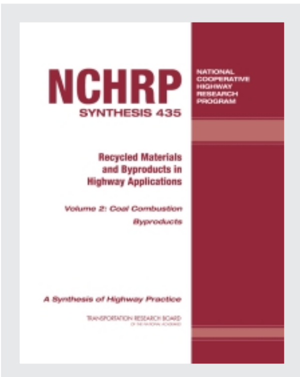

Recycled Materials and Byproducts in Highway þÿApplications Coal Combustion Byproducts, Volume 2

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 435

Recycled Materials and Byproducts in Highway Applications

Volume 2: Coal Combustion Byproducts

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP SYNTHESIS 435: Volume 2

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FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jon M. Williams
Program Director
Transportation Research Board

Recycled materials and industrial byproducts are being used in transportation applications with increasing frequency. There is a growing body of experience showing that these materials work well in highway applications. This study gathers the experiences of transportation agencies in determining the relevant properties of recycled materials and industrial byproducts and the beneficial use for highway applications. Information for this study was acquired through a literature review, and surveys and interviews with state department of transportation staff. The report will serve as a guide to states revising the provisions of their materials specifications to incorporate the use of recycled materials and industrial byproducts, and should, thereby, assist producers and users in "leveling the playing field" for a wide range of dissimilar materials.

Mary Stroup-Gardiner, Gardiner Technical Services LLC, Chico, California, and Tanya Wattenberg-Komas, Concrete Industry Management Program, California State University, Chico, California, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

The report is presented in eight volumes, the first of which is available in hard copy and on the Internet. The next seven volumes are available through the Internet only and can be found at: http://www.trb.org/Publications/NCHRPSyn435.aspx. The eight volumes are:

Volume 1 *Recycled Materials and Byproducts in Highway Applications—Summary Report*
Volume 2 *Coal Combustion Byproducts*
Volume 3 *Non-Coal Combustion Byproducts*
Volume 4 *Mineral and Quarry Byproducts*
Volume 5 *Slag Byproducts*
Volume 6 *Reclaimed Asphalt Pavement, Recycled Concrete Aggregate, and Construction Demolition Waste*
Volume 7 *Scrap Tire Byproducts*
Volume 8 *Manufacturing and Construction Byproducts*

CONTENTS

CHAPTER ONE

INTRODUCTION

The first section in this chapter provides general information on coal combustion byproducts, production and usage, and basic cost information. An additional byproduct, fluidized bed combustion (FBC) ash, while not yet used in highway applications, is also discussed in the background section. The second section presents a summary of the agency survey responses for current byproducts used in a range of highway applications.

The major coal combustion byproducts are bottom ash, boiler slag, fly ashes, and flue gas desulfurization (FGD). A separate section is dedicated to each byproduct and includes summaries of data found for engineering-related physical and chemical properties, environmentally related properties for assessing leaching potential, and historical use and production. Highway applications using any of the byproducts are summarized next. When possible, key engineering properties relevant to each application are also included.

Separate sections are included for environmental issues, economic issues, and barriers to use associated with the byproducts found in the literature and as identified by the agencies in their responses to open-ended survey questions. Additional background and research information can be found at the:

- American Coal Ash Association (ACAA) trade organization website: www.acaa-usa.org
- Energy and Environmental Research Center, University of North Dakota: http://www.undeerc.org/
- Recycled Materials Resource Center www.rmrc.unh.edu/
- Turner–Fairbanks Highway Research Center http://www.fhwa.dot.gov/research/tfhrc/.

BACKGROUND

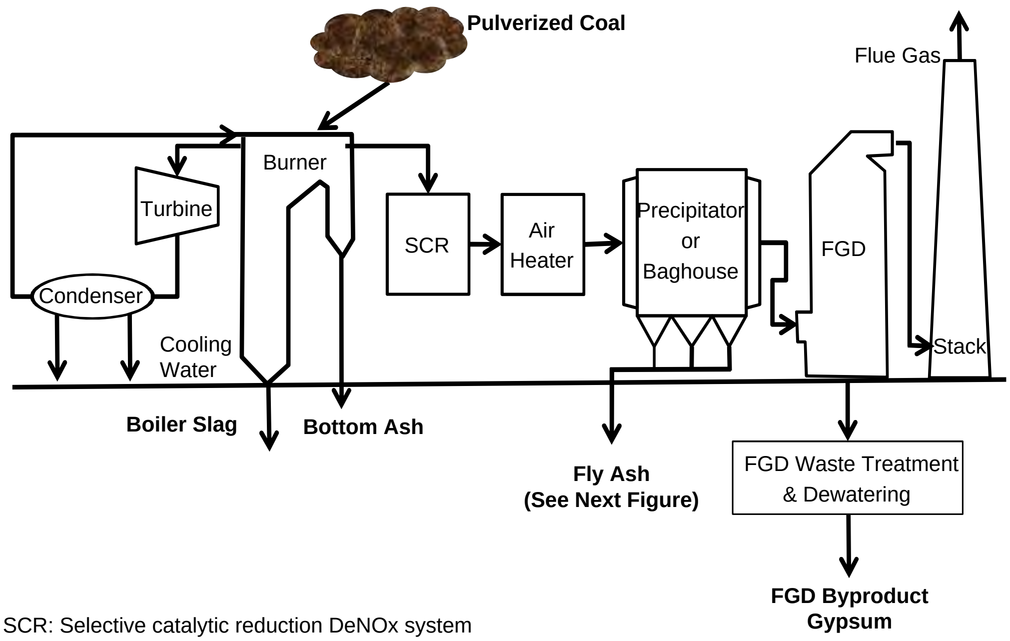
Coal fired power plants produce residue that can be landfilled, recycled as raw materials into other products or applications, or used as products themselves (Figure 1). Historically, the residue was landfilled as waste. In the last couple of decades of the last century, recycling applications for portions of the waste were identified, which were then referred to as "recycled byproducts."

Sufficient experience and research with the byproducts has led the ACAA to refer to residue as coal combustion products (CCPs) (EPA 2010). Fossil fuel electric power generation is the largest generator of coal combustion byproducts. These power plants produce about 50% of the electricity demand in the United States. Although the coal combustion byproducts are produced at the power plant, most power plant owners do not market the coal combustion byproducts and they continue to landfill them as a waste product. There are about 40 to 50 commercial ash marketing firms operating in the United States, except Hawaii (EPA 2008). At this time, there are a number of coal combustion byproducts that are marketed for various uses, including bottom ash, fly ash, boiler slag, and FGD materials (Kalyoncu 2000; EPA 2010). Each coal combustion byproduct is obtained from a different location in the typical steam generating system (Figures 1 and 2).

Brief descriptions of these four coal combustion byproducts and their general quantities and characteristics (Table 1) are provided here:

- Boiler slag: Obtained from molten ash collected in wet-bottom boilers where the molten ash is water cooled. The molten ash shatters into black angular pieces that range in size from coarse sand to fine gravel and have a smooth appearance (Butalia and Wolfe 1999; EPA 2008).
- Bottom ash: Collected from the bottom of dry-bottom boilers and ranges in size from fine gravel to fine sand (Butalia and Wolfe 1999; EPA 2008).
- Fly ash: Entrained particles in the exhaust gases leaving the combustion chamber. This consists of the finest particles that are collected from coal burning processes (Figure 2).
- Flue gas desulfurization (FGD): FGD is a mixture of gypsum ($CaSO_4$), calcium sulfite ($CaSO_3$), fly ash, and unreacted lime or limestone that results from the removal of sulfur dioxide (SO_2) from the exhaust (Kalyoncu 2000). This is also referred to as synthetic gypsum.

There are four types, or ranks, of coal that can be used in the power plants: anthracite, bituminous, sub bituminous, and lignite. Not much anthracite coal is burned so the primary composition of coal combustion byproducts is controlled by the differences between bituminous, sub bituminous, and lignite coal. The common components between the types of coal are silica, alumina, iron oxide, and calcium oxide, with varying amounts of unburned carbon. Sub bituminous and lignite coals have higher concentrations of calcium and magnesium oxide but reduced percentages of silica and iron



SCR: Selective catalytic reduction DeNOx system
FGD: Flue gas desulfurization system

Schematic after Using Coal Ash in Highway Construction: A Guide to Benefits and Impacts. EPA April 2005

FIGURE 1 Typical coal burning power plant schematic (after EPA 2005).

oxide and a lower unburned carbon content [i.e., loss on ignition (LOI)] compared with bituminous coal (Table 2).

Most of the coal burning power plants use high-sulfur bituminous coal, particularly in the eastern and Midwestern portions of the United States. The FGD systems are included in the plants to reduce environmental issues with acid rain. These systems remove large amounts of SO_2, which results in the production of synthetic gypsum that is comprised of gypsum, calcium sulfite, fly ash, and unreacted lime or limestone (Kalyoncu 2000).

RECENT COAL COMBUSTION BYPRODUCT

FBC ash is a new byproduct from coal burning power plants. FBC is the result of new boiler technology within the conventional coal burning power plant. Figure 3 shows where the new technology fits within the schematic shown in Figure 1.

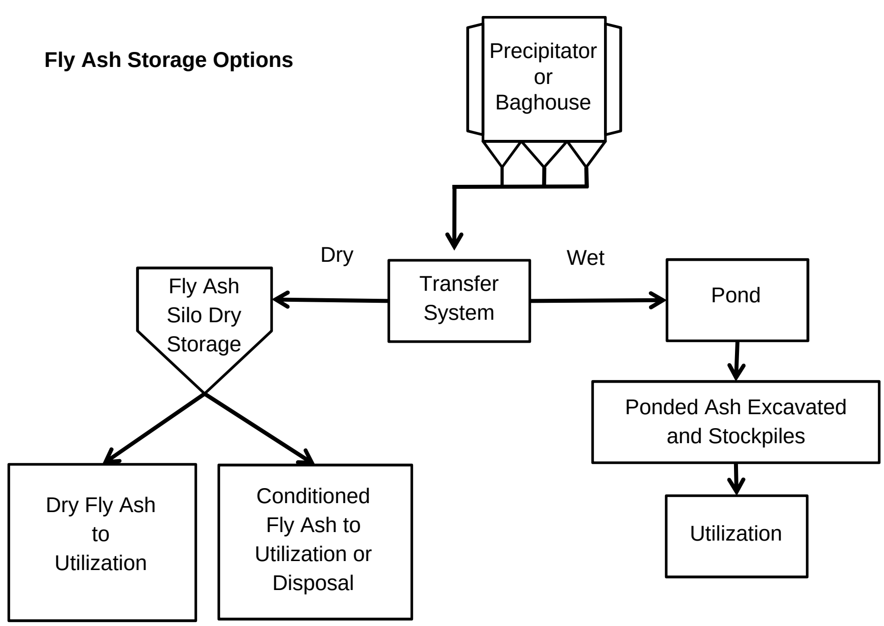


FIGURE 2 Fly ash storage options (continued from previous figure; after FHWA 2005).

TABLE 1
GENERAL QUANTITIES AND CHARACTERISTICS OF COAL COMBUSTION BYPRODUCTS

Coal Combustion Byproduct Type	Characteristic	Texture	Amount Typically Generated per ton of Coal Burned (lb)	Major Component
Boiler Slag	Material collected in wet-bottom boilers or cyclone units	Glassy, angular particles	100	Si, Al, Fe, Ca
Bottom Ash	Material collected in dry-bottom boilers, heavier than fly ash	Sand-like	40	Si, Al, Fe, Ca
Fly Ash	Noncombustible particulate matter removed from stack gases	Powdery, silt-like	160	Si, Al, Fe, Ca
FGD	Solid or semi-solid material obtained from flue gas scrubbers	Fine to coarse (dry or wet)	150	Ca, S, Si, Fe, Al

After Butalia and Wolfe (1999).

TABLE 2
TYPICAL COMPOSITION OF COAL SOURCES

Compounds and LOI for Coal	Bituminous (%)	Sub Bituminous (%)	Lignite (%)
SiO_2	20–60	40–60	15–45
Al_2O_3	5–35	20–30	10–25
Fe_2O_3	10–40	4–10	4–15
CaO	1–12	5–30	15–40
MgO	0–5	1–6	3–10
SO_3	0–4	0–2	0–10
Na_2O	0–4	0–2	0–6
K_2O	0–3	0–4	0–4
LOI	0–15	0–3	0–5

After RMRC (2008).
LOI = loss on ignition.

FBC is a process of burning coal in which the coal is inserted in a bed of particles that are suspended in the air and that react with the coal to heat the furnace more cleanly. With the FBC technology, coal is burned at a slightly lower temperature, which helps prevent some nitrogen oxide gases from forming (ACAA 2007). This lower temperature can also form concentrations of free lime (see Table 3). However, with exposure to moisture and weathering the free lime will hydrolyze to $Ca(OH)_2$ or $CaCO_3$. Coal combustion is accomplished by combining the coal with a sorbent such as limestone or other bed material. The fuel and bed material mixture is fluidized during the combustion process so that complete combustion can be accomplished along with the removal of sulfur gases. FBC materials are a combination of unburned coal, ash, and spent bed material used for sulfur control. The spent bed material, removed as bottom ash, contains reaction products

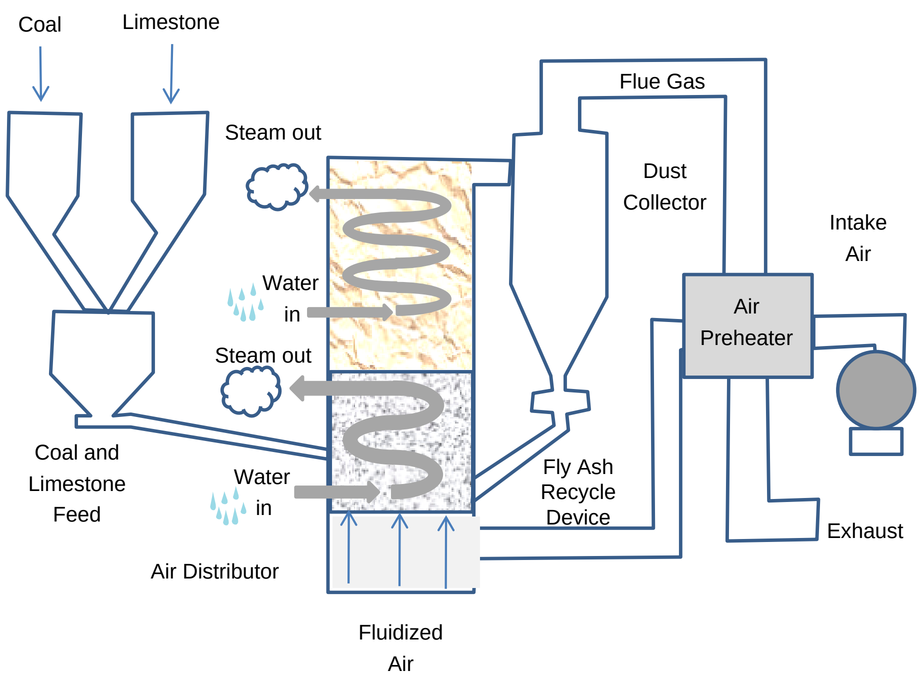


FIGURE 3 Schematic of a fluidized bed combustion boiler (EERC 2009).

TABLE 3
COMPARISON OF FBC BYPRODUCTS TO TYPICALLY USED BOTTOM AND CLASS F FLY ASH

Compound	Composition, % by Weight				
	Bottom Ash (typical)	Class F Fly Ash (typical)	Unaged FBC Fly Ash	Unaged FBC Bottom Ash	Stockpiled (aged) FBC Ash
SiO_2	45.90	54.90	37.04	22.88	41.74
Al_2O_3	25.13	26.10	12.34	6.88	13.94
Fe_2O_3	14.35	2.70	6.44	4.20	4.24
MgO	5.21	2.40	1.63	0.92	2.70
CaO	1.40	10.6	27.90	34.88	19.70
Free Lime	—	—	8.20	7.46	—
SO_3	4.56	0.30	8.13	20.19	6.94
LOI	0.53	0.10	0.69	7.85	8.42

After Saylak et al. (2001).
— = no data provided.

from the absorption of gaseous sulfur oxides such as SO_2 and SO_3 (EERC 2009). Atmospheric FBC systems may be either bubbling or circulating. Pressurized FBC is a new combustion technology.

The U.S. Geological Survey (2006) only shows records for annual production for FBC starting in 2002. In 2002, 1,130,000 metric tons were produced and 865,000 metric tons were used. The annual amounts were 723,000 and 239,000 metric tons for 2003, and 787,000 and 430,000 metric tons for 2004, for production and use, respectively.

Kazonich and Kim (2009) evaluated leaching of trace metals in solutions with pH values ranging from 1 to 11. Limestone is added to the FBC boiler so the leachates are more alkaline. Only arsenic, chromium, selenium, and alkali metals had concentrations greater than detection limits. These researchers noted the FBC reacted with the aqueous solutions that formed a cementitious mass that stopped liquid flow and prevented additional leaching. It was noted that FBC ash solidified by rainfall was also evaluated for leachate.

Naik et al. (2005) evaluated FBC coal ash in the manufacture of hollow blocks, solid blocks, and paving stones by replacing up to 45% (by weight) of the portland cement with FBC and up to 9% of the natural aggregate with low-lime, coarse coal ash. The freeze/thaw resistance (durability) of the blocks was significantly decreased with increasing ash contents.

FBC research in highway applications is in its infancy and needs to be evaluated in any future assessments of byproducts in highway applications. Table 3 provides a comparison of chemical composition of typical bottom ash and fly ash with FBC ashes. It should be noted that the free lime in unaged FBC ashes was removed when subjected to natural weathering of the stockpile. Typical heavy metals found using the Toxicity Characteristic Leaching Procedure (TCLP) for evaluating typical coal ash byproducts and the TCLP limits are shown in Table 4.

TABLE 4
TYPICAL COAL BYPRODUCT HEAVY METALS AND ALLOWABLE LIMITS FROM TCLP LEACHATE TESTING

Element	Extract (mg/L)	TCLP Maximum Limits (mg/L)
Arsenic, As	0.3	5.0
Barium, Ba	<0.1	100.0
Cadmium, Cd	<0.1	1.0
Chromium, Cr	<0.02	5.0
Lead, Pb	<0.02	5.0
Mercury, Hg	0.06	0.2
Selenium, Se	0.3	1.0
Silver, Ag	<0.1	5.0

After Saylak et al. (2001).

CHAPTER TWO

AGENCY SURVEY RESULTS

A survey matrix was used to collect coal combustion byproduct information from state agencies. The matrix (Table 5) included choices of coal combustion byproducts (rows) and major categories of highway applications (columns). The question included short definitions for the terms. The respondents could check all choices that applied to their agency. A total of 45 agencies replied to the survey.

The results showed that the primary use for Types C and F fly ash is in portland cement concrete (PCC) applications, followed by flowable fill and soil stabilization uses. A limited number of states used coal ash, boiler slag, and combustion ash (unknown or other). No states are currently using FGD in highway applications. Table 6 and Figure 4 show the states that used coal combustion ash byproducts in multiple highway applications.

TABLE 5
2009 AGENCY SURVEY QUESTION FOR USE OF COAL COMBUSTION BYPRODUCTS IN HIGHWAY APPLICATIONS

Question: Is your state using, or has ever used, these byproducts in highway applications? If you are not sure of the specific type of combustion byproduct that has been used in your state, check the category "Combustion ash, unknown type" at the bottom of the list. The respondents could check all that applied to their agency.

- Coal ash: particulate in flue of coal fired boiler
- Boiler slag: collected at the bottom of wet-bottom coal fired boilers
- Type C fly ash: coal combustion flue gas particulate with more than 20% lime
- Type F fly ash: coal combustion flue gas particulate with less than 10% lime
- FGD: particulate captured by flue gas desulphurization (FGD) technology added to coal fired power plants.

Byproduct	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embankments	Flowable Fill	HMA	Pavement Surface Treatments (non-structural)	PCC	Soil Stabilization
Coal Ash	1	1	1	9	8	4	3	4	1
Boiler Slag	0	1	1	4	1	8	5	2	0
Type C Fly Ash	0	0	1	5	19	5	0	33	15
Type F Fly Ash	0	0	0	3	19	4	0	41	7
FGD Scrubber Ash	0	0	0	0	0	0	0	0	0
Combustion Ash, Unknown Type	4	2	1	4	2	2	3	1	3

TABLE 6
STATES USING COAL COMBUSTION BYPRODUCTS IN HIGHWAY APPLICATIONS FROM SURVEY

Number of Highway Applications	States					
	Coal Ash	Boiler Slag	Type C Fly Ash	Type F Fly Ash	FGD	Combination or Unknown
8	—	—	—	—	—	ID
7	VA	—	—	—	—	—
6	—	—	—	—	—	—
5	—	—	—	—	—	—
4	—	—	IA, KS, KY, MO, MS, VA	IA, MS, VA	—	—
3	MD, MO, NC	IL, WV	CO, DE, OH, OR, TX, WA	CO, DE, KY, ND, WA	—	FL, NC, UT
2	VT	KY, MO	AL, DC, FL, GA, LA, MN, ND, NY, SC, UT, WV	AL, CT, DC, MN, NC, NY, OH, PA, SC, TX, UT, VT, WV	—	KS
1	AL, GA, IN, NH, NJ, NY, OH, PA, WI	AL, FL, IN, KS, MA, MS, NC, NJ, OH, TX, VT, WI, TX	AK, AR, AZ, CT, IL, IN, NE, NJ, NM, OR, WI	AR, AZ, GA, ID, IL, IN, KS, LA, MA, ME, MO, NC, NE, NH, NJ, NM, NV, OR OK, WI	—	AL, NC, PA

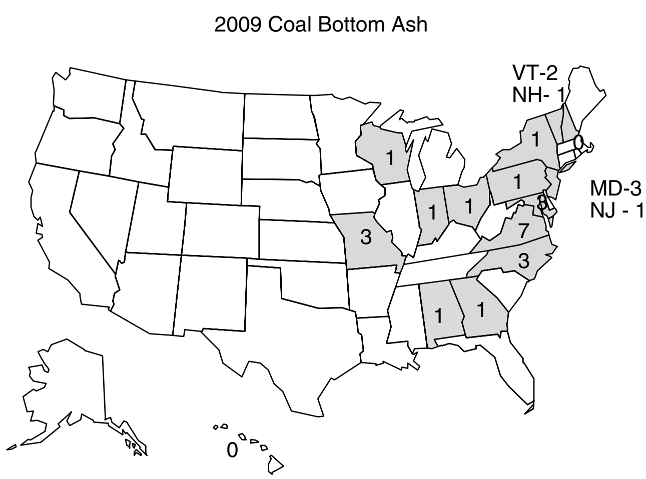


FIGURE 4 2009 agency survey results for coal combustion products.

CHAPTER THREE

LITERATURE REVIEW

The Recycled Material Resource Center (RMRC) in New Hampshire was in the process of conducting a separate survey on the quantities and sources of byproducts in the United States at the same time this synthesis was underway. The results on production and usage quantities from the RMRC survey had not been processed at the time this synthesis was developed. Readers are referred to the RMRC website for updated production and use information. Historical views of use and production are provided here so that the survey information can be generally compared.

HISTORICAL U.S. COAL COMBUSTION BYPRODUCT PRODUCTION AND USE

More than 125 million tons of coal combustion byproducts were produced in 2007, including fly ash, bottom ash, boiler slag, and FGD (Kalyoncu 2000). Table 7 shows how these products were used. Fly ash was by far the most common of the coal combustion byproducts with 71 million metric tons being produced, followed by bottom ash (18.1 million metric tons), FGD wet scrubbers (16.6 million metrics tons), and gypsum (12.3 million metric tons). Boiler slag, FGD from dry scrubbers, and other FGD materials ranged from 1.8 to 2.5 million metric tons.

HISTORICAL INTERNATIONAL COAL COMBUSTION BYPRODUCT PRODUCTION AND USE

The European Union countries are combined under the European Coal Combustion Products Association and include Belgium, France, Germany, Greece, Ireland, the Netherlands, Poland, Portugal, Spain, and the United Kingdom. More than 90% of the non-U.S. coal combustion byproducts were produced by the countries in the European Coal Combustion Products Association in 1999 (Kalyoncu 2000). Other countries not in formal associations that produced coal combustion byproducts were Canada, India, Israel, Japan, and South Africa. Japan used a higher percentage of the coal combustion byproducts produced than the others because of the high cost of disposal. Table 8 provides some information on the international production and use of coal combustion byproducts. Note that the production of coal combustion byproducts from the international community was less than half of that in the United States.

COAL COMBUSTION BYPRODUCT SPECIFICATIONS AND GUIDELINES

In 2005, Dockter and Jagiella (2005a, b) published a summary of existing state specifications and guidelines; a report sponsored by the U.S. Department of Energy National Energy Technology Laboratory Combustion Byproducts Recycling Consortium with support from the ACAA and the Utility Solid Waste Activities Group. The information presented in this report was obtained from a rigorous Internet search of published agency specifications and guidelines. Personal contacts were also used as needed to fill in the survey content. Table 9 shows states with either specifications or guidelines used by the Federal Lands Highways as reported in this document. Requirements for the use of coal combustion byproducts varied between the states; however, most used either ASTM and AASHTO standards or state-specific variations of these standards.

By far, fly ash byproducts were the most commonly specified using either ASTM C618 or AASHTO M295 (Tables 10 and 11). The AASHTO version required a lower LOI and included requirements for the available alkali content. The main use for fly ash was as a cement replacement with a common upper limit of 15% of cement replaced with 20% fly ash. Several states were evaluating or using higher percentages of fly ash as a cement replacement. Several states were found to have specifications and guidelines for flowable mortar fill, which were referred to as controlled low strength materials and control density fill (Dockter and Jagiella 2005a, b).

COST INFORMATION

The bulk of coal combustion byproducts are landfilled each year. Costs for landfilling vary widely depending on whether or not the power plants have captive landfills. Power producers without captive landfills will incur higher costs because of hauling and outsourcing landfilling operations. The economics of landfilling versus coal combustion byproduct reuse will therefore be plant-specific and vary widely. Around the year 2000, the cost of plants with captive landfills was between $3 and $15 a ton, whereas they were between $10 and $35 a ton for plants without this capability (Butalia and Wolfe 1999).

The coal combustion byproduct Ohio Extension Program at the Ohio State University developed an Excel-based software program to calculate the cost of landfilling CCPs

TABLE 7
2007 COAL COMBUSTION BYPRODUCT PRODUCTION AND USE

Coal Combustion Byproduct Applications	Production of Coal Combustion Byproducts, Metric Tons Gross Weight							
	Fly Ash	Bottom Ash	Boiler Slag	FGD Gypsum	FGD Material Wet Scrubbers	FGD Material Dry Scrubbers	FGD Other	FBC Ash
Production Use	63,000,000	16,600,000	2,176,054	18,000,000	11,700,000	10,622,601	76,288	12,524,796
Concrete/Concrete Products/Grout	9,796,483	555,996	0	239,376	0	18,555	0	0
Blended Cement/Raw Feed for Clinker	2,435,904	720,828	0	420,994	0	0	0	0
Flowable Fill	264,611	113,395	0	0	0	16,997	192	20,000
Structural Fills/Embankments	4,646,626	2,944,354	64,727	413,790	484,379	162,997	53,982	145,000
Road Base/Subbase	198,507	765,181	0	0	0	0	160	4,443
Soil Modification/Stabilization	670,035	188,504	1,200	0	0	3,332	0	94,045
Mineral Filler in Asphalt	0	0	45,275	0	0	0	0	0
Snow and Ice Control	0	207,250	45,275	0	50,302	0	0	0
Blasting Grit/Roofing Granules	47,710	78,156	1,617,755	0	0	0	0	0
Mining Applications	2,148,171	480,180	43,511	195,526	567,049	124,320	0	11,425,386
Gypsum Panel Products	0	0	0	7,286,404	0	0	0	0
Waste Stabilization/Solidification	3,515,289	5,867	0	108,869	0	35,937	13,337	59,500
Agriculture	102,908	3,696	0	282,386	0	0	0	0
Aggregate	87,317	452,066	34,700	0	0	0	0	0
Miscellaneous/Other	803,104	467,192	27,089	3,970	0	0	0	0
Category Use to Production Rate	39.2%	43.7%	84.2%	50.3%	7.7%	3.3%	88.7%	93.8%

Source: ACAA (2007).

(Butalia and Wolfe 1999). This is a large multi-worksheet Excel program with inputs for state regulations, annual quantity of coal combustion byproducts, life of landfill, scrubber inputs (type and operating details), landfill geometry (flat terrain, valley fill, and side hill), capital costs, operating and maintenance costs, post-closure costs, and economic inputs. The program outputs include an itemized list of capital costs, operating and maintenance costs, and post-closure costs for the selected landfill geometry. The input and output information are comprehensive; however, the macros to run the Excel program may or may not work as designed with the newest versions of Excel.

CCP HISTORY

- **1937** First research on fly ash reported in *Proceedings of the American Concrete Institute.*
- **1949** U.S. Bureau of Reclamation used fly ash on large scale in the construction of Hungry Horse Dam in Montana.
- **1968** ACAA founded in Alexandria, Virginia to advance the use and management of CCPs.
- **1976** Resource Conservation and Recovery Act (RCRA) enacted and is the primary statute governing the use of CCPs.
- **1985** Coal Ash Resources Research Consortium (CARRC) founded.
- **1990** Clean Air Act and subsequent amendments regulated SO_2 emissions.
- **1990** Clean Air Act Amendments restricted sulfur oxide emissions.
- **1997** Combustion Byproducts Recycling Consortium (CBRC) established.
- **2000** EPA published regulatory determination that CCPs did not pose a significant danger to the environment under 3001(b)(3)(C) but determined regulations under (D) when disposed of in landfills or surface impoundments.
- **2008** Tennessee Valley Authority reported breach in coal combustion byproduct impound, which resulted in a spill estimated at about 1 billion gallons.
- **2010** EPA released two proposed options to implement stricter requirements.

TABLE 8
PARTIAL INFORMATION ON THE PRODUCTION AND USE OF COAL COMBUSTION BYPRODUCTS INTERNATIONALLY

Application	Production and Use, Thousands of Metric Tons					
	Fly Ash	Bottom Ash	Boiler Slag	FGD Gypsum	Total	% Use
European production of coal combustion byproducts, thousands metric tons	37.14	5.62	2.42	7.57	54.50	—
Cement raw material	3.74	0.05	—	—	3.79	6.8
Blended cement	1.93	—	—	—	1.94	3.5
Concrete addition	5.44	0.02	0.16	—	5.65	10.2
Aerated concrete blocks	0.67	0.07	—	—	0.74	1.3
Non-aerated concrete blocks	0.59	1.23	—	—	1.83	3.3
Lightweight aggregate	0.24	0.08	—	—	0.32	0.6
Bricks and ceramics	0.07	—	—	—	0.07	0.1
Grouting	0.52	—	0.16	—	0.68	1.2
Asphalt filler	0.09	—	—	—	0.24	0.4
Subgrade stabilization	0.33	0.03	—	—	0.36	0.7
Pavement base course	0.21	0.33	1.25	—	1.78	3.2
General engineering fill	1.30	0.37	—	—	1.70	3.1
Structural fill	1.39	0.18	—	—	1.57	2.8
Soil amendment	—	—	—	—	0.09	0.2
Infill	1.38	—	—	—	2.05	3.7
Blasting grit	—	—	0.73	—	0.73	1.3
Plant nutrition	—	—	0.04	—	0.07	0.1
Set retarder for cement	—	—	—	0.47	0.47	0.8
Projection plaster	—	—	—	0.62	0.62	1.1
Plaster boards	—	—	—	4.04	4.04	7.3
Gypsum blocks	—	—	—	0.24	0.24	0.4
Self leveling floor screeds	—	—	—	1.25	1.25	2.3
Other uses	0.20	0.13	0.09	—	0.65	1.2
Total	18.17	2.50	2.42	6.62	30.86	55.6
Landfill, reclamation, and restoration	15.43	2.07	—	0.42	18.35	33.0
Temporary stockpile	0.72	0.03	—	0.45	1.19	2.1
Disposal	3.81	1.06	—	0.09	5.12	9.2
Production by Country						
Canada						
Production	5.0	1.60	—	0.42	7.02	—
Use	1.10	0.20	—	0.57	1.87	27.0
India						
Production	—	—	—	—	90.0	—
Use	—	—	—	—	11.7	13.0
Israel						
Production	—	—	—	—	1.20	—
Use	—	—	—	—	1.05	87.0
Japan						
Production	6.50	1.20	—	1.50	9.10	—
Use	5.25	0.90	—	1.50	7.65	84.0
South Africa						
Production	1.70	—	—	—	1.70	—
Use	—	—	—	—	—	—

Kalyoncu (2000).

TABLE 9
STATES WITH COAL COMBUSTION BYPRODUCTS SPECIFICATIONS OR GUIDELINES IN 2003

State CCP Specifications and Guidelines	Federal Lands Highways	
Alabama	Florida	New Jersey
Alaska	Georgia	New Mexico
Arizona	Hawaii	New York
Arkansas	Idaho	North Carolina
California	Illinois	North Dakota
Colorado	Indiana	Ohio
Connecticut	Iowa	Oklahoma
Delaware	Kansas	Oregon
Texas	Kentucky	Pennsylvania
	Louisiana	Rhode Island
	Maine	South Carolina
	Maryland	South Dakota
	Massachusetts	Tennessee
	Michigan	Texas
	Minnesota	Utah
	Mississippi	Vermont
	Missouri	Virginia
	Montana	Washington
	Nebraska	West Virginia
	Nevada	Wisconsin
	New Hampshire	Wyoming
	District of Columbia	

After Dockter and Jagiella (2005a, b).

TABLE 10
ASTM C618-03 FOR CHEMICAL AND PHYSICAL SPECIFICATIONS FOR FLY ASH

Chemical Requirements	Mineral Admixture Class		
	N	F	C
Silicon Dioxide, Aluminum Oxide, Iron Oxide ($SiO_2 + Al_2O_3 + Fe_2O_3$), min., %	70.0	70.0	50.0
Sulfur Trioxide (SO_3), max., %	4.0	5.0	5.0
Moisture Content, max., %	3.0	3.0	3.0
Loss on Ignition, max., %	10.0	6.0	6.0
The use of Class F pozzolan containing up to 12.0% loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.			
Physical Requirements	N	F	C
Fineness: Amount Retained When Wet-Sieved on 45 µm (No. 325) sieve, max., %	34	34	34
Strength Activity Index: B with Portland Cement at			
7 day, min., % of control	75C	75C	75C
28 day, min., % of control	75C	75C	75C
Soundness Water Requirement, max., % of control	115	105	105
Autoclave Expansion or Contraction, max., %	0.8	0.8	0.8

Min. = minimum; max. = maximum.

TABLE 11
AASHTO M295 FOR CHEMICAL AND PHYSICAL SPECIFICATIONS FOR FLY ASH

Chemical Requirements	Mineral Admixture Class		
	N	F	C
Silicon Dioxide, Aluminum Oxide, Iron Oxide ($SiO_2 + Al_2O_3 + Fe_2O_3$), min., %	70.0	70.0	50.0
Sulfur Trioxide (SO_3), max., %	4.0	5.0	5.0
Moisture Content, max., %	3.0	3.0	3.0
Loss on Ignition, max., %	5.0	5.0	5.0
Available Alkalis, as Na_2O, max., %	1.5	1.5	1.5
Applicable only when specifically required by the purchaser for mineral admixture to be used in concrete containing reactive aggregate and cement to meet a limitation on content of alkalis.			
Physical Requirements	N	F	C
Fineness: Amount Retained When Wet-Sieved on 45 µm (No. 325) sieve, max., %	34	34	34
Strength Activity Index: B with Portland Cement at			
7 day, min., % of control	75C	75C	75C
28 day, min., % of control	75C	75C	75C
Soundness' Water Requirement, max., % of control	115	105	105
Autoclave Expansion or Contraction, max., %	0.8	0.8	0.8

CHAPTER FOUR

INDIVIDUAL COAL COMBUSTION BYPRODUCTS

FLY ASH

Physical and Chemical Properties

The important compounds of interest to the highway industry are primarily the cations silicon, aluminum, iron, and calcium with traces of magnesium, potassium, sodium, titanium, and sulfur. No information was found for anionic constituents. Fly ash particles are comprised of glass and have a spherical shape with sizes ranging from 10 to 100 microns (Figure 5). The shape of the glass spheres improves the workability and flow characteristics of concrete products as well as flowable fills. The size helps promote pozzolanic reactivity because of the high surface area when used in concrete products (FHWA and ACAA 2003).

The color of the fly ash indicates general chemical composition (Figure 6). The fly ash can be tan to dark gray. Light gray and tan colors are associated with high lime content. A brownish color indicates high iron content. A dark gray color will occur when there is a high unburned carbon content. The color of the fly ash is usually very consistent for a given power plant and coal source.

There are four common laboratory tests used to control the properties of fly ash products: (1) LOI to determine unburned carbon content, (2) fineness to control reactivity, (3) chemical composition (cations and metals only), and (4) uniformity expressed as variability in test results. Fly ash products are commonly separated into Type C and Type F classifications per either the ASTM or AASHTO standard, where the properties of the fly ash are specified. When Type C and Type F fly ashes are used in concrete products or other applications where the control of the properties is critical to the performance of the application, they are usually required to meet the requirements in either ASTM C618 or AASHTO 295 (see Tables 8 and 9).

Table 12 shows typical chemical information found on fly ash; note that the fly ash chemistry is dependent on the type of coal. Anthracite coal is rarely used; therefore, chemistry for this type is not included. This table shows that there will be significant difference in calcium, magnesium, silica, and iron oxides based on the type of coal.

Environmentally Related Properties

When used in unencapsulated (or unbound) applications, the leaching potential of the fly ash in a given application is environmentally related to properties such as the trace metals and organic compounds. Tests used to evaluate the potential environmental issues include TCLP, distilled water ASTM D3987, and Extraction Procedure Toxicity Leachate tests. These tests are briefly described in Table 13. Tables 14 and 15 provide a range of results reported in the NCHRP 4-21 database (Chesner et al. 2000). These tables present information collected from a number of published sources. Trace organics were not reported in the NCHRP 4-21 database.

Relatively high concentrations of arsenic, barium, beryllium, cadmium, chromium, lead, mercury, selenium, and vanadium are found in some fly ash sources that may exceed some environmental standards. The wide ranges of concentrations that can be found in fly ash indicate that the leaching properties of each fly ash source should be evaluated prior to using in unencapsulated applications. The concentrations depend on changes in the configuration of the power plants or the addition of newer plant technologies. This highlights the need for periodic testing of fly ash source leachate concentrations. It should be noted that the solubility of trace metals in the fly ash will be highly dependent on the alkalinity and pH of the fly ash, which can vary from acidic to alkaline depending on the chemistry of the coal source. The typical expression of alkalinity or acidity of the fly ash is expressed as a ratio of calcium and magnesium oxides to sulfates and aluminum oxides. Solubility will also be dependent on the pH and alkalinity of the water in and around the application.

As with all fine material in unencapsulated applications, fugitive dust is always a concern but can be mitigated with moisture or covering with other materials (e.g., overburden and base aggregate).

Fly Ash Production and Use

The economics involved with the transportation of the coal combustion byproducts tend to limit their use to where they are locally available. By 1994, fly ash (no specific type specified) was being both widely researched and used in the United States (Chesner et al. 2000). The 2009 survey results of the state materials engineers are separated by the type of fly ash (Type C or F) (Figures 7 and 8). The numbers on this figure indicate the number of highway applications used in each state for each type of fly ash. In most cases, states use both types of fly ash in at least one application. States that reported using only Type F include Maine, Massachusetts, Nevada, New Hampshire, and

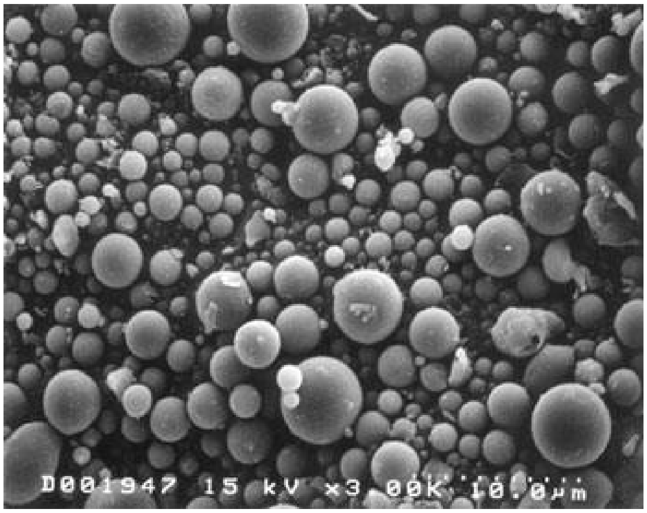


FIGURE 5 Fly ash at 2,000× magnification (FHWA and ACAA 2003).

FIGURE 6 Examples of fly ash colors (FHWA and ACAA 2003).

TABLE 12
TYPICAL FLY ASH CHEMISTRY BASED ON TYPE OF COAL

Compounds	Coal Source, % by weight		
	Bituminous	Sub Bituminous	Lignite
SiO_2	20–60	40–60	15–45
Al_2O_3	5–35	20–30	10–25
Fe_2O_3	10–40	4–10	4–15
CaO	1–12	5–30	15–40
MgO	0–5	1–6	3–10
SO_3	0–4	0–2	0–10
Na_2O	0–4	0–2	0–6
K_2O	0–3	0–4	0–4
LOI	0–15	0–3	0–5

Chesner et al. (2000).

TABLE 13
SUMMARY OF EXTRACTION CONDITIONS FOR LEACHING TESTS FOR FLY ASH

Test Procedure	Method	Purpose	Leaching Medium	Liquid–Solid Ratio (vol:mass)	Particle Size	Time of Extraction
Water Leach Test	ASTM D3987-06	To provide a rapid means of obtaining an aqueous extract	Deionized water	20:01	Particulate or monolith as received	18 h
Toxicity Characteristics Leaching Procedure (TCLP)	EPA SW-846 Method 1311	To compare toxicity data with regulatory level; RCRA requirement	Acetate buffer	20:01	<9.5 mm	18 h
Extraction Procedure Toxicity (EP Tox)	EPA SW-846 Method 1310	To evaluate leachate concentrations; RCRA requirement	0.04 M acetic acid (pH = 5.0)	16:01	<9.5 mm	24 h
Multiple Extraction Procedure	EPA SW-846 Method 1320	To evaluate waste leaching under acid condition	Same as EP toxicity, then at pH = 3.0	20:01	<9.5 mm	24 h extraction per stage
Synthetic Precipitation Leaching Procedure (SPLP)	EPA SW-846 Method 1312	For waste exposed to acid rain	Deionized water, pH adjusted to 4.2 to 5	20:01	<9.5 mm	18 h

After RMRC (2008).

TABLE 14
LEACHATE PROPERTIES AS REPORTED AS TYPICAL FOR FLY ASH

Constituent	TCLP-(A) (mg/L)	TCLP-(B) (mg/L)	TCLP-(c) (mg/L)	TCLP-(D) (mg/L)	ASTM (A) (mg/L)	ASTM (B) (mg/L)	EP Tox (mg/L)
Ag	<0.01–0.05	<0.2–<1	<0.01	<0.1	<0.13	<0.01	<0.01
As	<0.002–47	<0.2–<1	0.01–2.7	0.06	0.0005–0.37	0.024	<0.002
B	<0.3–2.4	<1	0.1–.07	<1	0.0004–3.8	<0.01	<0.1
Cd	<0.005–1.3	<0.2	<0.01–0.56	0.02	0.0001–0.01	<0.005	0.005
Cl	—	—	—	—	—	0.96	—
Cr	<0.04–21	<0.2–0.87	<0.01–4.6	0.15	0.0005–0.5	<0.05	<0.05
Cu	—	—	—	—	—	<0.02	<0.02
Fe	—	—	—	—	—	0.27	—
Hg	<0.0004–0.005	<0.004–0.005	<0.0001	<0.002	<0.00012	<0.0008	<0.004
Ni	0.11–0.42	—	—	—	—	0.04	0.11
Pb	<0.05–4	<0.2–<1	<0.2–2.8	<0.1	<0.0001–0.25	<0.001	—
SO_4	—	—	—	—	—	52.1	—
Se	<0.002–0.075	< 0.2–<1	<0.001–0.15	<0.02	<0.0005–0.48	0.047	<0.002
Zn	0.01–0.6	—	<0.02 -103	—	—	<0.005	0.1
TDS	—	—	—	—	—	—	—
pH	—	—	—	—	—	7.8	5.1

After Chesner (2000).
— = data not provided.
TCLP allowable limits can be found in Table 4.

Vermont. It can be noted that Type C and Type F classifications in a number of state applications indicated general classifications of fly ash and did not specify the type of fly ash.

BOILER SLAG

Physical and Chemical Properties

Wet-bottom boilers (two types), slag-tap (burns pulverized coal), and cyclone (burns crushed coal) have a solid base with an orifice that is periodically opened to drain the molten slag. The molten slag is quenched with water, which fractures by contraction of the solidifying material, crystallizes, and forms pellets. High pressure water jets wash the boiler slag from the hopper to collection basins for dewatering. Some post-collection processing can be done at this point such as crushing, screening, or stockpiling. The general physical characteristics of the boiler slag can be described as a coarse, angular, glassy, black material. Typical properties for boiler slag are shown in Table 16. Table 17 shows the range of typical engineering properties for the boiler slag. In general, these properties indicate that the material can be expected to have good to fair toughness (LA abrasion) and good durability (soundness). The angle of internal friction is comparable to granular aggregates, with a good to very good support value (CBR). As with the fly ash, there are a number of trace metals in boiler slag. Table 18 shows the range of trace metal concentrations in the boiler slag products. Table 19 shows boiler slag chemistry that might need to be considered in certain chemistry-dependent applications such as soil stabilization, clinker manufacture, and portland cement applications.

Environmentally Related Properties

Trace metals in the boiler slag will reflect the trace metals in the original coal source. Of the trace metals listed in Table 18, the ones that may need to be specifically monitored include arsenic, barium, cadmium, chromium, and vanadium (Chesner et al. 2000). The trace organic compounds were not found in the literature, most likely the result of the very high temperature that produces the boiler slag. The high temperature process that produces the boiler slag is also responsible for the glass-like appearance of the boiler slag; this formation will make it difficult for metals to be leached out of the product. No documented issues were found in the literature; however, this should be checked to confirm this assumption.

Boiler Slag Production and Use

In 1994, the availability of boiler slag in the United States was limited and there were no sources in the western states. Some states that produce boiler slag reported using it in highway applications, while a number of other states (e.g., Texas) were using boiler slag but may not have had a local source. Of the 2.1 metric tons of boiler slag produced in the United States in 2007, 1.7 metric tons were used rather than landfilled. The

TABLE 15
ADDITIONAL LEACHATE PROPERTIES AS REPORTED IN THE NCHRP 4-21 DATABASE

Constituent	TCLP-(A) (mg/L)	TCLP-(B) (mg/L)	TCLP-(c) (mg/L)	TCLP-(D) (mg/L)	ASTM (A) (mg/L)	ASTM (B) (mg/L)	EP Tox (mg/L)
Benzene	<0.005	—	—	<0.1	—	—	—
Carbon tetrachloride	<0.005	—	—	<0.1	—	—	—
Chlordane	<0.005	—	—	<0.01	—	—	—
Chlorobenzene	<0.005	—	—	<0.1	—	—	—
	0.002						
Chlororoform	0.004	—	—	<0.1	—	—	—
o-cresol	<0.01	—	—	—	—	—	—
m-cresol	<0.01	—	—	—	—	—	—
p-cresol	<0.01	—	—	—	—	—	—
total cresol	—	—	—	<0.1	—	—	—
2,4-D	<0.005	—	—	<0.02	—	—	—
1,4-dichlorobezene	<0.01	—	—	<0.1	—	—	—
1,2-dichloroethane	<0.005	—	—	<0.1	—	—	—
2,4-dinitrotoluene	<0.01	—	—	<0.1	—	—	—
Endrin	<0.0001	—	—	<0.002	—	—	—
Heptachlor	<0.00005	—	—	<0.002	—	—	—
Hexachlorobenzene	<0.01	—	—	<0.1	—	—	—
Hexachlor-1,3							
Butadiene	<0.01	—	—	<0.1	—	—	—
Hexachloroethane	<0.01	—	—	<0.1	—	—	—
Lindane	<0.00005	—	—	—	—	—	—
Methoxychlor	<0.00005	—	—	<0.002	—	—	—
Methyl ethyl ketone	—	—	—	—	—	—	—
Nitrobenzene	<0.01	—	—	<0.1	—	—	—
Pentachlorophenol	<0.05	—	—	<0.25	—	—	—
Pyridine	<0.01	—	—	<0.25	—	—	—
Tetrachloroethylene	<0.005	—	—	<0.1	—	—	—
Toxaphene	<0.001	—	—	<0.1	—	—	—
Trichloroethylene	<0.005	—	—	—	—	—	—
2,4,5, trichlorophenol	<0.01	—	—	<0.25	—	—	—
2,4,6-trichlorophenol	<0.01	—	—	<0.25	—	—	—
2,4,5 TP (Silvex)	<0.0005	—	—	<0.005	—	—	—
Vinyl chloride	<0.005	—	—	<0.2	—	—	—
Number of samples	22	58	—	1	—	—	—

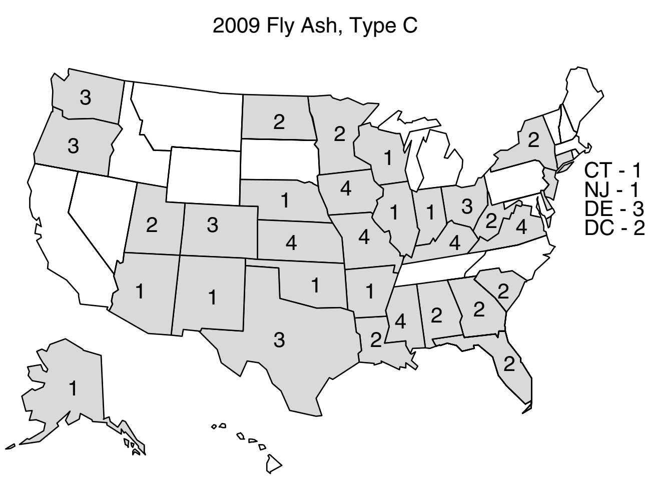


FIGURE 7 2009 agency survey results for fly ash (numbers indicate number of applications in which fly ash is used in each state).

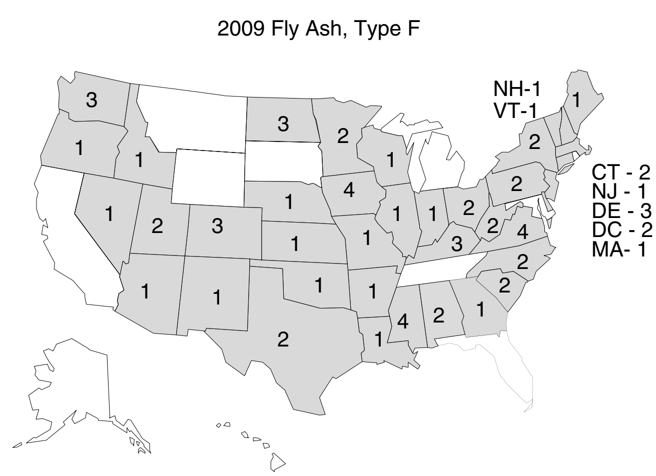


FIGURE 8 2009 agency survey results for boiler slag (numbers indicate number of applications in which fly ash is used in each state).

TABLE 16
TYPICAL PARTICLE SIZE DISTRIBUTION OF BOILER SLAG

Property	Range of Properties
Cumulative Percent Passing	
4.75 mm	90%–99%
2.36 mm	62%–89%
1.18 mm	16%–46%
0.60 mm	4%–23%
0.30 mm	2%–12%
0.15 mm	1%–7%
0.075 mm	0%–5%
Specific Gravity	2.3–2.9
Dry Unit Weight	60–90 lb/ft^3
Water Absorption	0.3%–1.1%
Plasticity	None

RMRC (2008).

TABLE 17
TYPICAL GEOTECHNICAL ENGINEERING PROPERTIES OF BOILER SLAG

Boiler Slag Geotechnical Engineering Property	Range of Values
Maximum Dry Density, lb/ft^3	82–102
Optimum Moisture Content, %	8–20
Los Angeles Abrasion, % loss	24–48
Sodium Sulfate Soundness, % loss	1–9
Internal Friction Angle (drained)	38°–42° 36°–46° (<9.5 mm)
California Bearing Ratio, %	40–70
Hydraulic Conductivity, cm/sec	10^{-1}–10^{-3}

RMRC (2008).

results from the 2009 survey indicated that 14 states were using boiler slag in highway applications (Figure 9).

BOTTOM ASH

Physical and Chemical Properties

Bottom ash is recovered from the dry bottom pulverized coal boiler by collection in a water-filled hopper. The bottom ash is removed from the hopper by means of high-pressure water jets and decanted in basins for dewatering (RMRC 2008). Table 20 shows the range of physical properties reported for bottom ash (estimated from figures in RMRC 2008). There are a wide range of bottom ash particle sizes. The maximum particle size can vary from 100% passing the 37 mm to 100% passing the 9.5 mm. Bottom ash tends to be more absorptive than the boiler slag, which tends to increase the water demand in cementitious applications and asphalt binder content in stabilized soils or hot mix asphalt (HMA) applications. The absence of plasticity is a desirable attribute for soil-replacement or soil-blending applications.

Table 21 provides information on the typical engineering properties for bottom ash used in geotechnical applications. As with the boiler slag, a wide range of optimum moisture contents is required to achieve an equally wide range of maximum dry densities. The toughness (LA abrasion) is marginal to good with regard to most highway aggregate requirements. The freeze/thaw durability (soundness) is good to very good. The angle of internal friction is more variable for the smaller particle sizes of bottom ash.

Table 22 shows key chemistry information that may be important if new applications for this product are evaluated. For example, the individual chemistry of materials and admixtures play a significant role in developing applications for cement clinker manufacture or portland cement applications. As noted earlier, bottom ashes generated in low-temperature boilers (e.g., fluidized bed) can contain up to 8% free lime, which could cause "popouts" in some concrete and masonry units. It is important that this potential problem be checked with ASTM C90 and C331.

Environmentally Related Properties

As with boiler slag, the composition of bottom ash is a function of the composition of the coal source. The trace

TABLE 18
GENERAL BOILER SLAG TRACE METAL COMPOSITION

Trace Metal	Concentration (mg/kg)	Trace Metal	Concentration (mg/kg)
Ag	25	K	7,300–15,800
Al	88,000–135,000	Mg	45,000–32,500
As	0.98–40.0	Mn	100–720
Ba	500–4,000	Mo	3–45
Be	3.0–10.6	Na	1,800–13,100
B	70–300	Ni	10–70
Ca	8,7400–50,600	Pb	5–35
Cd	<0.5–<250	Se	0.08–7.7
Co	3.6–380	Si	180,000–273,000
Cr	15–270	Sr	170–1,800
Cu	2.8–720	Ti	3,300–7,210
Fe	27,000–203,000	V	44–670
Hg	0.01–<4.0	Zn	24–950

Chesner et al. (2000).
TCLP allowable limits can be found in Table 4.

TABLE 19
REPORTED CHEMISTRY OF BOILER SLAG

Compound	Coal Source, % by Weight		
	Bituminous	Sub Bituminous	Lignite
SiO_2	48.9–53.6	—	40.5
Al_2O_3	21.9–22.7	—	13.8
Fe_2O_3	10.3–14.3	—	14.2
CaO	1.4	—	22.4
MgO	5.2	—	5.6
Na_2O	0.7–1.2	—	1.7
K_2O	0.1	—	1.1
SO_3	48.9–53.6	—	40.5

Chesner et al. (2000).
— = no data reported.

TABLE 20
TYPICAL PARTICLE SIZE DISTRIBUTION OF BOTTOM ASH PHYSICAL

Bottom Ash Properties	Cumulative Percent Passing
37 mm	97%–100%
19 mm	95%–100%
9.5 mm	72%–100%
4.75 mm	52%–98%
2.36 mm	31%–91%
1.18 mm	17%–72%
0.60 mm	10%–65%
0.30 mm	5%–56%
0.15 mm	2%–36%
0.075 mm	1%–20%
Specific Gravity	2.1–2.7
Dry Unit Weight	45–100 lb/ft^3
Water Absorption	0.8%–2.0%
Plasticity	None

elements found in the literature are shown in Table 23. These data were developed for Eastern coal fired power plants (Connecticut and New York); therefore, the concentrations will likely change for coal sources from the Midwest.

Tables 24 and 25 show the trace organics for semi-volatile and volatile, dioxane/furan phenols, as reported from testing bottom ash (Chesner et al. 2000). Although the high coal burning temperatures would be expected to eliminate any significant organic compounds, some values can be obtained through testing. However, significant levels of organics are not expected.

Leaching characteristics of bottom ash found in the literature are shown in Table 26. The test results reported are for the Toxic Characteristic Leaching Procedure (TCLP), Synthetic Precipitation Leaching Procedure, Extraction Procedure Toxicity Test, and ASTM D3887 distilled water leaching procedures. All of the values reported in these tables are below the EPA hazardous waste criteria. When bottom ash is used in encapsulated applications such as asphalt concrete or stabilized base material, these trace metals and organic compounds are not expected to pose an environmental problem. However, when they are used in unbound applications such as aggregate base or fill, care needs to be taken to ensure that there are no significant environmental concerns. As with fly ash, fugitive dust emissions need to be addressed.

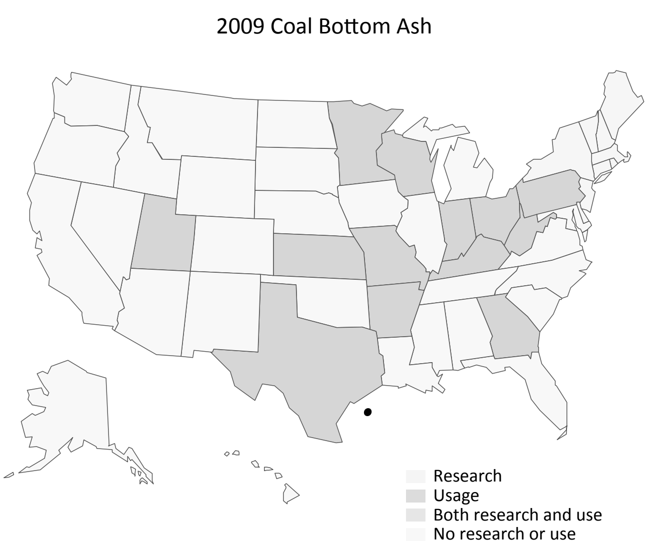


FIGURE 9 2009 survey results for use of coal bottom ash.

Bottom Ash Production and Use

Chesner et al. (2000) reported there were about 400 utility-sized coal burning power plants that produce bottom ash in the United States. The eight states that did not produce bottom ash coal combustion byproducts were Alaska, California, Hawaii, Idaho, Maine, New Hampshire, Rhode Island, and Vermont. In 1994, there were a number of states with sources of bottom ash that were neither researching nor using this coal combustion byproduct. As of 2009, 13 states report using coal bottom ash in the United States (Figure 9).

FLUE GAS DESULFURIZATION

FGD is considered a high-quality gypsum product for the manufacture of wallboard. In a number of cases, wallboard production facilities have been constructed near power plants to minimize the transportation distance of the raw product. However, FGD is in direct competition with the mining of naturally occurring gypsum (Kalyoncu 2000). The percentages of each compound depend on the type of coal burned, how it is prepared prior to burning, and the plant operating conditions.

Wet FGD systems add a spray of alkaline sorbent (lime or limestone) into the exhaust gas where the alkali reacts with the SO_2 to form calcium sulfate ($CaSO_4$) in a liquid slurry (RMRC 2008). Forced oxidation in these wet systems can

TABLE 21
TYPICAL GEOTECHNICAL ENGINEERING PROPERTIES OF BOTTOM ASH

Bottom Ash Engineering Property	Range of Values
Max. Dry Density, lb/ft^3	75–100
Optimum Moisture Content, %	12–24 (usually less than 20)
Los Angeles Abrasion, % loss	30–50
Sodium Sulfate Soundness, % loss	1.5–10
Internal Friction Angle (drained)	38°–42° 32°–45° (<9.5 mm)
California Bearing Ratio, %	21–110
Resilient Modulus, Mr, Regression Coefficients	K_1 = 5–12 MPa K_2 = 0.52
Hydraulic Conductivity, cm/sec	1–10^{-3}

TABLE 22
REPORTED CHEMISTRY OF BOTTOM ASH

Compound	Coal Source, % by Weight		
	Bituminous	Sub Bituminous	Lignite
SiO_2	24.4–60.1	45.4	70
Al_2O_3	6.9–28.3	19.3	15.9
Fe_2O_3	5.2–42.0	9.7	2
CaO	0.4–18.5	15.3	6
MgO	0.1–5.7	3.1	1.9
Na_2O	0.1–1.0	1	0.6
K_2O	0.2–2.3	—	0.1
SO_3	0.6–3.3	—	—

Chesner et al. (2000).
— = not reported.

TABLE 23
TRACE ELEMENTS IN BOTTOM ASH

Trace Constituents	Concentration (mg/kg)	Trace Metal	Concentration (mg/kg)
Ag	0.01–<5	K	229–240
Al	634–14,500	Mg	<620
As	<1–168	Mn	4–769
Ba	14–5,790	Mo	4–21
Be	—	Na	—
B	<0.1–5.2	Ni	<4–258
Ca	<4,130	Pb	<4–90.6
Cd	<0.5–4.7	Se	<0.2–20
Co	<4–60.4	Si	—
Cr	<4–895	Sr	170–1,800
Cu	2–300	Ti	2
Fe	638–212,000	V	12–377
Hg	<0.95–4.2	Zn	<2–4,000

Chesner et al. (2000).
— = not reported.
TCLP allowable limits can be found in Table 4.

help produce calcium sulfate rather than the unoxidized form of calcium sulfite. Calcium sulfate has a larger crystalline structure than calcium sulfite and can be more readily filtered or dewatered. Wet systems make up about 85% of the FGD scrubbers in the United States. Dry FGD systems spray slaked lime into the flue gas; the main product is calcium sulfite with minor amounts of calcium sulfate. Because these processes are applied to the flue gases, FGD products are also likely to have some fly ash content. Figure 10 shows alternative paths for FGD sludge.

Physical and Chemical Properties

Table 27 provides potential FGD product users with key chemistry information that may be important if new

TABLE 24
TRACE ORGANICS: SEMI-VOLATILES FOUND IN BOTTOM ASH

Compound	Concentration, mg/kg	Compound	Concentration, mg/kg
1,2,4-Trichlorobenzene	—	Chrysene	—
1,2-Diphenylhydrazine	—	Dibenzo (aH) Anthracene	—
1,3-Dichlorobenzene	<0.02	Diethylphthalate	—
1,4-Dichlorobenzene	<0.02	Dimethylphthalate	—
2,4-Dinitrotoluene	—	Di-N-Butyl Phthalate	<0.2
2,6-Dinitrotoluene	—	Di-N-Octyl Phthalate	<0.2
2-Chloronaphthalene	—	Fluoranthene	<0.2
3,3-Dichlorobenzidine	—	Fluorene	<0.2
4-Bromphenyl Phenyl-Ether	—	Hexachlorobenzene	<0.2
4-Chlorophenyl Phenyl-Ether	<0.2	Hexachlorobutadiene	—
Acenaphthene	<0.2	Hexachlororethane	<0.2
Acenaphthylene	—	Indeno (1,2,3-cd) Pyrene	—
Anthracene	<0.2	Isophorone	—
Benzidine	—	Naphthalene	<0.2
Benzo (a) Anthracene	<0.2	Nitrobenzene	—
Benzo (a) Pyrene	<0.2	N-Nitrosodi-N-Propyl	—
Benzo (b) Fluoranthene	<0.2	N-Nitrosodiphenylamin	—
Benzo (k) Fluoranthene	<0.2	Phenanthrene	<0.2
Bis (2-Chloroethoy) Methane	—	Pyrene	<0.2
Bis (2-Chloroethyl) Ether	—		
Bis (2-Chloroisopropyl) Ether	<0.02		
Bis (2-Ethyhexyl) Phthalate	<0.2		
Butyl Benzyl Phthalate	<0.2		

Chesner et al. (2000).
— = not reported.

TABLE 25
TRACE ORGANICS: VOLATILES, DIOXANE/FURAN, AND PHENOLS FOUND IN BOTTOM ASH

Compound	Concentration, mg/kg	Compound	Concentration, mg/kg
Chloromethane	—	Trichloroethene	—
Vinyl Chloride	<0.05	Bromodichloromethane	—
Bromomethane	—	2-Hexanone	—
Chloroethane	—	Cis-1,3-Dichloropropene	—
Acetone	<0.005	Toluene	<0.005
1,1-Dichloroethene	—	1,1,2-Trichloroethane	<0.005
Methylene Chloride	<0.005	4-Methyl-2-Propanone	—
Carbon Disulfide	—	Dibromochloromethane	<0.005
Tran-1,2-Dichloroethene	<0.005	Tetrachloroethene	—
Methyl Tertiary Butyl Ether	<0.2	Chlorobenzene	<0.005
1,1-Dichloroethene	<0.005	Ethylbenzene	<0.005
2-Butanone	<0.005	m- & p-xylene	<0.005
Cis-1,2-Dichloroethene	<0.005	Bromoform	<0.005
Chloroform	<0.005	Styrene	<0.005
1,11-Trichloroethane	<0.005	Oxylene	—
1,2-Dichloroethane	<0.005	1,1,2,2-Tetrachloroethane	<0.005
Benzene	<0.005	Total Phenols	<0.2
Carbon Tetrachloride	<0.005		
1,2-Dichloroethane	<0.005		

Chesner et al. (2000).
— = not reported.

TABLE 26
LEACHATE PROPERTIES REPORTED FOR BOTTOM ASH

Constituent	TCLP (B) (mg/L)	SPLP (mg/L)	EP Tox (A) (mg/L)	EP Tox (B) (mg/L)	ASTM (mg/L)
Ag	<0.1	<0.01	<0.0002	<0.001–0.001	ND
As	<0.002	<0.02	<0.001–0.11	0.005–0.02	ND–0.004
B	0.7	0.09–0.15	0.006–0.14	0.098–0.136	ND
Cd	0.021	<0.002–<0.01	<0.0001–0.0007	0.0004–0.025	ND
Cr	<0.05	<0.02	<0.001–0.0076	0.0005–0.0012	ND–0.11
Cu	0.2	<0.01	—	—	ND
Fe	0.7	—	—	—	ND–1.5
Hg	<0.0002	<0.002	<0.0002–0.0006	<0.0001–0.0002	ND
Ni	0.11	<0.02	—		—
Pb	0.15	<0.005–<0.02	<0.001–0.07	<0.001–0.007	ND–0.09
Se	<0.02	<0.005	<0.002–0.014	0.003–0.005	ND–0.01
V	—	0.01	—	—	—
Zn	0.048	<0.01	—	—	ND

Chesner et al. (2000).
— = not reported; ND = not detectable.
TCLP allowable limits can be found in Table 4.

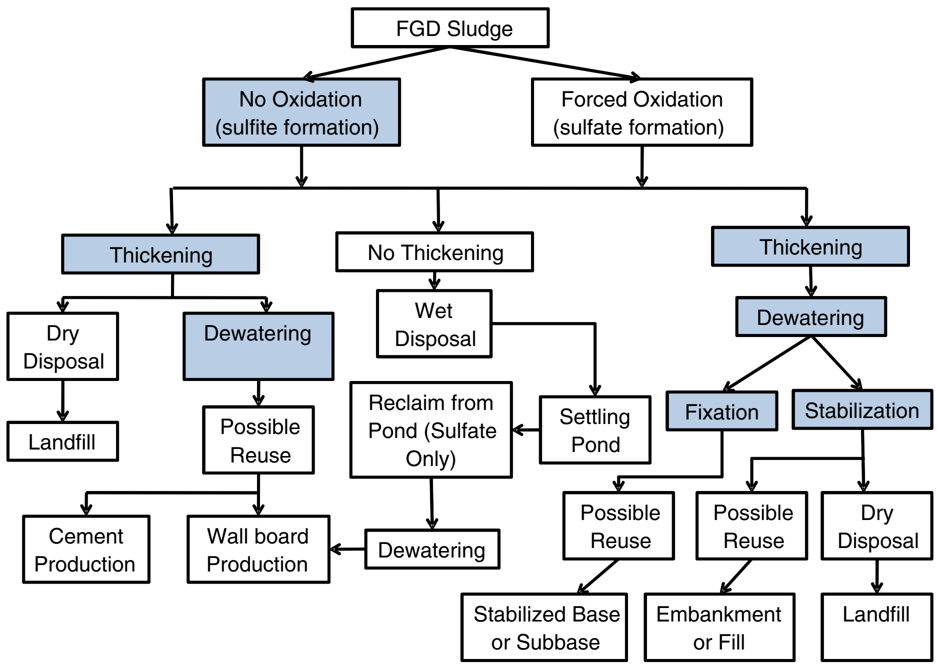


FIGURE 10 Flow chart for FGD sludge to product or landfill (after RMRC 2008).

TABLE 27
CHEMISTRY PROPERTIES OF FGD FOR VARIOUS COAL SOURCES AND SCRUBBING PROCESSES

Compound	Coal Source					
	Bituminous				Lignite	Sub Bituminous
	Scrubbing Process					
	Lime	Lime, Forced Oxidation	Limestone	Dual Alkali (calcium–sodium)	Class C Fly Ash	Limestone
$CaSO_3$, %	50–94	0–3	19–23	65–90	0–5	0–20
$CaSO_4$, %	2–6	52–65	15–32	5–25	5–20	10–30
$CaCO_3$, %	0–3	2–5	4–42	2–10	0	20–40
Fly Ash, %	4–44	30–40	20–43	0	40–70	20–60

Chesner et al. (2000).

applications for this product are evaluated. For example, the individual chemistry of materials and admixtures play a significant role in developing applications for cement clinker manufacture or portland cement applications. FGD chemistry is influenced more by the reagents used in the process, the amount of water used to distribute the reagent in the flue gas, the operating temperature, pressure, and degree of oxidation within the scrubbing unit (RMRC 2008). Reported trace metals in FGD are shown in Table 28.

TABLE 28
TRACE METALS IN FGD SCRUBBER MATERIAL

Trace Metals	Concentration, mg/kg
As	0.8–52
Ba	42–530
Cd	0.06–25
Cr	1.6–180
Cu	6–340
Hg	0.005–6
Pb	0.25–290
Se	2–60
Number of Samples	12

Chesner et al. (2000).
TCLP allowable limits can be found in Table 4.

Engineering Properties

Lower solids content can be expected with the dewatering process path compared with either the stabilized or fixated paths (Figure 10). The hydraulic conductivity is higher for the dewatered process followed by the stabilized and then the fixated. The hydraulic conductivity of both the stabilized and fixated process products is comparable to those used for low permeability clay liners. The dewatered process product has no measureable unconfined strength, the stabilized process material has very little, and the fixated process product has a measureable unconfined strength that exhibits a slow but substantial strength gain (Table 29). The only particle size information found is shown in Table 30. In general, oxidizing the FGD scrubber material produces coarser particles than if it is not oxidized. This table also indicates estimated values for specific gravity.

TABLE 29
TYPICAL PHYSICAL AND LIMITED ENGINEERING PROPERTIES OF UNOXIDIZED FGD PRODUCT

Property	Calcium Sulfite FGD Scrubber CCP*		
	Dewatered	Stabilized	Fixated
Solids Content, %	40–65	65–80	60–80
Wet Unit Weight, lb/ft^3	90–110	90–110	95–115
Dry Unit Weight, lb/ft^3	60–80	75–95	80–102
Absorption, %	0.63–7.5 (process not specified)		
Maximum Dry Density lb/ft^3	N/A	N/A	66–79
Optimum Moisture Content, %	N/A	N/A	27–37
Angle of Internal Friction	20^o	35^o–45^o	35^o–45^o
Hydraulic Conductivity, m/sec	10^{-4}–10^{-5}	10^{-6}–10^{-7}	10^{-6}–10^{-8}
Unconfined Compressive Strength, lb/in^2			
28-day, psi	None	25–50	50–200
90-day, psi	None	None	142–667
CBR, %	36–60, soaked 38–70, unsoaked (process not specified)		

Chesner et al. (2000); RMRC (2008).
*Shaded paths in Figure 10.
N/A = not available.

TABLE 30
TYPICAL PARTICLE SIZE DESCRIPTIONS OF CALCIUM SULFITE AND CALCIUM SULFATE COAL COMBUSTION BYPRODUCTS

FGD Property	Calcium Sulfite (unoxidized)	Calcium Sulfate (oxidized)
General Particle Size Description, %		
Sand Size, %	1.3	16.5
Silt Size, %	90.2	81.3
Clay Size, %	8.5	2.2
Specific Gravity (estimated)	2.57	2.36

RMRC (2008).

TABLE 31
CONSTITUENTS IN LIME SLUDGE

Constituent	EP Lime Sludge Midwest Coal (mg/L)	EP Lime Sludge Lignite (mg/L)
As	0.06	0.04
Ba	1.6	<0.40
Cd	0.05	<0.025
Cr	0.047	<0.01
Hg	0.002	<0.01
Pb	0.016	<0.50
Se	0.031	0.11
Ag	—	<0.06

After Chesner et al. (2000).

Environmentally Related Properties

Constituents in FGD leachate are shown in Table 31 (Chesner et al. 2000).

Flue Gas Desulfurization Production and Use

Chesner et al. (2000) indicated there were a number of potential sources of FGD products; however, the original 1994 survey did not include questions about this coal combustion byproduct. About 24 states were reported as having power plants equipped with FGD scrubbing systems in 2000, with Florida, Indiana, Kentucky, Ohio, Pennsylvania, and Texas having the most operating units with wet scrubbers. The NCHRP 4-21 database shows that both Kentucky and Pennsylvania had used FGD. However, the 2009 state survey showed that while there were a number of sources no states reported using FGD in any highway applications.

CHAPTER FIVE

APPLICATIONS FOUND IN THE LITERATURE

PORTLAND CEMENT AND PORTLAND CEMENT CONCRETE APPLICATIONS

Clinker Manufacturing

Bhatty et al. (2002) used high carbon fly ash as a substitute for slate or clay in the raw material feed producing portland cement clinkers in a preheater kiln system and production of the clinker proceeded without any processing changes. The LOI of the fly ash was estimated at over 20%, which could provide a fuel value in excess of 318 Btu/lb. The amount of fly ash used had to be limited to a maximum of 6% in the raw mix owing to the chemical variations in the fly ash. The thermal contributions of the fly ash resulted in improved calcinations, reduced fuel costs, improved flow in the preheater cyclones (smooth and plug-free movement), and increased kiln feed rate. A 10% improvement in clinker production and a 4% energy usage reduction was achieved.

EPA (2008) indicated the restrictions on nitrogen oxide (NO_x) emissions led to higher carbon content fly ash, which could exceed the limits set for use in cement and concrete, a major user of fly ash. An alternative use for high carbon content coal combustion byproducts was identified as clinker manufacturing. Using high unburned carbon content fly ash had the potential to reduce the fuel consumption during clinker manufacture. An additional benefit could be the reduction for the additional virgin silica, iron, and alumina. Coal combustion byproducts also required less pre-processing before clinker manufacture and would have a lower emission level than virgin materials. However, they could introduce higher pollutants such as mercury than the virgin materials. Life-cycle impact of coal combustion byproducts in clinker manufacture was not assessed because of the wide range of usages and virgin material replacement percentages.

Portland Cement Concrete

Zayed et al. (1998) noted there were differences between Type C and Type F fly ash. Type F fly ash provided sufficient silica, along with minimum calcium oxide, to react with alkali hydroxide in the portland cement. Type C did not provide the improved durability achieved with Type F. Their laboratory study found the sodalite phase and tricalcium aluminate (Bogue method) resulted in lowering the durability of concrete when using Type C fly ash. The authors recommended limiting the use of Type C to less than 2% tricalcium aluminate.

Estakhri (2004) reported on Texas field experiences that documented historical performance. In Texas, about 60% of Type C fly ash was used, whereas only 25% of the Type F fly ash was currently used. Both agency staff and industry indicated Type C fly ash had a slow set time, which was good for placing concrete in the hot Texas climate. Over the years, agency staff and industry also noted problems with alkali–silica reactivity (ASR), and some individuals believed that the Type C currently being used may be contributing to the durability problem. Estakhri evaluated Type F fly ash in the lab with favorable results, with up to 58% replacement of cement with fly ash. This performance history supports the recommendations of Zayed et al. (1998) for restricting the use of Type C fly ash in concrete applications where durability is an important performance property.

Vargas (2007) noted that fly ash was a commonly used mineral admixture in PCC applications because of the benefits provided by the fly ash to the final PCC product. Benefits included reduced permeability and improved freeze/thaw durability. The author attributed this benefit to the fly ash combining with calcium hydroxide to create more cementitious material, prevention of calcium hydroxide leaching out and leaving voids, and filling up void space. The additional cementitious compounds result in fewer voids, capillary channels, and interconnectivity of voids. This was also reported to help with improved corrosion resistance, which was a benefit also reported by Civjan et al. (2003), and improved resistance to ASR. Type F fly ash helped improve sulfate resistance because it combined with the calcium hydroxide that would otherwise be available for reaction with the sulfate.

Juenger et al. (2008) conducted research for the Texas Department of Transportation (TxDOT) for identifying slow setting PCC mixtures using fly ash as a supplementary cementitious material. The research addressed two main points: prevention of delayed setting time and early identification of potential problems with delayed set time. Testing included evaluations of heat generation over time (maturity testing) and the compressive strengths of the cylinders at various times during curing. The time of set, bleeding, plastic shrinkage, and early strength were also measured.

The results showed a minimum compressive strength of 500 psi at 24 hours after curing specimens at anticipated field conditions was a good indicator of set time. Recommendations included close monitoring of mixture proportions to ensure the mix tested represents the mix delivered to the project. If the compressive strength was below 500 psi, the mix design needed to be evaluated to identify the cause of the delayed set. Any changes in mix components required retesting for the impact on set times. The dosage of chemical admixtures should not exceed the manufacturer's recommendations, which may also delay set times.

High Carbon Content Fly Ash Concrete

The article "Penn State Researchers Study Use of Coal Byproducts" (1999), explored the possibility of removing the unburned carbon content from the fly ash. Research at Pennsylvania State University developed a promising method to separate the unburned carbon from the fly ash using water and gas purification processes.

Kalyoncu (2000) conducted research to evaluate the blending of high carbon content fly ash with acceptable sources of fly ash to meet specifications. The high unburned carbon content fly ash, if used as-is in PCC production, reduced the freeze/thaw resistance by capturing the air entraining agents.

Zayed (2000) conducted laboratory testing that showed blending fly ash with LOI of 0.1%, 4.88%, and 14% to achieve a blended LOI of less than 6%. The recommendations from this research indicated that if blending was used testing was required to determine performance. The researcher suggested a better alternative for this out-of-specification coal combustion byproduct could be as a fuel source itself since high carbon content fly ash is seen as a high energy byproduct.

High-Volume Fly Ash

Saylak et al. (2001) used various coal combustion byproducts in the subgrade, base, and surface courses of an all-coal combustion byproduct demonstration project at Texas A&M University in 1999. Twelve inches of the subgrade was an expansive montmorillonite clay subgrade stabilized with 2% quick lime and 5% Class F fly ash (i.e., low lime fly ash). The 8-in.-thick road base was stabilized using an asphalt cutback and 10% high-volume fly ash (HVFA) cement. The HVFA cement was composed of 4.2% Type I portland cement, 5.8% Class F fly ash, 50% sulfur-modified bottom ash, and 40% FGD by weight. This mix reduced asphalt cement demand from 14% to 6.5% and improved the crushing strength of the untreated bottom ash. Stabilizing the subgrade increased the CBR value from 11 for the untreated soil to 43 after stabilizing. The road base CBR was 242, which is considered useful as a base for high traffic volume roadways by the TxDOT. The use of the Class F fly ash significantly reduced any expansive reactions resulting from interactions between the FGD and portland cement. After 18 months of traffic, the roadway was performing well.

Vargas (2007) evaluated HVFA concrete, which referred to a concrete with at least 50% of cementitious material as fly ash. Suitable applications such as foundations where compressive strengths of between 3,000 and 4,000 psi were acceptable and high early strengths were not required would be one possible application for this coal combustion byproduct. When low water to cementitious material ratios (w/cm) were used, high range water reducers were needed to help increase workability (i.e., increase slump). Benefits of using HVFA were identified as very little bleeding and longer set time for a longer finishing time. HVFA would also be good for hot weather concreting because of the lower heat of hydration. Other advantages to HVFA concretes were low permeability, high resistance to sulfate attack, high resistance to ASR, comparable freeze/thaw resistance, and high resistance to chloride penetration and hence higher resistance to corrosion of steel reinforcing. A major disadvantage was the reduced workability that could be improved by using a high range water reducer.

The characteristics of hardened HVFA concrete included a continual but slow increase in compressive and tensile strengths of up to 1 year. Because of pozzolanic reactions, HVFA concrete had a higher Young's modulus than traditional concrete for the same compressive strength and a significant decrease in creep compared with traditional concrete.

HVFA concrete was evaluated by Hazaree and Ceylan (2006). They used a combination of gap-graded aggregate and HVFA mixes as paving mixtures. An optimum cost savings of from 40% to 50% with minimized influence on concrete properties was obtained with fly ash.

Estakhri et al. (2004) conducted research to determine the potential for reduction in CO_2 emissions from the use of HVFA concrete. These researchers estimated that if 60% of Texas concrete was HVFA, the annual reduction in carbon dioxide would be 6.6 million tons. They also noted more experience is needed with regard to performance and actual environmental benefits. A major barrier noted for using HVFA concrete, at least in Texas, is that currently this state only allows up to 35% fly ash in their concrete applications

Reiner and Rens (2006) evaluated HVFA concrete using a range from 40% to 70%; this researcher found a range of 50% to 60% fly ash was optimum. Potential benefits noted include a reduction in environmental impact and fuel usage compared with using portland cement.

ASPHALT CONCRETE PAVEMENTS

Churchill and Amirkhania (1999) examined the effect of coal combustion byproducts (combination of fly ash and bottom ash) as a partial replacement for fine aggregates. Variables in the experiment included three aggregate sources, two ash sources, three ash percentages (0%, 6%, and 8%), and hydrated lime. Laboratory results indicated a moderate decline in mix properties with fly ash mixtures. A limited field study evaluated the environmental effects of the fly ash mixtures by monitoring the heavy metal concentrations in nearby soils. Monitoring results three months after placement showed there were not any substantial changes. Limited field trial showed heavy metal concentrations in soils were not substantially altered after three months.

Kalyoncu (2000) found a number of uses for coal combustion byproducts in asphalt concrete mixes. He noted that bottom ash can be used as fine aggregate in paving mixtures, although bottom ash with pyrites or porous particles is not suitable because of the high absorption and adhesion concerns. Kalyoncu also noted that these coal combustion byproducts are more commonly used in cold mix emulsified mixes that have less restrictive specifications for gradation and durability. Boiler slag can be used as fine aggregate because it has good toughness and durability. It is usually blended with other aggregates to obtain the desired gradation, since the boiler slag is typically uniformly sized.

Saylak et al. (2001) placed a 2-in.-HMA overlay surface course on the HMA plant haul road using sulfur-modified bottom ash. HMA used 50% virgin aggregate and 50% bottom ash that was coated with sulfur to minimize the high absorption characteristics and improve the crushing strength of the untreated bottom ash. After 18 months of truck traffic, the overlay was still performing well.

Asi and Assa'ad (2005) in Amman, Jordan, used fly ash as a replacement for minus 0.075 mm aggregate fraction. Laboratory testing of the mixes indicated that replacing 10% of the fines with fly ash achieved the best improvement in the mechanical properties.

Ksaibati and Sayiri (2006) conducted laboratory and field tests to evaluate the use of bottom ash in Wyoming HMA mixes. The materials included two aggregate sources (limestone and granite), three sources of bottom ash at 15%, one gradation, and one asphalt cement (PG 64-22). Mixes were prepared with and without lime, which was used to minimize the moisture sensitivity of the mix. Mixes were evaluated in the laboratory to determine indirect tensile strength (wet, dry), loaded wheel rutting, and low temperature properties with thermal stress restrained specimen test. The pavement condition index was determined for the test sections before and after placement of the overlay. The structural capacity was evaluated using FWD testing.

Nitrogen analysis was used to assess the chemical nature of the asphalt stripping potential in the presence of water. Pyridine-treated water was used to estimate the adsorption–desorption of water from the aggregate surface. Pyridine is used because it simulates the actions of anti-strip additives and basic nitrogen compounds in asphalt that are thought to be beneficial in reducing water damage.

Results showed comparable performance in laboratory and field tests. The nitrogen analysis suggests bottom ash may be useful as a means of reducing the moisture sensitivity of HMA.

GEOTECHNICAL APPLICATIONS

Soil Stabilization and Base Applications

Bergeson and Mahrt (1999) reported on the Iowa research using Class C fly ash alone (referred to as reclaimed hydrated Class C fly ash) for roadway base material. At the time of the research projects, only one of 11 sources of fly ash was Class F. The raw fly ash is transported to the disposal area where it is dozed into the sluice pond and allowed to hydrate. The hydrated fly ash (HFA) is reclaimed using conventional recycling–reclaiming equipment and then stockpiled for use as a construction material. The strength of the reclaimed fly ash aggregates was highly variable and became finer during the construction process. At the start of construction, sieve analyses were conducted to assess the consistency of the material as reclaimed rather than to document the gradation in-place. The gradations as-produced were consistent for both construction periods.

During construction, standard Proctor testing was conducted to verify that the optimum moisture and density was obtained. Nuclear gauges and rubber balloon compaction testing (ASTM D2167) was also completed for comparison (Table 32). The rubber balloon in-place density was consistent throughout the construction with about 94% being achieved for the upper 6 in. and about 90% for the bottom 6 in. of the 12 in. layer. The nuclear gauges always reported higher densities and much lower moisture contents. The researchers believed the density measurements could be corrected to represent the Proctor and rubber balloon testing, but the moisture content measurements were not well correlated with standard moisture content testing.

The in-place strength in terms of the California bearing capacity (CBR) of the reclaimed fly ash layer was estimated from dynamic cone penetrometer (DCP) results (Table 33). The results showed the lower 6 in. of the layer had lower strengths than the upper 6 in.; however, the variability in the test results make it difficult to statistically confirm significant differences. In general, the strength tended to increase with time. Samples were taken and laboratory CBR testing was completed for comparison. The laboratory results indicated that the results were variable with an average of 40.2 and a standard deviation of 12.8 at 0.1%. Strength of the material was not dependent on the moisture content of the reclaimed fly ash, but was dependent on the moisture content at the time of compaction.

The main problem encountered after the roadway was opened to traffic was the development of numerous unstable areas when subjected to heavy traffic. The reclaimed fly ash broke down into a fine powder and quickly dried out. Several causes for this problem were thought to be related to

TABLE 32
RESULTS FROM CONSTRUCTION TESTING ON RECLAIMED
FLY ASH AGGREGATE

Properties	Construction Period			
	Fall 1998		Summer 1999	
	Average	Standard Dev.	Average	Standard Dev.
Total Number of Tests	19		22	
Dry Unit Weight, lb/ft^3	94.7	1.8	93.7	2.5
Moisture Content, %	23.8	1.8	24.0	2.9
Cumulative Percent Passing for As-Produced Material, %				
37 mm	89.5	5.3	90.7	4.3
25 mm	83.1	7.0	82.0	6.0
19 mm	75.5	8.3	72.2	6.8
12.5 mm	67.5	8.9	62.7	6.3
9.5 mm	58.5	8.9	53.3	6.9
4.75 mm	41.7	8.5	36.9	7.2
2.36 mm	27.6	6.7	25.0	7.1
Nuclear Density Testing				
Total Number of Tests	33		75	
Density, lb/ft^3	119.7	3.2	114.9	4.0
Dry Density, lb/ft^3	110.5	2.7	105.5	3.3
Moisture Content, %	8.3	1.0	8.9	1.2
Rubber Balloon Compaction Testing*				
	0 to 6 in. Depth of Testing			
Number of Tests	30		80	
Dry Unit Weight, lb/ft^3	94.4	4.8	93.8	3.6
Moisture Content, %	22.1	2.2	20.8	2.9
Compaction, %	96.3	4.9	85.7	3.7
	6 to 12 in. Depth of Testing			
Number of Tests	5		18	
Dry Unit Weight, lb/ft3	92.4	2.4	87.5	3.0
Moisture Content, %	22.6	1.1	21.7	1.9
Compaction, %	94.3	2.5	89.3	3.0

After Bergeson and Mahrt (1999).
*Percent compaction based on maximum dry unit weight of 98 lb/ft^3.

TABLE 33
CBR FROM DCP TESTING FOR RECLAIMED FLY ASH SECTIONS

Properties	Fall 1998				Summer 1999			
	Ave.	Standard Dev.	Ave.	Standard Dev.	Ave.	Standard Dev.	Ave.	Standard Dev.
Depth of Testing	0 to 6 inch		6 to 12 inch		0 to 6 inch		6 to 12 inch	
Age when Tested: 0 Days								
Total Number of Tests	23	N/A	23		79	N/A	79	N/A
CBR	23.8	8.7	18.8		34.0	19.9	30.5	17.3
Age when Tested: 3.5 Days								
Total Number of Tests	—	—	—	—	26	N/A	26	N/A
CBR	—	—	—	—	101.3	71.8	73.8	53.8
Age when Tested: 7 Days								
Total Number of Tests	28	N/A	28	N/A	—	—	—	—
CBR	57.1	16.2	34.3	18.2	—	—	—	—
Age when Tested: 9 Days								
Total Number of Tests	12	N/A	12	N/A	—	—	—	—
CBR	92.3	19.9	68.9	43.0	—	—	—	—

After Bergeson and Mahrt (1999).
— = no data were collected. N/A = not available.

TABLE 34
AVERAGE PROPERTIES OF SOILS IN ILLINOIS STUDY

Properties	Project 1	Project 2	Project 3
AASHTO Classification	A-6	A-4	A-3
IDOT Textural Classification	Clay	Silt	Sand
Liquid Limit, %	39	29.7	ND
Plasticity Index	19.6	8	Non-plastic
Sand, %	0	0.9	97.3
Silt, %	45.6	85	0.8
Clay, %	54.4	14.2	1.9
–0.075 mm, %	100	Not tested	1.9

After Heckel (2001).
IDOT = Illinois Department of Transportation; ND = not determined.

under-compaction of the areas, placement in cold weather that inhibited the strength gains, construction during the rainy time of year, and a very soft subgrade (CBR of less than 6). Nearly all of the unstable areas occurred in the lane used by haul trucks.

Several guidelines were noted for the use of the reclaimed fly ash in roadway construction. Designs for reclaimed fly ash aggregates need to include sealing the surface of the layer to protect the integrity of the structure. Construction needs to limit the operation of heavy vehicles on the unprotected reclaimed fly ash layer. Repair any unstable areas noted during construction by rewetting and recompaction; however, this additional compaction will likely result in further degradation of the material. Moisture control is needed during construction to ensure adequate density and it is important that construction be done during warm, dry seasons. Rollers for initial compaction should be a heavy sheep's foot roller. Finish rolling is accomplished with either a steel-wheeled or pneumatic roller. Temporarily place surfacing materials for layer protection during construction and for curing before final lift placement.

Suggestions included allowing for the use of reclaimed fly ash in the construction of flexible pavements. Quality control and quality assurance of in-place density and moisture should use non-nuclear gauge method(s). Determine the in-place strength using either the DCP or Clegg hammer method. Place a granular surfacing of at least 2 in. if the roadway is to be subjected to traffic before the final surfacing is placed.

Heckel (2001) reported on the findings from three Illinois projects constructed to compare the effectiveness of stabilizing a soil with CBR values of less than 5. Two materials, byproduct hydrated lime and Class C fly ash, were used to stabilize the three soil types (Table 34).

Mix design procedures were developed for the byproduct hydrated lime and Class C fly ash using a moisture density immediate bearing value relationship over a range of moisture contents. Specimens were mix cured uncompacted for 1 hour, and then compacted according to AASHTO T99 method C. The CBR value using the load at 5 mm of penetration was designated as the immediate bearing value measurement. A minimum value of 10 for the immediate bearing value was selected for samples compacted at the anticipated field moisture content. The curing time at room temperature for the fly ash mixtures was increased to 48 hours. When fly ash was used to treat granular soils, compressive strength testing was used after specimens cured for 24 hours at room temperature. A minimum strength of 310 kPa was used. Laboratory testing showed water contents below optimum resulted in excessive drying that may then lead to raveling of the treated soil. Table 35 shows the amount of additive used for each project.

The compaction for Projects 1 and 2 used a sheep's foot roller in vibratory mode and finish rolling used a steel-wheeled unit. During construction of Project 3 (sand), the contractor needed to adjust the process by using a rotary speed mixer to pull the spreader trucks over the length of the section as the spreaders were losing traction on the sand. Large ruts in the soft subgrade made it difficult to spread. The byproduct hydrated lime was allowed to cure for 24 hours between mixing and compaction and no traffic was allowed on the section during this time. The fly ash-soil section for Project 2 needed 48 hours for curing (silt section). The standard 2 hours of curing worked well with the fly ash and sandy soil. A motor grader was used to seal the lime-soil mixture and provide proper drainage.

TABLE 35
PERCENT OF BYPRODUCT SELECTED FOR MINIMUM STABILITY REQUIREMENTS

Project	Byproduct Hydrated Lime	Class C Fly Ash
Project 1—clay	4%	11%
Project 2—silt	11%	20%
Project 3—sand	Not used	13%

After Heckel (2001).
Quantities were increased slightly to compensate for construction losses of material.

TABLE 36
WEATHER CONDITIONS DURING CONSTRUCTION OF ILLINOIS TEST SECTIONS

Project	Soil Temperature, °F	Ambient Air Temperature, °F	
		Range	Average
Project 2—silt	46 to 48	40 to 60	50.9
Project 3—sand	46 to 48	50 to 62	53.6

After Henkel (2000).
40°F considered reasonable lower limit for hydration to occur.

Weather conditions during construction are shown in Table 36. The soil temperature is important for adequate hydration and is of particular importance to Type C fly ash mixtures. Temperatures above freezing are adequate for lime stabilization but fly ash-soil mixtures can be more sensitive to low temperatures, substantially slowing strength gains. Other researchers suggest a minimum soil temperature of 40°F. Precipitation is also a concern if it occurs between the mixing and compaction processes (i.e., during curing) as the resulting premature hydration prevents the desired fly ash-soil cementitious reactions. It also results in the HFA clumping in-place.

Performance and subgrade modulus (Projects 1 and 3) using falling weight deflectometer (FWD) was monitored about three years after construction. There was only one small area of distress in the lime-soil section of Project 1. The average subgrade modulus was found to be consistent between all of the test sections (about 12,500 psi).

Findings noted were that either the byproduct hydrated lime or Class C fly ash were acceptable for stabilizing soils; however, the fly ash is most suitable such as silts and sands that do not respond to lime treatments. The treatment amount when using fly ash with clayey soils requires two to three times the material compared with using lime. The coarse particle size of the byproduct hydrated lime requires a significant amount of water to achieve optimum moisture and is best used when the subgrade soil is very wet. The document contains recommended mix design procedures, materials specification, and construction specifications in an appendix that can be found at the web address in the reference section for this chapter.

Beeghly (2003) compared lime-stabilized with lime fly ash stabilized soils. This research showed stabilization with lime alone works well to stabilize clay soils, but a combination of lime and fly ash works well for lower plasticity (PI < 20) and higher silt content (>50%) soils. The fly ash provides the pozzolanic reactants, silica, and alumina that are typically lacking in these soils. The approval process for accepting a source of fly ash needs to include determining an acceptable lime–pozzolanic reactivity by ASTM C593, which is defined as the mortar cube strength minimum of 600 psi after 7 days of curing. The inclusion of moisture susceptibility is recommended using molded cylinders that are exposed to a capillary soak after curing.

Beeghly also evaluated the cost benefits of using fly ash as a stabilizing component compared with cement stabilization. Lime fly ash costs approximately 50% less than cement stabilization. Stabilization in general allowed a reduction of at least 20% as a result of a thinner pavement thickness used over the improved base stiffness.

Bischoff (2004) evaluated the use of screened and unscreened bottom ash as a base material for asphalt concrete pavement for the Wisconsin DOT. The material properties evaluated for various ash–aggregate blends included gradation, specific gravity, absorption, maximum dry density, soundness, plasticity, and CBR. The CBR results were found to be the most important factor in estimating the optimum blend of bottom ash and aggregates. A minimum value for CBR of 50 was recommended for designing blended base course materials, which was a reduction of about 30% for tradition base materials used in Wisconsin. For this study, 8% of bottom ash and aggregate met this CBR value.

Recommendations to the Wisconsin DOT included further research to investigate higher percentages of bottom ash in crushed aggregate base, use bottom ash as a structural fill for embankments as an alternative use, conduct research using bottom ash and/or sulfur-modified bottom ash for use in asphalt and portland cement concrete applications.

The seven-year performance for the roadway section using the screened bottom ash and four years for the unscreened bottom ash showed that the recycled material both provided similar performance as a crushed limestone base. However, the lack of information on the freeze/thaw durability data resulted in a recommendation to discontinue use until these data can be collected.

White et al. (2005) evaluated the nonuniformity of PCC pavement support and found the uniformity of support for PCC pavements was improved with stabilized bases. These researchers studied HFA, self-cementing fly ash-stabilized subgrade, and granular subbases, and then compared their results to natural subgrade soils. One notable finding was estimates of support variability. The natural subgrade (unstabilized) variability was 71%. The variability in the support stiffness only ranged between 16% and 22% for any of the other coal combustion byproduct stabilized materials. Construction testing included DCP, Clegg Impact Hammer, geogauge stiffness, and nuclear density gauge. A further

ISLAB 2000 statistical analysis was used to evaluate benefits to pavement distress formation.

Arora and Aydilek (2005) evaluated the use of Class F fly ash and soil mixtures. This research showed that the strength of the compacted mixtures was dependent on the curing period, compactive energy, and water content at the time of compaction.

Grosenheider et al. (2006) concluded that fly ash-stabilized soil (7% to 20% w:w) reduced shrinkage and swelling of base material and Trzebaitowski (2005) confirmed increases in CBR, modulus, and FWD results when using Type C fly ash for stabilizing sandy clay soils.

Ramme et al. (2006) evaluated a combination of reclaimed asphalt pavement (RAP) and Type C fly ash in full-depth reclamation. These researchers found that the fly ash-stabilized sections of a roadway in Waukesha County, Wisconsin, were 49% stiffer than untreated sections after one year and 83% stiffer higher after two years.

Felker and Parcells (2007) explored a new use for fly ash in asphalt concrete pavement preservation. They used a fly ash slurry injection method successfully in Kansas to fill in voids under transverse cracks in HMA pavements. In this process, holes were drilled for injection of the slurry, the pavement surface was cold milled to remove any surface irregularities, and then the old surface was overlaid. Test sections, each 800 ft long, were constructed in 2003. One section was the control section and the other three each used 15% of each source of bottom ash. Pavement condition was monitored at one year after construction.

Ghosh and Subbarao (2007) conducted laboratory studies to investigate the properties of fly ash-stabilized base materials. This research found using Type F fly ash combined with 10% lime and 1% gypsum significantly improved unconfined compressive strength and cohesion.

Li et al. (2007) evaluated a combination of RAP and Type C fly ash that can also be used as stabilized base material during full-depth reclamation of asphalt pavements. The CBR and resilient modulus were 3 to 9 times the unmodified values. FWD testing showed the increased stiffness (support) was maintained after freeze/thaw cycles during the first winter.

Hatipoglu et al. (2008) evaluated Type C fly ash and off-specification fly ash as a way to improve the support of roadway base. After 7 days of curing, the CBR and modulus values were approximately twice those of the untreated material.

Little and Nair (2009) developed guidelines for selecting the most effective material for stabilizing bases (Figure 11). Either Class C alone or Class F with lime as an activator can be used to stabilize a wide range of soil types with at least 25% fines passing the 0.075 mm (no. 200) sieve. Lime stabilization works well with medium, moderately fine, and fine-grained soils by decreasing the plasticity and swelling potential while increasing workability and strength. Cement stabilization works best with well-graded aggregates with enough fines to fill the void space between particles. Fly ash can be used with a wider range of soils. In coarser gradations fly ash acts like a pozzolan and/or filler. An activator such as lime is used with the Class F fly ash at about 20% to 30% of the fly ash in the blend.

Once an additive has been selected based on the soil properties, the organic content needs to be determined by ASTM D2974. A typical limit on organic contaminates is 1%, although soils with higher contents have been successfully stabilized. Sulfate contents also need to be determined per modified AASHTO T290. Water-soluble sulfate levels

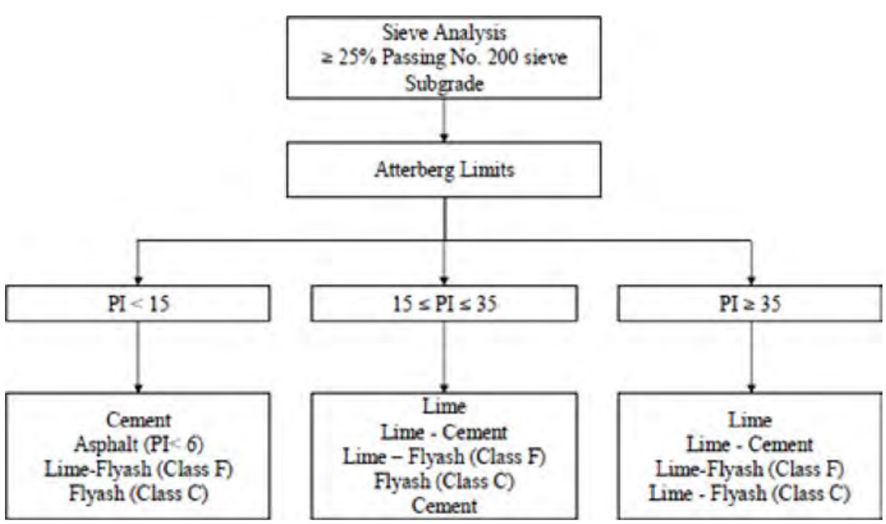


FIGURE 11 Flow chart for selecting additive for stabilizing soils (after Little and Nair 2009).

greater than 0.3% are suggested as the upper value for limiting expansive reactions.

Design recommendations for fly ash mixtures start with determining the cementitious properties of the fly ash by ASTM D5239. This test method only evaluates the fly ash characteristics and not the suitability of the stabilized soils. There is currently no standard test method for designing stabilized soils with self-cementing fly ash (Type C); however, the ACAA recommends using moisture density and moisture strength relationships for designs. The primary consideration for the design is the rate at which fly ash hydrates when exposed to water. An additional design consideration when selecting the optimum fly ash content is determining the optimum moisture content needed to provide a maximum strength. The optimum moisture content can range from 1% to 8% below that needed for maximum dry density.

For fly ashes that need an activator (Type F), first determine how the stabilized soil is to be used. If the goal is to achieve maximum strength and durability in an aggregate base course, then the design approach is to fill in voids between the aggregate particles to achieve maximum density. If the goal is to achieve a minimum level of strength for either soils or base courses, a trial and error approach based on experience is needed to identify the optimum blend of fly ash and activator.

Embankment Fill

Kim et al. (2006) evaluated high fly ash content/bottom ash blends for use in embankment fills. They found that these blends are somewhat more compressible than compacted sands at the same compaction level. They attributed this to higher crushability of the fly and bottom ash. The deformation increased as the percentage of bottom ash to the fly ash content was increased. The optimum moisture content and maximum dry density gradually increased as the fly ash content increased more than 50%. The dry densities were dependent on the source of the fly ash as specific gravity of fly ash is source/plant dependent. The shear strength of blends was equal to or higher than sands at similar compaction levels and the angle of internal friction increased about 2% for every 25% of bottom ash. Dilation and other volumetric behavior were found to be similar to sands.

In designing the embankment, the slope stability of blends met requirements when heights were less than 20 m with a horizontal to vertical ratio of 2:1 or flatter with a factor of safety higher than 1.3. Kim et al. also noted that compaction was important to achieving desired embankment properties. Preconstruction testing included determining the fly ash/bottom ash properties:

- Specific gravity (ASTM D854-00)
- Optimum moisture content and maximum dry density (ASTM D698)
- Grain size analysis
- Chemical composition.

Test pad construction testing included density with nuclear gauge (ASTM D2922) calibrated with sand cone tests, microwave moisture content (ASTM D4643), and dynamic cone penetrometer (ASTM D6951) testing. Short- and long-term monitoring was accomplished by the placement of piezometers, settlement plates, and vertical and horizontal inclinometers. Previous research was used to determine leaching of trace metals and environmental issues include limiting water flow through the embankment. The authors noted that the blended material may be potentially corrosive and the routing of pipes through blended fill limited.

MINE TAILINGS STABILIZATION

Shang et al. (2006) evaluated using fly ash to neutralize acid generation from mine tailings in the Sudbury mine, England. Reactions between fly ash and acid mine drainage reduced the conductivity of the fly ash by three orders of magnitude. The time required for acid mine drainage to break through the fly ash increased up to ten times (from 17 to 150) as compared with that of water.

SYNTHETIC AGGREGATE PRODUCTION

There has been a limited amount of laboratory research into using a combination of fly ash and FGD (synthetic gypsum), combined by disk pelletization using moderate temperatures to cure the resulting pellets, to form aggregates. The process was developed by Consol Energy Corp (Aggregates Manager 2000). This is a new possibility for future market expansion for coal combustion byproducts.

AGENCY SURVEY RESPONSES FOR CONSTRUCTION QUESTION

Table 37 gives the construction-related responses.

AGENCY SURVEY RESPONSES FOR APPLICATION PERFORMANCE QUESTION

The agency survey included an open-ended question asking the respondents to comment on experiences with either good or poor performance. Table 38 presents a summary of the responses.

TABLE 37
AGENCY SURVEY RESPONSES FOR THE PERFORMANCE OF COAL COMBUSTION PRODUCTS IN CONSTRUCTION OF HIGHWAY APPLICATIONS

Performance Categories	Performance Comments	States with Comments
HMA	*SMA:* difficulty controlling volumetrics during construction	KY
PCC	*Cement substitute*: use fly ash 20% as a cement substitute	AR
	Workability: to enhance the placement of concrete	MS
Soil	*Stabilized Soils:* Optimum moisture content needs to be maintained. Moisture contents no higher than optimum value and no more than 2% below the optimum value are necessary for successful performance.	KY
	Fly ash stabilization is viewed and a construction only treatment not for the life of the overlying pavement	MS
	Fill: monitoring wells used to monitor ground-water quality	MD

TABLE 38
AGENCY SURVEY RESPONSES FOR PERFORMANCE EXPERIENCE

Question: Comment on your experience with the *performance* of the application(s) that used any combustion byproduct.		
Performance Categories	Performance Comments (number of states)	States with Comments
Acceptable and/or Improved Performance	*PCC:* increases performance (all listed); ASR mitigation (3); high performance concrete applications (1)	AK, AL, AZ, CO, DE, IL, IN, IA, KY, LA, MA, MO, MS, NC, ND, NE, NH, NV, NY, OH, PA, TX, VA, VT, WI, WI, WA
Poor Performance	*Embankments:* Boiler slag is less stable than virgin aggregate or recycled concrete materials.	NJ
	HMA: Type F fly ash in SMA mixture was not successful because of volumetric problems.	KY
	PCC: Problems with compressive strength (2), low air contents (2), variable LOI (1)	DC, PA, VT

SMA = stone mastic asphalt; ASR = alkali–silica reactivity; LOI = loss on ignition.

CHAPTER SIX

ENVIRONMENTAL ISSUES

The U.S. EPA has delegated the responsibility of regulation of coal combustion byproducts to the states (RMRC 2008), with each state responsible for the development of specifications and environmental regulations. As an example, the Wisconsin Department of Natural Resources Regulation 538 is used to present a fully developed state regulation for using byproducts in highway applications. The Natural Resources 538 (NR 538) Wisconsin Administrative Code details the Beneficial Use of Industrial Byproducts and includes specific guidance on the topics shown in Table 39. Figures 12–15 show, through the use of flow charts, how NR 538 regulates recycled materials and byproducts in highway applications. The code separates the regulations into four general highway application topics:

- General Use
- Transportation Embankments
- Unconfined Geotechnical Fills
- Surface Course Materials and Road Abrasives.

All of the flow charts start with assessing the applicability of the byproduct for use in highway applications, excluding water and wastewater facilities. All byproducts need to be evaluated to determine that there are no environmental concerns when used in the individual applications, which are categorized in the lower tiers of the flow chart. This regulation is applicable to all of these materials; it is not limited to the use of coal combustion byproducts.

In 2010, the EPA posted two proposed options for tighter regulations to address environmental concerns encountered as a result of the December 2008 coal combustion byproduct impound breach in Tennessee, which resulted in a spill of about 1 billion gallons. The differences between the two options are shown in Table 40.

ENVIRONMENTAL MODELING OPTIONS

There are a number of software programs that are available for estimating ground-water contamination from leachates. There are several programs that are in the public domain software (RMRC 2008):

- Estimates of environmental impacts in US highway applications
- Environmental testing programs for byproduct assessment
- Economic and environmental cost information
- Assessments of recyclability at the end of the service life of the application (i.e., sustainability).

SCREENING TOOL FOR USING WASTE MATERIALS IN PAVING PROJECTS

The Screening Tool for Using Waste Materials in Paving Projects (STUWMPP) software is the only public domain software specifically designed to evaluate the environmental impact of coal combustion byproducts; therefore, only this program will be used as an example of simple environmental software in this chapter.

It can be noted that the program was developed for materials, coal combustion byproducts, and environmental conditions in Minnesota. However, it can provide a general “what if” preliminary evaluation of leaching potential (Friend et al. 2004). Three EPA methods (3050, 3051, and 3052) for determining leachate were evaluated during the development of the software (Grosenheider et al. 2006). Method 3050 is commonly used in environmental cleanup assessment and is a leachate method. The 3050 method is an alternative to 3051 and expected to produce results similar to 3051. Limitations include that elements bound in silicate structures will not be totally dissolved. The 3052 method is a total digestion method that breaks down the entire sample matrix to determine the certificate of compliance (COC) concentrations and is considered more time-consuming and more expensive than the other two methods. The final recommendation was to use Method 3051.

The Minnesota Pollution Control Agency (MPCA) developed the analysis using a risk-based decision-making approach. The site evaluation provides a preferred decision-making methodology that considers human health and the environment at site locations. A three-tiered approach that represents increasingly complex exposure scenarios is considered. The extent of the data required decreases with increasing tier levels. The pathways for contamination include soil direct contact, soil leaching into the ground water, ground water (ingestion), surface water (ingestion and direct contact), air (inhalation), sediments (direct contact), and biota (food chain). The soil reference values (SRVs) indicate the contaminate concentrations above which there is an unacceptable risk to human health. SRVs were derived

TABLE 39
SECTION COVERED IN NR 538

NR Section	Section Title	NR Section	Section Title
NR 538.01	Purpose	NR 538.10	Beneficial Uses
NR 538.02	Applicability	NR 538.12	Beneficial Uses for Specific Categories of Industrial Byproducts
NR 538.03	Definitions	NR 538.14	Reporting
NR 538.04	Performance Standards	NR 538.16	Storage and Transportation Requirements
NR 538.05	Solid Waste Rules Exemptions	NR 538.18	Public Participation
NR 538.06	Industrial Byproduct Characterization	NR 538.20	Environmental Monitoring
NR 538.08	Industrial Byproduct Categories	NR 538.22	Property Owner Notification

After WE Energies (2004).

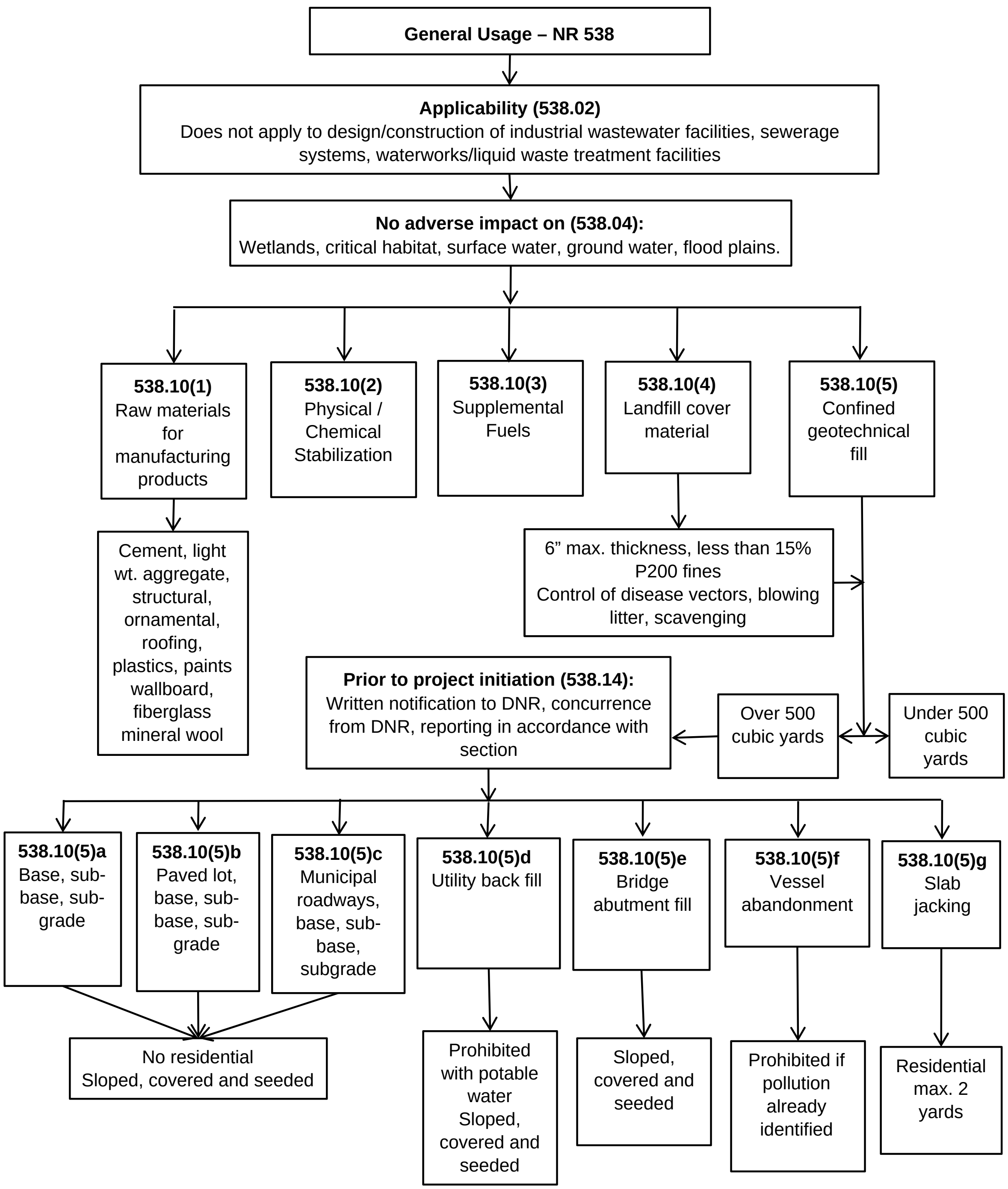


FIGURE 12 NR 538 General Usage Sections 538.1 through 538.5 (after WE Energies 2004).

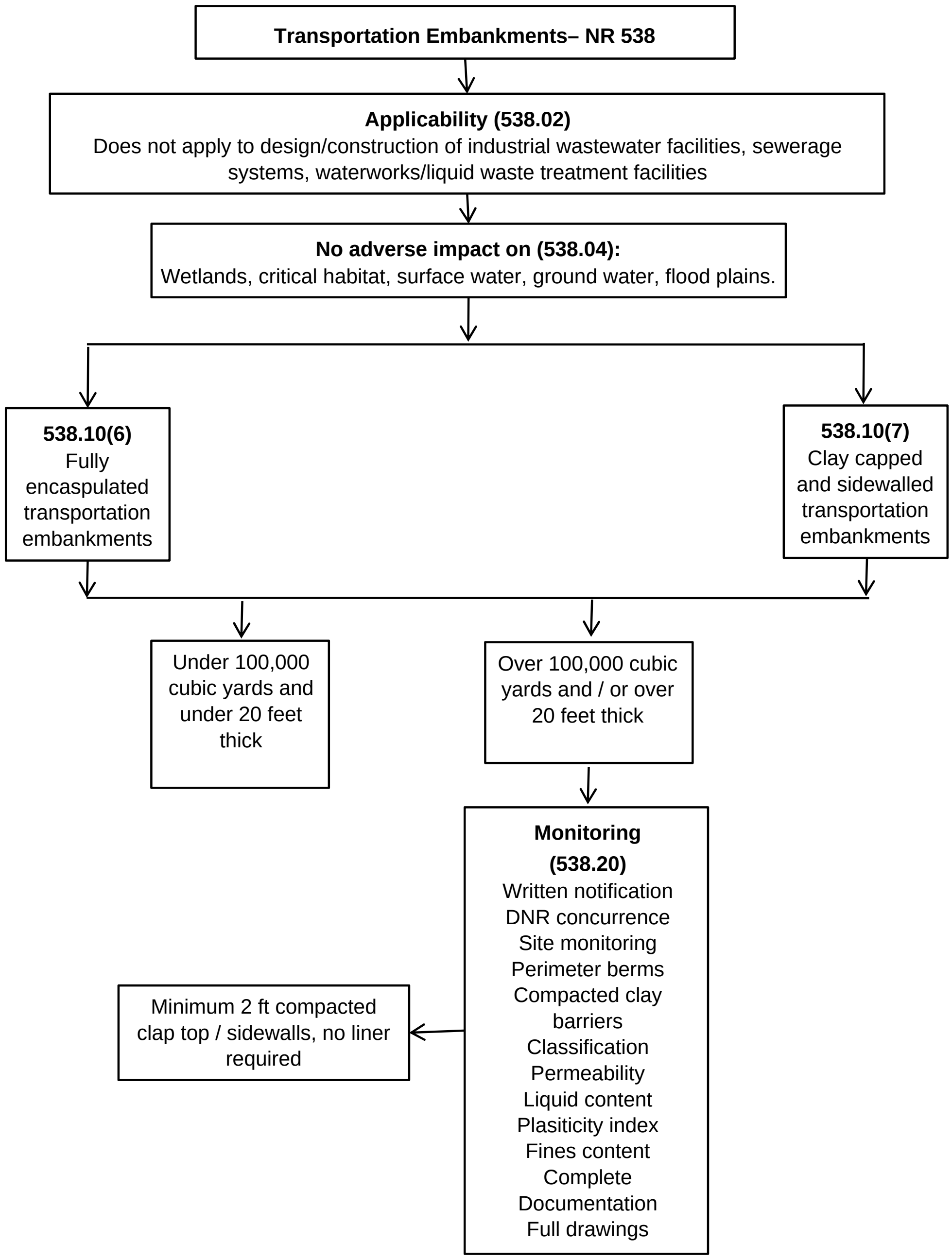


FIGURE 13 NR 538 Transportation Embankments Sections 538.6 and 538.7 (after WE Energies 2004).

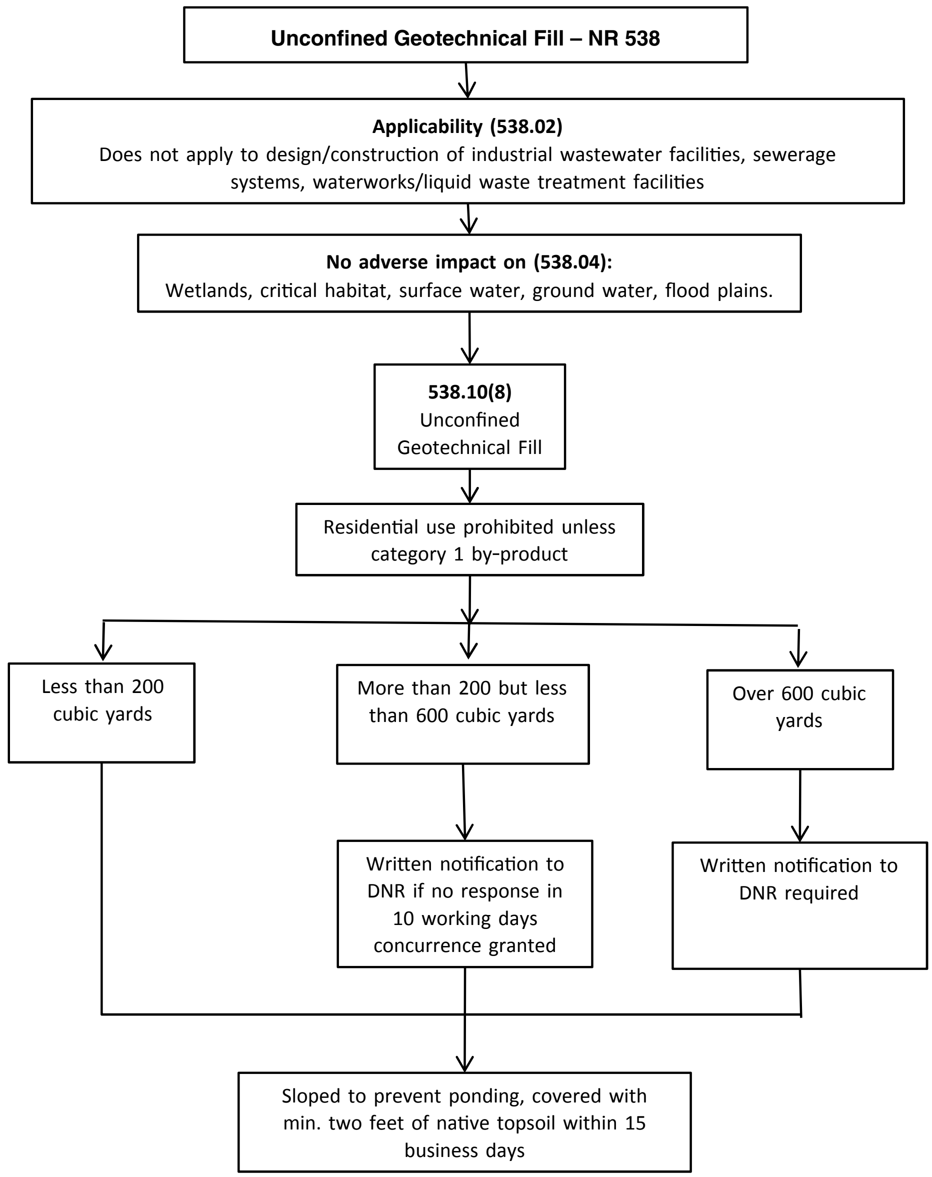


FIGURE 14 NR 538 Unconfined Geotechnical Fill Section 538.8 (after WE Energies 2004).

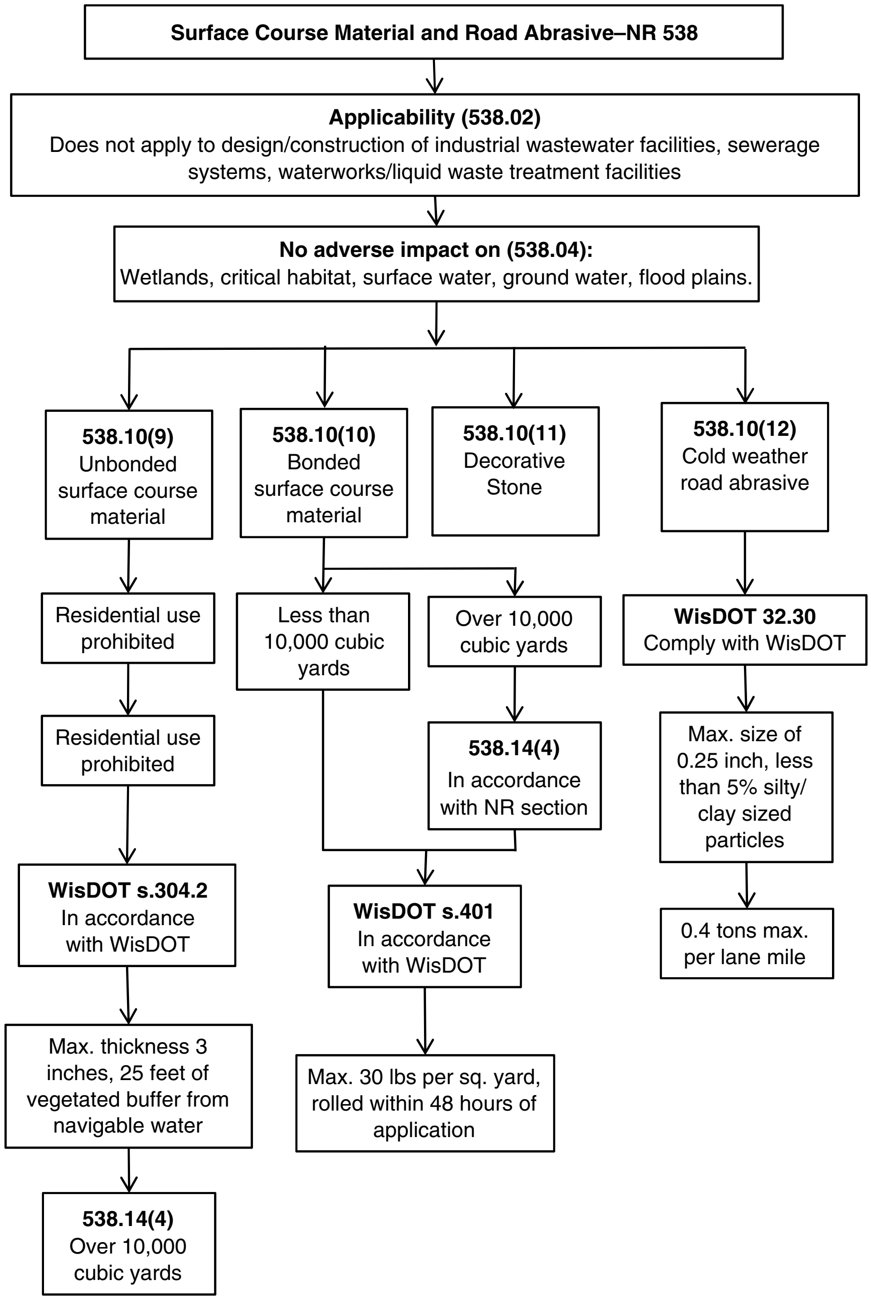


FIGURE 15 NR 538 Surface Course Material and Road Abrasive Sections 538.9 through 538.12 (after WE Energies 2004).

TABLE 40
KEY DIFFERENCES BETWEEN SUBTITLE C AND SUBTITLE D OPTIONS

Key Topics	Subtitle C	Subtitle D
Effective Date	Timing will vary from state to state, as each state must adopt the rule individually—can take 1–2 years or more	Six months after final rule is promulgated for most provisions: certain provisions have a longer effective date.
Enforcement	State and federal enforcement	Enforcement through citizen suits; states can act as citizens.
Corrective Action	Monitored by authorized states and EPA	Self-implementing
Financial Assurance	Yes	Considering subsequent rule using CERCLA 108 (b) Authority
Permit Issuance	Federal requirement for permit issuance by states	No
Requirements for Storage, Including Containers, Tanks, and Containment Buildings	Yes	No
Surface Impoundments Built Before Rule Is Finalized	Remove solids and meet land disposal restrictions; retrofit with a liner within five years of effective date. Would effectively phase out use of existing surface impoundments	Must remove solids and retrofit with a composite liner or cease receiving CCRs within 5 years of effective date and close the unit.
Surface Impoundments Built After Rule Is Finalized	Must meet Land Disposal Restrictions and liner requirements. Would effectively phase out use of new surface impoundments	Must install composite liners. No Land Disposal Restrictions
Landfills Built Before Rule Is Finalized	No liner requirements, but require ground-water monitoring	No liner requirements, but require ground-water monitoring
Landfills Built After Rule Is Finalized	Liner requirements and ground-water monitoring	Liner requirements and ground-water monitoring
Requirements for Closure and Post-Closure Care	Yes, monitored by states and EPA	Yes, self-implementing

After EPA (2010).
CCR = crushed concrete aggregate.
http://www.epa.gov/osw/nonhaz/industrial/special/fossil/ccr-rule/ccr-table.htm).

by MPCA using risk assessment methodology, modeling, and risk management policy. The risk characterization compares the maximum soil concentrations to the Tier 1 SRVs, which assumes that human exposure to contaminants is chronic and occurs in a residential setting. The Tier 2 characterization assumes the exposure is for industrial and recreational property use. If the estimated concentrations from the model exceed the SRVs, then there is an unacceptable risk to human health.

Soil leaching values (SLVs) represent the contaminant concentrations expected in the ground water above which there is an unacceptable risk to human health. The SLVs were developed by the MPCA using the SESOIL model. The risk characterization compares the maximum soil concentrations directly with Tier 1 SLVs, which assumes human exposure to the contaminants is chronic. The Tier 2 SRVs incorporate site-specific information and result in values that are greater than Tier 1 SLVs. As with the SRVs, if the estimated concentrations exceed the SLVs then there is an unacceptable risk to human health. Site-specific information needed for Tier 2 values includes depth to water table, soil porosity, soil water content, soil organic carbon content, soil pH, annual recharge rate, aquifer conductivity, aquifer hydraulic gradient, dimensions of source area, and chemical adsorption coefficient. Some of the reported advantages to this analytical approach were that it provided a consistent approach, included a range of chemicals and pathways, and was flexible to a range of site conditions.

Table 41 (soils) and Table 42 (fly ash) show examples of data used to develop the default values in the STUWMPP program for soils and fly ash, respectively.

AGENCY SURVEY RESPONSES FOR ENVIRONMENTAL TESTING

Table 43 shows the responses to the survey question about what recycled materials and byproducts were tested by agencies and which test methods they were using. Eleven states indicated they did not conduct environmental testing. Additional comments indicated it was either not the agency's responsibility or was another agency's responsibility, such as EPA, to require and monitor environmental testing or iden-

TABLE 41
SUMMARY STATISTICS FOR ALL SOILS

Constituents of Concern	Typical Values for Soils, ppm							
	SRV Tier 1 (1999)	SRV Tier 1 (2006)	SLV tier 2 typical site/soil	Minimum	Mean	Maximum	Std. Dev.	Upper 95% confidence interval
Be	55	55	5.44	0.34	0.60	0.88	0.14	0.87
B	3,000	6,000	582	6.57	17.6	32.2	6.86	31.3
Co	2,000	600	120	7.53	13.6	23.4	4.62	22.8
Ni	520	560	353	15.6	25.6	37.4	5.79	37.2
Cu	100	11	1,610	10.5	15.8*	22.4*	3.36	22.5*
Zn	8,700	8,700	6,020	33.4	49.2	69.4	11.2	71.61
As	10	5	58.5	1.67	5.45*	9.56*	2.28	10.0*
Se	170	160	5.46	0.59	0.87	1.24	0.21	1.29
Sr	N/A	18,000	77,200	24.9	48.3	107	29	106
Mo	N/A	N/A	24.3	0.27	0.63	1.70	0.37	1.37
Ag	N/A	160	15.9	0.47	2.06	12.5	3.29	8.63
Cd	35	25	17.6	0.17	0.38	0.55	0.12	0.62
Sn	15,000	9,000	11,900	0.21	0.71	1.50	0.43	1.56
Sb	14	12	10.9	0.02	0.09	0.23	0.07	0.24
Ba	1,200	1,200	3,380	83.4	150	222	44	238
Tl	3	3	N/A	0.21	0.40	0.73	0.15	0.69
Pb	400	300	2,100	5.52	9.99	13.2	2.05	14.1
Cr	71	87	73	12.4	21.3	44.0	8.71	38.7
Mn	1,400	3,600	N/A	219	675	1,350	284	1,240
V	210	30	2,000	12.5	25.6	43.9*	9.15	43.9*
Hg	0.70	0.50	6.58	0.01	0.03	0.05	0.01	0.05

After Grosenheider et al. (2006).
*Exceeded the 2006 SRV.
N/A = not available.

tify other guidelines. A total of 14 state respondents were not sure if their states were conducting environmental testing. Only three indicated their state had done or requires environmentally related testing. Texas was the only state that indicated established guidelines for environmental requirements. Their standard is outlined here.

TEXAS DEPARTMENT OF MATERIALS SPECIFICATIONS

The Texas Department of Materials Specifications (DMS) 11000 detailed its state's process for evaluating nonhazardous recycled materials (NRM) not addressed by other Texas specifications (TxDOT 2004). Recycled materials and byproducts covered by other Texas specifications included aluminum, compost, glass beads, ground granulated blast furnace slag, shredded brushes, steel, tire, rubber, ceramics, glass cullet, plastics, and crushed concrete from nonindustrial sources; RAP, fly, and bottom ash from electrical utility plants; and department-owned materials.

The NRM product approval process for eligibility to be used on TxDOT projects required that the NMR product:

- Meet all applicable department engineering specifications and other engineering evaluations.
- Contain only NRMs that meet the requirements for control of material (Item 6, Article 6.9 "Recycled Materials," of the Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges).
- Contain only NRMs that are managed and protected from loss, as would be raw materials, ingredients, or products.
- Be used without the need for short-term or long-term management, such as special worker protection precautions, tracking, monitoring, special handling after the project, or special engineering controls.
- Not present an increased risk to human health, the environment, or waters in the state when applied to the land or used in products applied to the land.

This last requirement included restrictions on the concentrations to be less than the COC concentrations found in the traditional material that is being replaced, equal to or below the corresponding Texas-Specific Background Concentrations, or less than the Tier 1 Residential Protective Concentration Levels for combined exposure pathways. Additional requirements stated that the NRM must meet either item 1 or 3 above,

TABLE 42
SUMMARY STATISTICS FOR ALL POWER PLANT FLY ASH TESTED (n = 138)

Constituents of Concern	Values for Fly Ash, ppm							
	SRV Tier 1 (1999)	SRV Tier 1 (2006)	SLV Tier 2 Typical site/soil	Minimum	Mean	Maximum	Std. Dev.	Upper 95% Confidence Interval
Be	55	55	5.44	0.70	3.00	5.54[*]	0.89	4.77
B	3,000	6,000	582	221	585[#]	1250[*]	238	1,060[*]
Co	2,000	600	120	2.14	20.4	201*	26.6	73.6
Ni	520	560	353	7.26	136	958[*+]	260	655[*#]
Cu	100	11	1,610	18.7[*]	152[*+]	348[*+]	76.3	304[*+]
Zn	8,700	8,700	6,020	33.7	484	8,659[*]	1,610	3,700
Zs	10	5	58.5	3.55	19.2[*]	99.1[+#]	16.4	52.0
Se	170	160	5.46	0.91	9.21[#]	20.4[*]	3.70	16.6[#]
Sr	N/A	18,000	77,200	701	3,000	7,030	1,520	6,030
Mo	N/A	N/A	24.3	2.06	20.01	111[*]	30.2	80.4[#]
Ag	N/A	160	15.9	0.20	1.63	8.43	1.07	3.77
Cd	35	25	17.60	0.53	1.87	10.1	1.51	4.88
Sn	15,000	9,000	11,900	0.18	0.99	5.59	0.79	2.56
Sb	14	12	10.9	0.01	0.15	1.07	0.13	0.42
Ba	1,200	1,200	3,380	917	4440[*+#]	12,300[*+#]	2,290	9020[*+#]
Tl	3	3	N/A	0.10	0.74	3.66[*+]	0.59	1.92
Pb	400	300	2,100	8.56	37.2	120	22.5	82.1
Cr	71	87	73	12.1	58.8	102[*+#]	21.3	101[*]
Mn	1,400	3,600	N/A	57.6	281	1,760[*+]	332	945
V	210	30	2,000	23.0	384[*+]	1,810[*+]	485	1,350[*+]
Hg	0.70	0.50	6.58	0.03	0.41	1.20*+	0.37	1.14[*+]

Grosenheider et al. (2006).
[*]Exceeded the 2006 SRV.
[+]Exceeded the 1999 SRV.
[#]Exceeded the SLV.
N/A = not available.

TABLE 43
AGENCY SURVEY RESPONSES FOR PERFORMANCE EXPERIENCE

Question: Environmental Issues: Were any of the recycled material(s) or byproduct(s) listed below tested by your organization for biodegradation, leaching, or ecotoxicity before use in highway application(s)?		
Environmental Testing	States	Comments
No	AK, CA, CO, DE, ID, KS, MS, ND, NE, NM, NV	Not agency's responsibility (OH)
		EPA defines as beneficial use materials, then they should run test (OH)
		State agency designates as beneficial use; environmental division sets testing for permit (PA)
		Work done under NCHRP 25-09 used as guide for evaluating bound materials and aggregates (WA)
Not Sure	AL, AR, AZ, CT, DC, GA, MA, NH, NJ, OK, OR, SC, WI, LA	Original use of byproducts historical (AL)
		Not done by respondents department (DC)
		Testing done by power company (fly ash)
Yes, All Byproducts	NY	Extensive work done before use
	TX	All recycled materials to conform to: ftp://ftp.dot.state.tx.us/pub/t--dot-info/cst/DMS/11000_series/pdfs/11000.pdf
Yes, Combustion Ash, General	NC	Leachate testing for ash embankments
Yes, Fly Ash	IA	Chemical composition tested for fly ash
	KY	Heavy metal concentrations monitored in embankments and stabilized soils
	NY	Extensive work done on fly ash (leaching; no other particulars given)

or that concentrations be measured in the leachate following a scientifically valid synthetic leaching procedure. The results needed to be less than the allowable Protective Concentration Levels for ground-water ingestion, or equal to or less than the leachate concentrations of the same COCs found in traditional materials.

Testing protocol for environmental criteria required collection and testing of NRMs for every 10,000 tons of materials delivered to the department, or have an established internal testing program that regularly measures and documents the environmental criteria.

The TxDOT NRM product certification section required NRMs not included in other specifications or on acceptable use lists to provide a certificate signed, sealed, and stamped by a registered engineer that the NRM meets all required environmental criteria. DMS includes a table for concentration criteria for NRM use in various highway applications.

CHAPTER SEVEN

ECONOMICS

BACKGROUND

Power plant operators viewed lower value coal combustion byproducts (e.g., bottom ash and scrubber ash) with a "cost avoidance" philosophy (Schimmoller 2003). They considered a revenue generator approach to higher value products such as fly ash and FGD (i.e., wallboard gypsum). These two philosophies tended to drive choices in power plant modifications for expending capital investments to make coal combustion byproducts more marketable. Capital investments driven by changes in regulations were another matter. In this case, plant changes were made to conform to the regulations, and the changes in the coal combustion byproducts may or may not have been considered. However, these changes could effectively alter the physical and chemical properties of the coal combustion byproducts. For example, recent changes in power plant operation resulted in some cases in changes in coal combustion byproduct properties by increasing the unburned carbon content. Ammonia contamination occurred from power plants equipped with a selective catalytic reduction system, selective NO_x catalytic reduction systems, or precipitator conditioning systems. Some of the new mercury removal technologies for flue gases resulted in higher concentrations of mercury in fly ash (Grosenheider et al. 2006). These changes could influence both the properties of the final highway application product (i.e., high unburned carbon content in fly ash) and/or potential leachate changes (e.g., mercury).

Changes in power plant burner fuel could also result in changes in properties (Grosenheider et al. 2006). Cyclone boilers produced higher carbon content ash, while adding waste tires and sewage sludge to the fuel mix resulted in five times the zinc level in one plant studied. Traveling grate boilers at another plant yielded ash with a higher arsenic content.

AGENCY SURVEY RESPONSES FOR COST

The survey did not specifically ask about costs associated with recycled materials in highway applications. When the open-ended questions were coded for organization of responses, the only cost noted was simply "expensive." Five states (Ohio, Missouri, North Dakota, North Carolina, and Washington) indicated additional testing was required because of byproduct nonuniformity, haul distances, and economically attractive and locally available virgin materials adversely influenced project costs.

CHAPTER EIGHT

BARRIERS TO USE

BACKGROUND

Potential barriers to either increased usage or new usage of coal combustion byproducts found in the literature include a number of references to:

- High cost of transportation coupled with the low unit value of coal combustion byproducts restricting their use to local use,
- Limited data on environmental and health effects,
- Compositional nonhomogeneity of coal combustion byproducts,
- Lack of state guidelines,
- Perception that EPA regulations are too complicated and rigid, and
- Designation by EPA as being regulated under Subtitle D as potentially hazardous in mining reclamation and backfill applications will limit their use.

AGENCY SURVEY RESPONSES TO BARRIERS

The open-ended questions in the agency survey were designed to capture current agency perceptions of barriers to expanded uses of combustion byproducts in highway applications. Agency survey respondents were asked to comment on *barriers* to the use of combustion byproducts in highway applications that have been either overcome or still exist. Table 44 summarizes the written responses for barriers. The responses, as written, are shown in Appendix A. The agency responses agreed with the barriers found throughout the literature and expanded the list. In addition, they included information as to why these concerns were barriers. For example, poor performance was a problem with fly ash-stabilized soils because of expansive crystal formation.

TABLE 44
AGENCY RESPONSES TO BARRIERS TO FURTHER USE OF COAL COMBUSTION BYPRODUCTS

Question: Comment on *barriers* to the use of combustion byproducts in highway applications that have been either overcome or still exist		
Barrier Category	Reasons for Classification as Barrier	States with Barrier Responses
Aesthetics	Types C and F fly ash can produce staining	KY
Availability	Transportation distance; not locally produced; not produced in sufficient quantities	CO, HI, MO, NC, ND, NE, NV, SC, WS
Contractor	Early strength requests by contractor do not address longer strength gains	VT
Cost	CCPs not economically competitive with natural materials, additional QC costs due to higher variability, transportation costs, or used in addition to (rather than replacement for) cement	HI, OH, MO, NC, ND, VT, WS
Experience	Lack of contractor experience	ID
Poor Performance	Fly ash in combination with lime or cement can cause crystal formations that can grow and cause problems if stabilized soils are near structures; lack of product uniformity, durability concerns with Type C and Type F fly ash in PCC.	DE, KY, MS, VA
QC/QA	Product variability and resulting material property variability	HI, NY
Regulations	Additional oversight requirements; additional controls needed for EPA; inconsistent EPA and/or state regulations and guidelines; state environmental regulation limits; insufficient guidelines; more rigorous emissions regulations; changing properties of CCPs	AK, GA, NH, OH, PA
Specifications	Limits on substitution of CCPs for portland cement limit amount used	IA
Storage	Lack of silo storage space	WA

CHAPTER NINE

DOCUMENT ASSESSMENT SURVEY RESULTS

A total of 144 documents were located and reviewed. Figure 16 indicates parts of the world conducting the research identified in this search. The literature search results followed the trends seen in the agency responses. Cement, PCC, and geotechnical applications were the main highway application categories where coal combustion byproducts were researched. Conventional concrete, soil stabilization, and embankments were the specific applications with the most information (more than 50 documents with information). Both bound (cement and PCC) and unbound (soil stabilization, flowable fill, fill material, and embankments) applications or uses can be produced using coal combustion byproducts. The documents showed that a much wider range of potential highway applications have been evaluated, primarily in laboratory settings with some field work.

The agency survey results that indicated the current use of coal combustion byproducts in highway applications showed the most use was in PCC applications (Figure 17). The literature reported a significant number of research projects supporting these applications. Geotechnical applications were used less frequently by agencies; however, a significant amount of research focused on these applications. The volume of researched highway applications using coal combustion byproducts is shown in Figure 18. This figure also compares the number of documents found in the literature and the reported applications used in the United States. Although the magnitude of the numbers is different, the trends of most researched/most used to least researched/least used were consistent. The most researched and used application category is geotechnical applications, followed by PCC applications. There was only a limited interest in HMA or pavement preservation applications.

LIST OF CANDIDATE BYPRODUCTS

Coal combustion byproducts used in highway applications come from one of three places in the power plant operation and include bottom of the boiler, flue gases, and sulfur removal systems. Variations in the equipment result in three types of boiler bottom byproducts:

- Bottom ash from dry-bottom boilers,
- Boiler slag from wet-bottom boilers, and
- FBC from new technology for boilers.

Both bottom ash and boiler slag byproducts have been used for a number of years in various highway applications. The FBC boiler technology has only recently been used in power plants so there is little history of use for this byproduct.

The particulates are removed from the exhaust stream, resulting in two commonly used types of fly ash (Type C and Type F). The main differences between Type C and F are in the lime content.

Sulfur removal systems were added to power plants to minimize the impact of coal burning on acid rain environmental problems in the late 1970s. These systems were added at the back end of the coal burning systems and resulted in a type of synthetic gypsum as a byproduct. This byproduct is usually used in the manufacture of wallboards.

Historically, the byproduct removed from power plants has been reasonably consistent over the years of coal burning power production. However, as processes and technology advance, the physical and chemical properties of each of the byproducts change. If landfilled sources of these byproducts are considered for use in highway applications, then care needs to be given to the type of plant technology in use at the time the particular byproduct was landfilled.

TEST PROCEDURES

A number of test methods associated with the testing of coal combustion byproducts and highway applications in which they were used are listed in Table 45. Testing of these byproducts focused on determining leaching characteristics and byproduct chemistry. Testing for using these byproducts in highway applications evaluated specified properties of virgin soils and aggregates, then compared these properties for the byproducts to existing material requirements.

Previous in-depth research into agency specifications indicated that most of the specifications for these byproducts were found in Federal Lands documents. The majority of standardized test methods used were found to be either ASTM or AASHTO standards.

MATERIAL PREPARATION AND BYPRODUCT QUALITY CONTROL

A summary of material preparation and quality control (QC) issues includes:

FIGURE 16 General locations of CCP research documents (stars indicate countries conducting research).

- Increased variability in the physical and chemical properties of the byproducts can increase the need for additional testing for QC.
- Few byproduct QC procedures were found, although the need for verification of physical and chemical properties can be found throughout the literature because of the dependency of the byproducts on coal source and power plant equipment configuration.
- There is a lack of byproduct specifications for purchasing material. This limits the ability of the agency to evaluate QC/quality assurance (QA) programs.

MATERIALS HANDLING ISSUES

A summary of materials handling issues for coal combustion byproducts includes:

- Byproducts from different sources need to be kept separate because the physical and chemical properties are dependent on the coal source used by each power plant.
- Leaching can be a concern and coal combustion byproducts need to be stored so that ground-water contamination is prevented.
- FBC solidifies when water is added. This will be a material stockpiling issue that needs to be addressed. It is possible that some highway applications would need to have a covered storage area.
- Depending on the highway application, an extra storage silo may be needed.
- Fugitive dust control needs to be considered when handling the byproducts.

TRANSFORMATION OF MARGINAL MATERIALS

There has been a limited amount of laboratory research into using a combination of fly ash and FGD (synthetic gypsum), combined by disk pelletization using moderate temperatures to cure the resulting pellets, to form aggregates.

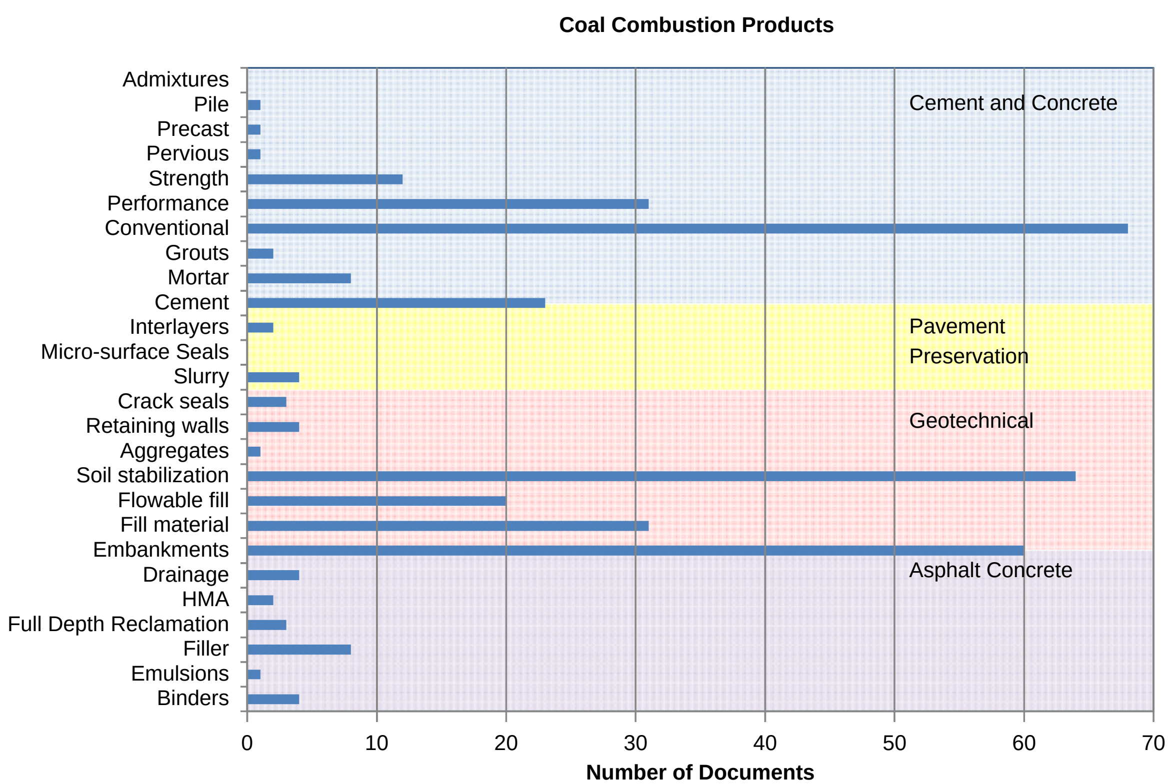


FIGURE 17 Documented information for highway applications using coal combustion byproducts.

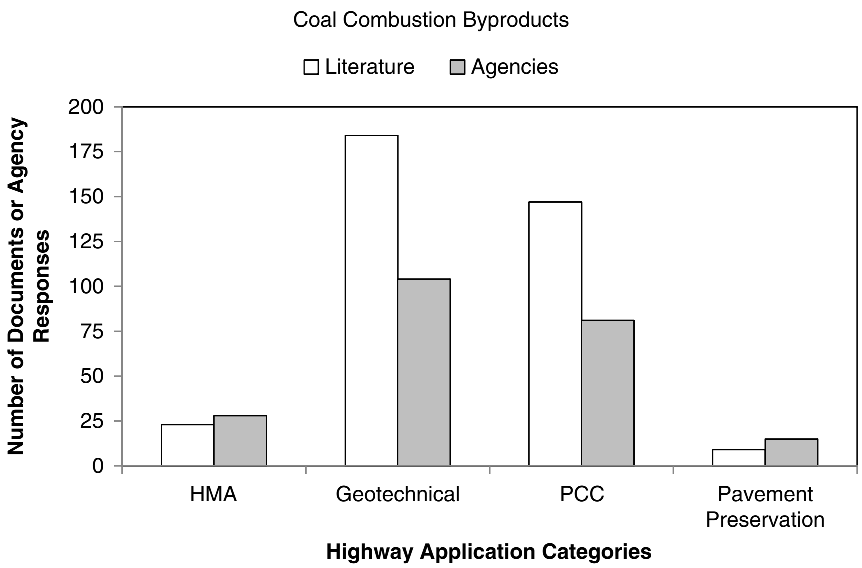


FIGURE 18 Comparison of the number of documents and agency responses for uses of coal combustion byproducts in highway applications.

TABLE 45
TEST METHODS USED TO EVALUATE COAL COMBUSTION BYPRODUCTS IN HIGHWAY APPLICATIONS

Test Method	Title
AASHTO M295	Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete
AASHTO PP56	Evaluating the engineering and environmental suitability of recycled materials
AASHTO PP59	Coal combustion fly ash for embankments
ASTM C535	Standard test method for resistance to degradation of large size coarse aggregate by abrasion and impact in the Los Angeles machine
ASTM C88	Standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate
ASTM C90	Standard specification for load-bearing concrete masonry units
ASTM C117	Standard test method for materials finer than 75-um (No. 200) sieve in mineral aggregates by washing
ASTM C136	Standard test method for sieve analysis of fine and coarse aggregates
ASTM C331	Standard specification for lightweight aggregates for concrete masonry units
ASTM C618	A standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete
ASTM D854	Standard test methods for specific gravity of soil solids by water pycnometer
ASTM D698	Standard test methods for laboratory compaction characteristics of soil using standard
ASTM D2922	ASTM D2922-05 standard test methods for density of soil and soil-aggregate in place by nuclear methods (shallow depth) (withdrawn 2007)
ASTM D4643	Standard test method for determination of water (moisture) content of soil by microwave oven heating
ASTM D6951	Standard test method for use of the dynamic cone penetrometer in shallow pavement applications
ASTM D3987-06	Standard test method for shake e-traction of solid waste with water
ASTM E2201	Standard terminology for coal combustion products
ASTM E2277	Standard guide for design and construction of coal ash structural fills
EPA SW-846 Method 1311	Test methods for evaluating solid waste, physical/chemical methods
EPA SW-846 Method 1310	Test methods for evaluating solid waste
EPA SW-846 Method 1320	Test methods for evaluating solid waste
EPA SW-846 Method 1312	Test methods for evaluating solid waste
EPA SW-846 Method 3050	Test methods for evaluating solid waste
EPA SW-846 Method 3051	Test methods for evaluating solid waste
EPA SW-846 Method 3052	Test methods for evaluating solid waste

DESIGN ADAPTATIONS

No design adaptations were documented in the literature. The main focus of research and applications to date has been to use these byproducts as substitutes for virgin materials, using the existing materials, design, and construction specifications. Alternatively, options that may be less restrictive were used with the byproducts. For example, bottom ash is more likely to be used in cold mix emulsified mixes, which have less restrictive requirements for gradation and durability than conventional HMA (Kalyoncu 2000).

When using coal combustion byproducts in embankments, the slope stability of blends met requirements when heights were less than 20 m with a horizontal to vertical ratio of 2:1 or flatter with a factor of safety higher than 1.3. Compaction was important to achieving the design requirements (Kim et al. 2005)

SITE CONSTRUCTION ISSUES

Construction issues that are to be considered include:

- Monitoring wells for water quality when using byproducts in fill applications.
- HMA QC/QA was likely to have to deal with a larger variability in in-place density when using these byproducts.
- Extra testing and monitoring of the optimum moisture content was needed when using byproducts in stabilized soils.

FAILURES, CAUSES, AND LESSONS LEARNED

No specific failures were identified in either the literature review or the survey responses. However, several comments were made that indicated difficulty in constructing projects:

- Additional testing was needed to account for byproduct variability in such specified properties as HMA density and achieving needed support from stabilized soils owing to inconsistent optimum moisture contents.
- Nonuniformity of the physical and chemical byproduct properties was a problem with achieving the desired application properties.
- Type C fly ash in PCC applications resulted in problems with durability of the concrete.

BARRIERS

Barriers found in the literature and agency survey responses included:

- Inconsistent federal and state regulations,
- Insufficient environmental guidelines,
- Lack of locally available physical and chemical property data for locally available byproducts,
- More rigorous emissions regulations that result in changes to the byproduct properties,
- Lack of byproduct homogeneity,
- Additional testing required to control the quality of the application resulting from the byproduct variability,
- Complicated and rigid EPA regulations,
- Potential designation as a hazardous material by the EPA,
- Transportation costs as a result of haul distances,
- Limited data on environmental and health effects,
- Byproducts not always economically competitive with virgin materials,
- Limitations on the percentage of allowable substitution of byproduct for virgin material (e.g., fly ash for cement), and
- Inadequate silo storage space.

COSTS

Only limited cost information was found in the literature, including:

- Power plant owners approached valuing lower value byproducts with a “cost avoidance” philosophy. The lower the market value of the byproduct, the less likely the plant owner will be to spend money on improving quality and consistency.
- Power plants without their own captive landfills had a higher economic incentive to find markets for byproducts. Typical plant landfill costs range from $3 to $15/ton for plants with captive landfills, which increases to $10 to $35/ton without landfills.
- Transportation costs limited the use of byproducts to local projects.
- Agencies and contractors had increased testing costs because of increased efforts needed for QC/QA.
- Little was found in the literature with regard to changes in construction costs.

GAPS

The most readily identifiable missing information in the literature and agency responses included:

- Consistent environmental guidelines,
- Byproduct specifications for physical and chemical properties,
- Environmental testing programs for byproduct assessment,
- QC/QA programs for applications using byproducts,
- Economic and environmental cost information, and
- Assessments of recyclability at the end of the service life of the application (i.e., sustainability).

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APPENDIX A

Agency Responses to Performance, Environmental, and Barrier Questions

TABLE A1
AGENCY RESPONSES TO OPEN ENDED QUESTION ON COMBUSTION ASH

State	Performance	Barriers
AK	OK	Lack of guidelines and research
AL	PCC routinely uses Type C & Type F fly ash and has been shown to increase performance. Type C and Type F fly ash are also routinely used in our stone matrix asphalt mixes.	
AR	Structural and paving concrete have performed well when fly ash is used as substitute (up to 20% by weight) for Type I cement.	
AZ	We have been utilizing Class F fly ash in PCC for many years with much success. I am not aware of any adverse affects due to the fly ash. Our specifications allow for both Class C and F; however, we have not seen any mix designs submitted using Class C.	
CO	The Type C and F fly ash are performing well. CDOT has incorporated the applicable AASHTO standards and tests for these products.	Some products are not produced in large enough quantities for practical use.
DC	We have experienced compressive strength problems in the past	No barriers
DE	No performance issues	Consistency with the fly ash in concrete applications
GA		Environmental regulations in our state limit the use of combustion ash. The demo project we are doing needed a special environmental approval and waiver.
HI		Availability, quality concerns, and cost
ID	We are using fly ash for ASR mitigation.	Not enough experience.
IL	Our biggest use for fly ash (either C or F) is as ASR mitigation in PCC mix designs. Both perform very well for this use.	
IN	Our experience with these products has been very positive and they are used routinely when available.	
IA	Performance tracked for PCC only. No problems.	Limits on cement substitution will always exist.
KS	It's permitted within HMA, but not used by contractors.	
KY	Concerning its use in embankments and stabilized soils, fly ash is a byproduct that works successfully when the optimum moisture content is maintained. In our experience, moisture contents no higher than the optimum value and no more than 2% below the optimum value are necessary for successful performance. Concerning HMA, Kentucky has attempted to utilize Type F fly ash in two SMA projects. One job was successful, and the performance of that SMA pavement has been satisfactory. Another SMA project was not successful. The volumetric properties of the SMA containing the fly ash were extremely inconsistent and, ultimately, the fly ash was not permitted as mineral filler in the SMA. Types C and F fly ash have provided acceptable results in flowable fill and PCC in Kentucky.	Concerning fly ash for embankments and stabilized soils; as mentioned previously controlling the moisture content is critical. Also, erosion control for embankments and stabilized soils containing fly ash is of the utmost importance. Concerning its use in HMA (specifically SMA in Kentucky), the spherical shape of the fly ash particulate seems to create issues within the equipment used to deliver the material into the asphalt mixing plant. The fly ash does not appear to "flow" into the asphalt mixing plant consistently. Regarding the use of Types C and F fly ash in PCC, Kentucky has experienced some environmental, durability, and aesthetic (staining) concerns.

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TABLE A1
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LA	Types C & F fly ash have been used successfully in PCC for several years.	Potential for alkali reactivity with certain aggregates with Type C ash.
MA	Fly ash & slag in concrete has worked well.	Still not sure of application value in other areas of transportation projects.
MD	Fly ash was used (late 1990) as fill embankment in one state project, all observations indicate that the embankment is stable and monitoring wells did not show any changes in ground water. MDE is investigating further. The fly ash was used as subgrade stabilization for a few projects in Maryland.	We need additional information to know more about the short- and long-term performance of these materials before using for highway projects.
ME	Used to reduce permeability of concrete—good performance	
MN		Long-term environmental concerns with unbound applications. Will it move? How far? What stuff moves in which type of soil?
MO	No problems with performance. Fly ash stabilization is viewed as a construction-only treatment not for the life of the overlying pavement.	Hazardous material leaching perceptions Stability of ash fills
MO	No loss in performance due to these materials.	Literature suggesting hazardous material content. Abundance of natural resources hinders cost-effectiveness of hauling too far from the source.
MS	Standard Type C or F fly ash replacement of cement is widely used in Mississippi to enhance the placement and in-place properties of concrete. The performance of concrete containing standard fly ash is very good.	Because combustion byproducts are "byproducts" there can be chemical and physical variations in the products due to changes in the combustion process. When looking at these materials as an engineered material that can sometimes be problematic.
NC	Performance problems not noted	Source proximity to construction site (transportation cost)
ND	Fly ash is used extensively in PCC pavements with good success.	Some of the products are not produced locally. Cost to ship in from other states.
NE	Type F fly ash is necessary in our PCC to mitigate ASR. Type C fly ash has worked well for our soil stabilization process.	Type F fly ash is changing and/or becoming less available.
NH	We commonly use Type F fly ash in our concretes and it performs satisfactorily. We allow for Type C fly ash in our specs, but it is not used. We have experimented with coal fly ash in flowable fill and I am not sure what the result of that was.	We are investigating using bottom ash for embankment. A manufacturer has approached us about seeing if there is a use for the particles that are too fine for use as blasting/grinding materials. We are testing the engineering properties of the particles. We can use them as long as it is not in a residential situation.
NJ	Boiler slag is not as good an embankment material (less stable) than virgin aggregate or recycled concrete aggregate. The Type F fly ash is used to mitigate ASR (alkali–silica reactivity) in PCC and has performed well.	With MSW concerns on possible contaminants makes this product impossible to use in our state.
NV	NDOT has experienced good performance using Type F fly ash in PCC.	Limited availability of other products in the geographic area
NY	NYS uses Class F fly ash, GGBFS, and silica fume. These products are used to enhance PCC performance as a part of high performance concrete mixture designs.	Variable quality of some materials makes uniform PCC production difficult.
OH	Fly ash (C and F) in concrete have been good performers, but have quality issues due to lack of ASTM controls for the product. We have limited experience with soil stabilization, but can work. Use in flowable fills has seemed to work reasonably well.	Costs versus natural materials. Correctly used there are often additional processing and control costs because of the non-uniformity of the byproducts and the additional oversight or unclear federal requirements for the materials. While government agencies push or even try mandates for use of byproduct materials, they don't actually define the additional controls needed or establish the environmental checks required. This leads to misleading information presented by suppliers and inconsistent environmental mandates from different arms of federal and/or state or even regional agencies.

TABLE A1
(*continued*)

PA	Type F fly ash has been used in PCC to mitigate ASR with good success. However, some fly ash results in low air contents in plastic and hardened PCC. Fly ash used in some soil stabilization (subgrade) projects and performance was satisfactory.	Clean, consistent product supply that translates into consistent performance. Stiffer emission regulations changing the characteristics of combustion byproducts.
SC	The use of fly ash is encouraged because it is believed to inhibit alkali–silica reactivity in PCC.	Supply, environmental concerns, lack of data on long-term performance
TX	Fly ash: Texas experience with Type C and F fly ashes, modified class F fly ash, and ultra-fine fly ash have been quite positive. In fact our standard specification for hydraulic cement concrete has 5 of 8 mix design options allowing some amount of cement replacement with fly ash. We have found that fly ash improves durability and can prevent or at least lessen the impact of alkali–silica reactivity. TxDOT Atlanta district has constructed six test pavements using hydrated fly ash as a base over a five-year period. All pavements have performed well, with only one pavement exhibiting a significant amount of distress, and that was in its eighth year of service. TxDOT has also been trying to use a combination of lime and Type F or GGBFS to mitigate the sulfate-induced soil heave problems. Bottom ash: HMA produced with bottom ash has performed well. When HMA is produced with bottom ash the optimum asphalt content (OAC) is generally greater than 6%, which produces a durable mix. The bottom ash stiffens the mixture, which makes it less prone to rutting and the high OAC produces a thicker film of asphalt and makes it less prone to cracking.	HMA: no significant barriers. Bottom ash makes the mix a little bit dry and a little harder to achieve the density. Type F fly ash can slow the heat of hydration of hydraulic cement concrete, but if considered in construction planning it is not an issue.
UT	Required to mitigate ASR in PCC	UDOT rarely requires formulation. Most of our specs are performance driven.
VA	Coal ash–PCC—In VA, contractors cannot use PCC unless a minimum of 25% of its content consists of fly ash. Type C and F fly ash—VA has had really good success in the use of these industrial products in embankments and PCC.	If coal ash needs to be stabilized by adding lime or cement sometimes crystal formations may grow that will cause problems if used near structures.
VT	Generally, we have had very good performance from coal ash and blast slag. Occasionally, variable LOI may be contributing to loss of air in the concrete. They are a principal agent in the fight against alkali–silica reactivity and required in all bridge decks in VT	Early strength requests by contractors routinely do not address longer-term strength gains. The cost savings is not realized because the pozzolans are supplementing cement rather than replacing—so, cementitious contents are high.
WI	Aiding fly ash allows the concrete to have more slump with the same quantity of water. Blending Class C with Class F fly ash is better than either Class C or Class F alone.	The higher the fly ash content the higher the scaling.
WA	Fly ash, micro silica, and GGBFS have all been allowed and used by WSDOT as alternative cementitious materials. The performance has been generally good.	Most barriers come from lack of availability, cost, and lack of silo storage space.

Abbreviations used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation