength. Cement or lime may be added to the mixture to increase strength for a particular use.

Laboratory Testing

Laboratory testing is needed to determine the chemical composition of the by-product. The by-product’s chemical and physical characteristics indicate its potential suitability for sludge stabilization. ASTM C 114 can be followed to determine the percentages of major oxides including CaO, SiO_2, Al_2O_3, and SO_4 present in the by-product. The SiO_2 and Al_2O_3 compounds react with CaO and water to form a cementitious product. The $CaSO_4$ combines with CaO, Al_2O_3, SiO_2 and water to form ettringite/thaumasite. The calcium content, an important factor for use as a stabilizing agent, can be determined using the procedures of ASTM C 25. These tests are suggested to determine the composition of the by-product and monitor material variability over time. Specific criteria have not been established, however, to evaluate by-products based on major oxide content. Generally, stabilization potential increases with CaO content.

The sludge producer can usually identify the type of sludge and provide a Material Safety Data Sheet (MSDS). The pH and solids content of the waste sludge should be determined in the laboratory. Trial test mixtures can then be designed based on the type of sludge, pH, and solids content of the sludge.

The primary components of test mixtures are the by-product and waste sludge, but other additives such as lime, cement, conventional fly ash, or cement kiln dust, also could be included in the mixtures, depending on the trial test results and strength requirement. The first step for sludge stabilization is to increase the pH of the sludge to the range of 10-12[3]. The ASC by-product alone may not have sufficient free lime content to raise the pH. In this case, lime can be added as a stabilizing agent.

For stabilizing non-hazardous waste sludge, the important considerations are to increase solids content and develop strength. Mixtures are prepared by adding a by-product to convert a liquid sludge to a semi-dry mass. The cementing/pozzolanic reaction would increase strength upon curing or aging. Since municipal sewage sludge has a high moisture content and low solids content, the high percentage of by-product (usually higher than 50% of sludge by weight) should be added to increase solids content and to improve dewatering characteristics. For stabilizing hazardous waste sludge, the most important consideration is the concentrations of trace elements in the leachate. For heavy metal ions which are immobile at high pH, the pH of the mixture should remain above 11.0[6].

Physical tests used to characterize wastes before and after stabilization/solidification are listed on Table 4-l. Complete descriptions of these tests are presented in Reference 7.

The ASC by-product is blended with sludge to increase both solids content and strength development of the blended sludge mixtures. Unconfined compressive strength and pH tests are recommended at 1, 3, 7, and 14 days. The unconfined compressive strength test can be performed in accordance with ASTM D 2166, which addresses the unconfined compressive strength of cohesive soils. Other strength test methods may be used depending on the intended application of stabilized sludge. If the sludge is stabilized into a cement-like form, the strength can be expected to increase significantly. ASTM C 109, compressive strength of hydraulic cement mortars, may be followed. Compressive strength data provide the basic information on the behavior of stabilized sludge. The EPA considers a stabilized/solidified material with a strength of 345 kPa (50 psi) to have a satisfactory unconfined compressive strength[5]. This minimum guideline of 345 kPa (50 psi) has been suggested as a stable foundation for construction equipment, impermeable caps, and cover material.

In addition to the compressive strength test, the permeability and leachate characteristics should be determined on selected high strength mixtures[6,7]. These tests are conducted at 14 days of curing. The permeability of a stabilized sludge is an important factor. It indicates the ability of a material to permit the passage of water and to limit the migration of contaminants to the environment. Sand, a highly permeable material, has a hydraulic conductivity on the order of 10^{-2} cm/s. Clay with a permeability of 10^{-6} cm/s or less, is considered a low permeability material. Thus a stabilized waste with a permeability similar to clay is desirable to reduce the possible transport of contaminants out of the waste. Typical hydraulic conductivities for stabilized wastes range from 10^{-4} to 10^{-8} cm/s. Hydraulic conductivities of less than

10^{-5} cm / s (upflow triaxial procedure) are recommended for stabilized waste destined for land burial. Alternative mixtures containing other additives (such as lime, cement, conventional fly ash) can be considered if the trial test results do not satisfy the desired properties for a particular use.

Environmental Considerations

Sludge stabilization is a process in which sludge is mixed with a stabilizing agent. The purpose of adding the by-product is to increase the sludge strength, decrease permeability, and reduce the leachate quantity. When sludge is blended with a by-product, the pozzolanic reaction increases the strength and decreases the permeability of the sludge mixture. This in turn reduces the quantity of leachate. The by-product hydration forms an expansion structure (ettringite) which can bind many of the leachable elements in the mixture (fixation). In general, a higher strength development of the stabilized product should result in a more effective reduction in leachate concentration. Depending on the chemical composition and trace element concentrations found in a given source of sludge, the sludge may require additional fixation in order to prevent or reduce leachate concentrations. In such cases, other additives such as lime, cement and conventional fly ash can be considered. Leachate quantity would be an important factor for overall evaluation. Leachate analyses should be performed to study the possible environmental impact.

Leachate extracts of stabilized hazardous waste, using the Toxicity Characteristics Leaching Procedure (TCLP) must not exceed the levels presented on Table 4-2. Leachate testing of the ASC by-products should be performed to show that the by-products are not the source of the contaminants. Liability issues related to waste stabilization are presented Section 1.

Table 4-1
Physical Testing Methods for Waste Stabilization

Test Procedure	Reference	Purpose
Index Property Tests		
Particle Size Analysis	ASTM D 422-63	To determine the particle size distribution of a material.
Atterberg Limits		
Liquid Limit	ASTM D 4318-84	To define the physical characteristics of a material as a function of its water content.
Plastic Limit	ASTM D 4318-84	
Plasticity Index	ASTM D 4318-84	
Moisture Content	ASTM D 2216-80	To determine the percentage of free water in a material.
Suspended Solids	USEPA Method 208C	To determine the amount of solids that do not settle from a column of liquids.
Paint Filter Test	USEPA Method 9095-SW846	To determine the presence of free liquids in a representative sample of bulk or noncontainerized water.
Density Testing		
Bulk Density - Drive Cylinder Method	ASTM D 2937-83	To determine the in-place density of soils or soil-like material.
Bulk Density - Sand-Cone Method	ASTM D 1556-82	To determine the in-place density of soils or soil-like materials.
Bulk Density - Nuclear Methods	ASTM D 2922-81	To determine the in-place density of soils or soil-like materials.
Bulk Density - Stabilized Waste		To determine the density of a monolithic stabilized waste.
Compaction Testing		
Moisture Density Relations of Soil-Cement Mixtures	ASTM D 558-82 ASTM D 1557	To determine the relation between moisture content and density of a material.

Table 4-1
(Continued)

Test Procedure	Reference	Purpose
Permeability Testing		
Falling Head Permeability	USEPA Method 9100-SW846	To measure the rate at which water will pass through a soil-like material.
Constant Head	USEPA Method 9100-SW846	To measure the rate at which water will pass through a soil-like material.
Strength Testing		
Unconfined Compressive Strength of Cohesive Soils	ASTM D 2166-85	To evaluate how cohesive soil-like materials behave under mechanical stress.
Unconfined Compressive Strength of Cylindrical Concrete Specimens	ASTM D 1633-84	To evaluate how cement-like materials behave under mechanical stress.
Compressive Strength of Hydraulic Cement Mortars	ASTM C 109-86	To measure the compressive strength of hydraulic cement mortars.
Flexural Strength	ASTM D 1635-87	To evaluate a material’s ability to withstand loads over a large area.
Cone Index	ASTM D 3441-79	To evaluate a material’s stability and bearing capacity.
Durability Testing		
Freeze-Thaw Durability	ASTM D 4842	To determine how materials behave or degrade after repeated freeze-thaw cycles.
Wet-Dry Durability	ASTM D 4843	To determine how materials behave or degrade after repeated wet-dry cycles.

ASTM - American Society for Testing and Materials.

USEPA - United States Environmental Protection Agency

Blank indicates no ASTM method or other reference method.

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

Table 4-2
Concentration of Metal Contaminants for the Toxicity Characteristic, EPA Hazardous Waste Criteria

Contaminant[a]	Regulatory Level[b] (mg/L)
Arsenic	5.0
Barium	100.0
Cadmium	1.0
Chromium	5.0
Lead	5.0
Mercury	0.2
Selenium	1.0
Silver	5.0

[a] Additional contaminants (organics) are listed in 40 CFR 261.

[b] Concentration in extract from a representative sample of waste, using the Toxicity Characteristic Leaching Procedure (TCLP).

(SOURCE: 40 CFR 261 Identification and Listing of Hazardous Waste, $261.24 Toxicity Characteristic, Revised 58 FR 46049, Aug. 31, 1993.)

Case Histories

EPRI Sponsored Laboratory Study[1,2]

Under EPRI Project 2708-1, ICF Northwest conducted a laboratory evaluation of by-product utilization. In this study, FGD sludge and municipal sewage sludge were stabilized. A furnace sorbent injection by-product, AFBC fly ash, and AFBC spent bed material were used with both sludges. Spray dryer by-product was only used for municipal sludge stabilization. Mixtures consisted of 90% sludge, 7% by-product, and 3% lime; and 90% sludge and 10% by-product. The mixtures were prepared by drying the sludge, adding water to obtain optimum moisture content, and then mixing sludge with by-products. The cylinder samples were prepared in accordance with ASTM C 593. The 28-day compressive strength of samples, except for those with AFBC spent bed material as stabilizing agent were higher than 670 kPa (100 psi). This strength is adequate for many structural fill uses.

Another mixture was prepared by mixing wet municipal sewage sludge with prehydrated AFBC spent bed material. The sludge had not been pretreated. The addition of AFBC spent bed material was 80% by weight of the wet sludge. After 36 hours, the unmolded samples were soft but held their shape. The samples could not withstand a compressive load even after 7 days of curing. It was suggested that a higher by-product to sludge ratio and longer curing time would improve the strength of stabilized sludge.

Western Research Institute's Study [3]

A laboratory study was conducted at the Western Research Institute to evaluate the ability of by-products to stabilize organic and inorganic constituents of hazardous wastes. The four by-products used in this study were: (1) Tennessee Valley Authority (TVA) atmospheric fluidized bed combustor (AFBC) residue, (2) TVA spray dryer residue, (3) Laramie River Station spray dryer residue, and (4) Colorado-Ute AFBC residue.

Four types of hazardous waste stream materials were obtained. The wastes included an API separator sludge, mixed metal oxide-hydroxide waste, metal-plating sludge, and creosote-contaminated soil. The API separator sludge and creosote-contaminated soil contained organic contaminants. The mixed metal oxide-hydroxide waste and metal-plating sludge contained high concentrations of heavy metals (cadmium or chromium).

To evaluate the ability of by-products to stabilize hazardous waste, the study involved: (1) identifying, collecting, and characterizing hazardous waste materials and by-products, (2) evaluating the ability of the by-products to stabilize the hazardous waste material using waste mixing ratio methodology, (3) studying the effects of simulated weathering on mixtures of by-products and hazardous wastes, (4) characterizing the mineralogical properties of by-product and hazardous waste mixtures, and (5) investigating the bonding interactions between the by-product and hazardous waste materials.

First the mixtures involving varying amounts of each of the by-products with each of the hazardous wastes were prepared, allowed to equilibrate, and then leached with deionized, distilled water. The leachates were analyzed for the hazardous constituent(s) using the Toxicity Characteristic Leaching Procedure.

It was found that chromium was leached from both the Laramie River Station spray dryer and TVA spray dryer by-products stabilized mixtures. However, the four by-products can be used to stabilize the cadmium found in the metal oxide-hydroxide hazardous waste.

Simulated weathering experiments were performed using mixtures of TVA AFBC / metal oxide-hydroxide, Colorado-Ute AFBC / metal oxide-hydroxide, and TVA

AFBC / API separator sludge. Evidence for stabilization of cadmium over time in the metal oxide-hydroxide mixtures and stabilization of organics in the mixture of the API separator sludge were observed.

X-ray diffraction, scanning electron microscopy, and energy dispersive X-ray analyses were performed on a number of by-products and hazardous wastes mixtures. Quartz and ettringite were the most dominant mineral phases in most of the mixtures. Other minerals identified include gypsum, portlandite, and calcite.

Solid-state C nuclear magnetic resonance study was used to investigate the adsorption of pentachlorophenol and TVA AFBC ash. A downfield chemical shift of the phenolic carbon resonance in pentachlorophenol was observed when adsorbed on the TVA AFBC ash relative to the “free” solid-state position. The magnitude of the observed shift suggests a strong interaction of pentachlorophenol with the TVA AFBC ash residue.

References

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5

STRUCTURAL FILLS

Overview

This section describes the potential use of advanced SO_2 control (ASC) by-products in place of natural soil borrow to construct engineered embankments and structural fills. Structural fills refer to properly designed and constructed applications of bulk fill material, such as for building sites and embankments for roads, railroads, dikes and levees. These fills are typically constructed in thin layers and compacted. The resulting fill must be stable and relatively incompressible.

In a previous study, *Utilization Potential of Advanced SO_2 Control By-Products*[1], EPRI concluded that calcium spray dryer by-products had a high potential as structural fill and that AFBC, FSI, and calcium in-duct injection by-products had a moderate potential. Sodium injection by-product was not considered suitable for use as structural fill material and will not be discussed further.

This section describes the design and construction procedures specific to engineered structural fills consisting of ASC by-products. The *Fly Ash Design Manual for Road and Site Applications, Vol. 1: Dry or Conditional Placement*[2] presents detailed guidance on traditional design methods and considerations, as well as information specific to fly ash. Much of that report is also applicable to ASC by-products. This report assumes that the reader is familiar with con-ventional fill design methods, and will focus on material properties and considerations specific to ASC by-products.

The major advantage to using an ASC by-product as fill material is its high unconfined compressive strength relative to soil. The major disadvantage is that it is a new material, and its long-term behavior is relatively unknown. Laboratory tests indicate leachate concentrations are well below toxicity levels for hazardous waste, but the pH is high, generally about 12. A potential concern with these by-products is dimensional stability (expansion). Although no reports of expansion of these by-products in fills have been identified, FBC materials have in some cases been expansive in road base. Also, these by-products may hydrate to form ettringite, a potentially expansive compound. In addition, erratic unconfined compressive strengths over time of laboratory samples have been attributed to “slow expansive reactions,” although change in sample length was not reported.

Finally, although the by-products are produced in large volumes per year, large volumes of material may or may not be readily available for immediate use in structural fills. ASC by-products are typically stored dry in silos at the plant, conditioned with water during discharge to control dusting, and trucked to a landfill. At the landfill they may be further watered and compacted by truck and dozer traffic. As ASC by-products are self-hardening, landfilled materials may be impractical to remove. Exposed stockpiles may result in changes in by-product reactivity. If excavating landfilled by-products and stockpiles are impractical, by-product fill volumes would then be limited to silo volumes, typically about 7650 to 11470 cubic meters (10,000 to 15,000 cubic yards).

State of Practice

A demonstration road project at Northern States Power Company's Sherburne County Power Plant in Becker, Minnesota was conducted under EPRI RP2708. A highway embankment incorporating spray-dryer by-products was constructed under the management of Radian Corporation and VFL Technology[3,4]. The road section is 187 meters (614-feet) long and 7.3 meters (24-feet) wide with a 1.7 meters (5½-foot) high embankment. Embankment fill sections were constructed of both 100% spray dryer by-product [4.6 meters (1 5-foot section)] and spray-dryer material mixed with borrow [three sections totaling 53 meters (175 feet)]. The Demonstration Road was completed in October 1991 and performed well from both engineering and environmental standpoints to date.

Another field demonstration project was conducted at Ohio State Highway 541. Dry FGD by-product was used to reconstruct the field portion of highway embankments[5]. In this project, dry FGD by-product demonstrated ease of installation and high early strength, with no significant environmental change of the surroundings. The Ohio State University developed an "intelligent decision support system" for embankment design using FGD by-products[6]. This system included a database, numerical processing programs, and dynamic graphic packages. The resultant practical design tools for geotechnical applications were used for slope stability analysis of the Highway 541 demonstration project. The calculated factors of safety and the observed embankment performance indicate that the field demonstration project was a success.

A truck ramp made from spray dryer by-product was constructed by the Ohio State University in Columbus[7]. Approximately 180 metric tons of by-product was used in the ramp structure. After over one year of service, there was no indication of erosion or rutting in the ramp surface.

Design Procedures

The design process for engineered fills and embankments involves the following series of steps.

- Conceptual Design. Project goals are assessed and a general scheme is developed to achieve the desired purpose.
- Characterization of Site and Materials. Detailed information about the site conditions, proposed fill materials, and other factors pertinent to the design, construction, and performance of the project are collected.
- Detailed Design. Project goals are balanced with the physical, economic, and institutional constraints to arrive at an acceptable detailed plan to complete the project.

Conceptual Design

Engineering Requirements. The design of an engineered fill involves developing conceptual plans which satisfy project needs, such as a sufficient area of land able to support loads without excessive settlement or failure, and which has adequate shear strength to provide stable slopes.

It is recommended that by-products are compacted to predetermined criteria, for example, 95% Standard Proctor dry density at the optimum moisture content. Although the compressive strength of cured, compacted ASC by-products may be several times that required for fill purposes, compacted materials are more likely to have consistent properties. Also, engineered fills which support buildings, highways or other structures are typically compacted.

ASC by-products may be less suitable for constructing dikes and dams. Long-term material behavior, including expansion, under saturated conditions and cycles of wetting and drying, should be tested for these uses. Structural fills which impound water require that considerable attention be given to subsurface drains and seepage forces and should be designed to prevent overtopping.

Pure VS. Blended By-Products. Structural fills may be constructed of layers of 100% ASC by-products or of mixtures of an ASC by-product plus soil. Use of pure by-product fills allow use of the maximum volume of by-product per area and avoids the added cost of blending materials. Use of blended fills, however, may be considered to lessen concerns associated with sulfates. The majority of the following section will address pure by-product fills and pre-sent available laboratory data. Available information on an ASC by-product blended with soil will be presented in the discussion of Northern States Powers' Demonstration Road Project.

Another option is blending two coal combustion by-products, such as AFBC SBM with AFBC fly ash, furnace sorbent injection material with conventional fly ash, or spray dryer by-product with FGD sludge. Mixtures which improve material strengths or reduce expansion or permeability are beneficial, although mixing costs may be prohibitive. Any mixture should be tested in the laboratory prior to use.

Site Location. A basic consideration for ASC by-products is transport time to the site. Set time of the material should be known, and a project site should be close enough that moisture-conditioned material will not set up enroute. For distant sites, pneumatic trucks can be used to transport dry material, which would then be conditioned at the site. Increased costs for pneumatic trucks, however, should be considered in the initial planning stages.

Environmental Considerations. Elemental concentrations in leachate from ASC by-products are generally low relative to hazardous waste criteria, and the low permeabilities of compacted cured by-products will result in minimal leachate generation. These by-products, however, are alkaline. Also, simply by virtue of being coal combustion by-products, these materials may be of concern to state environmental officials. Conceptual design considerations which are optional but which can further reduce environmental concerns include thick, cohesive soil covers; remote or confined locations; and locations with low groundwater or thick surface clay layers.

At the Sherburne County Road, which was constructed in 1991, runoff and groundwater were monitored through 1994. No environmental impact could be measured.

Based on 18 months of monitoring of storm runoff and leachate water at a LIMB stockpile, no significant environmental impacts were determined[8].

Note that alkaline backfills may be environmentally beneficial in areas of acid mine drainage. In some states, alkaline by-products have been permitted for strip mine backfill without liners with the thought that the high pH backfill may mitigate acid mine drainage.

Liability issues related to the environment are discussed in Section 1.

Characterize Materials

To provide parameters for site design, the physical, engineering, and chemical characteristics of the ASC by-product must be determined.

The following information should be determined for the ASC by-product fill material:

- Compaction characteristics
- Unconfined compressive strength - short-term and long-term
- Effect of conditioning
- Heat of hydration
- Dimensional stability
- pH
- Leachate chemistry
- Other properties, including permeability and radioactivity

Although ASC by-product structural fill field data is not available, laboratory data is available on many of these properties. Most of the laboratory data presented in the following section were determined in the various laboratory characterization studies by ICF Technology Incorporated[9-13] as described in the waste management design guidelines[14-16] for each material by Baker/TSA Inc. with ICF Technology Incorporated. Where laboratory data is not available, commentary on ASC by-product experience in landfill disposal or other uses is presented.

Compaction Characteristics. Fine-grained materials are often moisture-sensitive with respect to compaction, that is, the density at a given compactive effort is dependent upon the water content of the material. The optimum moisture content (OMC) is defined as the amount of free moisture in the material which results in the maximum dry density achieved at the given compactive effort. Moisture-density relationships can be determined using either ASTM D 698 or ASTM D 1557.

Due to the reactive nature of ASC by-products, two precautions should be addressed for representative test results. The time a moist sample stands before compaction can affect results of the moisture-density test. A sample needs to stand long enough for the hydration reactions to take place, but steps need to be taken to prevent the sample from hardening due to cementitious reactions. Depending on the soil classification of the waste, ASTM specifications require different minimum standing times. For inorganic silt with a liquid limit of 50% or less, which is the likely classification of many of these by-products, a minimum standing time of 18 hours is specified. However, the specification needs to be adjusted to address the reactive nature of the by-products. The second precaution concerns drying the sample to determine moisture content. The ASTM test protocol (D 2216) typically requires a drying temperature of 110ºC; however, for materials with significant quantities of hydrated water, such as conditioned ASC by-products, ASTM D 2216 recommends 60°C.

As part of EPRI Project RP2708, moisture-density relationships were developed by Radian Corporation for samples of each of the ASC by-products. As shown on Table 5-1, two different moisture contents were used to define the optimum moisture content for AFBC and FSI by-products. However, due to the hydration reactions associated with by-products neither of these moisture contents represents a true optimum moisture content. The higher of the two moisture contents is based on moisture added to the sample and includes moisture steamed off during hydration of the waste. Consequently, this value can be useful to estimate an approximate value for conditioning by-products to achieve the optimum moisture content. The lower moisture content corresponds to the moisture lost upon oven drying the sample at 110 ± 5ºC. Because of the high drying temperature used, the resulting moisture content includes some water of hydration.

Maximum dry density values reported on Table 5-l were calculated by dividing the wet density (determined by weighing a specimen of known volume) by one plus the moisture con-tent based on moisture added. By calculating dry density in this manner, the wet weight is assumed to contain moisture which was steamed off. Consequently, the calculated dry density values are believed to be lower than the actual in-place dry densities.

Table 5-1
Compaction Characteristics of AFBC and Furnace Sorbent Injection By-Products (ASTM D 698)

		Optimum Moisture Content (%)		
By-Product	**Sample**	**Moisture Added**	**Oven Dried at 110°C**	**Maximum Dry Density (kg/m^3)**
AFBC SBM		32	13	1510
AFBC Char		36	22	1180
AFBC Fly Ash		50	40	1120
AFBC Composite		39	26	1250
FSI	SRI-SR07	52	34.3	1090
FSI	SRI-SR09	36	22.5	1280
FSI	Ont-Hydro OL03	42	27.1	1100
FSI	Ont-Hydro OL04	40	22	1100
FSI	Ont-Hydro OL08	38	NA	1160

(SOURCE: Baker / TSA Inc. *Design Guidelines for a Furnace Sorbent Injection Waste Management System*. June 1989. Baker / TSA Inc. and ICF Technology Inc. *Atmospheric Fluidized-Bed Combustion Waste Management Design Guidelines*. December 1988 .)

Table 5-2 presents moisture contents and dry densities reported in literature for calcium spray dryer by-products.

Test values for calcium injection by-products are available only for two Arapahoe samples. These values are OMC of 44% at a maximum dry density of 1150 kg/m^3 (71.8 pcf) and 42% at 1190 kg/m^3 (74.4 pcf).

Unconfined Compression Strength. Natural soil borrow, granular fill, fly ash, and other embankment or structural fill materials are typically tested by direct shear or triaxial tests to determine their shear strength. Cementitious materials such as ASC by-products, however, are more appropriately tested by the unconfined compression (UC) test. In this test, an unconfined sample of material is vertically loaded to determine its resistance to compressive loads.

For comparison, flowable fill is another cementitious material which can be used as a substitute for compacted soil. Although flowable fill may be designed to have high UC loads for use under high loads, this material is typically designed for an unconfined compression strength of 345 to 1030 kPa (50 to 150 psi) at 28 days. (Note that this strength may continue to increase with time.) Strengths lower than 345 kPa (50 psi) are insufficient for use as structural fill. Higher strengths than 1030 kPa (150 psi) at 28 days could result in long term strengths which will not allow excavation. UC strengths of tested samples of ASC by-products varied from less than 690 kPa (100 psi) to over 13790 kPa (2000 psi). While materials with high UC strength are useful for supporting heavy loads, placement of these materials should be considered permanent. These materials should not be considered for use around pipes, utility lines, or other locations which may need to be accessed.

Also, note that UC strengths vary over time. A material which develops sufficient UC strength at 28 days may not be competent for loading at one day. Also, in laboratory testing, some ASC by-product strengths decreased between 28 and 56 days. For most of the materials whose strengths increased then decreased over time, the lowest long-term strength was still adequate for use as a compacted soil replacement.

To examine the effect of curing time, curing humidity, and sample moisture content, extensive unconfined compression (UC) tests were conducted as part of EPRI RP2708. Samples were prepared at optimum moisture content (OMC), 5% above OMC and 5% below OMC using three curing conditions and 6 curing periods. UC tests were conducted after 1, 3, 7, 14, 28, and 56 days curing at a 100% relative humidity (wet cycle). In addition, UC tests were conducted on samples cured 56 and 28 days at 51% relative humidity (air dried) and 7 day wet/dry cycle. Graphs of the test results for by-product samples are presented on Figures 5-l through 5-13.

Table 5-2
Compaction Characteristics of Spray Dryer By-Products

Sample	Moisture Content (%)	Dry Density (kg/m^3)
Reactive NHG:	29[a]	1410
Reactive NHG:	35[a]	1230
Reactive NHG:	35[a]	1230
Low-Reactive NHG:	NR	1310
Low-Reactive NHG:	28[a]	1380
Low-Reactive NHG:	20[a]	1630
Low-Reactive NHG:	22[a]	1310
Non-Reactive NHG:	22[a]	1330
Non-Reactive NHG:	20[a]	1350
Lignite (USA) - Reactive Product	45	1170
Subbituminous (USA) - Reactive Product	40	1220
Bituminous (USA) - Low Reactive Product	60	880
Ruhr (BRD) Non-Reactive Product	20	1400
Steinkohle (RI) Non-Reactive Product	32	1130
Lignite	40	1220
Subbituminous	45	1110
A-2-N	47-45[a]	980
B-l-D	28[a]	1340
B-2-V	18[a]	1460

[a] Reported as optimum moisture with corresponding maximum dry density.

NHG - Niro Heat Generation Test

(SOURCE: ICF Northwest. *Calcium Spray Dryer Waste Management: Design Guidelines*. September 1989.)

Of the **AFBC by-products**, the AFBC fly ash samples developed the greatest overall strengths. Although, as Figure 5-l shows, test results fluctuated widely, making conclusions on the effect of curing time, curing humidity, and sample moisture content difficult. Interestingly, the 56 day UC values for all the samples at OMC and minus 5%

of OMC decreased from their corresponding 28 day values, while for the plus 5% OMC samples the UC values increased. The decrease in strength could be attributed to slow expansive reactions due to sulfates.

As shown on Figure 5-2, the AFBC composite (AFBC SBM plus AFBC fly ash) samples showed the second highest UC values. While the composite samples did not develop UC values comparable to the AFBC fly ash samples, they did continue to gain strength when cured 56 days. The more favorable gradation and lower sulfate concentrations possibly contributed to this continued strength development.

The UC results were successively lower for the char and SBM samples presented on Figures 5-3 and 5-4, respectively. As with AFBC fly ash, char and SBM samples at plus 5% OMC continued to gain strength when cured to 56 days.

Graphs of test results for each of the Ontario Hydro **FSI by-product** samples are presented on Figures 5-5 through 5-7. Since a limited amount of by-product was available from the Southern Research Institute (SRI) only a reduced number of unconfined compressive strength tests could be conducted (see Figure 5-8).

As the plots of FSI unconfined compressive strength show, the test results fluctuated widely, making conclusions on the effect of curing time, curing humidity and sample moisture con-tent difficult. One frequent trend was a decrease in unconfined strength from 28 to 56 day curing (20 of 29 samples). Also, it does appear that after 56 days of curing samples prepared at OMC developed the greatest strength followed by samples prepared at OMC plus 5%.

Graphs of test results for eight **calcium spray dryer by-product** samples are presented on Figures 5-9 through 5-12. As shown in these figures, strength ranged from 140 to 5450 kPa (20 to 790 psi) at 28 days and 970 to 11380 kPa (140 to 1650 psi) at 56 days. The wide range of strengths are different in chemical composition of by-products which are obtained from different sources.

Two possible strength development problems have been reported in literature. A testing program conducted at the University of Tennessee included a waste sample that possessed insufficient cohesive strength to test for unconfined compressive strength. After 7 days the test specimen cracked and disintegrated. In a second test, the specimen was wrapped during curing and resulted in strength development of 3090 kPa (448 psi) after 56 days[17]. Another case of unexpectedly low strength development occurred on waste generated at the Riverside Demonstration Facility. The sample from a burn of Sharpy Creek subbituminous coal did not develop adequate strength under initial testing. Yet, when preconditioned for 24 hours before compaction and retested, it developed a 1090 kPa (158 psi) compressive strength after 56 days curing[18].

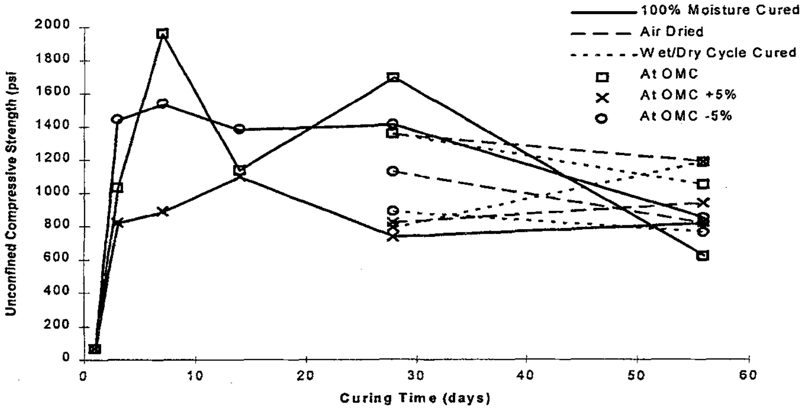


Figure 5-1
AFBC Fly/Ash Waste Unconfined Compressive Strength, TVA Shawnee Plant, Sample TV05

(SOURCE: Baker / TSA Inc. and ICF Technology Inc. *Atmospheric Fluidized-Bed Combustion Waste Management Design Guidelines.* December 1988.)

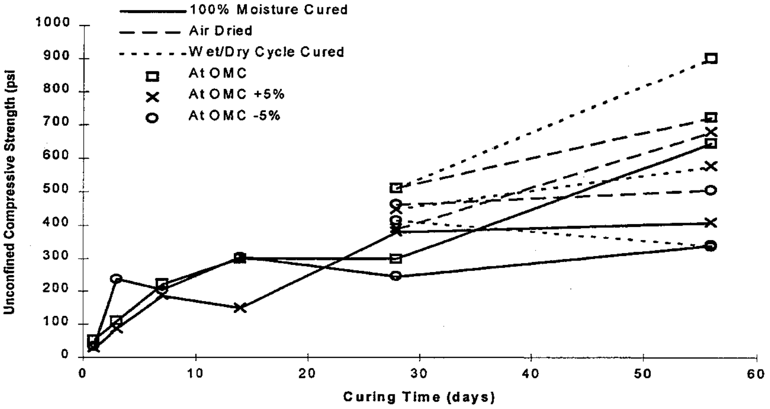


Figure 5-2
AFBC Composite Waste Unconfined Compressive Strength, TVA Shawnee II, Sample SF06

(SOURCE: Baker / TSA Inc. and ICF Technology Inc. *Atmospheric Fluidized-Bed Combustion Waste Management Design Guidelines.* December 1988.)

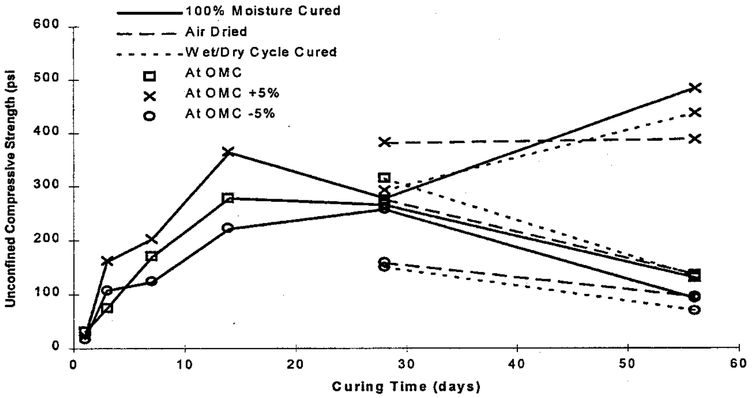


Figure 5-3
AFBC Char Waste Unconfined Compressive Strength, TVA Shawnee Plant, Sample TV04

(SOURCE: Baker / TSA Inc. and ICF Technology Inc. *Atmospheric Fluidized-Bed Combustion Waste Management Design Guidelines.* December 1988.)

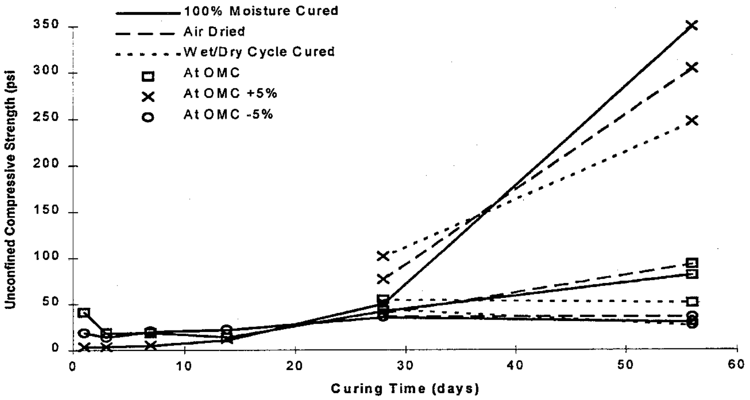


Figure 5-4
AFBC SBM Waste Unconfined Compressive Strength, TVA Shawnee Plant, TV03

(SOURCE: Baker / TSA Inc. and ICF Technology Inc. *Atmospheric Fluidized-Bed Combustion Waste Management Design Guidelines.* December 1988.)

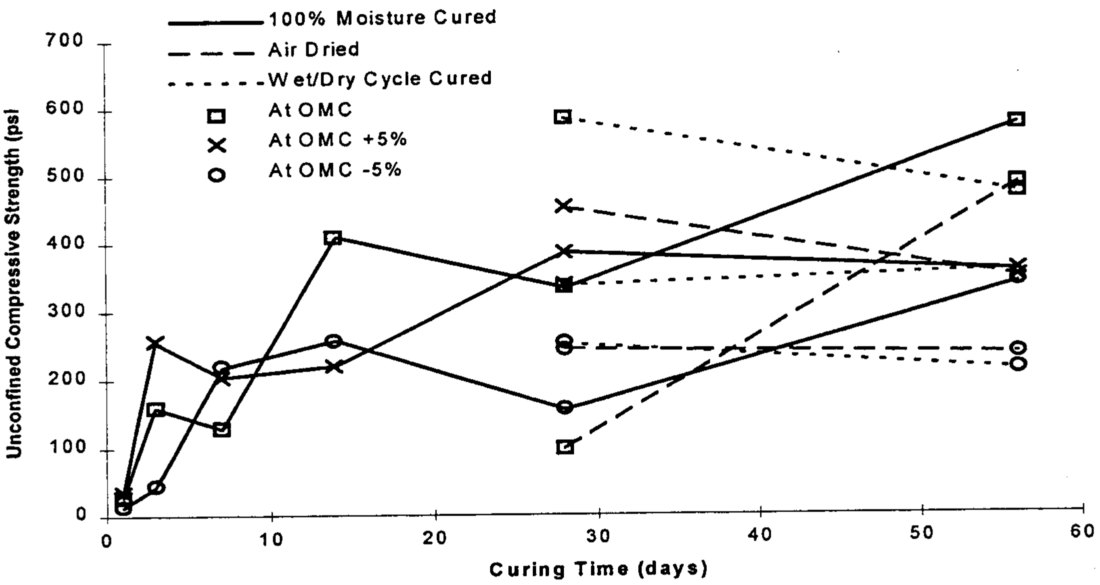


Figure 5-5
FSI By-Product Unconfined Compressive Strength, Ontario Hydro, Sample OL03

(SOURCE: Baker / TSA Inc. *Design Guidelines for a Furnace Sorbent Injection Waste Management System.* June 1989.)

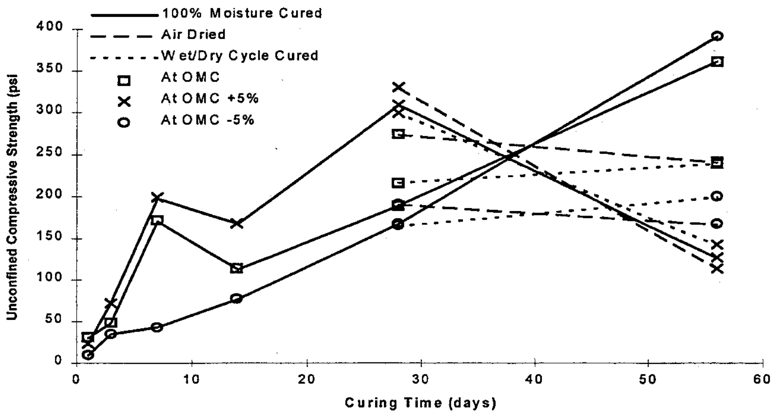


Figure 5-6
FSI By-Product Unconfined Compressive Strength, Ontario Hydro, Sample OL04

(SOURCE: Baker / TSA Inc. *Design Guidelines for a Furnace Sorbent Injection Waste Management System.* June 1989.)

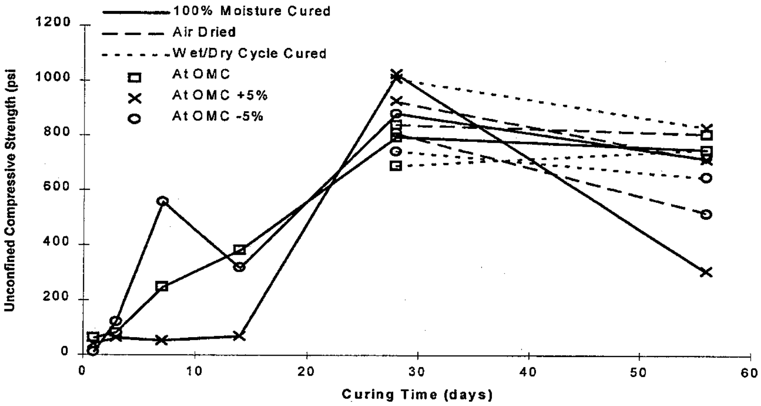


Figure 5-7
FSI By-Product Unconfined Compressive Strength, Ontario Hydro, Sample OL08

(SOURCE: Baker / TSA Inc. *Design Guidelines for a Furnace Sorbent Injection Waste Management System.* June 1989.)

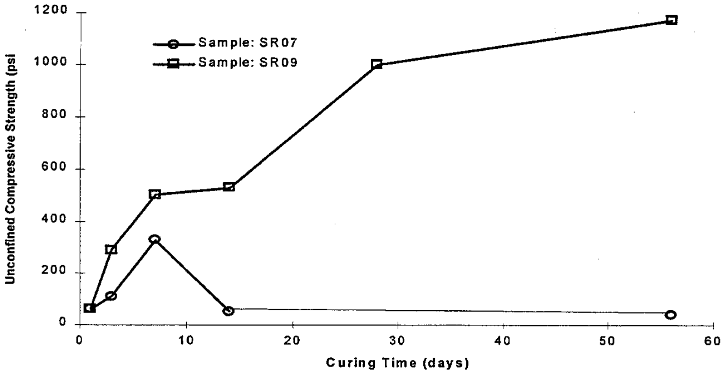


Figure 5-8
FSI By-Product Unconfined Compressive Strength, Southern Research Institute Samples

(SOURCE: Baker / TSA Inc. *Design Guidelines for a Furnace Sorbent Injection Waste Management System.* June 1989.)

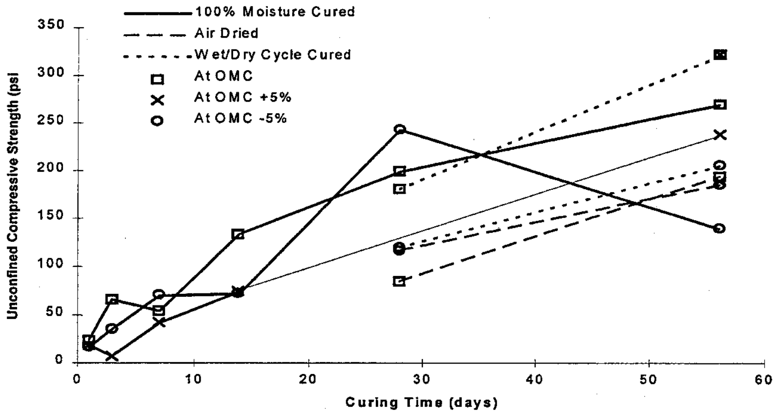


Figure 5-9
Spray Dryer By-Product Unconfined Compressive Strength, Arapahoe Plant, Sample AR07

(SOURCE: ICF Northwest. *Calcium Spray Dryer Waste Management: Design Guidelines.* September 1989.)

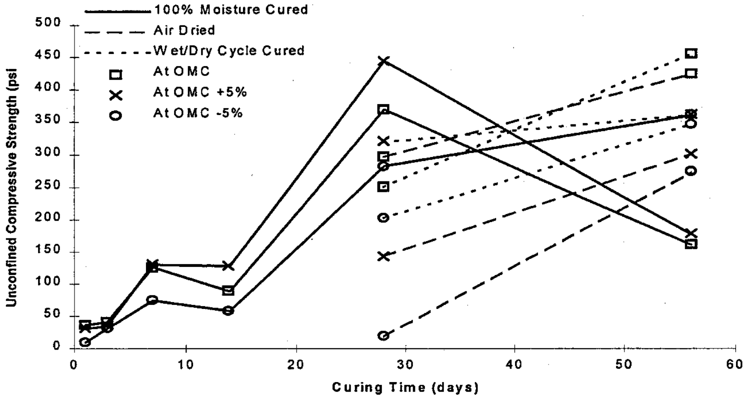


Figure 5-10
Spray Dryer By-Product Unconfined Compressive Strength, Stanton Plant, Sample ST07

(SOURCE: ICF Northwest. *Calcium Spray Dryer Waste Management: Design Guidelines.* September 1989.)

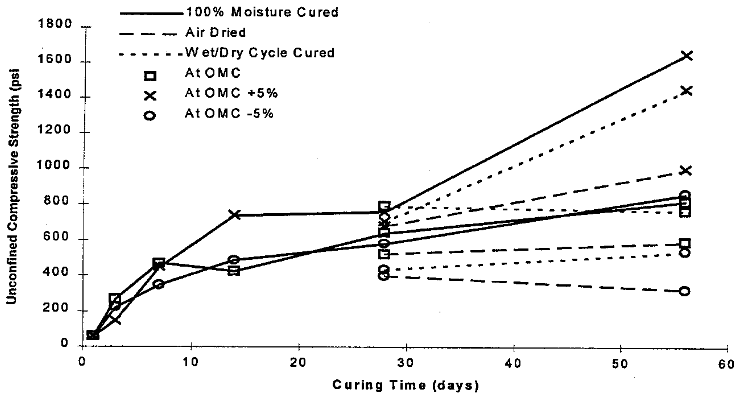


Figure 5-11
Spray Dryer By-Product Unconfined Compressive Strength, Laramie Plant, Sample LR07

(SOURCE: ICF Northwest. *Calcium Spray Dryer Waste Management: Design Guidelines.* September 1989.)

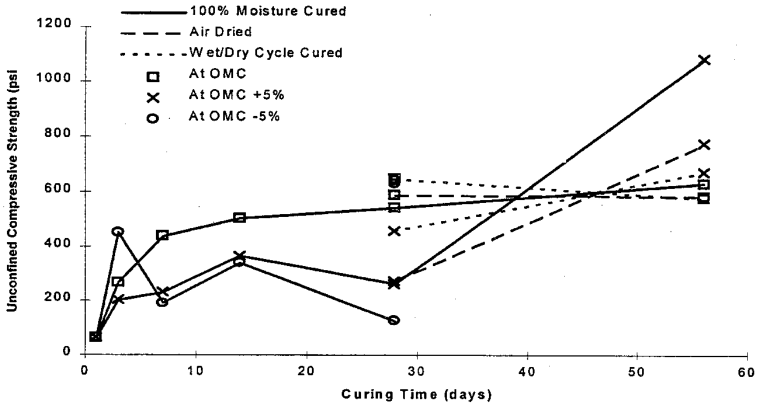


Figure 5-12
Spray Dryer By-Product Unconfined Compressive Strength, Holcomb Plant, Sample HS05

(SOURCE: ICF Northwest. *Calcium Spray Dryer Waste Management: Design Guidelines.* September 1989.)

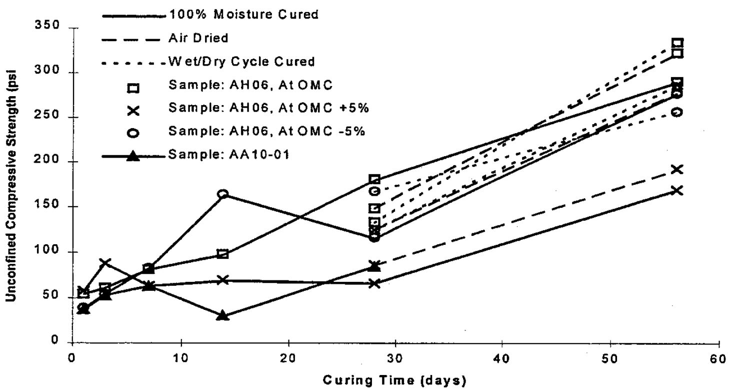


Figure 5-13
Calcium Sorbent Injection By-Product Unconfined Compressive Strength, Arapahoe IV, Sample AA10 and Arapahoe III, Sample AH06

(SOURCE: Baker/TSA Inc. *Design Guidelines for a Furnace Sorbent Injection Waste Management System.* June 1989.)

The researchers involved in these test programs have proposed some explanations of the results of these tests. Phillips, in the University of Tennessee study, hypothesized that atmospheric moisture dissolved calcium sulfates and sulfites, which then reacted with aluminum silicates. This pozzolanic reaction formed compounds with high specific volume which caused cracking and then structural failure. Phillips further suggested that the lack of unreacted $Ca(OH)_2$ in the sample tested contributed to this unsoundness[17].

In the Riverside Demonstration project, the sample's low strength development was attributed to a rapid initial set followed by disruptive expansion reactions which may be attributed to high calcium and low sulfur contents[18].

UC strengths of **calcium in-duct injection by-products** are plotted on Figure 5-13. These material strengths consistently increased between 28 and 56 days, and are adequate for typical embankment requirements.

Conditioning. For background information, this section will discuss the effect of the addition of water (conditioning) on lime, gypsum and fly ash. Reported effects of conditioning on ASC by-products will be presented.

- Fly Ash - The two general types of fly ash are Class F and Class C. Water is often added to Class F fly ash to control dusting and aid in compaction. Water alone will not cause Class F fly ash to set up, but water and lime together will cause fly ash to harden pozzolanically. This reaction is slow and generates little heat. Class C fly ash sets up with the addition of only water. Depending on the specific ash, the reaction may be immediate (flash set), or it may be possible to spread and compact Class C fly ash up to a week after conditioning. Increased time delays between mixing water and compacting Class C fly ash have resulted in decreased UC strength of the cured, compacted fly ash.

- Gypsum - Significant amounts of anhydride ($CaSO_4$) and half-hydrate ($CaSO_4 \cdot ½H_2O$) are reported in ASC by-products. With the addition of water, these compounds will hydrate to form the hard interlocking phase of gypsum, $CaSO_4 \cdot 2H_2O$.

- Lime -"Lime" may refer to quicklime (CaO) or hydrated lime ($Ca(OH)_2$). With the addition of water, quicklime hydrates to $Ca(OH)_2$. Although ASC processes inject hydrated lime or limestone ($CaCO_3$) into the system, heat drives off the moisture or $S0_2$. Thus, much of the unreacted lime in the by-product is in the form of quicklime. Most lime uses, such as soil stabilization, road base, and grout, specify hydrated lime. To create hydrated lime, quicklime must be slaked (hydrated).

  As hydration occurs, the volume increases and heat is generated. The quality of slaking depends upon the reactivity of the quicklime, the lime to water ratio, how the water is added, the degree of agitation, and the water temperature. Too much water which is too cold can result in the outside material hydrating without penetration of the water, resulting in incomplete hydration. Too little water which is too hot can "burn" the lime - too much water is lost as steam, and the intense heat can dehydrate the hydrated lime, again resulting in incomplete hydration. Sulfites and sulfates in slake water retard slaking and reduce the quality of the hydrated lime. Thus, while quicklime can be slaked by adding water, the degree of hydration depends not only on the quantity of water, but on the slaking conditions[19].

- ASC By-Products - ASC by-products are composed of combinations of lime, unhydrated gypsum (anhydrite), fly ash and other compounds of Ca, S, Si, Al and Fe. The reaction of these by-products to conditioning is difficult to predict and varies with ASC by-product type and source. Some ASC by-product utilization studies reported that preconditioning of the ASC by-product gave better results. As presented in Section 2, road base mixtures incorporating AFBC residue (SBM) report reduced expansion when the material was properly preconditioned with water. Laboratory tests on AFBC and FSI by-products show variable unconfined compressive strengths with time, attributed to slow expansive reactions, as previously discussed. A laboratory study on a spray dryer by-product found that one source initially would not develop adequate strength, but when preconditioned for 24-hours before compaction and retested achieved strength adequate for use in a structural fill.

- Recommended Practice - ASC by-product components may include unreacted quicklime, anhydrite and Class C fly ash, all of which react with water. Conditioning with water may hydrate and harden the different components at various rates. Not all by-products have developed excessive expansion in road base, and little information is available on ASC by-products in a structural fill. For cases in which the possibility of expansion is suspected, previous studies indicate that preconditioning by-products will control expansion or result in more consistent unconfined compression strengths. It is suggested that various water contents, mixing methods, and time delays prior to compaction be tested for sources which demonstrate excessive expansion or erratic unconfined compression strengths. Methods to evaluate preconditioning are described in Section 2, “Road Base. ”

Heat of Hydration. Heat of hydration refers to the heat generated during reaction of ASC by-products with water. In massive fills, there is potential for the heat of hydration to buildup and have detrimental effects on the material’s strength or the structural integrity of the fill. The magnitude of the temperature rise depends on the reactivity of the material and the conditioning method employed. A thoroughly mixed, highly reactive sample that allows adequate steam generation and dissipation could attain a maximum temperature of 100ºC (212ºF), the boiling point of water. For by-products which experience a rapid rise in temperature upon hydration, conditioned material should be spread in thin lifts, adequately watered, and any steam allowed to dissipate prior to compaction and / or additional lifts.

In general, AFBC and FSI by-products had high heats of hydration, while spray dryer and calcium sorbent injection by-products had no significant heat of hydration. Note that spray dryer and calcium sorbent injection by-products had significant long-term strengths. No correlation is apparent, using currently available data, between heat of hydration and strength development.

Temperature versus time measurements were taken on samples of FSI and dry calcium injection by-product conditioned to optimum moisture. The maximum temperatures for FSI ranged from approximately 49ºC to 100ºC (120ºF to 212ºF) and occurred within 4 to 28 minutes. Samples which reached lower maximum temperatures consistently had longer reaction times and lower hydroxide levels.

Tested dry calcium injection by-products exhibited a very low temperature rise and calcium spray dryer by-products exhibited no significant heats of hydration.

Heat generated by hydration of tested AFBC by-product samples varied from a maximum temperature rise to approximately 82ºC (180ºF) in 20 minutes to a rise to 43ºC (110ºF) in 20 minutes.

Dimensional Stability. Dimensional stability refers to a material’s potential to maintain consistent length or volume over time. Some natural soils tend to expand or shrink in response to varying water content, which can pose difficulties when used as a building foundation area. Because ASC by-products contain or react to form chemical compounds which are potentially expansive, dimensional stability of the specific by-product and source should be determined prior to its use in a structural fill.

Many of the ASC by-product utilization tests in previous studies did not exhibit expansion. However, swelling potential was observed in a series of laboratory tests. AFBC by-product swell at 100 days ranged from 0.4% to as high as 25.7%) depending on the curing age and its original chemical components[20]. Also, some road base studies have experienced expansion of mixtures incorporating AFBC and suggest using smaller portions of by-product and preconditioned by-product. Variable unconfined compressive strengths over time have also been attributed to slow expansive reactions, although expansion was not reported. Therefore, expansion of by-product fills has not been directly reported, but warrants examination. For any projected by-product use, allowable expansion should be determined, and the material should be tested for linear stability over the long term. Expansion testing is discussed in Section 2, “Road Base. ”

Sampling and analysis of a 1500 ton LIMB stockpile over a 2½ year period determined that aging allowed expansive reactions to take place prior to use, but that the aged material is less cementitious. A uniformly high moisture content throughout a stockpile would most effectively reduce expansion potential[8].

pH. ASC by-products are generally alkaline, with many pH values near 12. Spray dryer leachate pH values ranged from 7.65 to 12 using the EP test and 9.8 to 12.1 using the Neutral Leachate Test. Calcium injection by-product leachate pH ranged from 7.8 to 12.4 and 11.6 to 12.0 using the EP and Neutral Leachate Tests, respectively[16].

Leachate Chemistry. Leachate characteristics for various samples of each by-product relative to Primary Drinking Water Standards (PDWS) are presented on Table 5-3. All of the leachates were far below toxicity levels (100 times PDWS). Only spray dryer sample AP07 passed the PDWS. Based on EP test results, by-products generally have a few parameters exceeding PDWS, with selenium exceeding ten times PDWS for both sodium injection samples and one of the FSI samples. The TCLP resulted in higher levels, with more parameters exceeding PDWS, and most samples exceeding ten times PDWS for arsenic and / or selenium. Calcium injection by-products had the lowest number of parameters exceeding PDWS from the TCLP test, with no metals exceeding ten times PDWS.

Table 5-3
Leachate Characteristics of ASC By-Products[a] Relative to Primary Drinking Water Standards

Sample No.		pH	RCRA EP		TCLP	
			Parameters > PDWS	Parameters > 10 Times PDWS	Parameters > PDWS	Parameters > 10 Times PDWS
AFBC; [b]	Bed	12.4	Cr,Ag		As, Cd, Cr, Pb, Se, Ag	As
	Char	12.1	Cr		As, Cd, Cr, Pb, Se, Ag	As
	Ash	12.1	Cr		As, Cr, Pb, Se, Ag	Se
	Composite	12.4	Cr, Ag		As, Cd, Cr, Pb, Se, Ag	As, Se
Spray Dryer:[c]	AR07	11.0	NO_3, Ba, Cr		NT	
	ST07	11.1	NO_3, Cr		NT	
	LR07	11.0	Cr		NT	
	HS05	8.45	NO_3, Cr, Se		NT	
	AP07	7.65			NT	
	NV04	12.0	Cr, Se, Ag		NT	
	RS05	8.7	NO_3, Cr, Se		NT	
	AV06	8.4	NO_3, Cr, Se, Ag		NT	
Furnace Injection:[d]	SR07	12.4	Cr, Se	Se	As, Cr, Pb, Se	
	SR09	12.4	Cr		As, Cr, Pb, Se, Ag	Se
	OL03	12.2	Cr, SE		As, Cd, Cr, Pb, Se, Ag	Se
	OL04	12.2	Cr		As, Cr, Pb, Se, Ag	Se
	OL08	12.2	Cr		As, Cd, Cr, Pb, Se, Ag	Se
Calcium Injection:[e]	AH06	12.4	NO_3, Ba, Cr	NO_3	Ba, Cr, Pb	
	AA10-01	8.2	NO_3		Cr	
	AA10002	7.8	NO_3, Cr, Hg, Ag		As, Ba, Cr, Pb	
Sodium Injection:[e]	NX04	8.7	As, NO_3, Se	NO_3, Se	As, Cd, Cr, Pb, Se, Ag	As
	NB04	4.95	As, NO_3, Cd, Se	NO_3, Se	As, Cd, Se	Se

Notes:

[a] NO_3 not tested in TCLP test.

NT Not tested

(Source: ICF Technology Inc.: [b]EPRI TR-105527; [c]EPRI CS-5782; [d]EPRI CS-5783; [e]EPRI GS-6622.)

Although sodium sorbent injection (SSI) by-products are not considered suitable for structural fills due to their low UC strength, they are listed on Table 5-3. Sodium injection PDWS parameters are similar to the other by-products, but sodium levels in the SSI leachate are high. Although sodium is not listed in toxicity, PDWS or secondary drinking water standards, high sodium levels are undesirable in drinking water.

Other Properties. Other properties related to structural fills of these by-products are permeability and radioactivity. Permeability is a measure of the rate at which a fluid passes through a material and, with leachate data, may be used to estimate possible impacts on groundwater quality. For comparison purposes, a permeability coefficient of 1×10^{-7} cm / set or lower is often required for clay liner materials in landfills. A 1×10^{-6} cm / set coefficient corresponds to a percolation rate of approximately 1 foot per year. Note that field permeabilities can be higher than laboratory permeabilities if cracks occur and are continuous throughout the fill thickness.

As part of EPRI RP2708, literature searches and laboratory tests were performed to establish material characteristics. Permeability tests were conducted by Radian on four AFBC waste samples. Each sample was prepared at optimum moisture and maximum dry density and cured for 28 days at 100% relative humidity. The test results ranged from 3.4×10^{-4} cm / set for SBM to 7.7×10^{-9} cm / set for AFBC fly ash. Limited permeability data was also found in two sources. One source reported values of 3.7×10^{-2} cm / set and 1.9×10^{-3} cm / set and 6.4×10^{-4} cm / set for AFBC fly ash; however, no information on test conditions were supplied[15]. A second source reported falling head permeabilities (Corps of Engineers Manual D2434) for SBM. For two samples, initial permeabilities of 1.03×10^{-3} cm / set and 1.26×10^{-3} cm / set decreased to 2.29×10^{-5} cm / set and 2.09×10^{-4} cm / set, respectively, after 28 days of curing[20].

Permeabilities of FSI by-products tested by Radian ranged from 3.8×10^{-9} cm / set to 2.8×10^{-5} cm / set, averaging 6.4×10^{-6} cm / set. Literature values for FSI waste permeability ranged from 5.8×10^{-6} cm / set to 7.35×10^{-6} cm / set, averaging 6.58×10^{-6} cm / sec[10,14]. All permeability measurements were made using the falling-head test method on samples compacted to Proctor density and cured for 28 days in a 100% moisture curing chamber.

For spray dryer by-products, the range of valid results varied from less than 9×10^{-10} cm / set to 9.7×10^{-5} cm / set [11,16] . For calcium injection by-products, permeabilities of three samples tested by Radian ranged from 2.9×10^{-7} to 7.4×10^{-6} cm / set, averaging 3.3×10^{-6} cm / sec[14].

Radian also reported data for radioactivity of by-products. EPA limits radiation levels for Ra-226 in soil to 5 pCi / g in the upper 15 cm and an average 15 pCi / g over any 15 cm interval below the upper 15 cm of soil. The radiation level of the AFBC fly ash samples exceeded this limit but levels in the composite sample were well below EPA limits. From this Radian data, it appears that by-products placed in a mixed condition would have radiation levels below EPA limits. The value reported for Ra-226 (pCi/g) for the AFBC fly ash sample was high in comparison with fly ash from conventional coal fired boilers.

FSI fly ash did not exceed radioactivity limits set by the EPA. The values reported by Radian for dry calcium injection showed that two of the three samples slightly exceeded the limit for the top 15 cm set by EPA (5 pCi/g) but were well within the below -15 cm interval limit (15 pCi/g). The average of the three dry calcium injection samples was less than both limits. Also, all four spray dryer samples measured below the 5 pCi/g limit.

Detailed Design

The detailed design phase includes the analyses for establishing final site geometry and for predicting the performance of the engineered fill. The following are pertinent design considerations that are typically evaluated in the design of engineered fills:

- Geotechnical considerations such as slope stability, foundation bearing capacity, embankment deformation and settlement
- Surface and subsurface drainage facilities
- Capillary action resulting in saturated material above the water table
- Corrosion protection for metal hydraulic structures
- Concrete protection against sulfate attack
- Frost heave
- Erosion control and prevention
- Dimensional stability

Many of these topics are discussed in detail in the *Fly Ash Design Manual for Road and Site Applications, Vol. 1*[2], and the reader is referred to that manual for instruction. Due to the cementitious nature of these by-products, concerns with many of these designed aspects are lessened for ASC by-products relative to fly ash. For example, cemented materials have a greater resistance to frost heave and erosion, and capillary rise does not present the risk of liquification in cemented materials. Also, settlement will be minimal if the UC strength is not exceeded. Settlement of ASC by-products is expected to be much less than that of a natural soil. Differential settlement between by-product and soil fill areas can be minimized by using a transition zone, rather than an abrupt change in fill materials.

Proper drainage remains critical for ASC by-product fills, as with conventional fills. Drains should be provided to control surface and subsurface waters and to prevent the build-up of hydrostatic pressure. A drainage system can be effective in minimizing ASC by-product swelling as it reduces the availability of moisture for absorption.

Corrosive Potential. Designers should evaluate the possibility of corrosion of pipes and structural members embedded in ASC by-product fill. Each ASC by-product should be individually evaluated. Several criteria have been published to evaluate corrosive potential. Resistivity monitoring is widely used to provide data for estimating the corrosivity of soil and, therefore, can be used as a basis for evaluating the corrosivity of ASC by-products. The Ductile Iron Pipe Research Association have proposed the following guidelines for resistivity for determining if a soil is corrosive to cast iron pipe:

- Less than 700 ohms-centimeter, the soil is definitely corrosive.
- Greater than 2000 ohms-centimeter, the soil probably will not be corrosive.
- Between 700 and 2000 ohms-centimeter, the soil could be corrosive depending on other factors such as pH, redox potential, sulfide presence in the soil, and moisture content (see Table 5-4).

Other published methods to evaluate corrosive potential are presented on Figure 5-14 and Table 5-5.

Where material shows corrosive potential, that material may not be suitable where leachate or the material will contact metal pipe. Alternatively, polyethylene sheeting, plastic pipe, bituminous coatings, or embedding and backfilling with inert material may be used to prevent corrosion.

Concrete Protection. The sulfate content of ASC by-product presents the possibility of sulfate attack on adjacent concrete structures. In some cases, the use of by-products adjacent to concrete should be avoided. In less severe cases, certain precautions may be advisable. These precautions consist of painting the adjacent concrete faces with tar, a bitumen paint, or a rubberized compound which also offers moisture protection to the concrete. The use of sulfate-resisting cement may be beneficial. To evaluate the potential severity of sulfate attack, Table 5-6 provides a guideline for the relationship of the sulfate content in ground water to the severity of deterioration which has occurred to exposed concrete. While this table has not been specifically developed for ASC by-products, it may be useful in the absence of more detailed information.

Table 5-4
Soil-Test Evaluation[a], Ten Point System, Ductile Iron Pipe Research Association

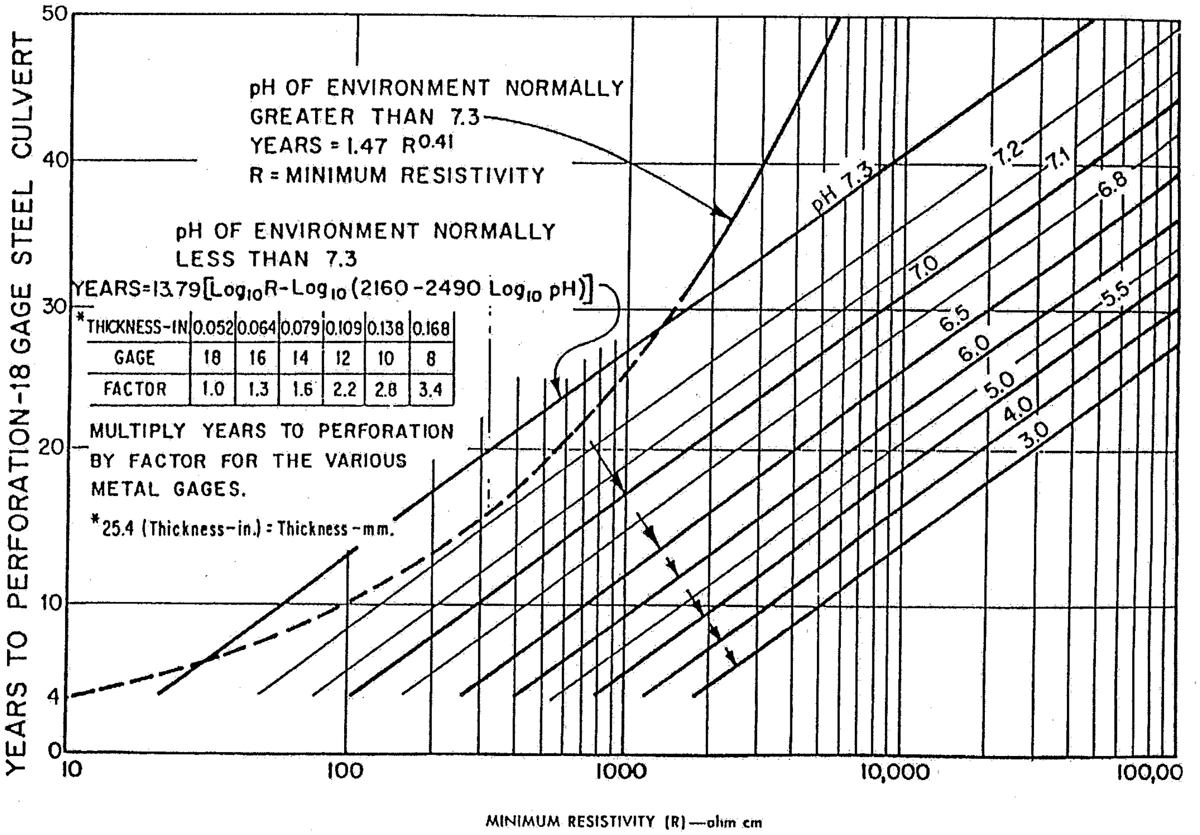
Soil Characteristics	Points[b]
Resistivity - *ohm-cm* (based on single probe at pipe depth or water-saturated Miller soil box);	
< 700	10
700 - 1,000	8
1,000 - 1,200	5
1,200 - 1,500	2
1,500 - 2,000	1
> 2,000	0
pH: 0 - 2	5
2 - 4	3
4 - 6.5	0
6.5 - 7.5	0[c]
7.5 - 8.5	0
> 8.5	3
Redox Potential:	
> + 100mV	0
+ 50 to + 100mV	3.5
0 to + 50 mV	4
Negative	5
Sulfides:	
Positive	3.5
Trace	2
Negative	0
Moisture:	
Poor drainage, continuously wet	2
Fair drainage, generally moist	1
Good drainage, generally dry	0

[a] Ten points - corrosive to gray or ductile cast-iron pipe; protection is indicated.

[b] This system developed by the Ductile Iron Pipe Research Association, commonly called *the ten point system*, is an attempt to use a multi-parameter approach to indicate the corrosive potential of soils. The table indicates the point ratings assigned to the different soil chemical parameters, with the total number of points indicating the quality of the soil. If the results of the ten point soil test evaluation are ten points or more, the soil is considered a corrosive environment to metallic pipe and the pipe needs to be protected. A point total of less than ten indicates corrosion is not a severe problem for gray cast iron or ductile iron pipe, therefore, protection of the pipe is not necessary.

[c] If sulfides are present and low or negative Redox potential results are obtained, three points shall be given for this range.

(SOURCE: From American Water Works Association, Proceedings from a Conference, “Corrosion Control,” May 16, 1982, No. 20165, p. 44.)



pH OF ENVIRONMENT NORMALLY GREATER THAN 7.3

YEARS = $1.47\ R^{0.41}$

R = MINIMUM RESISTIVITY

pH OF ENVIRONMENT NORMALLY LESS THAN 7.3

YEARS=$13.79[\mathrm{Log}_{10}R-\mathrm{Log}_{10}(2160-2490\ \mathrm{Log}_{10}\ \mathrm{pH})]$

*THICKNESS-IN	0.052	0.064	0.079	0.109	0.138	0.168
GAGE	18	16	14	12	10	8
FACTOR	1.0	1.3	1.6	2.2	2.8	3.4

MULTIPLY YEARS TO PERFORATION BY FACTOR FOR THE VARIOUS METAL GAGES.

*25.4 (Thickness-in.) = Thickness-mm.

Figure 5-14
Chart for Estimating Years to Perforation of Steel Culverts

(SOURCE: Califorina DOT, Division of Construction, Califorina Test 643, Figure 2.)

Table 5-5
Evaluation Criteria for Corrosivity of Fill Material[a]

Burried Structure	Minimum Resistivity[b] (ohm-cm)	pH[c]	Chloride[d] $^{-}$(ppm)	Sulfates[d] (ppm)
Steel Structures	> 1500	> 5.5	< 200 (< 0.02%)[e]	<1000 (< 0.1%)[e]
Reinforced Concretes	> 1000	> 5.5	< 500 (<0.05%)[e]	< 2000 (<0.2%)[e]

[a] Ash not meeting any one criterion is judged corrosive.

[b] Performed on crushed samples finer than the No. 8 sieve. Following California Test 532 or 643.

[c] Following California Test 422

[d] Following California Test 417

[e] Expressed as % (by weight)

(SOURCE: Ke, T-C., *The Physical Durability and Electrical Resistivity of Indiana Bottom Ash*, FHWA/IN/JHRP-90/6, Purdue University, April 1990, p. 286.)

Table 5-6
Attack on Concrete By Soils and Waters Containing Various Sulfate Concentrations

Relative Degree of Sulfate Attack	Percent Water-Soluble Sulfate (as SO_4) in Soil Samples	PPM Sulfate (as SO_4) in Water Samples
Negligible	0.00 to 0.10	0 to 150
Positive	0.10 to 0.20	150 to 1,500
Severe	0.20 to 2.00	1,500 to 10,000
Very Severe	Over 2.00	Over 10,000

(SOURCE: U. S. Bureau of Reclamation. *Concrete Manual*. Washington, D.C.: Government Printing Office, 1981, p.11)

Table 5-7
Types of Cement Required for Concrete Exposed to Sulfate Attack

Sulfate Exposure	Percent Water-Soluble Sulfate (as SO_4) in Soil Samples	PPM Sulfate (as SO_4) in Water Samples	Cement Type
Negligible	0.00 to 0.10	0 to 150	-
Moderate	0.10 to 0.20	150 to 1,500	II
			IP (MS)
			IS (MS)
Severe	0.20 to 2.00	1,500 to 10,000	V
Very Severe	Over 2.00	Over 10,000	V Plus Pozzolan

(SOURCE: Kosmatka, S. M. and Panerse, W, C. *Design and Control of Concrete Mixtures*. Portland Cement Association. Skokie, IL, 1988, p. 16.)

Radian testing presents both total soluble sulfur (mg/g as S) and leachate sulfate levels for SD, AFBC, FSI, and calcium injection samples. Using total soluble sulfur results and Table 5-6, these materials would be classified as causing severe to very severe sulfate attack. Using leachate sulfate levels, however, various material levels ranged from negligible to severe. Also, long-term tests show a great reduction in sulfate in leachate over time. For example, sulfate levels in one FSI sample dropped from 2200 ppm to 14 ppm in 79 days. One calcium injection by-product sample of sulfate leachate was only 8 ppm, dropping to 1 ppm in 28 days, while material from another calcium injection source was 3900 ppm dropping to 1040 ppm in 152 days. In conclusion, project-specific testing from the chosen source should be performed. Consideration of long-term versus short-term sulfate levels to predict sulfate attack depends upon groundwater and surface water flow conditions.

For elevated sulfate levels, sulfate resistant cement is suggested. Cement types for various levels of sulfate exposure are presented on Table 5-7.

Dimensional Stability. Finally, allowable expansion of the fill material should be determined for each particular application. If expansion potential of the selected by-product is suspected, long-term expansion tests such as those described in Section 2, “Road Base, ” should be performed.

Construction Details

The major items to be considered during construction of an ASC by-product fill include:

- Material conditioning, transport and storage
- Site preparation
- Placement and compaction
- Quality control
- Cover
- Post construction maintenance / evaluation

Material Conditioning, Transport and Storage

Based on the experience of plant operators with ASC by-product disposal, these materials are typically conditioned with water during silo discharge to control dusting and trucked in dump trucks. Difficulty in unloading due to early setting of materials has generally not been a problem. As the material is tacky and sets up over time, truck beds may require liners and / or frequent cleaning to reduce buildup of wastes. These material handling practices may also be applied to structural fill applications.

Control of dusting is critical for ASC by-products, as quicklime is a caustic irritant and can burn the exposed skin and eyes of workers. Although these materials can be transported dry in pneumatic trucks, transporting conditioned material in covered dump trucks adequately controls dusting and is more cost effective. Where long transport distance would allow the conditioned by-product to set up, pneumatic trucks can be used. Due to increased loading and unloading time, transport costs using pneumatic vehicles compared to dump trucks are an estimated 20% higher for a 50 mile hauling distance (2½ hours round-trip running time) and 60% higher for a 15 mile hauling distance (45 minutes round-trip).

Typically, 20 to 25% water by weight must be added to AFBC, SD, or FSI materials to control dusting, as the water content must be sufficient to both hydrate an dampen the materials. Procedures to determine the water content to completely prehydrate a by-product are presented in Section 2, “Road Base. ”

For most ASC by-product structural fills, the by-product would be discharged from the truck and immediately spread in place. Unless trial field tests indicate that the by-product will not become overly stiff during stockpiling and that delayed compaction will provide sufficient strength, stockpiling will not be practical.

A study by Minnick on stockpiling AFBC residue determined that stockpiles which were protected either by polyethylene sheets or by being indoors developed a slight crust but did not harden appreciably after a period of months. Evaluation of warehouse stored materials showed that after 1 ½ years, surface reactivity due to carbonation was decreased while interior material remained relatively reactive. Uncovered outdoor stockpiles developed a crust within a week and a 15 cm (6-inch) depth of cemented material after one month, which increased with time. 0.05-cubic meter (two-cubic foot) compartment volumes, which were open to the weather, hardened into solid monolithic masses during a six month period of time.

Site Preparation

Site preparation is generally specific to the location or function of the structural fill. Most sites require cleaning, grubbing, stripping of topsoil, and placement of erosion control prior to fill placement. Many sites also require placement of drainage layers or structures. Zones of soft surface soils are often removed and replaced with competent soil. The soil foundation should be smoothed to an even grade.

Use of by-products may require protection of concrete or metal appurtenances. Also, areas which may require later excavation should be identified by lines of demarcation if the by-product UC strength exceeds 1030 kPa (150 psi) at 28 days.

Placement and Compaction

For cohesive soils, compaction near the maximum density results in minimizing compressibility and permeability, maximizing shear strength, and providing the most stable material when subject to wetting and drying. To achieve proper compaction requires the correct moisture content, lift thickness, type of roller, speed of roller travel and number of passes. For each natural soil type, these combinations of parameters are well known. For ASC by-products, however, the best method has not been established.

As general guidance, structural fills are usually placed to have compacted lift thicknesses of 15 to 30 cm (6 to 12 inches). A 15 cm (6-inch) compacted lift would require a loose lift of 20 to 23 cm (8 to 9 inches). Materials typically are strongest at the optimum moisture content, as determined by ASTM D 698 or ASTM 1557. In general, smooth-drum and vibratory rollers are suitable for non-cohesive or granular materials and have worked well on Class F fly ash, while sheepsfoot rollers, which have long, thin feet, are effective in cohesive or clayey soils and Class C fly ash. Pad-foot rollers with short, wide, pegged feet have also worked well on fly ash. Roller type for specific ASC by-products or by-product:soil mixtures should be based on the nature of the material and field trials.

As discussed in the *Fly Ash Design Manual* test strips are useful to determine the most efficient/effective method to reach the required density. The result of a test strip would be a method specification (lift thickness, type of roller, moisture content, number of passes, etc.) to be followed by the contractor. Effectiveness of the method would be periodically checked by quality control testing.

An alternate means of specifying compaction is by performance specifications. This method allows material within a specific moisture content range to be placed and depends on frequent QC testing to confirm that adequate compaction is being achieved.

Surveys of disposal practice indicate that when sufficient water to control dusting is added at the silo, an additional 10% moisture must be added at the site for AFBC, SD, and an additional 20 to 30% added to FSI by-products.

For by-products with rapid temperature rise upon hydration, compaction should be delayed until “steaming” ends. Material placement in alternating areas may be used to allow the heat of hydration to dissipate prior to adding successive lifts.

Quality Control

Field moisture and density tests must be performed to control compaction. Oven drying to determine moisture content should be done at 55°C to avoid driving off hydrated water. Use of the speedy moisture tester or microwave oven should be calibrated with the conventional oven for each by-product source to confirm the accuracy of these methods. Field densities can be determined using the sand cone (ASTM 1556) or rubber balloon methods (ASTM D 2167). Use of the nuclear density gage to measure density should be calibrated with the sand cone or balloon method and confnm accuracy of this method.

Cover

In structural fill applications in which the ASC by-product is covered by pavement or a building foundation, adequate surface drainage should be provided. If the by-product leachate has sulfate levels which may be deleterious to concrete, directional surface drainage or a separation layer should be provided to prevent contact of the by-product fill, runoff, or leachate with concrete.

For most other structural fill uses, the final surface should be covered with soil and seeded. Although erosion and freeze-thaw are less critical for materials with high UC strengths, soil must be placed as a final cover to grow vegetation. In addition to aesthetic requirements (and highway specifications), a vegetated cover will reduce alkaline runoff.

Post-Construction Maintenance/Evaluation

During construction, monitoring the activities of construction crews should be conducted, and after construction is completed, observing the long-term behavior of the structural fill should be continued. Testing of fill should be conducted periodically for one year. Measurements generally can consist of settlement, piezometer readings, standard test borings, strength development, and selected physical properties, i.e., moisture content, loss-on-ignition (LOI), pH, and unconfined compressive strength.

Case Histories

Sherburne Plant Haul Road [3,4]

Radian Corporation, under contract to EPRI through ICF-Kaiser, constructed a demonstration road to test the performance of spray-dryer by-product used in road construction. This road section was 187 meters (614 feet) long with a 1.7 meters (5½ foot) embankment. The section is part of a haul road located on NSP property. Traffic includes 14 loaded 30-ton trucks per day, 7 days per week. Spray dryer by-product from Northern States Power's Sherburne Plant was used in mixtures in asphaltic and portland cement pavement, subbase, and embankment layers. The demonstration road section layout and cross-section are shown on Figures 5-15 and 5-l 6. Discussion of the pavement and subbase are presented in Section 8, "Cement Production and Replacement" and Section 2, "Road Base. "

The demonstration road was constructed from September 26 to October 10, 1991. In the embankment portion of the project, spray dryer by-product was used in Test Sections 1, 3, and 4 in a 5050 mix by weight with borrow soil, and in Section 5 as a 15 cm (6-inch) thick layer of 100% by-product.

Conditioned spray-dryer by-product was hauled to the site in 13 m^3 (17-yd^3) open-top dump trucks. Travel and wait times for hauling averaged 18 minutes, with a maximum of 45 minutes. In the mixed embankment sections, a 10 cm (4-inch) loose layer of common borrow was placed, followed by a 15 cm (6-inch) loose layer of spray-dryer by-product. This ratio resulted in a mixture of 50% by weight. The materials were mixed by four to six passes of a disk harrow pulled by a four-wheel drive tractor. After mixing, water was added by a minimum of two passes of a rear-discharge water truck.

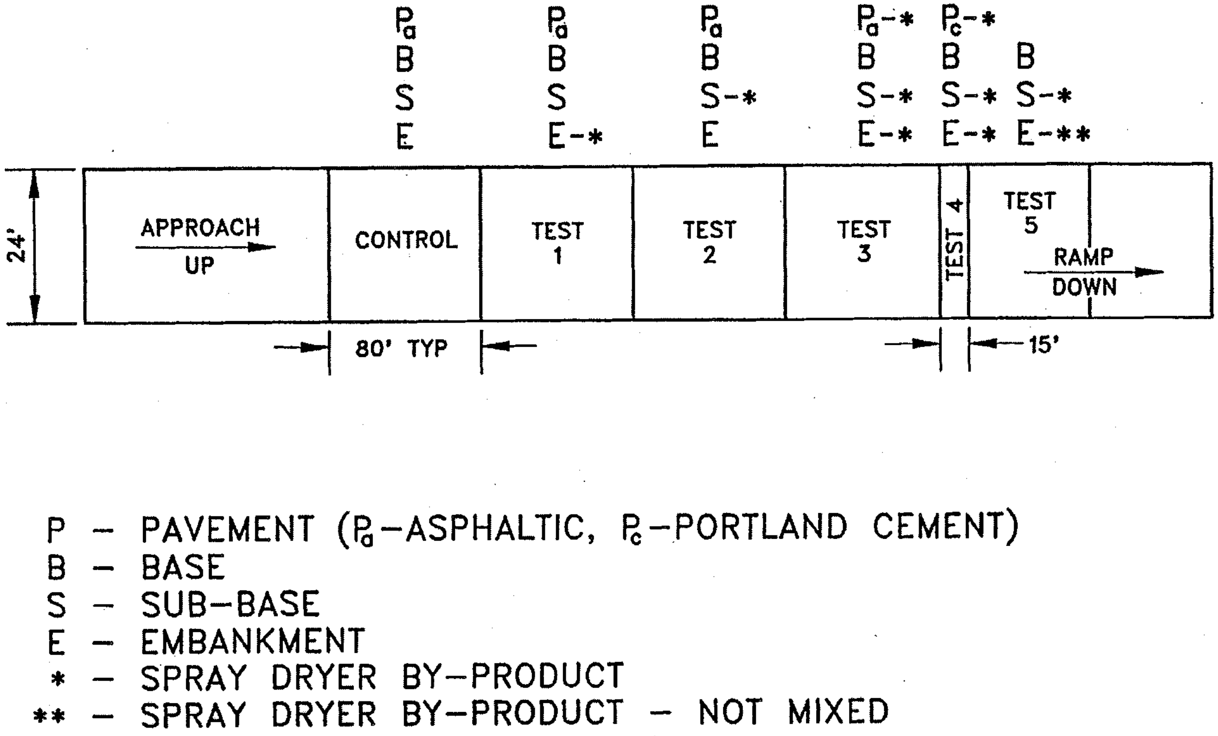


Figure 5-15
Demonstration Road Test Section Layout

(SOURCE: Radian Corporation. *Year-End Summary Report for EPRI's Demonstration Road at Northern States Power Company's Sherbune County Power Plant in Becker, Minnesota.* Revised Draft. Vol 1 of 2. Austin, TX. May 8, 1992)

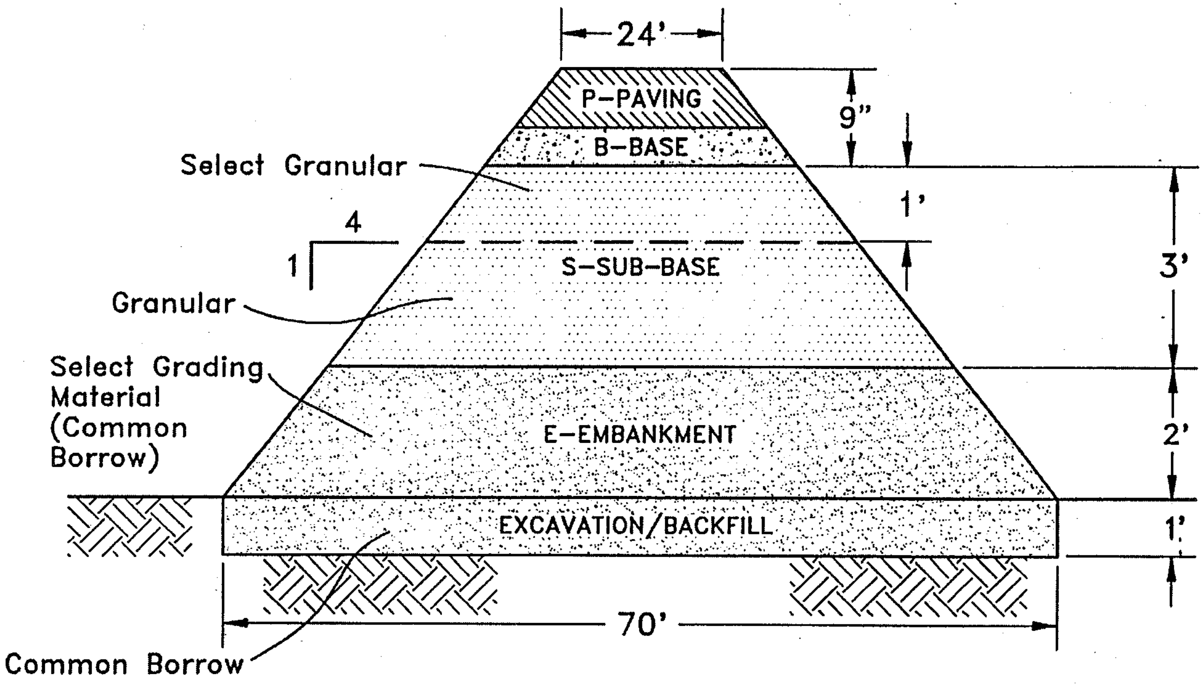


Figure 5-16
Demonstration Road Cross-Section

(SOURCE: Radian Corporation. *Year-End Summary Report for EPRI's Demonstration Road at Northern States Power Company's Sherbune County Power Plant in Becker, Minnesota.* Revised Draft. Vol 1 of 2. Austin, TX. May 8, 1992)

Next, the surface was graded. The material was compacted to 95% maximum density by 8 to 10 passes per lift of a vibratory sheepsfoot roller. (Fewer passes were needed for the mixture than for the common borrow alone.) The process was repeated until the embankment was brought to a 0.6-meter (2-foot) thickness. In Test Section 5, a 15-cm (6-inch) solid layer of compacted by-product was placed.

Density was measured using the Troxler density gage. The speedy moisture tester was used to monitor water content. The maximum dry density of the mixture was 1750 kg/m^3 (109.2 pcf) at an optimum moisture content of 13.1% . The thickness of the material was calculated by the weight of truckload and number of truckloads per lift.

The by-product was conditioned with approximately 12% moisture at the plant to help minimize dust emissions. Even after as long as a 45 minute wait time, no observed changes were seen in the workability or mixing ability of the spray dryer by-product.

Five-cm (2-inch) cube molds of by-product were tested in the laboratory. The compressive strength of the spray-dryer by-product was 10.4 MPa (1503 psi) at 7 days and 18.6 Mpa (2699 psi) at 28 days. Compressive strength of the 50:50 by-product:borrow mix was 3050 kPa (442 psi) at 7 days and 17.6 MPa (2546 psi) at 28 days.

Dynamic core penetrometer (DCP) tests were conducted on the embankment by Minnesota Department of Transportation (Mn/DOT) representatives in October 1991. At the top of the spray-dryer/borrow compacted lift in Test Section 1 penetration decreased from 2 to 0.4 cm (0.8 to 0.15 inches) blow, demonstrating soil strength gains where the spray dryer by-product was added. At Test Sections 3 and 4, the DCP showed decreased penetration to 0.08 cm (0.03 inches) blow. The penetration index of the monolithic layer of spray dryer by-product approached zero.

In the post-construction field study, Braun Intertec performed borings of the embankment layers. The blow counts were consistent with the Mn/DOT penetration tests, again demonstrating strength gains where spray dryer by-product was added.

Due to the availability of the embankment material (on-site pit) and the job size, the expense of blending the materials exceeded the savings from the low cost of the spray-dryer by-product.

The cost estimate on a large job, however, using *Means Site Work Cost Data*, assuming spray dryer by-product is provided at no cost but including hauling costs, indicates potential cost savings.

Environmental assessment data were obtained during preconstruction and post-construction monitoring. Table 5-8 lists the elemental concentrations from EPA Method 1312 on preconstruction samples, as compared to proposed Minnesota Pollution Control Agency (MPCA) drinking water limits. The spray dryer by-product and spray dryer by-product with common borrow exceeded the barium limit, and the selenium limit is exceeded in the common borrow with spray dryer by-product.

Immediately before construction of the demonstration test road, environmental data were collected on the construction mixtures to be used. The test data were obtained using TCLP and ASTM D 3987.

Table 5-8
Average Elemental Concentrations in EPA Method 1312 Extracts of Construction Materials Containing Spray Dryer By-Product (all values in ppb, μg/L)

Analyte[a]	Spray Dryer By-Product	50% Common Borrow[b] + 50% Spray Dryer By-Product	MPCA[c] Proposed Drinking Water Regulatory Limits
Arsenic	3	2	50
Barium	1,012	1,130	1,000
Cadmium	< 0.2	< 0.2	5
Chromium (VI)	26	< 6	50
Copper	< 1	2	1,300
Lead	< 1	< 1	20
Manganese	< 1	27	50
Mercury	< 0.2	< 0.2	1.1
Nickel	28	36	150
Selenium	9	11	10
Silver	3	< 1	50
Zinc	141	< 2	5,000

[a] Arsenic, selenium, lead, and cadmium analysis by graphite furnace atomic absorption, mercury analysis by cold vapor atomic absorption. Hexavalent chromium by EPA Method 7196 (colorimetry). All other elements by inductively coupled plasma emission spectroscopy.

[b] Combined by weight percent.

[c] Minnesota Pollution Control Agency.

Table 5-9
Range of Analyte Concentrations From TCLP Leachate of Construction Materials Collected During Construction (all values in ppm mg/L)

Analyte	Blank	Spray Dryer By-Product	MPCAA[a] Limits For Construction Materials
Arsenic	< 0.002	0.002 to 0.043	0.05
Barium	0.99 to 1.11	0.15 to 0.27	2.0
Boron	0.35 to 1.09	2.38 to 13.9	0.6
Cadmium	< 0.0004	< 0.0004 to 0.0008	0.004
Chromium	0. 008 to 0. 009	< 0.005 to 0.163	0.1
Copper	< 0.005	< 0.005	1.0
Lead	< 0.002 to 0.002	< 0.002	0.02
Manganese	0.005 to 0.009	< 0.005 to 4.45	0.6
Mercury	< 0.0002	< 0.0002	0.001
Nickel	0.052 to 0.053	0.032 to 0.161	0.14
Selenium	< 0.002	0.003 to 0.015	0.02
Silver	< 0.002	< 0.002 to 0.009	0.02
Tin	< 0.10	< 0.10 to 0.13	4000.0
Zinc	0.41	0.02 to 0.06	1.4

[a] Minnesota Pollution Control Agency

Table 5-9 lists some elemental concentrations of by-product leachate from the EPA TCLP procedure. The boron and chromium concentrations exceeded the proposed MPCA limits in the spray dryer by-product and embankment with spray dryer by-product.

Using the ASTM Shake Extraction of Solid Waste with Water (D3087) leachate test, spray dryer by-product did not exceed any of the limits, although barium levels were exceeded for embankment materials.

Boron concentrations in the control core sample from the earthen subbase exceeded the limit set for the construction materials. Manganese concentrations exceeded the limit in the control core sample from the embankment. Barium and boron concentrations in the embankment containing the spray dryer by-product exceeded the limit. The manganese limit was exceeded in the earthen subbase and embankment[4]. This result would be expected in the earthen materials because of the higher manganese content in the unamended earthen materials. These core results suggest that the spray dryer by-product addition to construction materials does not significantly affect the environmental characteristics of the unamended construction materials.

Using the ASTM D 3987 leachate test, barium and boron exceeded the limit in the embankment material containing the spray dryer by-product[3,4].

Four samples were collected from a storm runoff collection system from 1992 through 1994. In addition, ground water samples were collected from upgradient and downgradient wells 2 to 4 times a year through 1994. No measurable environmental affects were detected[21].

Ohio State Highway 541 [5,6]

Ohio State Highway 541 has suffered significant surface settlement and has exhibited features indicative of slope failure. Dry FGD by-product was used to construct a continuous wall at the base of the embankment to prevent further slippage along an existing failure plane. The existing embankment was excavated. Before the placement of dry FGD by-product, a geo-textile filter and drain tile were installed at the base. Self-loading scrapers delivered the by-product to the site as bulldozers spread it evenly over an area 12 meters wide by 30 meters long. The first lift of approximately 60 cm was placed and rolled at the end of the first day. By the next morning, the by-product was already strong enough that 40 metric ton scrapers could move freely over it without any noticeable settlement. Approximately 4 to 5 meters of the by-product have been placed in this embankment site. On top of the by-product, the original embankment material was replaced that totalled 3 to 4 meters. The second by-product layer measured 1 meter in depth, 10 meters in width, and 20 meters in length was placed from the center of the road to within 2 meters of the leading edge of the original embankment. On top of the fill, 5 meters of clay shale was placed. The parameters, such as pH, total dissolved solids, total alkalines, hydroxide alkalines, SO_2 and Cl, have been measured. No significant differences have been observed in the pre-construction and post-construction values.

Truck Ramp Construction [7]

The construction of a truck ramp made from spray dryer by-product was demonstrated on the campus of the Ohio State University in Columbus. Prior to the start of construction, the area on which the ramp was to be located was covered with an impermeable geomembrane. Drain lines were installed on top of the geomembrane so that water that might leach through the ramp could be collected. The by-product was placed on the geomembrane in 20 to 30 centimeter lifts by Ohio State University maintenance personnel without special equipment. A drain line was installed across the toe of the ramp to intercept surface runoff, and a wearing surface of 7 to 15 centimeters of crushed limestone was placed over the compacted by-product. A total of 180 metric tons of by-product was used in this ramp structure. One year after con-struction, there was no evidence of distress, nor any problems with the performance of the structure. Tests performed on the leachate and runoff water have shown high pH levels, but concentrations of metals fall below the established limits.

Summary

In summary, ASC by-products have been used successfully in a limited number of structural fill projects. Laboratory testing indicates that ASC by-products develop significant unconfined compressive strengths. Although UC strengths vary with type and source of by-product, as well as with time and curing conditions, for most samples tested both short- (7 day) and long-term UC strengths were adequate for typical structural fill designs. Optimum moisture contents of compacted ASC by-products must be determined differently than for soil due to hydration reactions and/or steaming. Of the materials tested, AFBC and FSI by-products generated significant heat during hydration, while spray dryer and calcium sorbent injection by-product did not. Long-term testing or field demonstrations are recommended to assess ultimate strength and dimensional stability. Preconditioning or stockpiling may mitigate problems with exothermic reactions or expansion should they occur.

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6

GROUT

Overview

Grouts are fluids used to fill voids or fissures accessible only by injection. Grouts are used either to increase the structural strength or to reduce the permeability of a subsurface location. Recently, use of FBC grout has been investigated to reduce acid production and direct water from acid producing material in reclaimed surface mines[1].

Suspension grouts are typically cement and water based, and may contain combinations of fly ash, lime and / or sand. Admixtures may also be used to control set or improve workability. In grout, advanced SO_2 control (ASC) by-products may be used to replace fly ash, lime and / or cement. Granular AFBC spent bed material may also serve as a replacement for sand in a grout mix. Preliminary laboratory strength tests and a market assessment performed under EPRI RP2708 indicate that nearly all of the ASC by-products have high potential for utilization in grout[2]. The exceptions include FBC spent bed material and SSI by-product, both of which have moderate potential. SSI test grouts developed significant strengths but have the potential for high solubility of the sodium sorbent. Long-term durability of these grouts have not been tested.

An EPRI laboratory study on by-product grouts tested compressive strength and flow of mixes with various SO_2 control by-products. Seven-day compression strengths for 3:1 and 1:1 cement:by-product mixes ranged from 2070 to 15860 kPa (300 to 2300 psi), and strength consistently increased between 7 and 28 days[3]. These results are very promising. The possible effects of expansion of these grouts, however, has not yet been addressed. In some situations, expansive grout can be beneficial. Uncontrolled or unexpected expansion, however, can damage adjacent structures. This property needs to be investigated further.

Another concern with by-product grouts is the potential for corrosion and sulfate attack of concrete and steel structures. When laboratory testing indicates high sulfur concentrations in leachate, and there is the possibility of leachate contact with concrete structures, either the structures must be protected prior to grouting or another type of grout should be selected. Sulfate attack and corrosion potential are discussed in Section 5, “Structural Fills. ”

Potential advantages of FBC fly ash, spray dryer, furnace sorbent injection, and calcium in-duct injection by-products include:

- Fine particle size
- Reduced segregation
- Low cost
- Excellent strength development

Fine particles allow grout penetration of fine voids. Lime, which is present in these by-products, tends to form a colloidal grout mix, reducing segregation and increasing pumpability. The cost of by-products is low relative to cement or lime, and strength development is in the range of design strengths for typical fly ash grouts.

FBC spent bed material may also be useful in grout, although this coarser-grained material would be suitable for larger voids and fissures.

Possible limitations to be considered include:

- Expansion
- Sulfate attack on concrete
- Time of set
- Heat of hydration

Although expansion of by-product grout has not been documented, the potential for expansion should be tested for any proposed SO_2 control by-product mixture. Expansion could cause failure of pavements or other adjacent structures. Expansive grouts are useful in some applications, however, and may be suitable as mine backfill. Potential for migration of high-sulfate leachate should also be considered. Finally, set time may control pumping distance for by-product grouts. For grouts with too fast a set, retarders may be necessary so that grout does not set up in the lines. Extended set time will also allow the use of fewer injection holes. Finally, by-products with a rapid rise in heat of hydration are not suitable for mass grouting. Excessive heat may cause reduced strength, cracking, or even blow-outs. Heat may be controlled by preconditioning or by placement in thin lifts, allowing heat dissipation prior to each subsequent injection.

For a general background on grouting and the use of fly ash grouts, the reader is referred to the *Fly Ash Design Manual for Road and Site Applications, Volume 2: Slurried*

Placement[4]. Injection technology, layout of holes, and quality assurance are typically determined by specialty firms and will not be covered in this report.

State of Practice

No documented use of any of the five ASC by-products on a grouting project was found. Available data on these by-products in grout mixes consists of laboratory compression strength and flow tests presented in *Advanced* SO_2 *Control By-Product Utilization: Laboratory Evaluation*[3]. Test results will be presented later in this section.

Design Parameters

Design procedures for an ASC by-product grout are similar to those of other suspension grouts. A general approach for grout design is presented in the *Fly Ash Design Manual for Road and Site Applications, Volume 2: Slurried Placement*[4].

Conceptual Design

Basic considerations for conceptual design include the choice of grout method and the decision to grout versus other methods of structure improvement. Additional factors to consider for by-product grouts are heat of hydration, sulfate attack, and expansion. Should laboratory test results indicate concern in any of these areas, use of by-product grout may be limited.

Suspension grouts are often used to fill voids, such as spaces around oil well casings, old mine workings, cavities under floor slabs, lost ground during tunneling, and subsealing pavements. Suspension grouts may also be used to permeate small interstitial voids or fissures in soil or rock. Based on particle size, fine-grained by-product grouts could be used as a permeation grout for coarse sand or gravel, but will not effectively permeate finer soils. Grout containing sand-sized FBC spent bed material would be too coarse for use as a permeation grout, but would be useful for void filling.

Mix Design

Grouts are designed to provide adequate penetration, strength, and durability. Penetration depends on the grout particle size and viscosity. Viscosity can be altered by varying the water content.

Strength is needed to resist both surface loading and hydraulic gradients (flow of ground water). Compressive strength can be tested by ASTM C 39, “Test Method for Compressive Strength of Cylindrical Concrete. ” Fly ash grouts are typically designed to have 345 to 3450 kPa (50 to 500 psi) for low strength applications, such as mine backfill, or 5520 to 15170 kPa (800 to 2200 psi) for high strength applications. High strength grouts are used under piles or pavements or to resist flowing water.

For grout curtains which serve as water barriers, strength of the grout seal affects overall permeability of the grouted zone. As contact between the grout and adjacent soil, rock or structure is reduced by grout shrinkage, slight expansion of the grout will improve contact and lower the permeability of the grout zone. Expansion prior to set can improve grout contact, but long term or excessive expansion can cause heave and damage surrounding materials.

Expansion of grout may be beneficial in mine voids to counteract rock heaving which results from the pressure relief upon removal of the mined material.

Finally, the grout must be able to resist deterioration and loss of strength. The durability of by-product grout is unknown. Durability can be tested by the fresh water soak test.

Mix Components. Possible components of a grout mix are as follows:

- ASC By-Products - Effect of by-product may vary with type and source of by-product. In general, some AFBC and FSI materials have shown a significant heat of hydration[5,6], while spray dryer and calcium in-duct injection by-products have shown a consistently low heat of hydration[7,8]. High heat hydration in grout may be resolved by prehydrating the by-product prior to mixing in grout. Set time may allow time to mix and pump without problems, although some sources of FSI have hardened in trucks during disposal operations, indicating a fast set time. Strength is difficult to predict and must be tested for each unique mix.

- Cement - Cement supplies strength to grout, but is generally kept to a minimum to minimize cost. Although the addition of cement will usually increase the strength of the mix, by-product grouts may not require cement to achieve design strengths. If durability is suspect, “sulfate resistant” or “high sulfate resistant” cements may provide more durable mixtures with ASC by-products.

  Fine-grained by-products may be used as a fly ash replacement to reduce shrinkage or segregation in a sanded mix. AFBC SBM may be used as a sand replacement, although one source indicates that during hydration, AFBC SBM converts from a sandy to a powdery materia1[3]. As by-products are reactive, their effect on strength, set time, heat of hydration, durability, and expansion should be evaluated.

- Water - The water content of a grout has a great effect on the grout properties. While an increase in the water content beyond hydration supplies fluidity, water content must be limited to control strength.

The three parameters which control the allowable water content are strength, pumpability, and penetration. The purpose of grouting determines which need dominates. For a cement-based grout, a slight increase in water content may result in a significant decrease in strength. For maximum strength, a pumpable mix should be designed near the saturation point. For fly ash-cement grouts and neat cement grouts, this point occurs at a water to solids ratio (WSR) of about 0.4. For penetration grouting, grouting may be initiated with a thin mix having a WSR of 3 or even 6. The WSR of an ASC by-product grout should be determined by testing of the by-product mix.

- Lime - Lime has been used alone as grout or with a pozzolan. When used alone, lime can react pozzolanically with certain soils to create hard grout seams. If no source of silica or alumina is available in the soil or other grout components, the lime slurry will remain colloidal under water rather than hardening. The addition of lime is expected to increase the strength of an ASC by-product grout, although this should be confirmed by laboratory testing.

- Sand - Sand is sometimes used as a fine aggregate in cement grouts. The addition of sand creates denser grouts with properties similar to concrete. Since sand has larger particle sizes than cement, the addition of sand to a cement grout reduces penetration and often makes pumping difficult. Sand is a common grout component for tunnel grouting, cavity filling, and grouted aggregate columns.

- Fly Ash - Class F fly ash generally has good flow properties, low heat of hydration, slow set, slow strength development, and improves the sulfate resistance of portland cement concrete. Class F fly ash develops strength by reacting pozzolanically with lime. As this reaction occurs slowly, fly ash may contribute significantly to strengths at periods longer than 28 days. Class C fly ash may harden without the addition of cement or lime. Some Class C fly ashes harden rapidly.

  Some fly ashes have a high loss on ignition (LOI). The major effect of a high carbon content is that porous carbon causes the fly ash to absorb water, similar to unsaturated aggregate, and stiffen the concrete mix. High LOI fly ash therefore requires a higher water content. Fly ash has also been shown to reduce shrinkage in sanded mixes.

- Admixtures - Numerous products are marketed as retarders and accelerators for cement-based mixes. These admixtures may affect time of set, workability, and strength. Their effect on by-product grouts is unknown.

  Additives which have effectively controlled time of set of Class C fly ash mixes include small amounts of cement, gypsum, borax, or commercial retarders.

Mix Design Steps. For an ASC by-product, the first step of mix design involves determining the water required for hydration, as discussed in Section 2, “Road Base.” If necessary, the ASC by-product should be prehydrated. Water should then be added to the hydrated ASC by-product in a measured quantity sufficient to achieve the desired flow. The resulting grout should be tested for strength. If the desired strength is achieved, time of set, heat of hydration, expansion, durability, and leachate should be tested. Strength generally increases with increased proportions of cement. Fly ash, lime, or additives may effect several properties. Sanded or AFBC SBM grouts should be tested for bleeding and segregation. Bleeding and segregation may be improved by increasing the paste content (cement, fly ash, lime or fine-grained by-product) of the mix.

Detailed Design

Detailed design of a grout program involves selection of the method of injection, hole layout and spacing. The reader is referred to the *Fly Ash Design Manual for Road and Site Applications, Volume 2: Slurried Placement*[4] for a general discussion of these topics.

Construction Details

Grouting equipment and quality control are discussed in general in the *Fly Ash Design Manual for Road and Site Applications, Volume 2: Slurried Placement*[4].

Of special interest for by-product grouts is material preparation. As was discussed in Section 5, “Structural Fills, ” some studies indicate that “conditioning” (prehydrating) ASC by-products, particularly AFBC residue (road base mixtures), reduces the potential for expansion. Preconditioning should be completed prior to mixing the by-product with the other grout components.

ASC by-products can be discharged from the silo at the plant in either a dry or conditional (moistened) state. Dry by-products must be transported in pneumatic trucks. If the size of the project requires on-site storage, dry by-product can be stored on-site in silos, although this cost may be prohibitive.

ASC by-products may also be discharged from the silo in a conditioned (moistened) state to control dusting and allow transport in covered dump trucks. Water addition during grout mixing would be reduced to account for conditioning water. Trial mixes would be needed to determine allowable delay times between conditioning and grout mixing. On-site storage may be limited to short-term or protected storage for conditioned by-products.

Quick limes are often hydrated or “slaked” using batch or continuous (detention) slakers. Detention slakers discharge a hydrated lime slurry ranging from a creamy suspension in the range of 30% solids to a thin slurry in the range of 10% solids. The detention slaker use an impeller-type mixer, which agitates the slurry to prevent local overheating and “hot spots” in the slaking chamber. Mechanical slakers serve to hydrate quick lime, as well as removing oversized particles (grit). Several manufactured lime slakers are currently on the market which may be suitable for hydrating ASC by-products. Slaking of by-products prior to mixing with other ingredients and / or injection may be useful for controlling the heat of hydration, unconfined compression strength, or expansion of the grout.

Environmental Considerations

The leachate concentrations for compacted by-products without cement are typically well below toxicity criteria for hazardous wastes; leachate concentrations of cemented by-products would be expected to be even lower. Also, laboratory tests have shown that permeability (and thus leachate generation) decreases over time.

Environmental concerns with ASC by-product grouts include high pH and sulfate levels in the leachate, although sulfate levels decreased over time in long-term laboratory studies. In many grouting applications, leachate would be in direct contact with ground water.

Sodium injection leachates show high levels of soluble sodium. Although sodium is not a regulated parameter for determining the characteristics of toxicity, as a criterion of primary or secondary drinking water standards, high sodium levels may not be desirable in water supply aquifers.

It is recommended that leachate tests be performed on any grout mix proposed for use in contact with groundwater. Leachate parameter levels, pH, long-term permeability, and use of the aquifer should be considered when evaluating appropriate use of the grout.

Case Histories

EPRI Laboratory Testing Program

A basic laboratory testing program for grouts was presented in *Advanced SO_2 Control By-Product Utilization: Laboratory Evaluation*, EPRI CS-60443. In this study, grout mixes were prepared with cement and ASC by-products at various proportions with sufficient water to achieve a flow in the range of 5 - 35 seconds. Four different cement to by-product ratios were used in the various mixes, as follows:

- 3 parts cement to 1 part ASC by-product
- 1 part cement to 1 part ASC by-product

- 1 part cement to 2 parts ASC by-product
- No cement (2 parts AFBC SBM to 1 part conventional fly ash)

The initial mixtures using three parts cement to one part by-product were prepared using all the by-products except the AFBC SBM and waste composite samples. All of the grout mixes achieved 28-day compressive strengths greater than 4480 kPa (650 psi) and, therefore, the same ASC by-product samples were used in the preparation of mixtures with one part cement to one part ASC by-product. The AFBC fly ash and spray dryer ash HS05 also were used in the one part cement to two parts by-product mixes. An additional mixture with two parts AFBC SBM and one part low calcium (5 percent CaO) conventional fly ash was selected based on work by TVA which used these proportions as a replacement for cement and fine aggregate in a concrete mix.

When preparing the grout mixes, dry materials were well blended before addition of water. After adding water, the grout was mixed for approximately two minutes; first a low speed for one minute than at a higher speed for one minute. 7.6-cm (three-inch) diameter cylinders were prepared for 7, 28, and 60-day compression strength testing and 15-cm (six-inch) diameter cylinders for an additional 60-day compression strength test. Compression strength cylinders were cured and tested in accordance with ASTM C 492 procedures.

As shown on Table 6-1, the 28-day compression strengths of the grout mixtures ranged from 4500 to 26150 kPa (653 to 3,792 psi). With three parts cement to one part by-product, the furnace injection, calcium injection, and spray dryer HS05 mixes achieved the highest strengths. At one part cement to one part by-product, mixture strengths increased for the AFBC ash, spray dryer, and sodium injection mixes and decreased for the furnace injection and calcium injection mixes. Only two ashes, TV05 and HS05, were used in mixes with one part cement to two parts ash; there mixes achieved 28-day compression strengths of 5980 and 10940 kPa (868 and 1,587 psi), respectively.

It is interesting to note that for the AFBC ash, both spray dryer sources, and the sodium injection by-product, the 1:1 cement: by-product mixture had higher 28-day compression strengths than the 3:1 mixtures. This indicates that more cement does not always improve the strength.

USBM Surface Mine Grouting [1]

The U.S. Bureau of Mines (USBM) is cooperating in a test of surface injection of grouts containing fly ash, lime, FBC ash and acid mine drainage sludge into a reclaimed surface mine[1]. Grouting was conducted over a 1920-ml^3 (3-acre) portion of the 23040-ml^3 (36-acre) site. Water samples from wells and seeps were analyzed to assess the affect on water quality. Acidity, iron, magnesium, manganese and sulfate concentrations subsequently decreased at monitoring wells in the grouted area. The concentration of calcium increased and small localized increases in lead, chromium, copper, cobalt and zinc were observed, but at levels that do not represent a hazard to surface or groundwater. Continued monitoring is planned.

Summary

In summary, all of the by-products show significant potential for use in grout based on laboratory compression strengths. Both low permeabilities and low leachate concentrations would result in minimal environmental concerns in most grout applications. Potential problems which would limit use of grout include: grouts with high sulfate levels in leachate are not appropriate near concrete structures; grouts with high heat of hydration are not appropriate for mass grouting; grouts which expand after set may damage adjacent materials. Also, long-term durability should be tested. Heat of hydration, expansion, and durability may all be improved for some ASC by-products by prehydration of the material. Laboratory tests should be performed on each proposed mixture to investigate these concerns.

Conventional grouting equipment would be suitable for ASC by-product grout mixing and injection. Commercial lime slaking equipment may be useful for prehydrating ASC by-product slurries. Field trials must be performed to determine the best method or necessity of conditioning or slaking the by-products prior to mixing.

Table 6-1
Grout - Laboratory Evaluation of Various ASC By-Products

		Mix Ratio Cement/ By-Product	Water Ratio Water/Dry	Flow[a] (sec.)	Compressive Strength[b] (MPa)			
					7-day	28-day	60-day	Cylinder
AFBC:	TV05	3/1	1.27	11	4.4	8.7	9.4	6.6
	(ash)	1/1	0.75	20	4.8	9.1	NA	NA
		½	0.84	35	3.0	6.0	NA	NA
Spray Dryer:	LR07	3/1	0.88	10	2.3	4.5	7.1	6.6
		1/1	0.56	13	10.1	19.3	NA	NA
Spray Dryer:	HS05	3/1	0.75	33	16.1	21.3	26.0	15.4
		1/1	0.51	34	13.8	26.1	NA	NA
		½	0.55	20	10.0	10.9	NA	NA
Furnace Injection:	OL03	3/1	0.53	16	14.8	22.9	NA	NA
		1/1	0.55	27	7.8	9.9	NA	NA
Furnace Injection:	OL08	3/1	0.49	20	9.1	18.7	NA	NA
		1/1	0.56	23	4.1	8.2	NA	NA
Calcium Injection:	AA10-02	3/1	0.51	23	13.5	24.7	NA	NA
		1/1	0.60	24	7.0	14.2	NA	NA
Sodium Injection:	NX04	3/1	0.75	23	3.7	5.2	6.6	5.5
		1/1	0.56	35	7.6	14.7	NA	NA
Control[d]		3/1	0.75	10	2.3	5.2	7.3	4.3

Notes:

[a] Flow determined in accordance with ASTM C 939.
[b] Average of three; determined in accordance with ASTM C 492.
[c] 15 cm diameter cylinder cured for 60 days. All other cylinders were 7.5 cm in diameter.
[d] The control mixture used Coal Creek conventional fly ash instead of ASC by-product.

(Source: *Advanced SO_2 Control By-Product Utilization: Laboratory Evaluation*, EPRI CS-6044)

References

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2. ICF Northwest. *Utilization Potential of Advanced SO_2 Control By-Products*. EPRI CS-5269. June 1987,

3. ICF Northwest. *Advanced SO_2 Control By-Product Utilization*: Laboratory Evaluation. EPRI CS-6044. Final Report, September 1988.

4. GAI Consultants, Inc. *Fly Ash Design Manual for Road and Site Applications, Volume 2: Slurried Placement*. EPRI TR- 100472. April 1992.

5. ICF Technology Incorporated. *Laboratory Characterization of Atmospheric Fluidized-Bed Combustion By-Products*. EPRI TR- 105527. Final Report, September 1995.

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7. ICF Technology Incorporated. *Laboratory Characterization of Advanced SO_2 Control By-Products: Spray Dryer Wastes*. EPRI CS-5782. Final Report, May 1988.

8. ICF Technology Incorporated. Laboratory Characterization of Advanced SO_2 Control By-Products: Dry Sodium and Calcium In-Duct Injection Wastes. EPRI GS-6622. Final Report, December 1989.

7

AGGREGATES

Overview

This section describes the use of advanced SO_2 control (ASC) by-products to produce synthetic aggregates. Synthetic aggregates are usually lighter in weight than natural aggregate, and are typically produced for use in lightweight block or concrete. The aggregate manufacturing processes and the laboratory testing methods are discussed in detail. The direct use of FBC spent bed material as aggregate in concrete is also discussed in this section. Several case histories are presented.

Methods for the manufacture of synthetic aggregate can be distinguished by the processes employed to form the aggregates. Most forming processes for synthetic aggregate production involve either mechanical agglomeration, briquetting, or forming large blocks. The sintering process, in which the “green” particles are kiln-fired at temperatures of 538°C to 1093°C (1000°F to 2000ºF), is well-established. Synthetic aggregates have been produced for many years by sintering expansive clays, slates, or shales. Sintered aggregates made from coal waste or fly ash have also been produced in the United States. For by-products, the sintering process is used following mechanical agglomeration. The residual carbon content of the coal waste or fly ash benefits the sintering process.

In addition to the sintering process, curing processes with lower energy requirements have been developed. These processes have attracted more attention in recent years. The aggregate in these processes is composed of chemically reactive materials such as cement, lime and fly ash. The aggregates are produced by briquetting or forming large blocks and then curing and crushing. The bonding strength between composite particles is developed by pozzolanic and cementitious reactions during curing. The properties of the aggregates are affected by the method of aggregate formation and the curing condition.

ASC by-products can potentially be used for synthetic aggregate production. Mechanical agglomeration, the briquetting process, or forming large blocks, followed by high temperature curing and crushing, are the most suitable procedures for production of synthetic aggregate using ASC by-products.

State of Practice

Synthetic aggregates have been produced from ASC by-products at a laboratory scale by ICF Northwest under an EPRI contract[1]. The by-products from AFBC, spray dryer, furnace sorbent injection, calcium sorbent injection, and sodium sorbent injection were investigated. Synthetic aggregates were produced by two processes, 1) mechanical agglomeration followed by kiln-firing and 2) briquetting followed by CO_2 environment bag curing and then moist room curing. The aggregates produced were light in weight and have desirable strength.

The Ohio Coal Development Office managed a project to produce artificial aggregates from a Coolside by-product, LIMB by-product, and FBC by-product[2,3]. The project included the production of synthetic aggregate and use of the aggregate in road construction. About 40 tons of aggregate were produced. The synthetic aggregates were tested for compressive strength, abrasion resistance, unit weight, specific gravity and grain size distribution. The test results indicated these aggregates were suitable for use as road construction material.

Production of synthetic aggregate from AFBC by-product combined with conventional fly ash has been reported by the Department of Energy (DOE)[4] and Iowa State University[5]. Aggregates were produced by forming large blocks or beams, then curing and crushing them to produce a small-sized aggregate. The gradation of the aggregate was controlled by screening. The characteristics of produced aggregate for use as road construction material were evaluated. The study showed that an acceptable aggregate could be produced from combinations of conventional fly ash and AFBC by-product.

Spent bed material from FBC technology is a granular material with a size distribution similar to that of natural sand. The use of unprocessed spent bed material as a fine aggregate in concrete was investigated by Iowa State University[6] and Southern Illinois University[7,8]. Concrete pavement slabs were constructed at a site located on the grounds of the Illinois Coal Development Park. The laboratory and field test showed encouraging results.

Aggregate Production

There are three design steps to produce aggregate from ASC by-products:

- Determination of the by-products characteristics and selection of mixture proportions.

- Selection of forming and curing method.

- Evaluation of the manufactured aggregates.

Determination of the ASC By-Products Characteristics and Selection of Mixture Proportions

First, the characteristics of ASC by-products should be identified. Minimum test requirements include the chemical composition and particle size distribution. The quality of manufactured aggregate depends on the cementing potential of the ASC by-product and the aggregate forming and curing processes. A cementitious reaction must occur to bond the individual particles.

For ASC by-products, the cementing potential depends on the available free lime and fly ash content.

The basic components of the mixture are ASC by-product and water. However, cement, lime, and conventional fly ash can be added to provide strength development. Sometimes preconditioning of the by-product is needed before mixing the by-product with other materials. A 7-day compressive strength of 3450 kPa (500 psi) (ASTM C 593 test method) may be used as a criteria for determining cementing ability of by-products and for evaluating the need for addition of other chemical additives.

Selection of Aggregate Forming and Curing Methods

There are three methods which can be selected to form synthetic aggregate from ASC by-products: mechanical agglomeration, briquetting, or forming large blocks. For any of these methods, moist curing at elevated temperatures can be used.

With mechanical agglomeration, the aggregates are formed by adding water to the ASC by-product to form spheroidal pellets in a mixer. This method uses agitation to consolidate the mixture. The agitation process of agglomeration causes the individual particles to ball together as a consequence of mechanical and capillary forces and is free of external compacting forces.

In the briquetting method, a briquetting machine is used. A briquetting machine uses molding pressures to compact the mixture within the mold.

Synthetic aggregates can also be produced by making large blocks or beams with ASC by-products and water. The block / beams are cured to a desired strength and then crushed and graded.

Fresh pellets, briquettes or blocks / beams do not have enough strength for most aggregate uses. The strength requirement of synthetic aggregate must be achieved by curing. The bonding between individual particles is attained by cementing and pozzolanic reaction. Moist curing at 38°C to 93°C (100°F to 200°F) will speed up the cementing and pozzolanic reactions. The pellets can be sintered in a kiln to develop strength but has the disadvantage of high energy costs.

Evaluation of the Manufactured Aggregate

In general, synthetic aggregates should meet standard requirements of the ASTM specifications in the expected application areas. Table 7-1 lists ASTM specifications related to aggregates and aggregate uses, while Table 7-2 lists ASTM test methods. ASTM standards for block and concrete are presented on Table 7-3.

Table 7-1
Specifications for Aggregates and Aggregate Uses

C 33	–	Standard Specification for Concrete Aggregates
C 90	–	Standard Specification for Load Bearing Concrete Masonry Units
C 144	–	Standard Specification for Aggregate for Masonry Mortar
C 331	–	Standard Specification for Lightweight Aggregates for Concrete Masonry Units
C 332	–	Standard Specification for Lightweight Aggregates for Insulating Concrete
C 404	–	Standard Specification for Aggregate for Masonry Grout
C 637	–	Standard Specification for Aggregates for Radiation-Shielding Concrete
D 242	–	Standard Specification for Mineral Filler for Bituminous Paving Mixtures
D 692	–	Standard Specification for Coarse Aggregate for Bituminous Paving Mixtures
D 693	–	Standard Specification for Crushed Aggregate for Macadam Pavements
D 1073	–	Standard Specification for Fine Aggregate for Bituminous Paving Mixtures
D 1139	–	Standard Specification for Aggregate for Single or Multiple Bituminous Surface Treatments
D 1241	–	Standard Specification for Materials for Soil-Aggregate Subbase, Base, and Surface Courses
D 2940	–	Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports

ASTM C 90, the standard for block, refers to ASTM C 33 and C 331 for requirements of normal weight and lightweight aggregate, respectively. Tests which are in turn referenced by these two standards are unit weight, grading, friable particles, length or volume change, and freeze-thaw resistance for both types of aggregate; soundness, wash loss, and reactivity, for normal weight block aggregates; and loss-on-ignition, popouts, and staining for lightweight aggregates. To assure that the aggregate is suitable for use in block, the block produced using the synthetic aggregate should also be tested. Block testing under ASTM C 90 includes shrinkage, moisture content, compressive strength, water absorption and oven dry weight.

In addition, possible concerns related to calcium sulfate compounds which occur in ASC by-product ash include: dimensional stability (expansion), long-term strength loss, and sulfate attack on mortar within or between concrete blocks. Use of prehydrated ASC by-product may mitigate long-term changes in dimensional stability and strength; however, a field demonstration wall of block produced with synthetic aggregate would be necessary to completely resolve concerns associated with calcium sulfate and related compounds.

Case Histories

ICF Northwest Laboratory Test Program [1]

Synthetic aggregate was produced using five different ASC by-products. Two production procedures were used: agglomeration followed by sintering, and briquetting followed by CO_2 environment curing. The AFBC fly ash, AFBC spent bed material, spray dryer by-product, furnace sorbent injection by-product, and sodium sorbent injection by-product were used to produce the synthetic aggregate.

To test the agglomeration method, the ASC by-product was mixed with water to form spheroidal agglomerates in a tilted five-gallon pail mixer. The resulting spheroidal particles were air-dried and then kiln-fired to 982ºC to 1177ºC (1800ºF to 2150ºF) to form light-weight aggregate. The aggregates so produced were tested for specific gravity and hardness visually observed.

To test the briquetting method, the briquettes were formed by pressing the ASC by-product and water mixture into 2.5-cm (one-inch) diameter by 2.5-cm (one-inch) deep molds and then compacting the material within the mold. The unmolded briquettes were cured in a bag which receives CO_2 from a gas cylinder for 20 hours, and then transferred to a moist room for additional curing. After five days of moist curing, the briquettes were tested for compressive strength and the specific gravity of the aggregate formed from the crushed briquettes was determined.

Table 7-2
Test Methods for Aggregates

ASTM Test Methods

C 29 – Standard Test Method for Unit Weight and Voids in Aggregate

C 88 – Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Surface

C 123 – Test Method for Lightweight Pieces in Aggregate

C 127 – Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate

C 128 – Standard Test Method for Specific Gravity and Absorption of Fine Aggregate

C 131 – Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

C 136 – Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates

C 142 – Test Method for Clay Lumps and Friable Particles in Aggregates

C 151 – Test Method for Autoclave Expansion of Portland Cement (Popouts)

C 157 – Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete (Shrinkage)

C 227 – Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations

C 289 – Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates

C 295 – Guide for Petrographic Examination of Aggregates for Concrete

C 342 – Test Method for Potential Volume Change of Cement-Aggregate Combinations

C 362 – Standard Test Method for Potential Volume Change of Cement - Aggregate Combinations

C 535 – Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

C 586 – Test Method for Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregates (Rock Cylinder Method)

C 641 – Test Method for Staining Materials in Lightweight Concrete Aggregates

C 666 – Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing

Table 7-3
ASTM Block and Block Aggregate Specifications

Reference ASTM Document (Partial List)	C 90 Standard Specification for Load-Bearing Concrete Masonry Units	C 33 Standard Specification for Concrete Aggregates	C 331 Standard Specification for Lightweight Aggregates for Concrete Masonry Units
C 29/C 29M Test Method for Unit Weight and Voids in Aggregate		✔	✔
C 33 Specification for Concrete Aggregates	✔		
C 88 Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate		✔[a]	
C 114 Test Methods for Chemical Analysis of Hydraulic Cement (Loss on Ignition)			✔
C 117 Test Method for Materials Finer then 75-μm (No. 200) Sieve in Mineral Aggregates by Washing		✔	
C 123 Test Method for Lightweight Pieces in Aggregate		✔	
C 131 Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine		✔[b]	
C 136 Method for Sieve Analysis of Fine and Coarse Aggregates		✔	✔
C 140 Method for Sampling and Testing Concrete Masonry Units	✔		
C 142 Test Method for Clay Lumps and Friable Particles in Aggregates		✔	✔
C 151 Test Method for Autoclave Expansion of Portland Cement (Popouts)			✔
C 157 Test Method for Length Change of Hardened Hydraulic Cement Mortar and Concrete (Shrinkage)			✔
C 227 Test Method for Potential Alkali Reactivity of Cement Aggregate Combinations (Mortar-Bar Method)		✔	

Table 7-3
(Continued)

Reference ASTM Document (Partial List)	C 90 Standard Specification for Load-Bearing Concrete Masonry Units	C 33 Standard Specification for Concrete Aggregates	C 331 Standard Specification for Lightweight Aggregates for Concrete Masonry Units
C 289 Test Method for Potential Reactivity of Aggregates (Chemical Method)		✔	
C 295 Guide for Petrographic Examination of Aggregates for Concrete		✔	
C 331 Specifications for Lightweight Aggregates for Concrete Masonry Units	✔	✔	
C 342 Test Method for Potential Volume Change of Cement-Aggregate Combinations		✔	
C 426 Test Method for Drying Shrinkage of Concrete Block	✔		
C 586 Test Method for Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregates (Rock Cylinder Method)		✔	
C 641 Test Method for Staining Materials in Lightweight Concrete Aggregates			✔
C 666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing		✔	✔
OTHER REFERENCED TESTING			
Linear Shrinkage	✔		
Moisture Content (Type I Units)	✔		
Finish and Appearance - Cracks, etc.	✔		
Compressive Strength	✔		
Water Absorption	✔		
Oven-Dry Weight Classification	✔		

[a] Fine aggregate failing soundness may be accepted, provided it gives satisfactory results in concrete subject to freezing and thawing tests (C 666).

[b] Requirements listed for coarse aggregate (plus $^3/8$ inch), but no requirements listed for fine (minus $^3/8$ inch) block aggregate.

The synthetic aggregate produced from ASC by-products had specific gravities of 2.0-2.6. Among the five by-product samples, the aggregate produced from the furnace sorbent injection by-product had the lightest weight and the greatest hardness. The briquettes produced from ASC by-products had average compressive strengths of 1110 to 10710 kPa (161 to 1554 psi) (see Table 7-4). The spray dryer by-product and furnace sorbent injection by-product produced the strongest briquettes with an average compressive strength of 10710 and 7430 kPa (1554 and 1077 psi), respectively.

Ohio Coal Development Office Demonstration Project[2,3]

The production of synthetic aggregate from Coolside, LIMB, and FBC by-products were demonstrated at the Ohio Edison Edgewater Station. A batch of pellets (about 30 kg) from each of the Coolside, LIMB, and FBC by-products was produced and characterized for use as synthetic aggregate in road construction. The ASC by-products were prehydrated, then mixed with water, pelletized, and steam cured [24 hours at 82°C to 99°C (180°F to 210ºF)]. The aggregates produced were tested in terms of compressive strength, abrasion resistance, unit weight, specific gravity, water absorption, and particle size distribution.

The size of aggregates were mostly in the range of 2.5-cm to 10-cm (1-inch to 4-inch) mesh. The particle size of aggregates complied with the ASTM specifications for use as coarse aggregates in road construction. These aggregates had a lower unit weight than conventional aggregates used in road construction. The specific gravity ranged from 1.51 to 2.00. The water absorption ranged from 2.6 to 11.6%. Most of the aggregates passed the abrasion resistance test (ASTM C 131 method) for use as synthetic aggregates in road construction.

Department of Energy Report[4]

This laboratory study demonstrated that an acceptable aggregate could be produced from a combination of conventional fly ash and AFBC residue. The mixture contained 30% AFBC residue and 70% fly ash. AFBC residue was completely hydrated prior to its use. Block and brick structural shapes were produced. First, a controlled amount of water was added to the dry materials and the combination was mixed in a pug mill. The material was then compacted into block or brick shapes. After curing, the blocks were crushed and screened to produce aggregate. These aggregates were tested for use as synthetic aggregate in an asphaltic resurfacing highway project. Tables 7-5 and 7-6 list the compressive strength and Marshall test results, respectively.

Table 7-4
ASC By-Product Aggregate Properties

	Produced by Mechanical Agglomeration		Produced by Briquetting
Sources	**Specific Gravity**	**Observed Durability and Hardness**	**Compressive Strength (kPa)**
AFBC:			
TV05 (ash)	2.4	Fair hardness	4600
TV03 (SBM)	—	—	2520
Spray Dryer:			
LR07	2.4	Slight hardness	
HS05	2.6	Fair hardness	10710
Furnace Injection:			
OL03	2.0	Good hardness	7430
Calcium Injection:			
AA10-02	—	—	1390
Sodium Injection:			
NX04	2.3	Crumbled when touched	1110

(SOURCE: *Advanced SO_2 Control By-Product Utilization: Laboratory Evaluation*, EPRI CS-6044. September 1988.)

Table 7-5
Composition and Compressive Strengths of AFBC Residue/Fly Ash Block (used for producing synthetic aggregate)

Mixture Composition		Compressive Strength (MPa)[a]		
AFBC/FA[b]	Sand	16 Days	28 Days	60 days
1	1	10.6	23.3	34.2
2	1	8.7	14.1	21.1
100%	0	--	20.4	27.4

[a] Blocks were stored out doors for 6 days prior to the controlled curing period.

[b] The ratio of AFBC Residue/FA was 3 to 7 by weight.

(SOURCE: L. John Minnick. *Development of Potential Uses for the Residue from Fluidized Bed Combustion Processes*. DOE/ET/10415-76 (DE83012575), December 1982.)

Iowa State University Research[5]

Two Class C fly ashes, one Class F fly ash, and two AFBC by-products were combined in various proportions to form thirteen mixtures. Aggregate beams were prepared by compacting mixtures into rectangular concrete beam molds in accordance with ASTM C 698 procedures.

After 28 days of humid curing, the beams were crushed to aggregate-sized particles. These particles were generally angular in shape. Laboratory tests were conducted to determine the gradation, specific gravity, absorption, crushing strength, and freeze-thaw durability of the synthetic aggregates. Tables 7-7 and 7-8 lists the aggregate mixture compositions and test results.

The synthetic aggregate exhibited the high absorption values and low specific gravities typical of lightweight aggregate. The crushing strength and freeze-thaw durability were satisfactory for use as low quality aggregate. The synthetic aggregates can be stabilized with 15 to 25% Class C fly ash to produce a base or subbase material meeting ASTM C 593 requirements for strength and freeze-thaw durability.

Table 7-6
Results of Marshall Tests on Bituminous Wearing Surface Mixes Containing Synthetic Aggregate

Mix Proportions (grams)				Marshall Test Results			
Mix No.	Specimen Height (cm)	Aggregate*	Asphalt	Asphalt** (%)	Stability (kg)	Flow (cm)	Air Voids (%)
1	6	1000	90	9.0 (8.26)	1090	27.9	9.0
2	6.2	1000	84	8.4 (7.75)	1340	25.4	9.1
3	6.4	1000	70	7.0 (6.54)	1180	26.7	11.3
4	6.2	1000	60	6.0 (5.66)	975	25.4	12.7

NOTE: Marshall mix design for Pennsylvania ID-2 wearing surface mixes are:

Stability - 545 kg minimum
Flow - range of 15 to 40
Air Voids - range of 3 to 5 percent

* Composed of 500 grams synthetic aggregate, 400 grams limestone screenings, and 100 grams fine sand.

** Expressed as percent by weight of aggregate in mix. Values in parentheses refer to percent of asphalt by total weight of mix.

(SOURCE: L. John Minnick. *Development of Potential Uses for the Residue from Fluidized Bed Combustion Processes*. DOE/ET/10415-76 (DE83012575), December 1982.)

Southern Illinois University Research [7,8]

This study investigated the use of FBC spent bed material as a fine aggregate in non-cement and partially cemented concrete. Natural limestone, coarse aggregate and conventional fly ash were used in non-cement (FBC and fly ash only) and partially cemented (FBC, fly ash and cement) mixtures. Mixture slump was kept constant at 10 ± 0.5 cm (4 ± ¼ inches) and no admixture was used. The water requirement was increased to obtain the required matrix consistency. An additional 12.5% by weight of water was added to precondition the by-product, which successfully reduced the heat of hydration. Fresh concrete properties (early volume change, settling time, air content, and unit weight), engineering properties (unconfined compressive strength, split-tensile strength, and modulus of elasticity), and durability (shrinkage/expansion, abrasion) were tested. The laboratory tests concluded that the FBC mixture was sensitive to testing conditions. Testing under wet conditions was worse than under air-dry or sealed conditions. A nearly 70% improvement in compressive strength was obtained when testing conditions changed from soaked to air-dry. The engineering properties of FBC mixtures with cement were comparable with those of conventional mixtures. A field test was conducted following the laboratory tests. Twenty-three concrete pavement slabs, measuring 1.8 m by 3.6 m by 0.2 m thick were constructed at a test site to form a one-lane road. The pavement is being subjected to normal weather and traffic conditions. The pavement will be monitored for nearly two years for an extensive engineering evaluation. The initial field results are very encouraging.

Table 7-7
Mixture Compositions and Conditions for Synthetic Aggregates

	Mixture				
Mix No.	AFBC* (%)	Fly Ash* (%)	Precondition Time (hours)	Optimum Moisture Content (%)	Actual Moisture Content (%)
1	15 (ISU)	85 (OT Class C)	1	15.6	13.0
2	15 (ISU)	85 (OT Class C)	0	15.6	14.8
3	15 (ISU)	85 (OT Class C)	0	15.6	17.6
4	15 (ADM)	85 (OT Class C)	0	15.6	15.0
5	15 (ISU)	95 (OT Class C)	1	15.6	13.3
6	15 (ISU)	85 (OT Class C)	0	17.0	15.6
7	15 (ADM)	85 (OT Class C)	0	17.0	-
8	15 (ISU)	85 (CB Class C)	0	15.6	13.0
9	15 (ISU)	85 (CB Class C)	0	17.0	15.3
10	15 (ADM)	85 (CB Class F)	0	17.0	-
11	15 (ISU)	85 (CL Class F)	0	15.6	14.7
12	30 (ISU)	70 (CL Class F)	0	25.0	24.6
13	30 (ADM)	70 (CL Class F)	0	25.0	-

* ISU - AFBC residue from the Iowa State University.
ADM - AFBC residue from the Archer Daniels Midland Plant in Cedar Rapids, Iowa.
OT - Fly ash from Ottamwa
CB - Fly ash from Council Bluffs
CL - Fly ash from Clinton

(SOURCE: K. L. Bergeson and J. W. Waddingham. “Synthetic Aggregates from Fly Ash and AFBC By-Products.” Proceedings: *11th International Symposium on Use and Management of Coal Combustion By-Products*. EPRI TR-104657, Vol. 2, pp. 54-l to 54-10, January 1995.)

Table 7-8
Properties of Synthetic Aggregate

	Coarse Aggregate		Fine Aggregate		Average Percent Loss*	
Mix. No.	Specific Gravity	Absorption %	Specific Gravity	Absorption %	Crushing Strength (kPa)	Freeze-Thaw (kPa)
1	2.8	30.3	---	---	58.7	14.6
2	2.6	19.4	---	---	25.6	7.7
3	2.6	19.6	---	---	28.9	4.0
4	2.6	18.5	---	---	28.4	13.9
5	2.6	30.4	---	---	51.3	16.5
6	2.7	20.1	2.7	22.4	30.7	7.4
7	2.6	18.6	1.5	25.4	31.2	12.8
8	2.6	21.0	---	---	26.0	3.1
9	2.8	28.1	2.8	31.1	37.1	24.9
10	2.7	18.3	2.8	25.1	29.9	35.0
11	2.3	36.7	---	---	48.4	98.5
12	2.6	33.2	2.7	39.0	28.2	90.3
13	---	---	---	---	29.3	76.4
Limestone	2.7	3.1			12.5	0.9

* Aggregate pass the #8 Sieve

(SOURCE: K. L. Bergeson and J. W. Waddingham. “Synthetic Aggregates from Fly Ash and AFBC By-Products.” Proceedings: *11th International Symposium on Use and Management of Coal Combustion By-Products*. EPRI TR-104657, Vol. 2, pp. 54-1 to 54-10, January 1995.)

University of Kentucky Research [9]

Synthetic aggregates prepared using an optimum mixture of circulating fluidized bed combustion (CFBC) by-product, fly ash and water was studied at the Center for Applied Energy Research, University of Kentucky. Anhydrite ($CaSO_4$) was a main mineral component of this CFBC material. Mixture proportions were CFBC: fly ash:lime at 60:20:20 (Mix 1) and 70:30:0 (Mix 2). Physical tests, X-ray diffraction and scanning electron microscope (SEM) were used to evaluate the materials. X-ray diffraction indicated that upon curing for 48 hours in a moist environment, ettringite had formed, which contributed to the pellet's strength. Initial physical tests were promising.

During curing, anhydrite did not hydrate to form gypsum. However, long-term exposure of the pellets to moisture resulted in recrystallization of anhydrite to gypsum, which was accompanied by a volume increase and typically caused pellets to fracture. The authors recommended using by-products composed of calcium-sulfite and gypsum (i.e, wet scrubbers) to avoid long-term disintegration of pellets due to delayed hydration of anhydrite to gypsum.

Summary

Synthetic aggregate can be produced from ASC by-products. Depending on the chemical composition, ASC by-products may need prehydration. Cement, lime, or conventional fly ash may be added to the mixture to promote strength development.

Production of aggregate includes the formation of pellets, briquettes or large blocks. These are then crushed, sintered and/or cured. Mechanical agglomeration can be used to form pellets and a briquetting machine used to form briquettes. Moist curing, elevated temperature curing, CO_2 environment curing, or sintering at high temperatures can be employed. After curing, briquettes/blocks are tested for compressive strength and then are crushed to produce aggregates. Aggregates should then be tested in terms of specific gravity, gradation, absorption, abrasion resistance and soundness in accordance with the corresponding ASTM test method.

ASC by-products have been used to produce artificial aggregates in various studies. Some by-product aggregates have shown promising test results. Results were specific to the by-product and production methods used.

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8

CEMENT PRODUCTION AND REPLACEMENT

Overview

The use of coal combustion by-products as raw materials for cement production is a high volume, low margin utilization option. Conventional fly ash has been used as a raw material in cement production for many years and is commonly used as a component in the manufacture of blended cement. The amount of fly ash used depends on the mineral requirement of the cement, and the chemical and physical characteristics of the fly ash.

The use of fly ash as a partial replacement for cement in concrete is a high volume, high margin utilization option. Replacement of 15 to 20% of Portland cement by conventional fly ash is a well established technology. The most important factors for fly ash replacement of cement in concrete are fineness, pozzolanic activity index, and water requirement.

Thus, three potential uses of ASC by-product will be examined in this section:

- as raw feed for cement production (by-product added prior to clinkering)
- for production of a blended cement (by-product added after clinkering)
- for partial cement substitution in concrete.

ASC by-products have a moderate potential for use as a small portion of the raw feed in cement production. However, adding a by-product later in the manufacturing process to produce a blended cement or for cement substitution in concrete typically requires high quality fly ash with low sulfur contents, and therefore, has a low potential for success with ASC by-products.

ASC by-products often have self-hardening characteristics due to the calcium component of the SO_2 emission control sorbents. The by-products may also contain a high percentage of fly ash (up to 70%). These are desirable characteristics for utilization in cement and concrete production. However, the SO_3 content of most by-products is higher than conventional fly ash, which limits their utilization potential. The maximum amount of by-product that may be introduced in cement production or as a cement replacement in concrete is often determined by the SO_3 content. A high SO_3 content may contribute to formation of sulfates in the concrete and lead to deterioration of the concrete due to sulfate expansion.

This section discusses the feasibility of ASC by-product utilization in cement production and as a cement replacement in concrete based on ASTM specifications. The results of several laboratory scale studies are presented.

State of Practice

ASC by-products are not currently being used at the commercial level for cement production or as a cement replacement in concrete in North America.

In Japan, FBC by-product has been used as raw feed material in 12 of 41 cement plants surveyed. A total of 96% of FBC by-product is used as argillaceous clay replacement since it has SiO_2 and Al_2O_3 composition similar to cement argillaceous material. One by-product source is used as fuel because of its high unburned carbon content. Most FBC by-products are introduced into the cement production process at the raw material blending stage, but a few are added after the grinding stage, since the by-products are dry and fine. FBC by-product use per cement plant ranged from 500 to 46,400 tpy.

Laboratory scale studies have investigated the use of by-product as a cement replacement in concrete[2-10]. Much of the research has focused on the microstructure and mineral composition of by-product particles. FBC by-products, spray dryer by-products, and furnace sorbent injection by-products have been tested in concrete mixtures and data is available regarding compressive strength, modulus of rupture, and freeze-thaw durability of the concrete.

Cement Production

This section discusses the use of ASC by-product as a material in Portland cement manufacture.

In this market, conventional fly ash can be used as:

- raw feed for cement production; and
- a component of blended cement.

Lime (CaO), silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), all of which are characteristic chemical components of fly ash, are necessary in cement manufacturing. The acceptability and amount of ash depends upon the mineral requirements of that type of cement, the chemical and physical properties of the ash, and which minerals are lacking in the locally available quarry rock.

Portland cement is produced in four steps. First, raw materials such as limestone, cement rock, shale, clay, iron ore and/or various other minerals, are mined, crushed, and stored separately. Fly ash or bottom ash may be substituted, in part, for these materials. The raw materials are then proportioned, ground, and mixed in either a dry or a wet slurry process. The blended raw materials are burned in a kiln to form clinker. As raw feed, fly ash or bottom ash may be added before grinding. Alternatively, fly ash may be added to ground materials in the kiln to form clinker. After the clinker is cooled and stored, it is mixed with proportioned quantities of gypsum (to retard set) and ground in a grinding mill. With a blended cement, fly ash is interground with the clinker or blended with the cement as a final step in the cement making process. The resulting product is stored in bulk storage, packaged, and shipped.

Several types of cement are produced. As shown on Table 8-1, Type I (normal) Portland cement has typical oxide compositions of 60 to 66 percent lime, 19 to 25 percent silica dioxide, 3 to 8 percent alumina oxide, 1 to 5 percent iron, 0 to 5 percent magnesium oxide, and 1 to 3 percent sulfur trioxide. ASTM chemical requirements for each cement type are presented in Table 8-2. ASC by-products may be useful substitutes for a portion of the conventional raw materials to provide some of these minerals. The proportion of added by-product must be limited, however, so as not to exceed the normal range of any of the minerals.

Table 8-1
Typical Range of Type I Cement, Major Oxides

Parameter	Type I Cement Typical Range (%)
SiO_2	19-25
Al_2O_3	3 - 8
Fe_2O_3	1 - 5
CaO	60 - 66
MgO	0 - 5
SO_3	1 - 3

(SOURCE: *Design and Control of Concrete Mixtures*, 11th Ed., Portland Cement Association, Skokie, IL, 1968, p. 16.)

ASTM C 150 provides standard specifications for Portland cement, including the chemical criteria for the final cement produced. There are no chemical composition requirements for the raw materials used to produce the cement. For Portland cement, sulfate (reported as sulfur trioxide) is limited in the final product (see Table 8-2). ASC by-products typically contain more than 4.0% sulfate, which means that the by-products can be considered for only small proportions of the mix for the chemical composition of the final product is satisfied.

Table 8-2
ASTM C 150 - Summary of Standard Chemical Requirements for Portland Cement

Cement Type	I and IA	II and IIA	III and IIIA	IV	V
Silicon dioxide (SiO_2), minimum percent	-	20.0	-	-	-
Aluminum oxide (Al_2O_3), maximum percent	-	6.0	-	-	-
Ferric oxide (Fe_2O_3), maximum percent	-	6.0	-	6.5	-
Magnesium oxide (MgO), maximum percent	6.0	6.0	6.0	6.0	6.0
Sulfur Trioxide (SO_3), maximum percent					
when (C_3A) is 8% or less	3.0	3.0	3.5	2.3	2.3
when (C_3A) is more than 8%	3.5	-	4.5	-	-
Loss-on-ignition, maximum percent	3.0	3.0	3.0	2.5	3.0
Insoluble residue, maximum percent	0.75	0.75	0.75	0.75	0.75
Tricalcium silicate (C_3S), maximum percent	-	-	-	35	-
Dicalcium silicate (C_2S), minimum percent	-	-	-	40	-
Tricalcium aluminate (C_3A), maximum percent	-	8	15	7	5
Tetracalcium aluminoferrite plus twice the tricalcium aluminate ($C_4AF+2(C_3A)$), or solid solution (C_4AF+C_2F), as applicable, maximum percent	-	-	-	-	25

The requirements for blended cements, ASTM C 595, “Standard Specifications for Blended Hydraulic Cements,” are summarized on Table 8-3. The requirements for pozzolans to produce blended cements are listed on Table 8-4. Several types of blended cement are recognized under ASTM C 595, including Portland-pozzolan cement, Types IP and P, and pozzolan-modified Portland cement, Type I (PM). Types IP and I (PM) are considered suitable for general concrete construction. Both IP and I(PM) cements can be specified for moderate sulfate resistance (MS), air entrainment (A), or moderate heat of hydration (MH). Type P is used where high strengths at early stages are not required, such as in large dams. If fly ash is used to create a blended (Portland-pozzolan) cement, additional fly ash cannot be added at a ready-mix plant when producing concrete.

ASTM C 595 specifies the pozzolanic content requirement for blended cement. For Portland-pozzolan cement, the pozzolan content is between 15 to 40% by weight of the blended cement product. For pozzolan modified Portland cement, the pozzolan content is less than 15% by weight of the blended cement product. ASTM C 595 specifies a maximum amount of sulfate that can be present.

ASTM C 595 also defines the physical criteria for pozzolans used in blended cements. The key requirements for the pozzolan are its fineness and pozzolanic activity with lime and Portland cement. The minimum pozzolanic activity index of 75% and the maximum residue retained on No. 325 sieve of 20% are required. Many of the ASC by-products can achieve a minimum pozzolanic activity index of 75%. Also, the by-products typically meet the fineness requirement.

Table 8-3
Summary of ASTM C 595 - Standard Specifications for Blended Hydraulic Cements

Cement Type	Type P (C595)	Type IP (C595)
Magnesium Oxide (MgO), max, %	5.0	5.0
Sulfur Reported as Sulfate (SO_3), max, %	4.0	4.0
Loss on Ignition, max, %	5.0	5.0
Air Content of Mortar, max, %	12	12
Compressive Strength (MPa) - 3 Days	—	12.4
Compressive Strength (MPa) - 7 Days	10.3	19.3
Compressive Strength (MPa) - 28 Days	20.7	24.1
Time of Setting (Vicat Test) Minutes (not less than)	45	45
Time of Setting (Vicat Test) Minutes (not more than)	420	420

Table 8-4
ASTM C 595 - Requirements for Pozzolans for Use in Blended Cement

Fineness:	
Amount retained when wet-sieved on 45µm (No. 325) sieve, maximum percent	20.0
Alkali reactivity of pozzolan for use in Types I (PM) and I (PM)-A cements, six tests, mortar bar expansion at 91 days, maximum percent	0.05
Pozzolan activity index:	
With Portland cement, at 28 days, minimum percent	75

In summary, the chemical composition of by-products should be analyzed to determine the technical feasibility of using by-product as a raw component for cement production. The evaluation of chemical composition can be carried out following ASTM C 114 procedures. ASTM C 150 and C 595 should be used as a basis for evaluating the suitability of by-product. Percent sulfates will limit the use of ASC by-products.

Cement Replacement in Concrete

Fly ash used as a pozzolan in concrete is widely accepted as a market product, rather than a solid waste, by government agencies. In fact, the U.S. Environmental Protection Agency (USEPA) has issued federal procurement guidelines encouraging the use of fly ash in concrete on federally-funded projects.

Fly ash which fulfills the ASTM Standard C 618, "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete," is commonly known as "spec ash." ASTM C 618 lists limits on various minerals proportions, fineness, loss-on-ignition (LOI), and physical properties. Optional requirements include available alkalis (maximum percent Na_2O). LOI values, an indicator of unburned carbon, are allowed to 6 percent; with acceptable performance records or laboratory test results, LOI values up to 12 percent may be accepted.

ASTM C 618 states that the definition of fly ash does *not* include residue resulting from "the injection of lime directly into the boiler for sulfur removal." Therefore, FBC and furnace sorbent injection by-products, by definition, cannot pass ASTM C 618.

Another fly ash specification commonly referenced by State DOT's is American Association of State Highway and Transportation Official (AASHTO) M 295. This specification is similar to ASTM C 618, with a maximum allowable LOI of 5 percent. Note that many state DOT's and contractors refer to ASTM C 618 or AASHTO M 295, but with more stringent requirements for LOI.

Table 8-5 lists ASTM C 618 requirements.

When considering the potential for use of an ASC by-product to replace cement in concrete, the by-product can be considered as a pozzolan, similar in nature to fly ash. Therefore, the by-product must satisfy ASTM C 618 requirements. ASTM C 618 requires a minimum of 50% combined content of $SiO_2 + Al_2O_3 + Fe_2O_3$ for mineral admixtures to be added to Portland cement concrete. Based on various EPRI projects[3,4,5,6], most of the ASC by-products had a combined content of SiO_2 $Al_2O_3 + Fe_2O_3$ lower than 50%, but higher than 40%. This suggests that by-product may be combined with high pozzolan content fly ash to be used as cement replacement in concrete.

ASTM C 618 states that the material to be used as a mineral admixture should have no more than 5% oxidized sulfur reported as sulfur trioxide (SO_3). This corresponds to 6% as sulfate/sulfite. Most of the ASC by-products have high sulfate/sulfite content, ranged from 6% to 20%. The high concentrations of sulfate/sulfite prohibit by-products from use as a mineral admixture for Portland cement concrete.

Table 8-5
Partial List of ASTM C 618 Physical and Chemical Requirements for Fly Ash in Portland Cement Concrete

	Class C
$SiO_2 + Al_2O_3 + Fe_2O_3$, min, %	50.0
Sulfur Trioxide SO_3, max, %	5.0
Moisture Content, max, %	3.0
Loss on Ignition, max, %	6.0
Fineness, Amount Retained When Wet-Sieved on 45 mm (No. 325) Sieve, max, %	34
Strength Activity Index, with Cement, % of Control	75
Water Requirement, % of Control	105
Autoclave Expansion, max, %	0.8

The LOI contents of ASC by-products are similar to conventional fly ash, and are often less than the ASTM C 618 maximum allowable limit. The physical properties of the by-product typically conform to ASTM C 618 requirements.

The physical and chemical characteristics of ASC by-products should be evaluated according to the ASTM C 618 specification. In addition, trial mixtures should be prepared. Compressive strength and setting time of concrete mixtures should be tested based on different percentage cement replacement. The tensile strength, flexural strength, modulus of elasticity of a selected high compressive strength concrete mixture should be tested. The properties of trial mixture should be compared with those of control mixture containing no by-product.

In summary, ASC by-products generally have low potential to be used as a partial cement replacement in concrete. If a specific by-product source fulfills ASTM C 618 criteria, however, it would have high potential for this use.

Case Histories

Laboratory Test (EPRI Project) [3]

Two sources of spray dryer by-product and one source of limestone furnace sorbent injection by-product were tested for partial cement replacement in concrete. The physical and chemical characteristics of these by-products were evaluated. The by-product was substituted for 30% by weight of Type I cement. Three by-product concrete mixtures, one conventional fly ash concrete mixture, and one control concrete mixture were prepared. All concrete mixtures employed water reducing and air entraining admixtures. The fresh concrete properties, including slump, air content, unit weight, temperature, and setting time were recorded. All cured concrete cylinders were tested for compressive strength (3, 7, 28 and 90 days), modulus of rupture (28 days), and freeze-thaw durability (at 28 days). Table 8-6 lists the by-products characteristics and concrete testing results.

The spray dryer by-product Sample 2 met the ASTM C 618 criteria except for higher SO_3 content. Spray dryer by-product Sample 1 and furnace sorbent injection by-product did not meet ASTM C 618 minimum requirements for the combination of silica, alumina, and iron oxides. Also, SO_3 content and LOI were over the ASTM C 618 limits. However, their fineness and pozzolanic activity indices meet the ASTM C 618 criteria. The autoclave expansion test results of using these by-products were within the ASTM C 618 limits.

The ASC by-product mixtures performed well with respect to the control mixture and conventional fly ash mixture. The concrete mixtures made with spray dryer by-products achieved higher compressive strength than that of the control mixture at all testing ages. The concrete mixture made with furnace sorbent injection by-product had a lower compressive strength than the control mixture at 3, 7, and 28 days, but its compressive strength at 90 days exceeded 41.4 MPa (6000 psi), which was higher than that of the control mixture. These three concrete mixtures also had very good freeze-thaw durability. The setting times of mixtures containing ASC by-products were substantially different than that of the control. The spray dryer by-product mixtures had longer setting times and furnace sorbent injection by-product had shorter setting time than the controls.

Table 8-6
Characteristics of Some ASC By-Products and Properties of Concrete Made With By-Products

	Spray Dryer Sample 1	Spray dryer Sample 2	Furnace Sorbent Injection	Control	PFA
$SiO_2 + Al_2O_3 + Fe_2O_3$, %	45.03	52.71	46.72	NA	59.0
SO_3, %	12.25	10.25	6.25	NA	NA
LOI, %	6.2	1.9	10.97	NA	NA
Fineness, Retained on No. 325 Sieve, %	10	3	20	NA	NA
Pozzolanic Activity Index	69	107	108	NA	NA
Autoclave Expansion, %	+0.05	+0.03	+0.08	NA	NA
Mixture Properties (1 m³)					
Cement, kg	243	243	243	350	243
By-Product, kg	107	107	107	0	107
Fine Aggregate, kg	819	819	819	819	819
Coarse Aggregate, kg	1113	1113	1113	1113	1113
Air Entrainment, kg	4.43	4.43	14.38	4.54	2.53
Water Reducer, kg	7.05	7.05	7.05	9.86	7.05
Water, kg	158	158	98	147	125
Fresh Concrete Properties					
Slump, cm	10.2	10.2	8.9	11.4	11.4
Air Content, %	5.8	5.6	4.5	5.6	6.0
Unit Weight, kg/m^3	2360	2350	2220	2330	2360
Concrete Temperature, ^{O}C	28	26	29	NA	NA
Initial set, hr:min	13:55	18:30	3:50	6:00	6:15
Final Set, hr:min	17:00	21:15	5:35	8:00	8:00
Compressive Strength, MPa					
3-day	24.3	24.9	14.2	22.6	21.7
7-day	31.4	32.0	17.8	29.5	28.3
28-day	39.2	35.1	26.1	34.1	36.6
90-day	43.7	43.7	41.9	38.8	46.5
Modulus of Rupture, MPa	4.1	4.3	3.7	5.3	4.8
Freeze-Thaw Durability					
Durability Factor	99.3	94.2	89.6	92.5	98.25
Length Change, %	0.04	0.04	0.07	-0.02	-0.11

(SOURCE: ICF Northwest. *Advanced SO_2 Control By-Product Utilization- Laboratory Evaluation*. September 1988.)

Research at Iowa State University[10]

FBC by-products from three Iowa Power Plants were tested as cement replacement in concrete. Particle size distribution, specific gravity, and chemical compositions of the by-product samples were determined before the concrete mixture was designed. The by-products are about 50% silt-sized and 50% fine sand-sized particles. The specific gravity of by-products are higher than sand and were found to be about 2.8 to 3.0. Chemical composition shows high calcium oxide and SO_2 contents. The by-products properties data are shown in Table 8-7. The high calcium oxide contents make the by-products attractive for use as a cementitious materials in the concrete. In this study, the water requirements of by-products are about 40% to 50% by weight of the sample in order to achieve normal consistency. The hydration reaction studies showed the principal hydration by-products are portlandite, ettringite and gypsum.

Concrete samples were made with one control mixture (100% cement); 60% , 80% , and 100% cement replacement with one selected FBC by-product; and 100% cement replacement with 50% FBC by-product and 50% Class C fly ash. River sand and crushed limestone were used as fine and coarse aggregates. All mixtures had 5 to 7.5 cm (2 to 3-inch) slumps. Concrete samples were cured in the moist room until tested. Flash setting and expansion were observed in the mixtures with high SO_3 contents. Concrete made with Sample 5 (4% SO_3 content) had no expansion and gained 70-day strengths up to 6.9 MPa (1000 psi) for 100% FBC by-product, 27.6 MPa (4000 psi) for 40% cement replacement, and 31.0 MPa (4500 psi) for 50% FBC by-product plus 50% Class C fly ash mixture.

Table 8-7
Properties of FBC By-Products from Three Iowa Power Plants

Sample Number	1	2	3	4	5
Specific Gravity	2.96	2.97	2.99	2.92	2.82
$SiO_2 + FeO_3 + Al_2O_3$, %	12.60	30.92	23.88	35.30	48.50
CaO, %	54.71	45.96	46.92	41.48	42.23
SO_3, %	31.87	23.55	24.72	15.92	4.06
LOI, %	3.13	1.75	1.56	2.45	15.65

(SOURCE: P. Rangaraju and C. L. Kilgour. “Hydration Reactions of FBC By-Products from Iowa Power Plants and Their Use in Concretes.” January 1995 .)

Sherburne Plant Haul Road [12]

A demonstration road was constructed incorporating spray dryer ash from Northern States Power's Sherburne Plant in the pavement, subbase and embankment, as described in Section 2, "Road Base" and Section 5, "Structural Fills."

Oxide composition of the spray-dryer by-product, compared with Class C fly ash, are shown on Table 8-8.

The demonstration road consisted of an 24.4 meters (80 foot) control section and five test sections. Portland cement concrete pavement incorporating 5% spray dryer was used on Test Section 4, a 4.6-meter (15-foot) section. Mix designs and strengths are presented in Tables 8-9 and 8-10. Laboratory tests indicate that compressive strengths increase with increased percent spray dryer, for all test ages from 3 to 94 days. However, the concrete containing spray dryer by-product required additional water to produce a more workable mix. In the field mix, an additional 159 kg (42 gallons) of water per 8 m^3 (9 yd^3) was needed to achieve a 10.8 cm (4½ inch) slump. The road was constructed in 1991. As of 1996, the road is still in regular use and has needed no maintenance or repair.

Summary

According to ASTM C 595 specifications for blended cement, and ASTM C 618 specifications for use of fly ash as a mineral admixture in concrete, ASC by-products show low potential for use as a cement replacement in concrete. The physical properties of the by-products may meet the ASTM criteria, but the high sulfate / sulfite content in these by-products typically prohibit by-products use in concrete. However, ASC by-products may prove useful as raw feed in cement production, if used in proportions such that the final cement composition meets ASTM C 150.

Table 8-8
Oxide Composition of the Spray Dryer By-Product and ASTM Class C Fly Ash Specifications

Oxide	Spray Dryer By-Product Composition Percent	Class C (ASTM C 618 Fly Ash) Composition Percent
Silicon Dioxide, SiO_2	28.12	
Aluminum Oxide, Al_2O_3	15.40	
Iron Oxide, Fe_2O_3	*2.81*	
Total	46.33	Min. 50.0
Calcium Oxide, CaO	31.94	
Magnesium Oxide, MgO	2.67	
Sodium Oxide, Na_2O	2.21	
Potassium Oxide, K_2O	0.44	
Titanium Dioxide, TiO_2	0.57	
Manganese Oxide, Mn_2O_3	0.10	
Phosphorus Pentoxide, P_2O_5	0.44	
Sulfur Trioxide, SO_3	14.76	Max. 5.0
Carbon (total)	0.31	
Moisture Content		Max. 3.0
Loss-on-Ignition		Max. 6.0

(SOURCE: Radian Corporation. *Year-End Summary Report for EPRI's Demonstration Road at Northern States Power Company's Sherburne County Power Plant in Becker, Minnesota.* Revised Draft, DCN 92-213-062-10, May 8, 1992.)

Table 8-9
Laboratory Mix Designs Prepared by the Center for By-Products Utilization for Sherburne County Road

Mix. No.	A-0-0	A-5-0	A-10-0
Design Strength, MPa	27.58	27.58	27.58
Spray Dryer By-Product, %	0	5	10
Cement, kg/m^3	363	344	326
Spray Dryer By-Product, kg/m^3	0	19	37
Water, kg/m^3	172	172	172
Water to Cementitious Ratio	0.47	0.47	0.47
Sand, SSD, kg/m^3	860	860	860
Max. ¾-inch aggregates, SSD, kg/m^3	1074	1074	1074
Slump, cm	8.9	7.6	5.7
Air Content, %	7	5.2	4.2
Air Temperature, °C	20	20	20
Concrete Temperature, °C	23	23	23
Concrete Density, kg/m^3	2320	2350	2390
Air Entraining Agent, DAREX, ml/m^3	393	393	393

(SOURCE: Radian Corporation. *Year-End Summary Report for EPRI's Demonstration Road at Northern States Power Company's Sherburne County Power Plant in Becker, Minnesota.* Revised Draft, DCN 92-213-062-10, May 8, 1992.)

Table 8-10
Concrete Test Results by the Center for By-Products Utilization for Sherburne County Road - 27 MPa (4000 psi) Design Strength

Mix. No.	A-0-0	A-5-0	A-10-0
Design Strength, MPa	27.58	27.58	27.58
Spray Dryer By-Product, %	0	5	10

Test Age, Days	Compressive strength, MPa[a]		
3	20.8	25.7	26.5
7	24.3	30.1	31.5
28	30.2	35.7	36.9
56	31.2	38.8	40.9
94	33.6	42.6	43.6

Notes:

[a] Average of three tests.

(SOURCE: Radian Corporation. *Year-End Summary Report for EPRI's Demonstration Road at Northern States Power Company's Sherburne County Power Plant in Becker, Minnesota.* Revised Draft, DCN 92-213-062-10, May 8,1992.)

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9

SOIL AMENDMENT

Overview

ASC By-Products as Substitutes for Agricultural Lime

ASC by-products can be used as soil amendments to raise the soil pH of both acidic mine soils and agricultural soils. With mine soil, the amended soil-by-product mixture provides a suitable medium to establish a permanent, low maintenance vegetative cover that will stabilize the soil from erosion. For agricultural uses, the purpose of the soil amendment is to provide a higher yield for a specific crop. For this use, the beneficial loading rate may occur over a narrower range and differs for different crops. Higher by-product loading rates are likely for mine soils, due to more extreme soil conditions and more tolerant plant species. However, larger potential acreages for by-product use are available on agricultural lands. For both uses, utilization potential is dependent upon the ability of the by-product to economically increase the vegetation yield without detrimental effects to plants or groundwater from trace elements, i.e., selenium, molybdenum, boron, cadmium, etc.

ASC by-products may improve a soil by:

- Neutralizing acid soil
- Adding plant-essential primary, secondary, and micro-nutrients

Concerns with using ASC by-products include:

- Variability of calcium carbonate equivalency (CCE) could result in incorrect application rates.
- Contamination of agricultural land by trace elements.
- High soluble salts will prevent seed germination on sandy soil.
- Materials handling methods may differ from those for standard agricultural lime.
- Crusting or hardening of the amended soil.

The first three “challenges” can be overcome by frequent sampling, testing, and diligent quality assurance practices. While the testing program presented herein addresses CCE, trace elements and soluble salts, frequent and regular testing would be needed to address ash variability and quality assurance.

Primary, secondary, and micronutrients, as well as nonessential and potentially toxic elements are presented on Table 9-l. Micronutrients are elements which are required by plants but in minute amounts. The benefits of pH adjustment is depicted on Figure 9-l.

Table 9-1
Plant Nutrients and Nonessential and Potentially Toxic Elements

Primary Nutrients[a]	Secondary Nutrients[a]	Micronutrients[a]	Nonessential and Potentially Toxic Elements[b]
Nitrogen (N)	Sulfur (S)	Iron (Fe)	Mercury (Hg)
Phosphorus (P)	Magnesium (Mg)	Manganese (Mn)	Aluminum (Al)
Potassium (K)	Calcium (Ca)	Boron (B)	Lead (Pb)
		Chlorine (Cl)	Nickel (Ni)
		Zinc (Z)	Cadmium (Cd)
		Copper (Cu)	Chromium (Cr)
		Molybdenum (Mo)	Arsenic (As)

[a] The Penn State Agronomy Guide
[b] Baker and Senft, 1995 (partial list)

Also, the rate of by-product amendment must be controlled to avoid creating alkaline soil conditions or an amended soil which crusts or hardens.

Based on research to date, the best agricultural use of AFBC residue is as a lime source for croplands, orchards, pastures, and reclaimed surface mines[1].

The use of agricultural liming materials is regulated in many states by state lime laws. In general, under these laws, agricultural liming materials must be registered with the state, properly labeled, and comply with minimum standards for CCE (lime equivalent) and fineness. Some state’s lime laws specifically allow ASC by-products, although few states have established environmental criteria for this use.

A market analysis of coal combustion by-products (CCBP) for use in agriculture and land reclamation has recently been published by EPRI. Four regions of the U.S. were studied. The study revealed that economics of CCBP use are generally marginal, but CCBP use may be economic when the power plant is in close proximity to the application area[2].

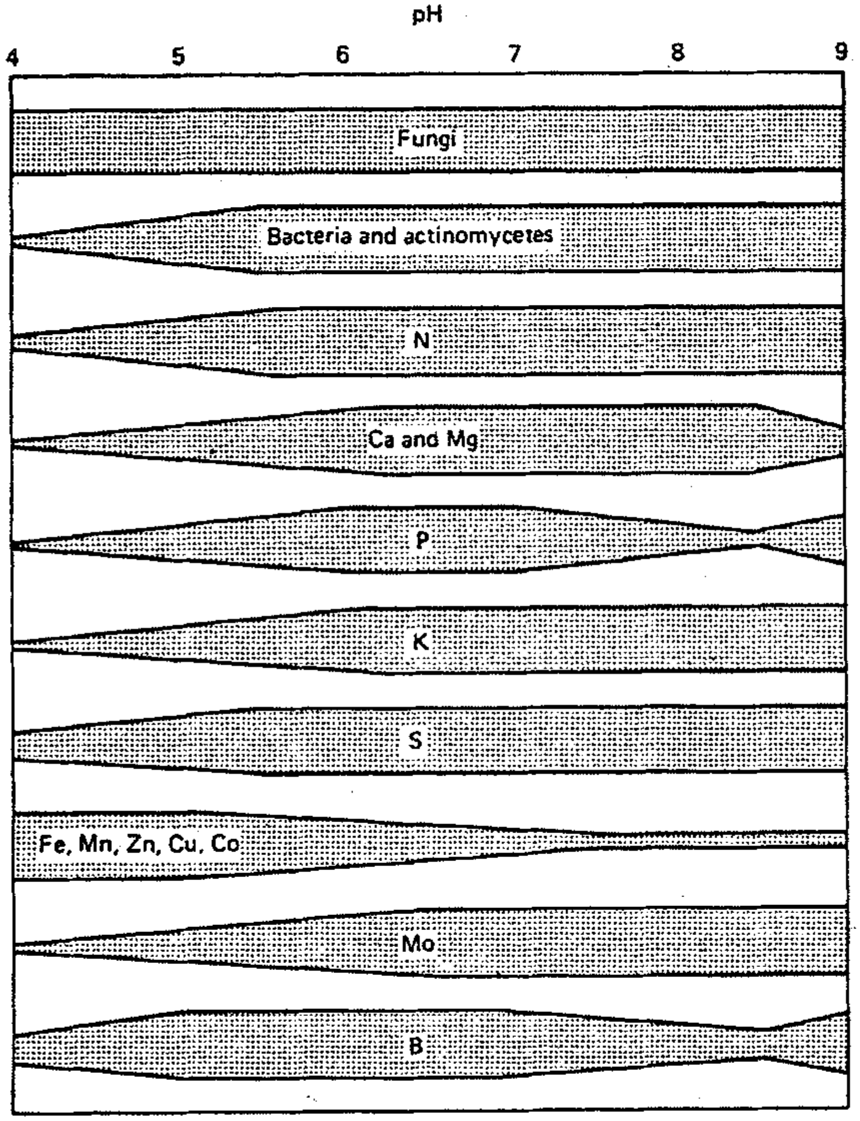

Figure 9-1
pH Influence on Metals Solubility - Relationships in soils: pH influence on the activity of micro-organisms and the availability of plant nutrients. The wide portions of the bands indicate the zones of the most ready availability of nutrients.

(SOURCE: Brady, N.C. *The Nature and Properties of Soils*. 8th Ed. New York. MacMillan Publishing Company, 1974, p. 388.)

ASC By-Products as Substitutes for Agricultural Gypsum

Natural gypsum has long been used in agriculture for both chemical and physical conditioning of soils. Gypsum ($Ca_2SO_4 \cdot 2H_2O$) provides a supplemental source of sulfur and calcium for specific crops, particularly peanuts, and to a lesser degree, legumes, potatoes and cotton[3].

As a soil conditioner, gypsum improves soil structure by loosening heavy, compacted soils and clays. This leads to an increase in permeability and thus improved aeration, drainage and penetration and retention of water in the soil. This can result in better growth and higher yields through improved germination and increased root growth. Also, surface applied fertilizers can penetrate to the roots more readily[3].

Sulfur is a secondary nutrient which is required by some crops for adequate growth. Gypsum, applied to soils deficient in this element, is a good source of plant nutrient sulfur (PNS) and provides sulfur in the form most commonly required by plants. Since natural gypsum is essentially neutral, in most soils it does not alter soil pH significantly[3].

In these applications, the natural gypsum is applied in products that are graded (i.e., multi-sized) so that gypsum can be spread with a lime spreader, and solubilization occurs over an extended period to provide a “time-release” effect over the growing season. Natural gypsum can also be applied as a finely ground powder (80-90 percent through 100 mesh). Rates of application vary depending on the crop and soil conditions[3].

Similar to natural agricultural gypsum, ASC by-products contain calcium and sulfur. These elements may or may not exist in the same form as in natural gypsum. Unlike gypsum, ASC by-products typically raise soil pH, and may harden, rather than loosen soil at high application rates. Some soils may benefit by properly applied ASC by-products. Some peanut cropland, for instance, could benefit by an increase in pH, as this would reduce the solubility of zinc and potassium in the soil, two elements which inhibit the growth of peanuts.

ASC By-Products Combined with Biosolids as Fertilizer

Fly ash and ASC by-products have been used in many revegetation studies and projects. These materials, however, do not provide essential nitrogen to plants. Some recent research studies have focused on the use of biosolids (sewage sludge) to provide organic matter and nitrogen. A study on mine soil by West Virginia University[4] found that biosolids increased the site’s biomass, but did not affect the pH, iron or lead contents of acid mine soils. Soil pH and other parameters could be improved by the addition of an alkaline by-product. At one site, high biosolids loading increased levels of soluble copper and zinc.

While combinations of biosolids and alkaline by-products may provide complementary plant nutrients, the use of two by-products may result in two sets of environmental regulations to comply with, as well as the logistical complications of additional transport, storage, mixing, and application methods.

N-Viro International Corporation produces N-Viro Soil™, a "soil substitute." In the N-Viro process, biosolids are treated using alkaline materials, which may include fly ash, FBC ash, or LIMB ash. In this patented process, the rise in heat and pH effectively kills disease-causing pathogens in accordance with EPA Part 503 Regulations and "Exceptional Quality Sludge" (EQS) criteria[5]. N-Viro uses over 300,000 tons of alkaline by-products per year[6].

As part of the project "Land Application Uses for Dry FGD By-Products," N-Viro success-fully demonstrated stabilization of municipal wastewater treatment sludge using a furnace sorbent injection by-product (LIMB) and a CFBC ash. The project was managed by the Dravo Lime Company, with technical work performed by Ohio State University[7-10].

State of Practice

FBC ash has been used successfully in numerous field trials on agricultural lands, and both FBC and LIMB have been used to reclaim mine lands[11-12] and commercially in N-Viro Soil™[6]

The USDA has issued a manual for applying FBC residue to agricultural lands. However, application of AFBC residues with lime equivalencies of less than 30 percent is not recommended by the USDA Research Service due to concerns with heavy metal loadings[1].

Design Procedure

The loading rate of an ASC by-product is determined by the rate required for proper pH adjustment. At that loading rate, it must then be determined that the following are not exceeded:

- Soluble salts
- Boron, molybdenum and selenium
- Heavy metals - both annual and lifetime cumulative loading rates

pH, Soil Fertility and Soluble Salts

To evaluate the benefit of adding ASC by-product to a soil, the by-product, soil, and by-product:soil mixtures are tested to measure the following parameters:

- pH
- Soluble salts
- Nutrient status

First, the CCE and pH of the ASC by-product must be tested. To test the effectiveness of ASC by-product to neutralize acid soils, the by-product must be mixed at various proportions with the local soil. The soil:by-product ratio required to achieve a neutral pH must be deter-mined. This mixture shall then be tested for soil fertility, soluble salts.

Soil fertility tests on the unamended local soil will determine the initial pH; phosphate, potash, and magnesium levels; and the recommended limestone requirement in tons per acre. From the soil analysis, recommendations can be made for the amount of calcium carbonate ($CaCO_3$) required to raise the pH of the soil to the desired level. The liming potential of the ash is related to the required amount of calcium carbonate; thus the agronomic rate of by-product to be applied, usually on a ton per-acre basis, can be determined.

The availability of nutrients and trace metals to plants is largely dependent upon the pH of the material in which they reside. The addition of an alkaline ASC by-product to an acid soil will result in a material with a pH value different than either the ASC by-product or the soil. Therefore, testing of the soil:by-product mixture should be performed after testing to determine suitable amounts of ash required for a neutral pH. The advantages of a neutral pH, both in terms of plant nutrients and metals solubility, is illustrated on Figure 9-l. Once the soil:by-product mixture which provides the optimum pH is determined, the nutrient status of this mixture is analyzed to determine the fertilizer requirements. Testing of by-product amended soils by a local Land Grant or agricultural university will determine the mixture pH, phosphate, potash, and magnesium levels relative to the optimum range, nitrogen amendments needed, the level of soluble salts, and list recommended crops suitable to soil parameter levels.

The soluble salts level of the optimum pH mix should also be determined, as it is an important indicator of potential limitations to the use of by-product. If the concentrations of soluble salts in a soil become too great, the osmotic pressure gradient from the soil to the inside of plant roots is disturbed and the plant’s ability to adsorb water is decreased. The effects of soluble salts levels varies with type of plant.

Boron, Molybdenum and Selenium

The levels of trace elements may also limit ash use. Plants may increase their uptake of boron, molybdenum, selenium, or other metals in soils amended by fly ash[13]. Thus, these parameters should be evaluated in ASC by-products. Many of these metal levels can be evaluated using the diagnostic soil test or the Baker Soil Test[14].

Boron toxicity may be expected if the hot water soluble boron level is greater than 20 mg/kg (20 ppm)[14]. For reclamation sites, however, boron levels above 20 mg/kg (20 ppm) may be acceptable. Symptoms used to describe boron phytotoxicity are often visual, such as discoloration of leaves. Visual symptoms of boron phytotoxicity may have little relationship to the survival or vigor of plants and reclamation success. On a West Virginia fly ash disposal site, robust growth of Crownvetch was observed growing directly in fly ash containing 109 mg/kg (109 ppm) hot water soluble boron. In a Pennsylvania fly ash disposal site revegetation study, robust growth of Crownvetch and Birdsfoot Trefoil, but somewhat stunted growth of grasses, were observed in 1:1 fly ash:soil mixtures containing about 49 mg/kg (49 ppm) hot-water-soluble boron[15].

Alfalfa requires yearly applications of about 0.2 mg/m^2 of boron for maximum yields, while sensitive crops have exhibited boron toxicities and decreased yields when boron was applied from 0.05 to 0.5 mg/m^2. Care should be taken when applying ASC by-products with high levels of boron to cherry, peach, lupine and kidney bean cropland, especially if the soil is sandy[14].

Molybdenum and selenium at certain levels are nontoxic to plants, but in forages may induce physiological disorders in livestock[13]. Molybdenum concentrations ranging from 5 to 20 mg/kg and selenium concentrations ranging from 4 to 5 mg/kg are potentially hazardous[16,17].

In summary, by-product:soil mixtures containing:

- 5 - 20 ppm Mo and/or
- 4-5 ppm Se

are not recommended as a growing medium for vegetation. Recommended boron levels are specific to plant type.

Other Plant Available and Total Sorbed Metals

Soils and soil:by-product mixtures can also be tested to determine the plant available and total sorbed metals levels using the Baker Test, Diagnostic Soil Test and EPA Test 3050. Although pure by-product is not suitable to be tested using the diagnostic soils test, total sorbed metals can be determined under sewage sludge (biosolids) testing programs.

Heavy metals are of concern, especially Cd, since they can cause serious metabolic problems in animals and humans when ingested in excessive amounts or when they accumulate in the food chain. Compared to sewage sludge, AFBC residues studied so far contain very low levels of heavy metals. Also, levels of heavy metals in AFBC residues are within ranges usually found in soils[1].

The levels of arsenic, molybdenum, zinc, selenium, or other metals in the by-product can be determined under university or state biosolids testing programs.

EPA allowable metals levels for use of sewage sludge for land application may be useful as a guideline for acceptable metals levels. (Note that ASC by-products for land application are not regulated by sewage sludge rules.) EPA limits for annual and cumulative metals loading rates for sewage sludge to land are shown on Tables 9-2 and 9-3. For Table 9-3, the relationship between the annual pollutant loading rate (APLR) for a pollutant and the annual whole sludge application rate (AWSAR) for sewage sludge is[18]:

$$\text{APLR} = \text{C} \times \text{AWSAR} \times 0.001$$

where

APLR = annual pollutant loading rate in kilograms per hectare per 365-day period.

C = pollutant concentration in milligrams, per kilogram of total solids (dry weight basis).

AWSAR = annual whole sludge application rate in metric tons per hectare per 365-day period (dry weight basis).

0.001 = a conversion factor.

Metals contents of natural soils can also be used as a standard of comparison (see Tables 9-4 and 9-5).

Table 9-2
Cumulative Pollutant Loading Rates

Pollutant	Cumulative Pollutant Loading Rate (kilograms per hectare)
Arsenic	41
Cadmium	39
Chromium	3000

Copper	1500
Lead	300
Mercury	17
Nickel	420
Selenium	100
Zinc	2800

(SOURCE: “EPA Standards for the Use or Disposal of Sewage Sludge,” 40 CFR 503, amended at 59 FR 9098, February 25, 1994, Subpart B - Land Application, § 503.13 Pollutant Limits.)

Table 9-3
Annual Pollutant Loading Rates

Pollutant	Annual Pollutant Loading Rate (kilograms per hectare per 365 day period)
Arsenic	2.0
Cadmium	1.9
Chromium	150
Copper	75
Lead	15
Mercury	0.85
Nickel	21
Selenium	5.0
Zinc	140

(SOURCE: "EPA Standards for the Use or Disposal of Sewage Sludge," 40 CFR 503, amended at 59 FR 9098, February 25,1994, Subpart B - Land Application, § 503.13 Pollutant Limits.)

Soil Texture

Additional properties of the by-product:soil mixtures relevant to plant growth include bulk density, moisture-holding capacity, particle size, and porosity. Additional factors related to ASC by-products include cementing or crusting of soils. All of these parameters are related to plant available moisture and root penetration, and all are interrelated. A low bulk density can result in increased seed germination, root penetration, and growth. The major reason for tilling soils is to loosen and aerate the soil, thereby decreasing its bulk density. Moisture holding capacity, particle size, and porosity are all related to plant-available moisture. Particle size distribution should ideally approach that of a silt loam (a specific mixture of sand, silt and clay-sized particles) for optimum plant growth. Both moisture holding capacity and porosity should be kept at a maximum in order to provide plants with the necessary amount of water and to minimize runoff and erosion.

Equipment and Application

For maximum benefit, ASC by-product would be used fresh or would require silo storage. Study of an exposed LIMB stockpile over 2½ years indicates that CCE content decreased significantly after 3 to 6 months, particularly on samples near the surface[19].

Standard agricultural lime can be loaded and hauled in dump trucks, even after being rained on. Standard lime is spread with twin-spinner lime trucks, which efficiently throw the lime across a 12-meter-wide path. Material passing the No. 100 sieve would create a dust cloud with this spreading method, which could be both a nuisance and a hazard. Alternative handling methods would be needed.

Some manufacturers sell a tractor-pulled spreader with a 9-meter boom designed for fine, dry powders. Custom-made and truck mounted spreaders can be purchased. More than one pass would be needed to apply most ASC by-product at the agronomic rate.

For use with biosolids, ASC by-product could be trucked from the power plant to the sewage treatment plant. To mix soil and by-product, a by-product silo and pugmill would be needed at the sewage treatment plant.

N-Viro Soil™ is used and spread similar to traditional agricultural fertilizers (with a lime spreader).

When applying an ASC by-product, the following should be avoided[1]:

- Applying by-product when cropland is too wet
- Spreading by-product where it may be washed into streams
- Allowing animals to graze on pastures treated with ASC by-product before there has been sufficient rain to wash the by-product from the herbage

The following should be practiced[1]:

- Apply the ASC by-product evenly
- Apply ASC by-product at the correct loading rate
- Allow sufficient time for soil reaction before planting the crop

Table 9-4
Representative Metal Content Typical of Soils

Element	Common Range for Soils (ppm)	Selected Average for Soils (ppm)
Arsenic	1 - 50	5
Barium	100 - 3,000	430
Beryllium	0.1 - 40	6
Boron	2 - 100	10
Cadmium	0.01 - 0.70	0.06
Cesium	0.3 - 25	6
Chromium	1 - 1,000	100
Cobalt	1 - 40	8
Copper	2 - 100	30
Gallium	5 - 700	14
Germanium	1 - 50	1
Lanthanum	1 - 5,000	30
Lead	2 - 20	10
Lithium	5 - 200	20
Manganese	20 - 3,000	600
Mercury	0.01 - 0.3	0.03
Molybdenum	0.2 - 5	2
Nickel	5 - 500	40
Rubidium	5 - 500	10
Scandium	5 - 50	7
Selenium	0.1 - 2	0.3
Silver	0.01 - 5	0.05
Strontium	50 - 1,000	200
Tin	2 - 200	10
Vanadium	20 - 500	100
Yttrium	25 - 250	50
Zinc	10 - 300	50
Zirconium	60 - 2,000	300

(SOURCE: U.S. EPA, *A Compendium of Superfund Field Operation Methods*, Vol. 2, EPA/540/P-87/001, 1987.)

Table 9-5
Average Contents and Range in Contents Reported for Elements in U.S. Soils and Other Surficial Materials

Element	Average	Range
Antimony	0.66	<1 - 8.8
Arsenic	7.2	<0.1 - 97
Barium	580	10 - 5,000
Beryllium	0.92	<1 - 15
Boron	33	<20 - 300
Chromium	54	1 - 2,000
Cobalt	9.1	<3 - 70
Copper	25	<1 - 700
Fluoride	430	<10 - 3,700
Lead	19	<10 - 700
Manganese	550	<2 - 7,000
Mercury	0.09	<0.01- 4.6
Molybdenum	0.97	<3 - 15
Nickel	19	<5 - 700
Selenium	0.39	<0.1 - 4.3
Silver	-	-
Strontium	240	<5 - 3,000
Tin	1.3	<0.1 - 10
Titanium	2,900	70 - 20,000
Vanadium	80	<7 - 500
Zinc	60	<5 - 2,900

(SOURCE: Shacklette & Boerngen (1984), as presented in Adriano, D. C., *Trace Elements in the Terrestrial Environment*, Springer-Verlag, New York. 1986.)

Case Histories

Numerous studies have been made in recent years to evaluate the beneficial effect of ASC by-products on soil. Studies have shown favorable results, with little evidence of introduction of toxic elements into the food chain[20,21,22]. However, root growth was affected when ash rates were high enough to cement the soil, as with the 24 percent LIMB amendment[11].

The USDA Agricultural Research Service in Beckley, West Virginia has published a manual for applying FBC residue to agricultural lands[1]. The manual includes a method for determining the application rate based on CCE and metals loading rates of the ash, but only recommends the agricultural use of FBC ash with a CCE greater than 30 percent[1]. In apples grown with FBC as a surface mulch, FBC residue was also found to enhance nutrient status and no indication of elevated trace elements was found[22]. In another experiment, maize dry matter yields doubled when 2 to 3 percent FBC products were added to the soil but decreased rapidly at higher rates[23].

Dry scrubber residues are being used as a fertilizer for peanut crops in North Carolina and Virginia[24]. The St. Johns River Power Park, a joint venture between Jacksonville Electric Authority and the Florida Power and Light Company, has become a source of gypsum for the peanut growing industry and anticipate that agriculture could be their biggest customer[3].

In an Ohio study[11], when acid mine spoil was reclaimed with dry FGD by-products (PFBC or LIMB ash) and sewage sludge, metal leachate concentrations decreased with FGD amendment. The addition of sewage sludge reduced leachate levels of iron and aluminum but not manganese or zinc, and had little effect on pH. Overall, the best results in plant growth were obtained with additions of both FGD by-product sufficient to achieve a neutral pH with 6 percent sewage sludge. At an FGD by-product loading rate approximately twice that of agricultural lime, concentrations of trace elements in the plant tissue were lower than those in unamended mine soil. Most monitored metals were below drinking water standards.

In a similar Ohio study on reclamation of acid mine land[12], it was found that amending soil with PFBC ash raised pH and improved plant growth but did not improve water holding capacity, pH buffering capacity, or biological activity. These soil properties can be improved, however, by mixing in an organic amendment, such as sewage sludge.

Ohio Edison's CCT By-Product Utilization Program[7-10]

The Dravo Lime Company, together with Ohio State University, performed a study using Ohio Edison's LIMB ash to stabilize sewage sludge (from National N-Viro Tech, Inc., facility at the City of Toledo Bay View Wastewater Treatment Plant) for land application. The LIMB process (Lime Injection Multistage Burner) is a furnace sorbent injection technology for con-trolling SO_2 emissions. This technology involves spraying lime as a finely atomized mist into the upper part of a suspension-fired boiler, where it reacts with SO_2. LIMB ash contains reaction by-products (calcium sulfate / sulfite), unreacted sorbent (lime), and fly ash. LIMB ash has chemical and physical properties that can generate high pH and heat of hydration. An experiment was conducted to replace cement kiln dust or lime kiln dust with LIMB ash. Cement kiln dust and lime kiln dust were normally used at the N-Viro Toledo Plant. The LIMB ash was taken from Ohio Edison Edgewater plant to the N-Viro Toledo plant. The sludge was mixed with LIMB ash. Depending on the available lime content in LIMB ash, a small amount of quicklime was added as necessary to raise the pH to greater than 12 and provide heat of hydration to achieve a desired temperature of 52-62ºC for 12 hours. The sludge was then aerated and dried for a period of about 7 days. The stabilized sludge was a soil-like product which was tested for acid neutralizing value, total and soluble metal content, and PFRP criteria (Process to Further Reduce Pathogens - USEPA Standards). The stabilized sludge was used as soil material at an active coal mine reclamation project. After successful stabilization of sludge with LIMB ash, the research group continued tests on sewage sludge stabilization with CFBC ash. These tests have also proven successful.

Summary and Conclusions

Based on laboratory chemical testing, many ASC by-products have potential as soil amendments. Laboratory testing must be performed to determine the correct agronomic rates.

The actual degree of benefit from an ASC by-product is expected to be specific to each crop, soil, and application rate, and can be best assessed by a field study. Reclamation would allow ash use at a higher rate of application, but be limited to mine lands.

Efforts should be made to register the by-product under the lime or fertilizer laws of each state. The by-product should be marketed as a low grade lime, by-product, or soil amendment, rather than an agricultural lime substitute (when allowed), so as not to mislead or disappoint farmers.

Due to by-product variability, nutrient and environmental testing should be performed frequently to protect public health, to reduce liability, and so that the by-product would be applied at the proper agronomic rate.

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A

APPENDIX A - PAVEMENT THICKNESS DESIGN

Introduction

This appendix describes pavement mixture design methods for advanced SO_2 control (ASC) by-product road base. The design procedures presented were developed for soil-cement pavements by the Portland Cement Association (PCA) and the American Association of State Highway and Transportation Officials (AASHTO), and for stabilized fly ash pavements by the American Coal Ash Association (ACAA).

PCA Method

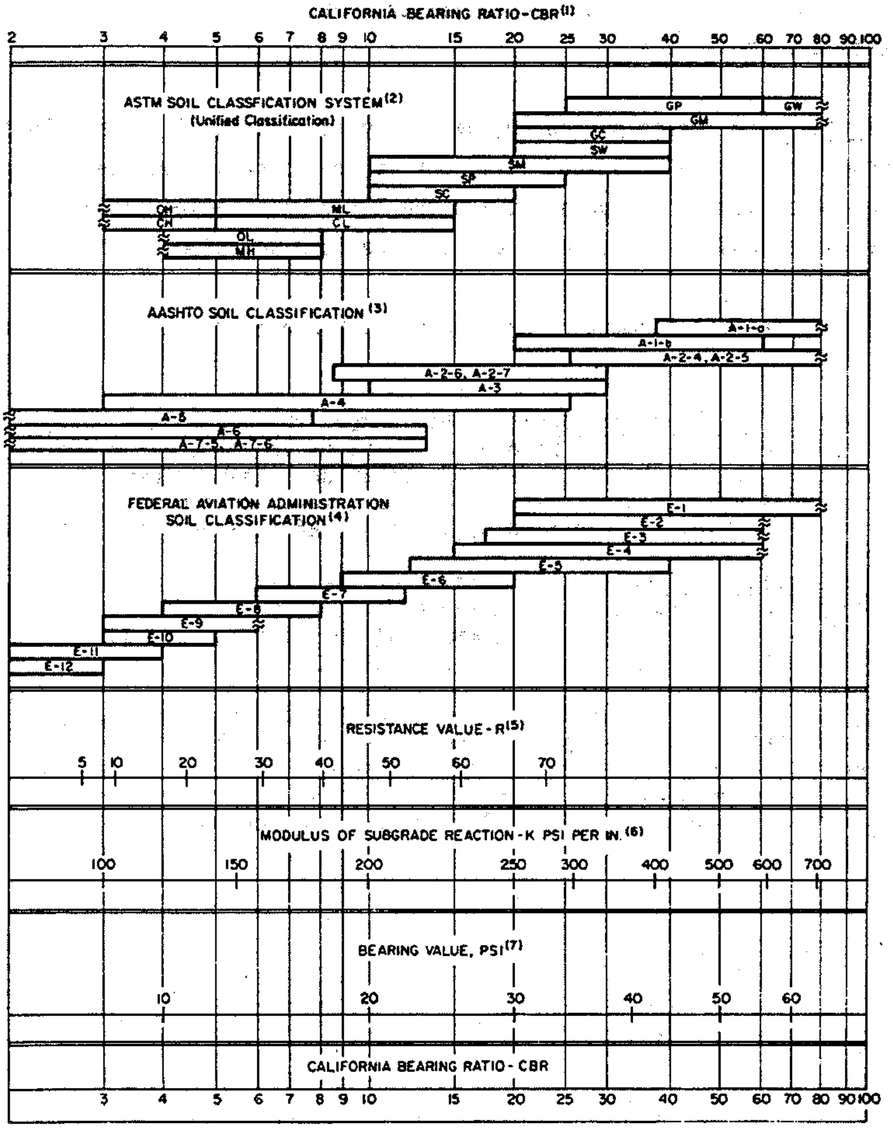
The thickness design procedure developed by PCA for soil-cement base course has been adopted for cement stabilized fly ash base course[1]. The design procedure consists of the determination of two parameters, the subgrade modulus and the fatigue factor, which are then entered into a design chart to yield an initial base course thickness. The required thickness of bituminous wearing surface is determined from the initial base course thickness. The base course thickness is then adjusted to account for the additional thickness of the wearing surface.

Subgrade Characteristics

The measure of subgrade strength used in this procedure is the subgrade modulus, k, as determined from field plate bearing tests. However, other acceptable methods of testing, such as California Bearing Ratio (CBR) and Resistance Value (R), can be used and converted to equivalent K-values using the broad relationships shown in Figure A-1[2]. Where light traffic conditions are expected, subgrade strengths can be estimated from the soil classification if field tests are impractical.

Design Period

The design period, n, generally assumed is 20 years. This does not represent the actual pavement life, but is considered to be the period of time between construction of the pavement and the first resurfacing or overlay[3]. Other design periods can be used at the designer’s discretion.



(1) For the basic idea see O. J. Porter, "Foundations for Flexible Pavements, "Highway Research Board Proceedings of the *Twenty-second Annual Meeting,* 1942, Vol. 22. pages 100-136.

(2) ASTM Designation D2487.

(3) "Classification of Highway Subgrade Materials, "Highway Research *Board Proceedings of the Twenty-fifth Annual Meeting,* 1945, Vol. 25. pages 376-392.

(4) *Airport Paving,* U.S. Department of Commerce, Federal Aviation Agency, May 1948, pages 11-16. Estimated using values given in FAA *Design Manual for Airport Pavements.* (Formerly used FAA Classification; Unified Classification now used.)

(5) C. E.Warnes, "Correlation Between *R* Value and *k* Value," unpublished report, Portland Cement Association, Rocky Mountain-Northwest Region, October 1971 (best-fit correlation with correction for saturation).

(6) See T. A. Middlebrooks and G. E. Bertram. "Soil Tests for Design of Runway Pavements." Highway Research Board *Proceedings of the Twenty-second Annual Meeting,* 1942. Vol. 22. page 152.

(7) See item (6). page 184.

Figure A-1
General Relationship Between Soil Classifications and Bearing Values

Traffic

Four traffic parameters are necessary for determination of the fatigue factor:

Average Daily Traffic (ADT). This number represents the daily anticipated volume (in both directions) of vehicles using the roadway during its first year of operation. This volume includes all vehicle types and can be developed from 24-hour traffic surveys or provided by various traffic agencies.

Percentage of Trucks. The portion of the average daily traffic comprised of trucks is expressed as a percentage and includes all single-axle, four-tire commercial vehicles as well as larger trucks with three or more axles.

Annual Traffic Growth Rate. The rate at which the average daily traffic volume is expected to increase yearly is expressed as a percentage of the ADT and is known as the annual traffic growth rate, r. The growth rate is used in conjunction with the design period to calculate the projection factor, P, from the relationship:

$$P = \frac{(1+r)^n - 1}{r}$$

Table A-1 contains values of the projection factor for given design periods and annual growth rates[3].

Axle Load Distribution. The number of axles within each load group that can be expected for a given number of trucks is expressed as the axle load distribution for that particular section of roadway. The distribution is developed from the actual count and weight of trucks observed at a loadometer station. The load groups are generally expressed in 2000 pound (907 kg) increments, and the number of axles to be expected in each group is generally based on 1000 trucks. Loadometer data is often available from state or municipal agencies for certain classifications of urban streets and rural roads. An example of an axle load distribution for an eastern city is shown in Table A-2[4].

For parking lots, an axle load distribution usually must be developed for the specific lot. The volume of traffic can be estimated from the capacity of the lot, and the volume and weight of the trucks based on the nature of the facility served by the lot. The truck volume and axle load distribution should be developed for the most heavily traveled portion of the lot and should be assumed to apply to the entire lot for design purposes.

Table A-1
Projection Factors

Design Period Years (n)	No Growth	Projection Factor, P, for Annual Growth Rate, r						
		2	4	5	6	7	8	10
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	2.0	2.02	2.04	2.05	2.06	2.07	2.08	2.10
3	3.0	3.06	3.12	3.15	3.18	3.21	3.25	3.31
4	4.0	4.12	4.25	4.31	4.37	4.44	4.51	4.64
5	5.0	5.20	5.42	5.53	5.64	5.75	5.87	6.11
6	6.0	6.31	6.63	6.80	6.98	7.15	7.34	7.72
7	7.0	7.43	7.90	8.14	8.39	8.65	8.92	9.49
8	8.0	8.58	9.21	9.55	9.90	10.26	10.64	11.44
9	9.0	9.75	10.58	11.03	11.49	11.98	12.49	13.58
10	10.0	10.95	12.01	12.58	13.18	13.82	14.49	15.94
11	11.0	12.17	13.49	14.21	14.97	15.78	16.65	18.53
12	12.0	13.41	15.03	15.92	16.87	17.89	18.98	21.38
13	13.0	14.68	16.63	17.71	18.88	20.14	21.50	24.52
14	14.0	15.97	18.29	19.16	21.01	22.55	24.21	27.97
15	15.0	17.29	20.02	21.58	23.28	25.13	27.15	31.77
16	16.0	18.64	21.82	23.66	25.67	27.89	30.32	35.95
17	17.0	20.01	23.70	25.84	28.21	30.84	33.75	40.55
18	18.0	21.41	25.65	28.13	30.91	34.00	37.45	45.60
19	19.0	22.84	27.67	30.54	33.76	37.38	41.45	51.16
20	20.0	24.30	29.78	33.06	36.79	41.00	45.76	57.28
25	25.0	32.03	41.65	47.73	54.86	63.25	73.11	98.35
30	30.0	40.57	56.08	66.44	79.06	94.46	113.28	164.49
35	35.0	49.99	73.65	90.32	111.43	138.24	172.32	271.02

(SOURCE: American Association of State Highway and Transportation Officials. *AASHTO Guide for Design of Pavement Structures.* Washington, DC, 1993.)

Table A-2
Example of a Truck Axle Load Distribution Matrix (Pittsburgh, PA)

Axle Load Group Pounds (kg)	Axles Per 1,000 Trucks
Single Axles	
14,000 - 15,999 (6,350 - 7,257)	81.8
16,000 - 17,999 (7,258 - 8,164)	86.9
18,000 - 19,999 (8,165 - 9,071)	36.8
20,000 - 21,999 (9,072 - 9,978)	19.4
22,000 - 23,999 (9,979 - 10,885)	6.32
24,000 - 25,999 (10,886 - 11,793)	1.84
26,000 - 27,999 (11,794 - 12,700)	0.24
Tandem Axles	
24,000 - 25,999 (10,886 - 11,793)	67.6
26,000 - 27,999 (11,794 - 12,700)	67.6
28,000 - 29,999 (12,701 - 13,607)	67.6
30,000 - 31,999 (13,608 - 14,514)	40.6
32,000 - 33,999 (14,515 - 15,421)	22.1
34,000 - 35,999 (15,422 - 16,329)	10.3
36,000 - 37,999 (16,330 - 17,236)	2.2
38,000 - 39,999 (17,237 - 18,143)	2.9
40,000 - 41,999 (18,144 - 19,050)	0.32
42,000 - 43,999 (19,051 - 19,957)	0.32
44,000 - 45,999 (19,958 - 20,864)	0.22
46,000 - 47,999 (20,865 - 21,772)	0.16
48,000 - 49,999 (21,773 - 22,679)	0.16

(SOURCE: GAI Consultants, Inc. *Guide for the Design and Construction of Cement-Stabilized Fly Ash Pavements.* Process and Technical Data Publication, National Ash Association, 1976 .)

Fatigue Factor

The fatigue factor represents the total fatigue consumption of the pavement over the design period for a given loading configuration. The fatigue factor is calculated in the following manner:

1. The total number of trucks anticipated during the design period is calculated.

2. The total number of axles in each load category expected during the design period is calculated from the results of Item 1 (above) and the given axle load distribution.

3. The fatigue effect contributed by each axle load group is determined from Item 2. (above) and the fatigue consumption coefficients listed in Table A-3[3].

4. The individual fatigue effects for each axle load group are added to yield the fatigue factor.

For residential streets and secondary roads where an axle load distribution is not available, the fatigue factor can be estimated from Table A-4[2].

Initial Base Course Thickness

Once the subgrade modulus and fatigue factor have been determined, they are entered into the design chart in Figure A-2 to yield an initial base course thickness[4]. This initial thickness can be further adjusted to account for the load-spreading capacity of the wearing surface.

Bituminous Wearing Surface Thickness

A bituminous wearing surface should always be placed on the ASC by-product base course to protect the base course from both water and abrasion. The thickness of bituminous wearing surface can be related to the initial base course thickness by the chart shown in Figure A-3[4]. In addition to a curve representing the minimum required thickness of wearing surface, Figure A-3 contains a curve of recommended thickness. This curve is for use in frost areas where snowplows are used, and in situations where it is desired to minimize reflective cracking, which may occur in the wearing surface as a result of shrinkage cracking in the base course, a phenomenon common to stabilized bases[5,6].

Adjusted Base Course Thickness

Although the actual structural contribution of the wearing surface thickness has not been fully determined, a reduction in the initial base course thickness can be made to account for the load-spreading capacity of the wearing surface thickness. The adjusted base course thickness can be determined from Figure A-4[4].

Table A-3
Fatigue Consumption Coefficients

Axle Load Group Pounds (kg)	Fatigue Consumption Coefficient
Single Axles	
10,000 - 11,999 (4,536 - 5,442)	0.0018
12,000 - 13,999 (5,443 - 6,349)	0.020
14,000 - 15,999 (6,350 - 7,257)	0.160
16,000 - 17,999 (7,258 - 8,164)	1.000
18,000 - 19,999 (8,165 - 9,071)	5.2
20,000 - 21,999 (9.072 - 9,978)	23.3
22,000 - 23,999 (9,979 - 10,885)	93.0
24,000 - 25,999 (10,886 - 11,793)	337.0
26,000 - 27,999 (11,794 - 12,700)	1,130.0
28,000 - 29,999 (12,701 - 13,607)	3,530.0
Tandem Axles	
18,000 - 19,999 (8,165 - 9,071)	0.0018
20,000 - 21,999 (9,072 - 9,978)	0.0081
22,000 - 23,999 (9,979 - 10,885)	0.031
24,000 - 25,999 (10,886 - 11,793)	0.107
26,000 - 27,999 (11,794 - 12,700)	0.341
28,000 - 29,999 (12,701 - 13,607)	1.00
30,000 - 31,999 (13,608 - 14,514)	2.74
32,000 - 33,999 (14,515 - 15,421)	7.1
34,000 - 35,999 (15,422 - 16,329)	17.5
36,000 - 37,999 (16,330 - 17,236)	41.1
38,000 - 39,999 (17,237 - 18,143)	93.0
40,000 - 41,999 (18,144 - 19,050)	203.0
42,000 - 43,999 (19,051 - 19,957)	431.0
44,000 - 45,999 (19,958 - 20,864)	890.0
46,000 - 47,999 (20,865 - 21,772)	1,790.0
48,000 - 49,999 (21,773 - 22,679)	3,530.0

(SOURCE: R. G. Packard. *Thickness Design for Concrete Highway and Street Pavements.* Engineering Bulletin, Portland Cement Association, Skokie, IL, 1984 .)

Table A-4
Representative Fatigue Factors for Light-Traffic Pavements

Type of Road	ADT	Total Trucks[1] Percent (approx.)	Heavy Trucks[2] Percent (approx.)	Fatigue Factor[3]
Residential Street (local)	300 to 700	8	3	5,000 to 12,000
Residential Street (collector)	700 to 4,000	8	3	12,000 to 20,000
Secondary Roads	Up to 2,000[3]	14 to 20	5 to 8	12,000 to 30,000

[1] All commercial vehicles, including two-axle, four-tire vehicles.

[2] Excludes panels, pickups, and other two-axle, four-tire vehicles that are seldom heavy enough to affect design thickness.

[3] Range are based on the following characteristics of street and secondary road traffic: (1) one-half the indicated number of heavy axle loads, one direction; (2) axle-load distributions varying from 12,000 to 20,000 lbs. on individual axles; and (3) weighted averages of axle loads varying between 13,000 and 16,000 lbs. on individual axles.

(SOURCE: R. G. Packard. *Thickness Design for Concrete Highway and Street Pavements*. Engineering Bulletin, Portland Cement Association, Skokie, IL, 1984.)

Pavement Design Example

The preceding thickness design procedure is illustrated in the following pavement design example[4].

Given: Commercial Collector Street

ADT = 3,000 vehicles
Percent Heavy Trucks = 3
Annual Growth Rate, r = 1.5 percent
Design Period, n = 20 years
Number of Lanes = 2
Subgrade Modulus, k = 125 psi/inch (34 MPa/m)
Axle Load Distribution = Pittsburgh (Table A-2)

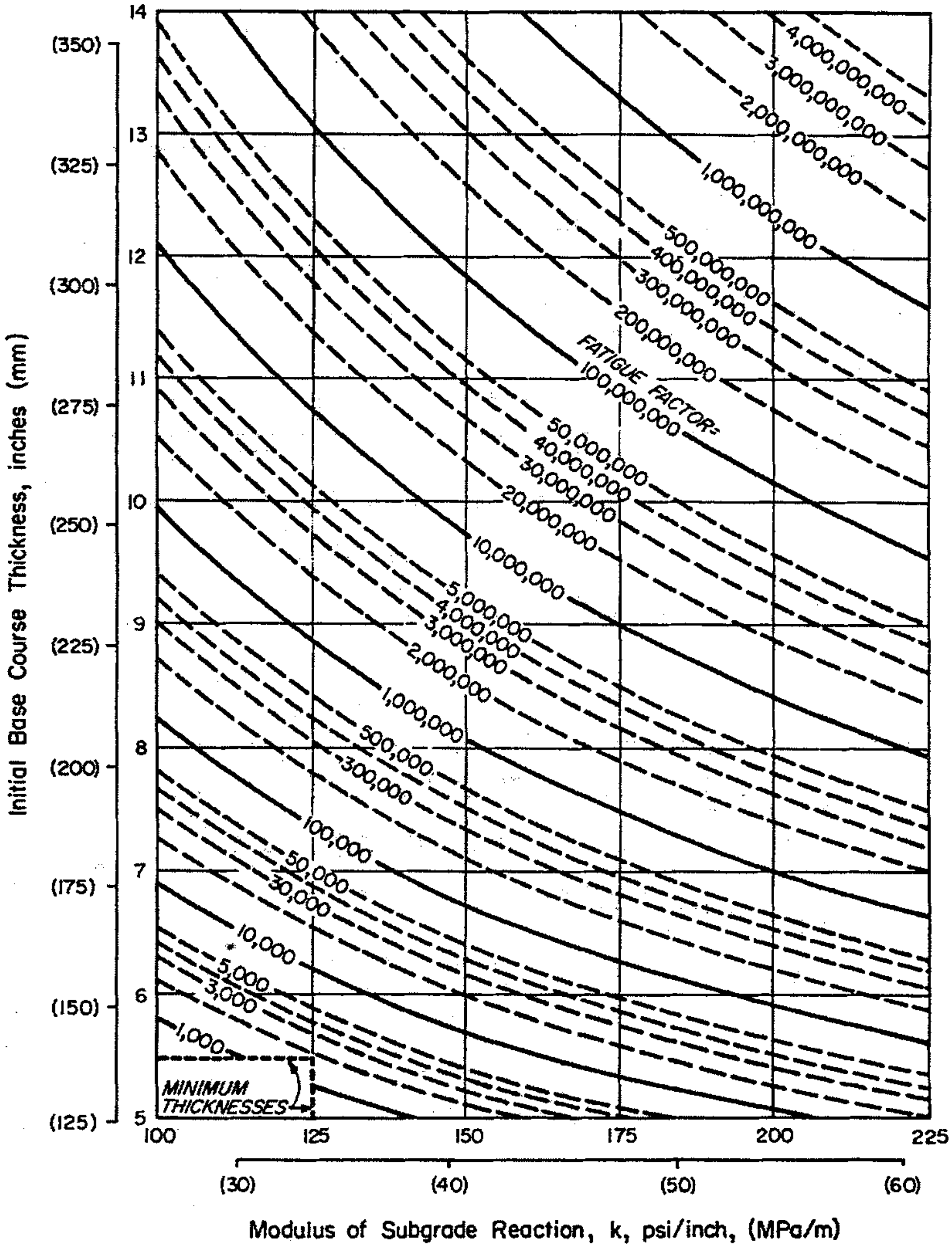


Figure A-2
Initial Base Course Thickness Design Chart

(SOURCE: GAI Consultants, Inc. *Guide for the Design and Construction of Cement-Stabilized Fly Ash Pavements.* Process and Technical Data Publication, National Ash Association, 1976.)

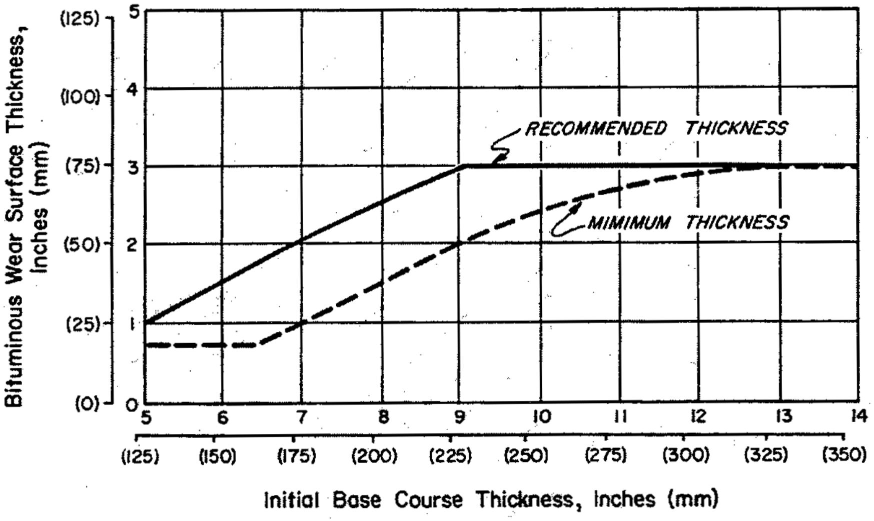


Figure A-3
Bituminous Wearing Surface Thickness Design Chart

(SOURCE: GAI Consultants, Inc. *Guide for the Design and Construction of Cement-Stabilized Fly Ash Pavements.* Process and Technical Data Publication, National Ash Association, 1976.)

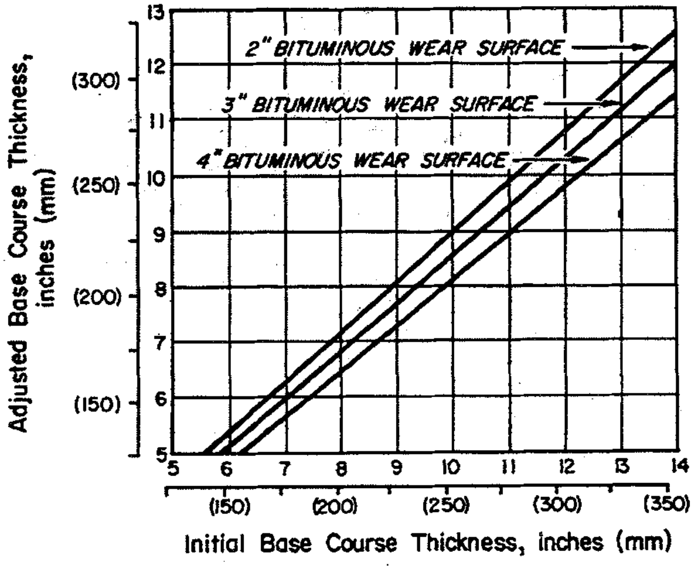


Figure A-4
Adjusted Base Course Thickness Design Chart

(SOURCE: GAI Consultants, Inc. *Guide for the Design and Construction of Cement-Stabilized Fly Ash Pavements.* Process and Technical Data Publication, National Ash Association, 1976.)

Step

1. Number of trucks per day in design lane
   3,000 vehicles / day ÷ 2 lanes x 3 percent = 45 trucks / day

2. Projection factor,
   for r of 1.5 percent and n
   of 20 years from Table A-1 = 23.12

3. Total truck traffic in design
   lane during design period
   45 trucks / day x 23.12 x 365 days / year = 379,750 trucks

4. Fatigue factor,
   from Table A-5 = 1,700,000

5. Initial base course thickness,
   from Figure A-2 = 9¼ inches (235 mm)

6. Bituminous wearing surface thickness,
   from Figure A-3 = 3 inches (76 mm)

7. Adjusted base course thickness,
   from Figure A-4 = 8 inches (203 mm)

8. Final pavement configuration:
   stabilized fly ash base course = 8 inches (203 mm)
   bituminous wearing surface = 3 inches (76 mm)

AASHTO Method

The pavement thickness design procedure developed by AASHTO is based on road tests, supplemented by existing design procedures, and has been periodically revised, most recently in 1993[3]. The basic equation for this method is:

$$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3$$

D_1, D_2, and D_3 are actual thicknesses (in inches) of surface, base, and subbase courses, respectively.

a_1, a_2, and a_3 are layer coefficients representative of surface, base, and subbase courses, respectively.

m_2 and m_3 are drainage coefficients for base and subbase layers, respectively.

SN is the design structural number of the pavement.

Table A-5
Example Calculations for Determining Fatigue Factor

Axle Load Group Kips A	Axles Per 1,000 Trucks B	Axle Loads in Design Period (B x Total Trucks/1,000) C	Fatigue Consumption Coefficient D	Fatigue Effect (C x D) E
Single Axles				
14 - 16	81.8	31,064	0.16	4,970
16 - 18	86.9	32,962	1.0	32,962
18 - 20	36.8	13,975	5.2	72,670
20 - 22	19.4	7,367	23.3	171,651
22 - 24	6.32	2,400	93.0	223,200
24 - 26	1.84	699	337.0	235,563
26 - 28	0.24	91	1,130.0	102,830
Tandem Axles				
24 - 26	67.6	25,671	0.107	2,747
26 - 28	67.6	25,671	0.341	8,754
28 - 30	67.6	25,671	1.00	25,671
30 - 32	40.6	15,418	2.74	42,245
32 - 34	22.1	8,392	7.1	59,583
34 - 36	10.3	3,911	17.5	68,443
36 - 38	2.2	835	41.1	34,319
38 - 40	2.9	1,101	93.0	102,393
40 - 42	0.32	122	203.0	24,766
42 - 44	0.32	122	431.0	52,582
44 - 46	0.22	84	890.0	74,760
46 - 48	0.16	61	1,790.0	109,190
48 - 50	0.16	61	3,530.0	215,330
			Fatigue Factor	1,664,629
			Rounded Off To	1,700,000

(SOURCE: GAI Consultants, Inc. *Guide for the Design and Construction of Cement-Stabilized Fly Ash Pavements.* Process and Technical Data Publication, National Ash Association, 1976.)

The SN equation does not have a single, unique solution, and there are many combinations of layer thicknesses that are satisfactory. When selecting a final design, it is necessary to consider costs as well as construction and maintenance constraints.

Structural Number, SN

The structural number (SN) represents the structural capacity of the pavement and is used to identify a thickness design to withstand a projected level of axle load traffic over a designated time period. This number is determined by the number and distribution of wheel-load applications, the subgrade soil support, the terminal Present Serviceability Index (PSI) value used, and a regional factor which takes into account environmental conditions which differ from those at the AASHTO Road Test site. A design monograph (Figure A-5) was developed by AASHTO to relate all of these factors[3].

W_{18}. W_{18} is the estimated future traffic for the performance period.

$$W_{18} = D_D \times D_L \times \overline{W}_{18}$$

D_D is the directional distribution factor, which is generally 0.5 for most roadways.

D_L is the lane distribution factor, which can be found on Table A-6.

$\overline{W}_{18}$ is the accumulative two-directional 18-kip single axle load equivalent (ESAL) units predicted for a specific section of highway during the analysis period.

R. Reliability design factor (R) accounts for chance variations in both traffic prediction and the performance prediction. Therefore, it provides a predetermined level of assurance that pavement sections will survive the period for which they are designed. Table A-7 presents recommended levels of reliability for various functional classifications[3].

S_o. Standard deviation (S_o) is 0.35 for flexible pavements as suggested by AASHTO[3].

M_R . M_R is the effective resilient modulus of roadbed material.

ΔPSI. The design serviceability loss (ΔPSI) is equal to the initial serviceability (P_o) minus the terminal serviceability (P_t). The P_o values observed at the AASHTO Road Test site were 4.2 for flexible pavement, but 4.1 is normally achieved in the state. A P_t index of 2.5 or higher is suggested for the design of major highways and 2.0 for highways with lower traffic volumes.

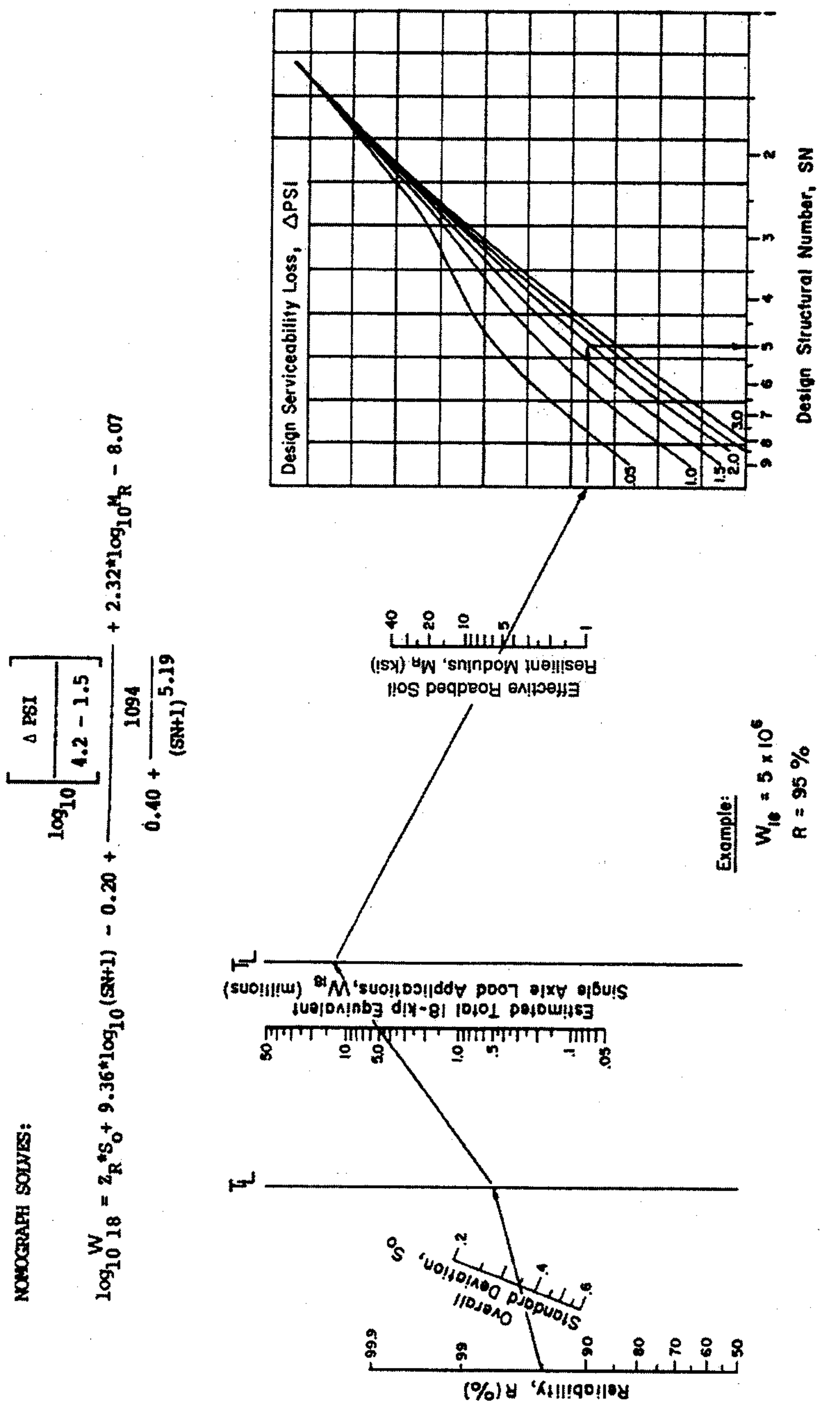


Figure A-5
Design Chart for Flexible Pavements Based on Using Mean Values for Each Input

(SOURCE: American Association of State Highway and Transportation Officials. *AASHTO Guide for Design of Pavement Structures*. Washington, DC, 1993.)

Table A-6
DL, Lane Distribution Factor

Number of Lanes in Each Direction	Percent of 18-kip ESAL in Design Lane
1	100
2	80 - 100
3	60 - 80
4	50 - 75

(SOURCE: American Association of State Highway and Transportation Officials. *AASHTO Guide for Design of Pavement Structures*. Washington, DC, 1993.)

Table A-7
Suggested Levels of R for Various Functional Classifications

	Recommended Level of Reliability	
Functional Classification	Urban	Rural
Interstate and Other Freeways	85 - 99.9	80 - 99.9
Principal Arterials	80 - 99	75 - 99
Collectors	80 - 95	75 - 95
Local	50 - 80	50 - 80

(SOURCE: American Association of State Highway and Transportation Officials. *AASHTO Guide for Design of Pavement Structures*. Washington, DC, 1993.)

Layer Coefficients, a_1, a_2, and a_3

The layer coefficient expresses the empirical relationship between SN and thickness, and measures the ability of the material to function as a component of the pavement. The values of $a_{1,}$ $a_{2,}$ and a_3 vary depending on the quality of the pavement materials being used. The main factors influencing the variation of $a_{1,}$ $a_{2,}$ and a_3 are the modulus of elasticity (E) and the compressive strength of pavement materials. The AASHTO Design Guide graphically depicts the relationship between the modulus of elasticity, strength, and the structural layer coefficient for the surface course a_1 (Figure A-6), base a_2 (Figures A-7, A-8, and A-9), and subbase a_3 (Figure A-10).

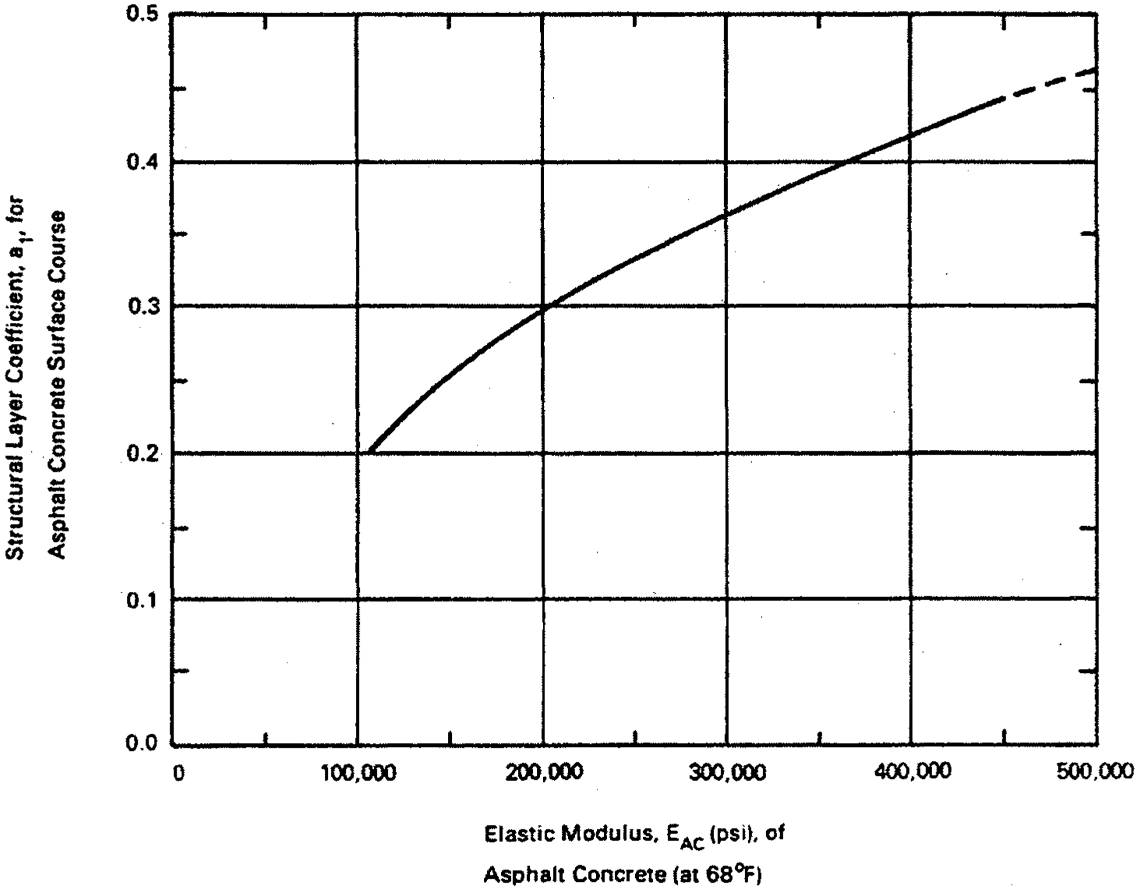
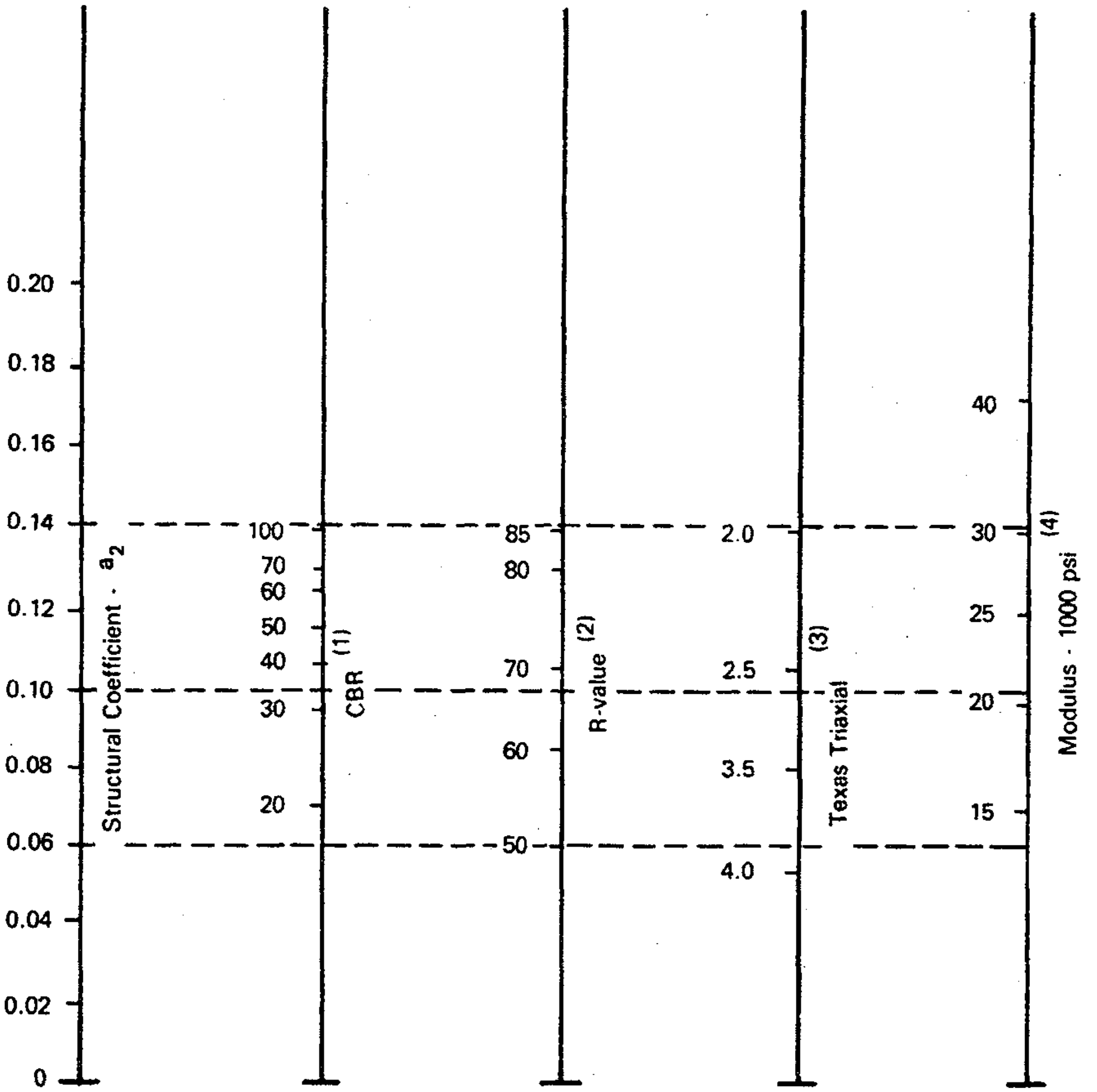


Figure A-6
Chart for Estimating Structural Layer Coefficient of Dense-Graded Asphalt Concrete Based on the Elastic (Resilient) Modulus

(SOURCE: American Association of State Highway and Transportation Officials. *AASHTO Guide for Design of Pavement Structures*. Washington, DC, 1993.)



(1) Scale derived by averaging correlations obtained from Illinois.
(2) Scale derived by averaging correlations obtained from California, New Mexico and Wyoming.
(3) Scale derived by averaging correlations obtained from Texas.
(4) Scale derived on NCHRP project.

Figure A-7
Variation in Granular Base Layer Coefficient (a_2) with Various Base Strength Parameters

(SOURCE: American Association of State Highway and Transportation Officials. *AASHTO Guide for Design of Pavement Structures*. Washington, DC, 1993.)

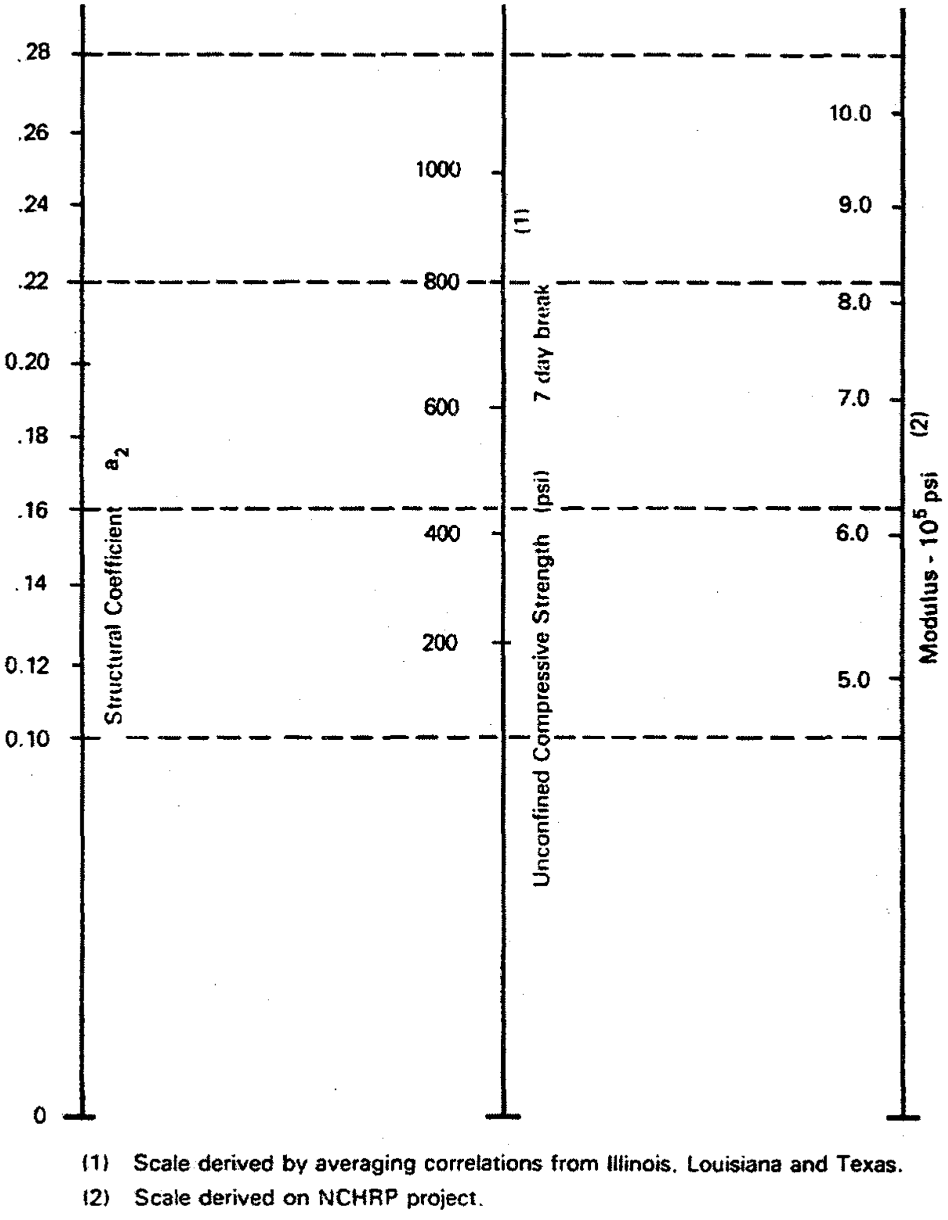
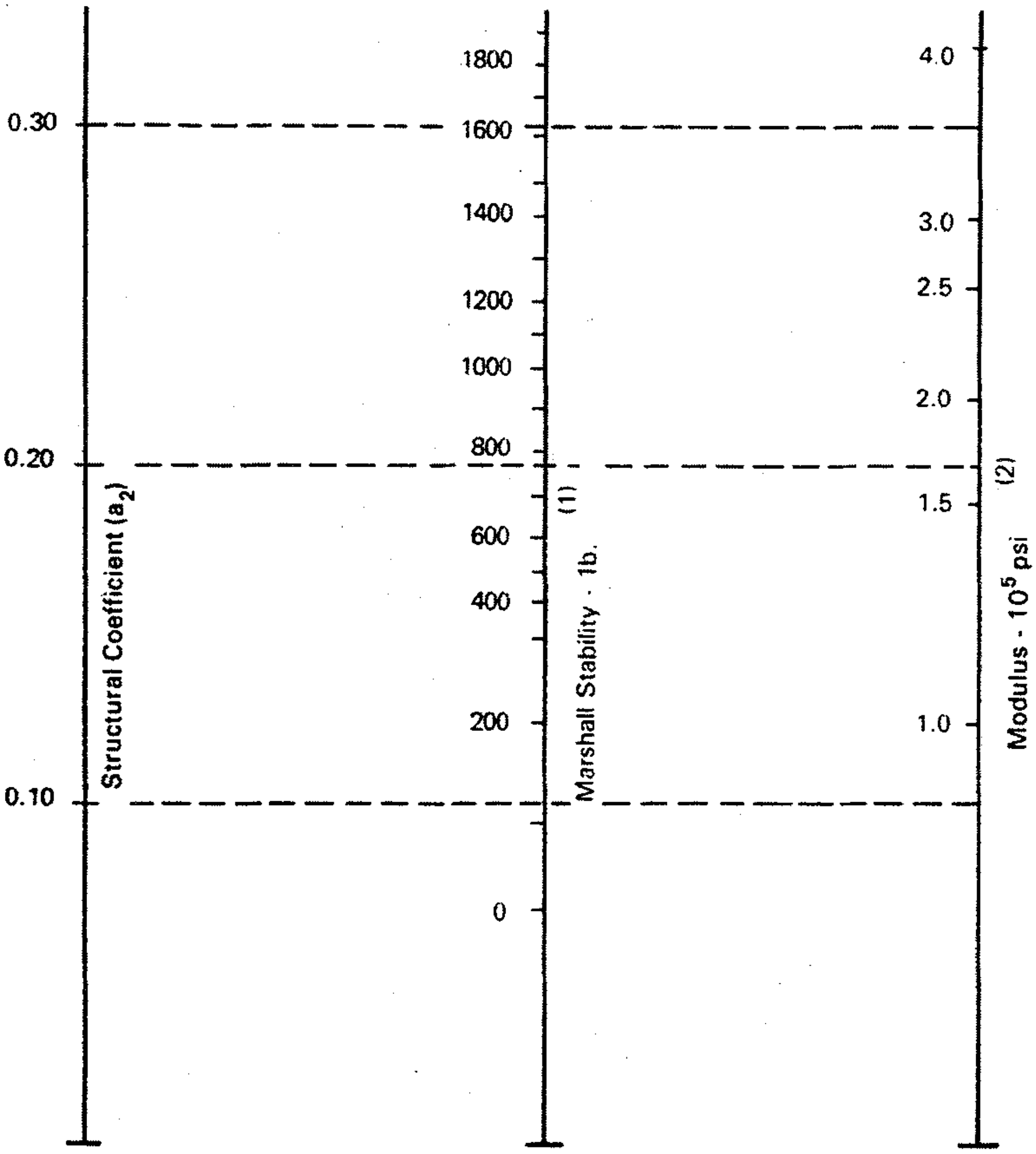


Figure A-8
Variation in a_2 for Cement-Treated Bases with Base Strength Parameter

(SOURCE: American Association of State Highway and Transportation Officials. *AASHTO Guide for Design of Pavement Structures.* Washington, DC, 1993.)

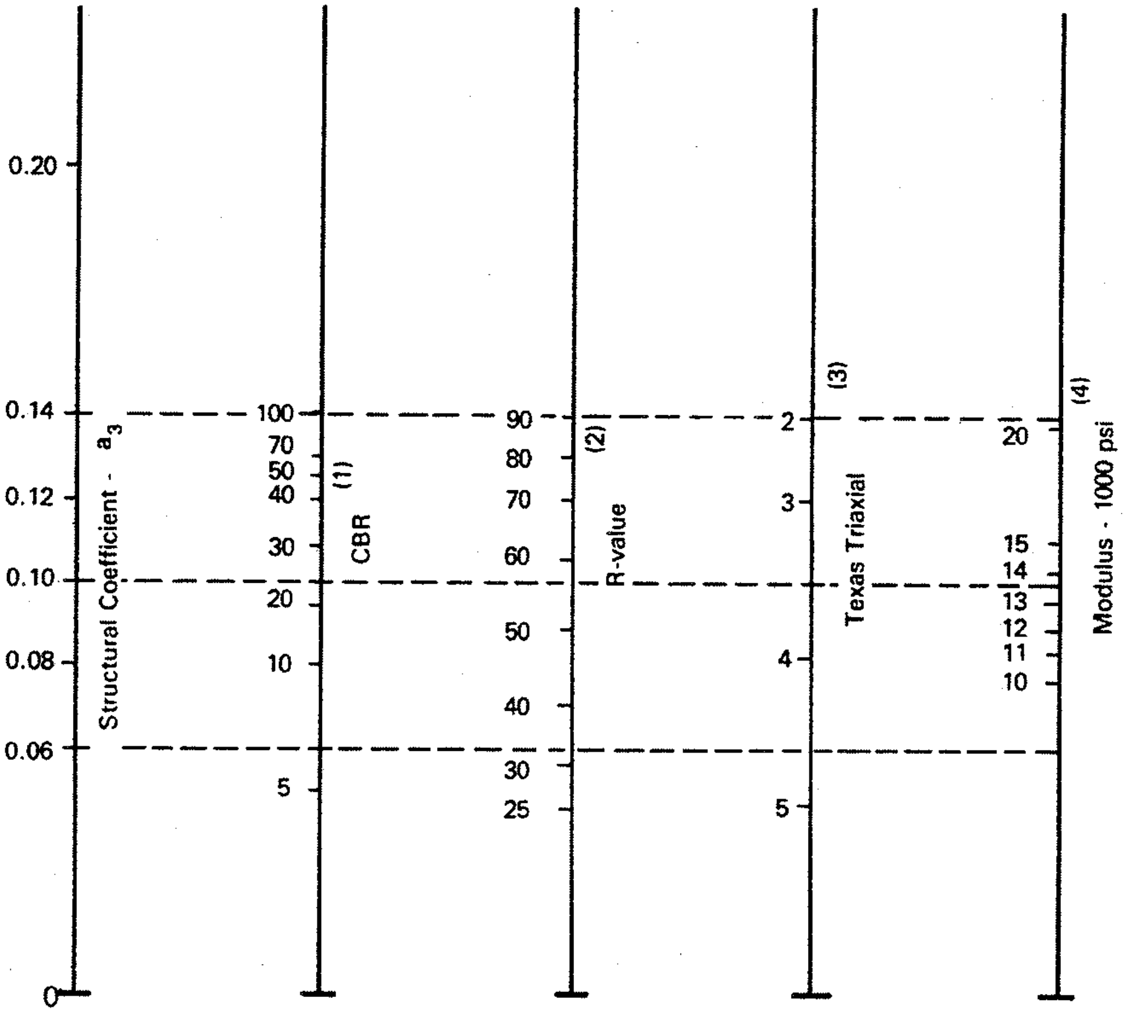


(1) Scale derived by correlation obtained from Illinois.

(2) Scale derived on NCHRP project.

Figure A-9
Variation in a_2 for Bituminous-Treated Bases with Base Strength Parameter

(SOURCE: American Association of State Highway and Transportation Officials. *AASHTO Guide for Design of Pavement Structures.* Washington, DC, 1993.)



(1) Scale derived from correlations from Illinois.

(2) Scale derived from correlations obtained from The Asphalt Institute, California, New Mexico and Wyoming.

(3) Scale derived from correlations obtained from Texas.

(4) Scale derived on NCHRP project.

Figure A-10
Variation in Granular Subbase Layer Coefficient (a_3) with Various Subbase Strength Parameters

(SOURCE: American Association of State Highway and Transportation Officials. *AASHTO Guide for Design of Pavement Structures.* Washington, DC, 1993.)

Drainage Coefficients, m_2 and m_3

The drainage coefficient is a factor for modifying the layer coefficient to account for expected levels of drainage from each layer. AASHTO recommends values for drainage that range from 1.4 for excellent drainage to 0.4 for very poor drainage, as listed in Table A-8[3].

Table A-8
Recommended m_i Values for Modifying Structural Layer Coefficients of Untreated Base and Subbase Materials in Flexible Pavements

	Percent of Time Pavement Structure is Exposed to Moisture Levels Approaching Saturation			
Quality of Drainage	**Less Than 1%**	**1 - 5%**	**5 -25%**	**Greater Than 25%**
Excellent	1.40 - 1.35	1.35 - 1.30	1.30 - 1.20	1.20
Good	1.35 - 1.25	1.25 - 1.15	1.15 - 1.00	1.00
Fair	1.25 - 1.15	1.15 - 1.05	1.00 - 0.80	0.80
Poor	1.15 - 1.05	1.05 - 0.80	0.80 - 0.60	0.60
Very Poor	1.05 - 0.95	0.95 - 0.75	0.75 - 0.40	0.40

Layered Design Analysis

Figure A-11 demonstrates the layer thickness calculation that should be followed in the design.

Pavement Design Example

The preceding thickness design procedure is illustrated in the following pavement design example:

Given: State Highway in Rural Area

Design Period, n = 20 years
First Year Traffic, $\overline{W}_{18}$ = 2.5×10^6 18-kip ESAL
Traffic Growth Rate, r = 3%

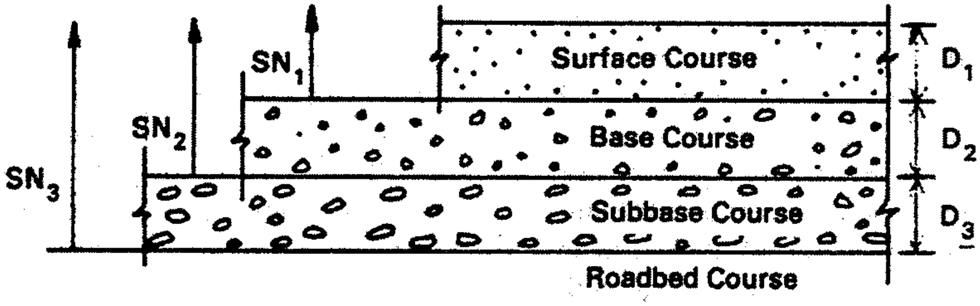
Annual Traffic Growth Rate,P

$$= \frac{(1+r)^n - 1}{r}$$

$$= \frac{(1+0.03)^{20} - 1}{0.03}$$

$$= 27$$

Two Directions (three lanes in each direction), M_R = 5,700 psi for roadbed soil



$$D^*_1 \geq \frac{SN_1}{a_1}$$

$$SN^*_1 = a_1 D^*_1 \geq SN_1$$

$$D^*_2 \geq \frac{SN_2 - SN^*_1}{a_2 m_2}$$

$$SN^*_1 + SN^*_2 \geq SN_2$$

$$D^*_3 \geq \frac{SN_3 - (SN^*_1 + SN^*_2)}{a_3 m_3}$$

1) a, D, m, and SN are as defined in the text and are minimum required values.

2) An asterisk with D or SN indicates that it represents the value actually used, which must be equal to or greater than the required value.

Figure A-11
Procedure for Determining Thickness of Layers Using a Layered Analysis Approach

(SOURCE: American Association of State Highway and Transportation Officials. *AASHTO Guide for Design of Pavement Structures*. Washington, DC, 1993.)

Step

1. First year W_{18} = D_D x D_L x $\overline{W}_{18}$
select D_D = 50% for two directions
select D_L = 80% from Table A-6
then, W_{18} = $0.5 \times 0.8 \times 2.5 \times 10^6$
= 1.0×10^6 18-kip ESAL
at 20 years,
W_{18} (at 20 years) = W_{18} x P
= $1.0 \times 10^6 \times 27$
= 27×10^6 18-kip ESAL

2. Reliability,
select R from Table A-7 = 95%

3. Standard deviation,
S_o = 0.35

4. Effective roadbed soil resilient modulus,
M_R = 5,700 psi

5. Serviceability loss,
ΔPSI = $P_o - P_t$
= 4.6 - 2.5
= 2.1

6. Three layers of pavement material,
asphalt concrete E_{AC} = 400,000 psi
select a_1 from Figure A-6 = 0.42

granular base E_{BS} = 30,000 psi
select a_2 from Figure A-7 = 0.14

granular subbase E_{SB} = 11,000 psi
select a_3 from Figure A-10 = 0.08

7. Drainage coefficient,
select m_2, m_3 from Table A-8 = 1.2
(for good drainage system and
1 to 5 percent moisture exposure
time)

8. Applying Figure A-5,

base E_{BS} = 30,000 psi, find $SN_1 = 3.5$

subbase E_{SB} = 11,000 psi, find $SN_2 = 4.9$

subgrade E_{SG} = 5,700 psi, find $SN_3 = 5.9$

9. Solving,

thickness of surface asphalt concrete,

$$
\begin{aligned}
D_1 &= SN_1 / a_1 \\
&= 3.5 / 0.42 \\
&= 8.3\text{, say 8.5 inches}
\end{aligned}
$$

$$
\begin{aligned}
SN_1^* &= a_1 D_1 \\
&= 0.42 \times 8.5 \\
&= 3.6
\end{aligned}
$$

thickness of base course,

$$
\begin{aligned}
D_2 &= (SN_2 - SN_1^*) / (a_2\, m_2) \\
&= (4.9 - 3.6) / (0.14 \times 1.2) \\
&= 7.7\text{, say 8 inches}
\end{aligned}
$$

$$
\begin{aligned}
SN_2^* &= a_2\, m_2\, D_2 \\
&= 0.14 \times 1.2 \times 8 \\
&= 1.34
\end{aligned}
$$

thickness of subbase,

$$
\begin{aligned}
D_3 &= [SN_3 - (SN_1^* + SN_2^*)] / (a_3\, m_3) \\
&= [5.9 - (3.6+1.34)] / (0.08 \times 1.2) \\
&= 10\text{ inches}
\end{aligned}
$$

It should be noted that this example does not consider the serviceability loss due to swelling and / or frost heave. If swelling and / or frost heave are expected, the following steps should be included in the design procedures:

Step

a. Select initial pavement structural number (SN_3) for conditions assuming no swelling and frost heave.

b. Select a trial performance period that might be expected under the swelling / frost heave conditions anticipated. This number should be less than the maximum possible performance period corresponding to the selected initial pavement structural number. In general, the greater the environmental loss, the smaller the performance period will be.

c. Develop the graph of cumulative environmental serviceability loss versus time using laboratory or field soil sample testing data. Estimating the corresponding total serviceability loss due to swelling and / or frost heave ($\Delta PSI_{SW, FH}$) that can be expected for the trial period from Step b.

d. Subtract this environmental serviceability loss (Step c.) from the desired total serviceability loss to establish the corresponding traffic serviceability loss.

$$\Delta PSI_{TR} = \Delta PSI - \Delta PSI_{SW, FH}$$

e. Use Figure A-5 to estimate the allowable cumulative 18-kip ESAL traffic corresponding to the traffic serviceability loss determined in Step d. Note that it is important to use the same levels of reliability, effective roadbed soil resilient modulus, and initial structural number when applying the flexible pavement chart to estimate this allowable traffic.

f. Estimate the corresponding year at which the cumulative 18-kip ESAL traffic (determined in Step e.) will be reached. This should be accomplished with the aid of the cumulative traffic versus time plot developed according to traffic data.

g. Compare the trial performance period with that calculated in Step f. If the difference is greater than one year, calculate the average of the two and use this as the trial value for the start of the next iteration (return to Step b). If the difference is less than one year, convergence is reached and the average is the predicted performance period corresponding to the initial SN_3. An overlay will be required before the end of the design performance period.

ACAA Method 1

ACAA suggests use of a mechanistic design procedure based on the concept of flexural fatigue consumption[7].

Flexural fatigue consumption is related to the number of load applications and the stress ratio, SR, which is calculated as follows:

$$SR = (\text{PSM Design Flexural Stress}) / (\text{PSM Flexural Strength})$$

where PSM refers to the pozzolanic stabilized mixture.

Figure A-12 shows permissible SR values for various design reliabilities and traffic conditions. Traffic conditions are expressed in terms of the number of 18-kip ESALs, or traffic factor.

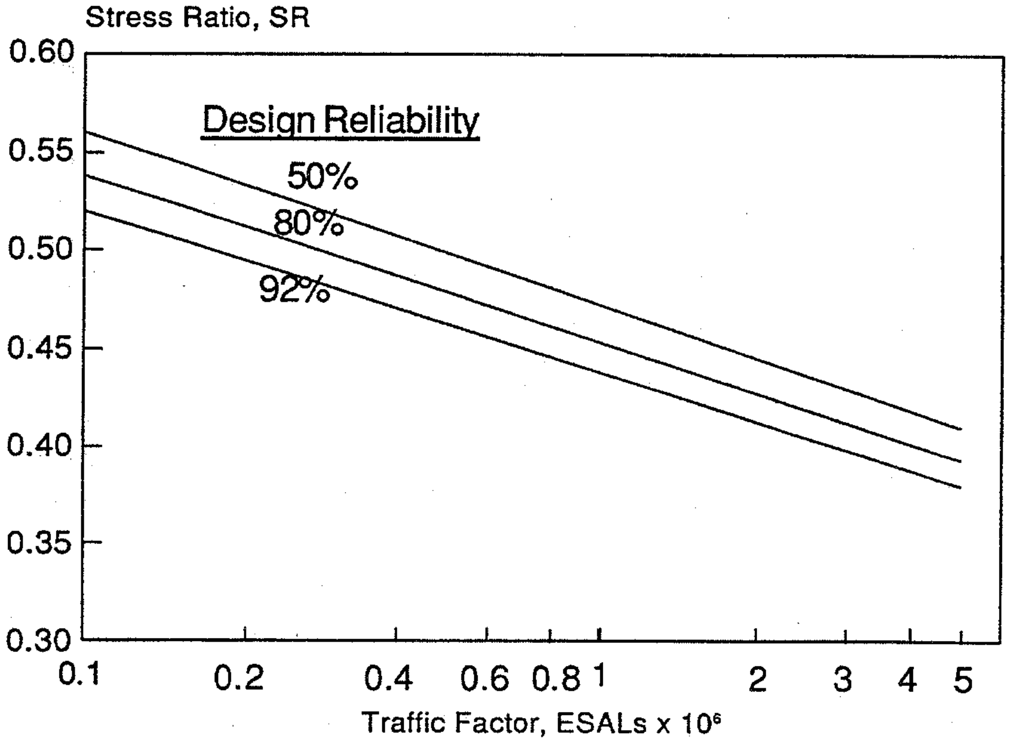


Figure A-12
Typical Relationship of Stress Ratio to Traffic Conditions (ESALs - 18-Kip Equivalent Single Axle Loads)

(SOURCE: American Coal Ash Association. *Flexible Pavement Manual Recommended Practice: Coal Fly Ash in Pozzolanic Stabilized Mixtures for Flexible Pavement Systems*.)

The basic equation for this method is:

$$T_{PSM} = T_{EQ} - T_{AC} (E_{AC} / E_{PSM})^{0.33}$$

T_{PSM} is the thickness of PSM.

T_{EQ} is the equivalent thickness.

T_{EQ} is controlled by design SR and the “field design compressive strength, ” CS. T_{EQ} can be found on Figure A-13. The maximum design SR that should be used is 0.65. The CS for a PSM is the unconfined compressive strength for curing conditions of 56 days at 73° F and 100 percent relative humidity.

T_{AC} is the asphalt wearing course thickness, which can be selected from Table A-9.

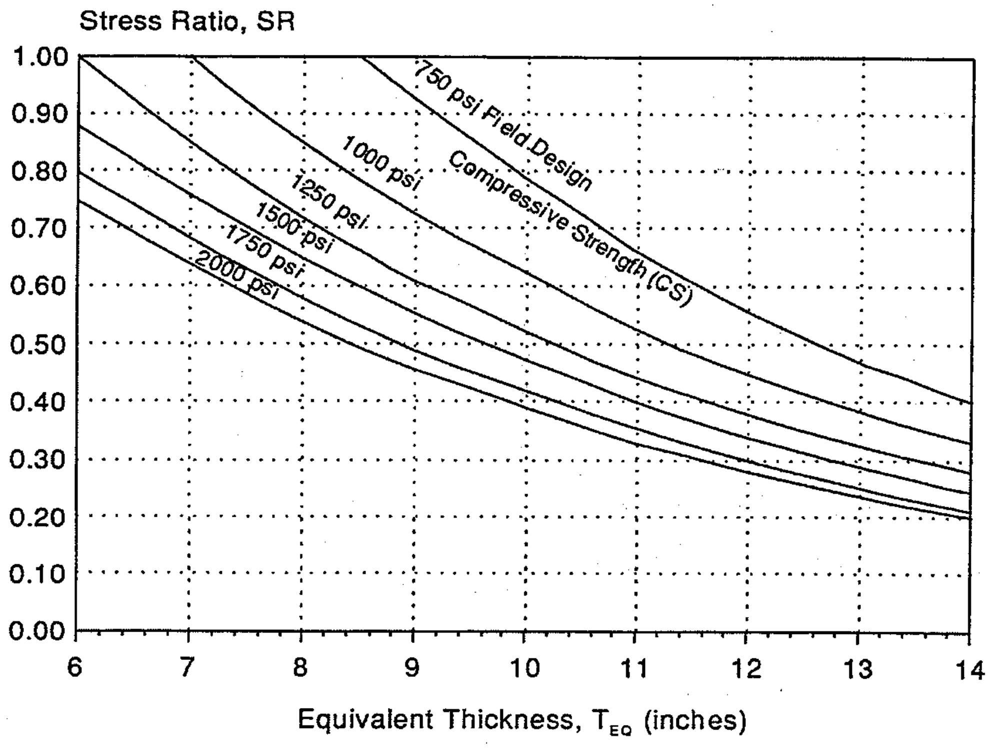


Figure A-13
Typical PSM Thickness Design Chart

(SOURCE: American Coal Ash Association. *Flexible Pavement Manual Recommended Practice: Coal Fly Ash in Pozzolanic Stabilized Mixtures for Flexible Pavement Systems*.)

Table A-9
Asphalt Wearing Course Thicknesses

Traffic Factor*	Asphalt Thickness, inches
< 50,000	1.0 (or surface treatment)
50,000 - 150,000	1.5
150,000 - 500,000	2.0
500,000 - 2×10^6	2.5
2×10^6 - 7×10^6	3.0
> 7×10^6	3.5

* The number of 18-kip ESALs in the “design lane.”

E_{AC} is the elastic modulus of asphalt wearing course.

E_{PSM} is the elastic modulus of PSM. E_{PSM} can be estimated from its unconfined compressive strength Qu, E_{PSM}(ksi) = 500 + Qu (psi). Typical modulus-compressive strength relationships are shown in Figure A-14 for high strength stabilized base materials.

The term $(E_{AC} / E_{PSM})^{0.33}$ is referred to as the “equivalence factor” for asphalt wearing courses. A plot of E_{AC} / E_{PSM} versus $(E_{AC} / E_{PSM})^{0.33}$ is shown on Figure A-15.

For typical asphalt mixtures with temperature conditions representative of moderate climates (such as the midwestern United States), an equivalence factor of 0.5 may be recommended. Therefore, the PSM base layer thickness is calculated as:

$$T_{PSM} = T_{EQ} - 0.5\ T_{AC}$$

The recommended minimum PSM base layer thickness is six inches.

Pavement Design Example

Given:

Traffic Factor	=	1×10^6
Design Reliability	=	92 percent
Field Design Compressive Strength (CS)	=	1,250 psi

Step

1. From Figure A-12, given the traffic factor and design reliability information above, determine the stress ratio (SR) to be 0.44.

2. From Figure A-13, using the stress ratio (SR) determined from Figure A-12 and given the field design compressive strength (CS), determine the equivalent thickness (T_{EQ}) to be 11.25 inches.

3. From Table A-9, determine the T_{AC} (asphalt layer thickness) to be 2.5 inches.

Finally, $T_{PSM} = T_{EQ} - 0.5\ T_{AC}$.

Thus, T_{PSM} = 11.25 inches - (0.5 x 2.5 inches) = 10.0 inches.

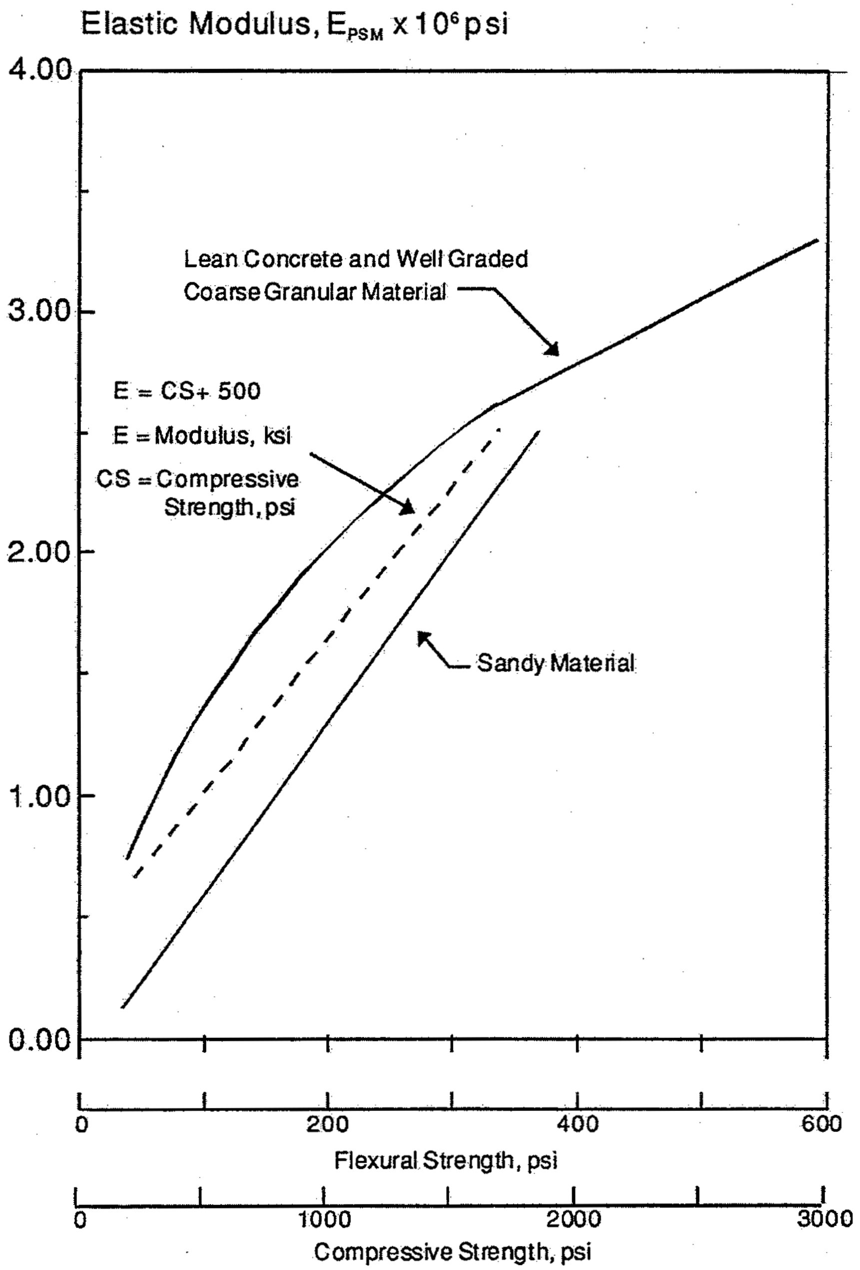


Figure A-14
Typical Elastic Modulus-Strength Relationships for High-Strength Stability Base Materials

(SOURCE: American Coal Ash Association. *Flexible Pavement Manual Recommended Practice: Coal Fly Ash in Pozzolanic Stabilized Mixtures for Flexible Pavement Systems*.)

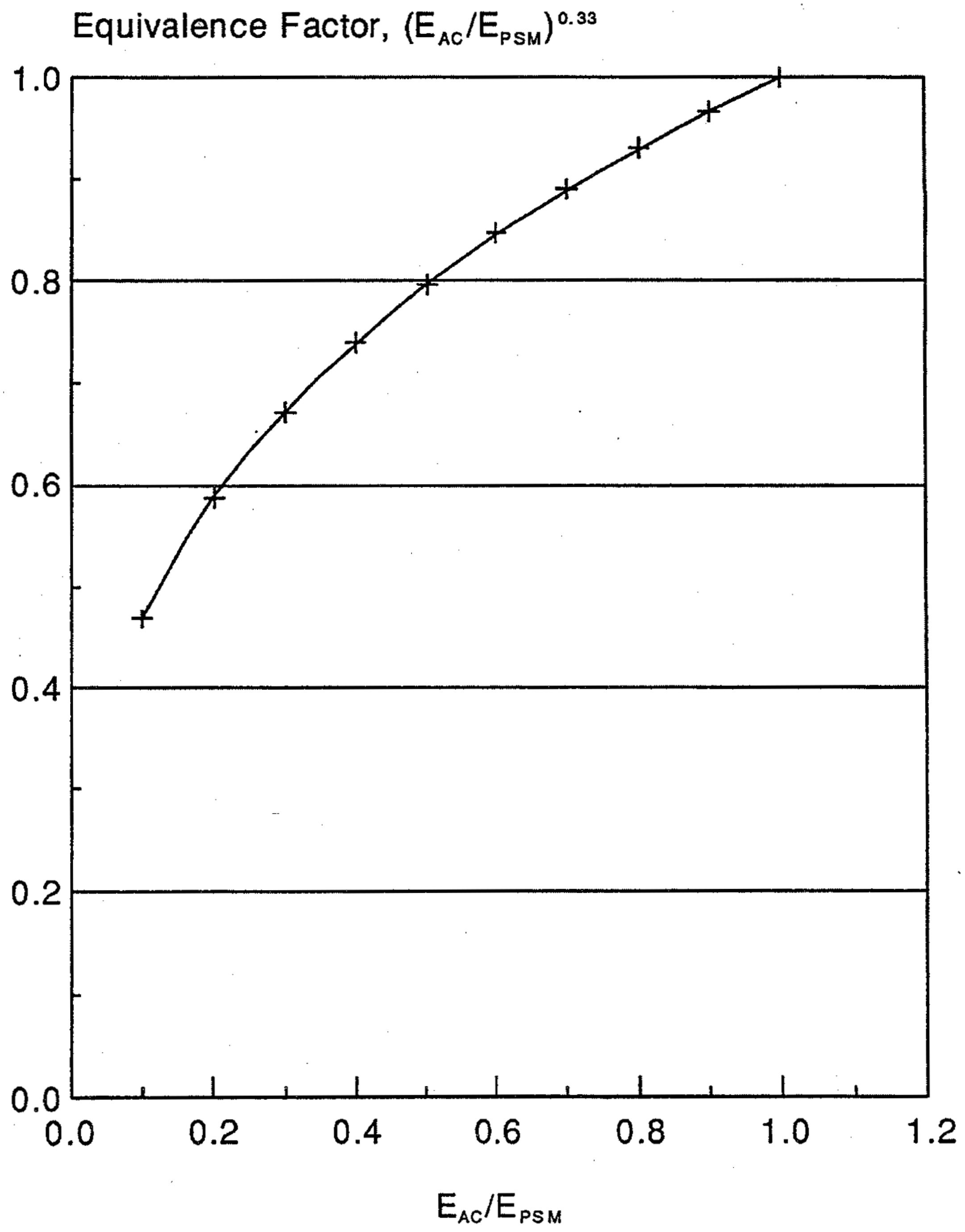


Figure A-15
Typical Equivalence Factors for Asphalt Wearing Course

(SOURCE: American Coal Ash Association. *Flexible Pavement Manual Recommended Practice: Coal Fly Ash in Pozzolanic Stabilized Mixtures for Flexible Pavement Systems*.)

ACAA Method 2

This method combines AASHTO thickness design of flexible pavements with mechanistic concepts.

In this method, the required design structural number (SN) is determined in the same manner as for the AASHTO method. However, the structural layer coefficient for the PSM base layer in this method relates not only to the compressive strength of the base, but also to the base layer thickness.

Table A-10 provides the means for selecting a structural layer coefficient (a_2) based on field design compressive strength (CS) and layer thickness of a PSM for a flexible pavement system.

Table A-10
Suggested AASHTO Structural Layer Coefficient (a2) for PSM Base Layers

	Coefficient (a_2) for PSM Base Layers PSM Base Layer Thickness (inches)				
Field Design Compressive Strength (CS), psi	**6**	**8**	**10**	**12**	**14**
750	0.20	0.20	0.20	0.30	0.40
1,000	0.20	0.20	0.30	0.40	0.40
1,250	0.20	0.26	0.38	0.40	0.40
1,500	0.20	0.37	0.40	0.40	0.40
2,000	0.30	0.40	0.40	0.40	0.40

For a layer coefficient of 0.2, the PSM strength at the time of initial traffic loading should be at least 500 psi. For a layer coefficient greater than 0.2, intact PSM base layer behavior is assumed, and early-lift traffic loadings must be restricted.

If vehicle loadings must be permitted on the PSM base layer prior to seven days of curing, it should have an in-place strength of 350 psi for passenger car loadings and for pavement surfacing equipment. Heavier loadings (3-kip to 18-kip axles) should not be permitted until the PSM has sufficient strength to accommodate such loadings without being over-stressed and initiating fatigue cracking.

References

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2. R. G. Packard. *Thickness Design for Concrete Highway and Street Pavements*. Engineering Bulletin, Portland Cement Association, Skokie, IL, 1984.

3. American Association of State Highway and Transportation Officials. *AASHTO Guide for Design of Pavement Structures.* Washington, DC, 1993.

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5. A. A. Lilley and R. I. T. Williams. *Cement-Stabilized Materials in Great Britain*. Highway Research Board, Record No. 442, 1973, pp. 70-82.

6. N. T. Norling . *Minimizing Reflective Cracks in Soil-Cement Pavements: A Status Report of Laboratory Studies and Field Practices.* Highway Research Board, Record No. 442, 1973, pp. 22-23.

7. American Coal Ash Association. Flexible Pavement Manual Recommended Practice: Coal Fly Ash in Pozzolanic Stabilized Mixtures for Flexible Pavement Systems.