JV TASK 120 – COAL ASH RESOURCES RESEARCH CONSORTIUM RESEARCH

Final Report

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EXECUTIVE SUMMARY

The Coal Ash Resources Research Consortium® (CARRC®, pronounced "cars") is the core coal combustion product (CCP) research group at the Energy & Environmental Research Center (EERC). CARRC focuses on performing fundamental and applied scientific and engineering research emphasizing the environmentally safe, economical use of CCPs. CARRC member organizations, which include utilities and marketers, are key to developing industry-driven research in the area of CCP utilization and ensuring its successful application. The U.S. Department of Energy is a partner in CARRC through the EERC Jointly Sponsored Research Program, which provides matching funds for industrial member contributions and facilitates an increased level of effort in CARRC.

CARRC tasks were designed to provide information on CCP performance, including environmental performance, engineering performance, favorable economics, and improved life cycle of products and projects. CARRC technical research tasks are developed based on member input and prioritization. CARRC special projects are developed with members and nonmembers to provide similar information and to support activities, including the assembly and interpretation of data, support for standards development and technology transfer, and facilitating product development and testing.

CARRC activities from 2007 to 2009 included a range of research tasks, with primary work performed in laboratory tasks developed to answer specific questions or evaluate important fundamental properties of CCPs. The tasks were included in four categories:

1) Environmental Evaluations of CCPs
2) Evaluation of Impacts on CCPs from Emission Controls
3) Construction and Product-Related Activities
4) Technology Transfer and Maintenance Tasks

CARRC topical reports were prepared on several completed tasks:

- A Review of Literature Related to the Use of Spray Dryer Absorber Material: Production, Characterization, Utilization Applications, Barriers, and Recommendations

- Impact of Carbon Dioxide Capture on Coal Combustion Products (CCPs)

CARRC 2007–2009 accomplishments included:

- Determination of the interactions between fly ash leachate and mine spoil sediments through laboratory experiments.

- Organization and presentation of the Third Biennial Coal Ash Professionals Training Course.

- Development of characterization information on CCPs generated under mercury emission control demonstrations.

- Evaluation of the performance of Class C fly ash for mitigation of alkali-silica reactivity in concrete.

- Demonstration of the use of CCPs in sustainable construction applications.

- Participation in industry events and communication with CCP stakeholders.

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1.0 INTRODUCTION

The Coal Ash Resources Research Consortium (CARRC) has worked to advance coal combustion product (CCP) management and utilization since 1985 and is a key research program at the University of North Dakota (UND) Energy & Environmental Research Center (EERC). The CARRC research approach has always focused on performing research and technology transfer activities that address industry needs as defined by CARRC members. CARRC leverages industrial research dollars by matching them with funds from the U.S. Department of Energy National Energy Technology Laboratory (DOE NETL) through the EERC's Jointly Sponsored Research Program (JSRP). CARRC also provides an information and discussion conduit between industry and DOE NETL. For the past 24 years, CARRC partnerships have focused on the overriding CARRC goal of promoting the environmentally safe, technically sound, and economically viable management of CCPs.

CARRC provides a forum for members to discuss and identify technical issues that are currently impacting and/or are expected to impact the management of CCPs. To address these issues, CARRC members and researchers work together to develop CARRC tasks. The tasks can be categorized as follows:

- Member-prioritized research tasks
- Technology transfer and maintenance tasks
- Special projects

All tasks are designed to work toward achieving the CARRC overall goal and supporting objectives. The various tasks are coordinated in order to provide broad and useful technical data for CARRC members. Special projects provide an opportunity for non-CARRC members to sponsor specific research or technology transfer consistent with CARRC goals.

This report covers CARRC activities from January 2007 through March 2009. These activities have been reported in CARRC Annual Reports and in member meetings over the past 2 years. CARRC continues to work with industry and various government agencies with its research, development, demonstration, and promotional activities nearing completion at the time of submission of this report. CARRC expects to continue its service to the coal ash industry in 2009 and beyond to work toward the common goal of advancing coal ash utilization by solving CCP-related technical issues and promoting the environmentally safe, technically sound, and economically viable management of these complex and changing materials.

1.1 CARRC Industry Members

Those who have been CARRC members during the 2007–2009 period are gratefully acknowledged for their participation and cooperation in CARRC activities:

- Alliant Energy

- Ameren
- Duke Energy
- Great River Energy
- Headwaters Resources
- Indianapolis Power & Light Company
- Lafarge North America
- Otter Tail Power Company
- Tennessee Valley Authority
- TransAlta
- U.S. Department of Energy National Energy Technology Laboratory
- Xcel Energy

The following industrial groups and government agencies have also provided funding for CARRC special projects from 2007 through 2009:

- American Coal Ash Association, Inc. (ACAA)
- Ash Grove Resources
- Basin Electric Power Cooperative
- Boral Material Technologies, Inc.
- Charah, Inc.
- Electric Power Research Institute (EPRI)
- Energy Efficient Combustion Technology
- Great River Energy
- Headwaters Resources
- Holcim (U.S.) Inc.
- Lafarge North America
- Mineral Resources Technologies, Inc.
- Nebraska Ash Company
- North Dakota Industrial Commission
- North Dakota Lignite Research Council
- Pozzi-Tech, Inc.
- Salt River Materials Group
- Santee Cooper
- Separation Technologies, LLC
- Temple-Inland
- Theodore Roosevelt Medora Foundation
- DOE NETL
- Utility Solid Waste Activities Group
- WE Energies
- Western Region Ash Group
- Xcel Energy

CARRC also gratefully acknowledges Mr. Robert Patton, DOE NETL Project Manager for CARRC, and the CARRC industry advisors: Mr. David Goss, Executive Director, ACAA; and Mr. Ken Ladwig, Program Manager, EPRI.

1.2 CARRC Research Staff

The EERC's multidisciplinary approach to research is well demonstrated in CARRC research and related activities. CARRC has the opportunity to draw from the diverse research staff at the EERC while maintaining a core staff that focuses on CCP utilization and disposal research. Key to this approach is communication among numerous individuals and groups as well as the coordination of sample identification, collection, distribution, and data manipulation. The core EERC CARRC research group consists of the following individuals:

Debra F. Pflughoeft-Hassett, CARRC Program Manager
Tera D. Buckley, Market Research Specialist
Bruce A. Dockter, Research Engineer
Kurt E. Eylands, Research Geologist
David J. Hassett, Research Chemist
Loreal V. Heebink, Research Chemist
Erick J. Zacher, Research Geologist
Kari Lindemann, Research Information Associate
Janelle Hoffarth, Research Technician
Darren Naasz, Student Research Assistant

2.0 BACKGROUND

Since its inception in 1985, CARRC (called the Western Fly Ash Research Development and Data Center [WFARDDC] until 1993) has evolved in its goals and its activities as well as steadily increased its membership. From 1985 to 1993, CARRC (WFARDDC) was funded solely by industry sponsors and focused on the utilization of western fly ash primarily in cementitious applications with the primary goal to develop the best means of characterizing those materials to ensure their technically sound use in concrete, concrete products, and other cementitious applications. Those activities were reported in "A Database of Chemical, Mineralogical, and Physical Properties of Coal Fly Ash—A Research, Utilization, and Disposal Aid" (Pflughoeft-Hassett, et al., 1991). Key conclusions from that work were:

- Standard testing applied to coal by-products provides mainly empirical information that is incomplete and can be scientifically misleading as well as misleading in engineering applications and research regarding these highly complex materials.

- Mineralogical characterization of crystalline phases provides a means of identification and quantification. This must be included as a part of a complete characterization scheme for coal by-products in addition to the nominal bulk chemical analyses and physical tests. In addition to these tests, a determination of the leaching characteristics should also be included.

- Chemical interactions between mineralogical phases within the coal by-product or other materials it may contact during utilization are key to understanding the engineering properties and chemical behavior of these materials.

- The scientific experience gained through this study of coal by-products has direct applicability in the development of coal by-products generated from emerging clean coal technologies. Protocols for the complete characterization of coal conversion solid by-products have been developed and await new materials.

CARRC activities from 1993 to 1998 included a variety of research tasks, with primary work performed in laboratory tasks developed to answer specific questions or evaluate important fundamental properties of CCPs. The results of those tasks were summarized in a report to DOE NETL and CARRC members (Pflughoeft-Hassett, D.F. et al., 1998). The tasks described in that report were 1) the Demonstration of CCP Use in Small Construction Projects, 2) Application of CCSEM (computer-controlled scanning electron microscopy) for Coal Combustion By-Product Characterization, 3) Development of a Procedure to Determine Heat of Hydration for Coal Combustion By-Products, 4) Investigation of the Behavior of High-Calcium Coal Combustion By-Products, 5) Development of an Environmentally Appropriate Leaching Procedure for Coal Combustion By-Products, 6) Set Time of Fly Ash Concrete, 7) Coal Ash Properties Database (CAPD), 8) Development of a Method for Determination of Radon Hazard in CCPs, 9) Development of Standards and Specifications, 10) Assessment of Fly Ash Variability, and 11) Development of a CCP Utilization Workshop. Key results for 1993–1998 were:

- Updating the CAPD to a user-friendly database management system and distributing it to CARRC members.

- ASTM International (ASTM) standard preparation for a guide to using CCPs as waste stabilization agents.

- Identification of specific mineral transformations resulting from fly ash hydration.

- Determination of the effects of fly ash on the set time of concrete.

- Statistical evaluation of a select set of fly ashes from several regional coal-fired power plants.

- Development and presentation of a workshop on CCP utilization focused on government agency representatives and interested parties with limited CCP utilization experience.

CARRC activities from 1998 to 2007 included a range of research tasks, with primary work performed in laboratory tasks developed to answer specific questions or evaluate important fundamental properties of CCPs. The results of those tasks were summarized in a report to DOE NETL and CARRC members (Pflughoeft-Hassett, D.F., 2008).The tasks summarized in that report were 1) Standards Development, 2) Determination of the Rate of Hydration and Reaction Products, 3) Assembly of NORM Data on CCPs, 4) Mercury Issues Related to CCP Utilization, 5) Evaluation of Fly Ash and Fly Ash Sorbent Blends for Mercury Release and Utilization Potential, 6) Use of CCPs in the Management of Feedlot Wastes, 7) Technical Evaluation of Rammed-Earth Products, 8) CCPs from Combustion of Coal with Other Fuels, 9) Buyer's Guide to Coal-Ash Containing Products, 10) Development of Beneficial Use Policy for Bottom Ash, 11) Evaluation of Coal Fly Ash Variability, 12) Comparison of Available Swell/Expansion Tests and Development of an

Expansion Test for CCPs, 13) Handling and Use of Wet and Dry FGD Material, 14) Utilization of Sulfite-Rich FGD Material, 15) Review of Literature on Spray Dryer Absorber Material, 16) Environmental Performance of CCPs, 17) Evaluation of Current Leaching Procedures, 18) Characterization of Ammoniated Ash, 19) FlexCrete Feasibility Study, 20) Sediment Attenuation Effects on Coal Ash Leachates, 21) Freeze–Thaw Study, and 22) Education and Training.

CARRC topical reports were prepared on several completed tasks:

- The Impact of Ammonia on the Leaching of Selected Constituents from Coal Fly Ash
- Review of Handling and Use of Wet and Dry FGD Materials
- Use of Fly Ash and Bottom Ash in Rammed-Earth Construction
- Comparison of Dry Scrubber and Class C Fly Ash in Controlled Low-Strength Materials (CLSM) Applications
- Evaluation of Variability of Coal Fly Ash from Midwestern Utilities
- Feedlot Stabilization Using Coal Combustion By-Products: An Annotated Bibliography
- Buyer's Guide to Coal Ash-Containing Products
- Turtle Mountain Band of Chippewa Flexcrete™ Production Market Feasibility Study
- Naturally Occurring Radioactive Materials in Coal Combustion By-Products

CARRC 1998–2007 accomplishments included:

- Development of several ASTM Standard Guides for CCP utilization applications.
- Organization and presentation of training courses for CCP professionals and teachers.
- Development of online resources including the Coal Ash Resource Center, Ash from Biomass in Coal (ABC) of cocombustion ash characteristics, and the Buyer's Guide to Coal-Ash Containing Products.
- Development of expanded information on the environmental performance of CCPs in utilization settings.
- Development of information on physical properties and engineering performance for concrete, soil–ash blends, and other products.
- Training of students through participation in CARRC research projects.

- Participation in a variety of local, national, and international technical meetings, symposia, and conferences by presenting and publishing CCP-related papers.

While the initial focus of CARRC was to develop a database of information on coal fly ash, the perspective of members and researchers changed when the CAPD became a research tool and no longer the primary research effort. The success in developing the CAPD through the CARRC team effort provided impetus to expand the activities performed, to include member-driven research tasks that required practical input from members and the technical expertise of CARRC researchers using the available university facilities. CARRC membership has remained relatively constant, with industrial members primarily concerned with the marketing and utilization of moderate- to high-calcium fly ash. These members have facilitated the development of significant information on fly ash chemistry, especially as it relates to the mobility of fly ash constituents on exposure to water, the hydration reactions of moderate- to high-calcium fly ash to improve the understanding of the performance of fly ash in utilization applications, comparative performance of a range of fly ash samples in numerous construction and engineering applications, and the best methods of testing and analyzing CCPs for accurate and reproducible results that are scientifically valid and legally defensible.

In recent years, an emphasis on information transfer has been added to the CARRC priorities in response to member and industry input. It was evident to CARRC members and researchers that technical reports alone did not meet the need for information dissemination. CARRC researchers needed to present results of CARRC activities in a variety of formats and levels of detail. Many current CARRC technology transfer activities are informal and include providing documents and/or verbal comments to government agencies, end users, citizen groups, students, and other interested parties. The EERC Web Site has encouraged many interactions about CARRC activities and general information on CCPs.

CARRC members and researchers have progressed together technically but have also jointly developed an understanding of the layers of social, regulatory, legal, and competition issues that impact the success of CCP utilization in a generic sense and with regard to specific projects and applications of significance to a single CARRC member. CARRC researchers and members feel confident in their ability to answer technical questions about CCP utilization that may be posed by potential users, regulators, and environmentalists. Technical research on CCPs is truly successful if it facilitates CCP utilization that meets the performance criteria of the customer. These criteria can include environmental performance, engineering performance, favorable economics, and improved life cycle of products and projects. Members bring to CARRC questions from their daily interactions with customers, end users, and the public. Technical research tasks are developed to address these questions, and members select annual activities by a prioritization ballot. This process limits the number of research tasks annually, but the selected tasks are of highest member priority or need. As stated earlier, CARRC researchers work to make results of technical tasks available to the group or individual who originated the question about CCP utilization.

DOE is a partner in CARRC through the EERC JSRP, which provides matching funds for industrial contributions and increases the level of effort in CARRC. In addition to providing funding, a DOE representative is invited to provide input to technical tasks and other activities. This input is valuable in providing a broad perspective from a federal agency. CARRC DOE representatives have also indicated that interaction with industry representatives provides perspective that is helpful relative to other DOE project areas and interests. DOE participation has been positive for CARRC and for the CCP industry in general.

3.0 OVERALL CARRC RESEARCH OBJECTIVES

The overall goal of CARRC is to promote the environmentally safe, technically sound, and economically viable management of CCPs. Supporting objectives are the following:

- To develop information on the environmental and engineering performance of CCPs in products and utilization applications.
- To develop scientifically valid characterization methods specific to CCPs as needed to support utilization of CCPs.
- To develop information on technologies that impact the production, collection, and management of CCPs and related materials generated by coal-based power generation facilities.
- To develop, test, and demonstrate products and processes for CCPs.
- To communicate with CCP industry stakeholders to disseminate information gained under CARRC and to educate students, educators, government officials, CCP users, CCP industry professionals, and the public.

4.0 2007–2009 TASKS AND ACCOMPLISHMENTS

CARRC tasks included work to evaluate the physical and engineering performance of CCPs related to use in multiple products; to evaluate and understand the environmental performance of CCPs in a variety of utilization applications and settings; to provide information to CARRC members, government agencies, and other industry stakeholders; and to educate and inform the industry, government, and the public.

4.1 Environmental Evaluations of CCPs

4.1.1 Evaluation of Leaching Procedures

This task was initiated prior to 2007, but continued into 2007–2008. The goal of this task was to work with other organizations to perform an informal interlaboratory comparison of common leaching techniques.

Leaching of CCBs using various batch laboratory methods has been performed under numerous CARRC and EERC projects, and it was determined that some common leaching methods were not scientifically sound and did not produce valid data. Other research groups and government agencies have also begun to agree that existing leaching methods are not appropriate for CCBs, and discussions were initiated that raised questions regarding which leaching methods are appropriate and how to determine their appropriateness. As a result of these discussions, CARRC researchers and several other laboratories participated in a DOE NETL-led interlaboratory comparison of four leaching tests, including synthetic groundwater leaching procedure (SGLP) and long-term leaching (LTL). CARRC initiated its evaluation using two fly ash samples with different characteristics. Results of all laboratory efforts were shared with all participants, and CARRC results were included in a paper presented by the DOE NETL researchers.

It has been well documented that pH and alkalinity of any material, including CCPs, have an impact on the leaching profile of components in the material. The pH and alkalinity also have an impact on the reactions that drive the environmental and engineering performance of CCPs in many utilization applications and disposal settings.

During leaching studies in 2007, CARRC initiated an evaluation of pH development in order to better understand the leachability of constituents from fly ash. The study included multiple pH measurements at short (10 minutes) and long (24 hours) equilibration times using different solutions. Changes in pH over time were dramatic for some samples, with some samples exhibiting a near-neutral 10–15-minute pH, but after 24 hours of stirring, the pH increased to an alkaline value. For a more limited sample set, the pH decreased with time. Examples of pH data are shown in Table 1.

The pH development data provide an indication of reactions occurring on exposure to water. These include solubility of specific phases or coatings, hydration reactions, or uptake of carbon dioxide from the atmosphere. CARRC researchers have long used pH as an indicator of the need for long-term leaching with samples exhibiting pH >10, but these data indicated that it is important to allow the pH to reach equilibrium before making that determination. It was also clear that the presence of activated carbon (AC) had the potential to impact the pH development, and further work is planned to evaluate that impact.

In parallel with other CARRC tasks, the pH study also included evaluations of spray dryer absorber (SDA) materials and wet nonoxidized flue gas desulfurization (FGD) materials. The pH of all SDA materials fell within a narrow range (approximately 12.4) regardless of duration of equilibration or the presence of AC. The pH for these samples is primarily a result of the presence of

Table 1. Examples of Fly Ash Samples Exhibiting Significant pH Change over a 24-hour Period

ID No.	Sample Type	Coal Type	10–15-min pH	24-hr pH	pH Change	LOI,[a] %
05-040	Fly ash + AC (post-primary PCD[b])	Lignite	7.03	11.36	4.33	9.68
03-083	Fly ash	Eastern bituminous	4.75	9.00	4.25	1.20
06-001	Fly ash + AC (post-primary PCD)	Lignite	7.20	11.37	4.17	11.62
05-024	Fly ash + AC (post-primary PCD)	Lignite	7.43	11.41	3.98	9.45
03-004	Fly ash	Eastern bituminous	4.54	7.08	2.54	3.34
05-013	Fly ash + AC (post-primary PCD)	Lignite	9.00	11.33	2.33	13.24
04-006	Fly ash	Western bituminous	11.56	10.38	−1.18	1.42
02-072	Fly ash	Eastern bituminous	10.09	8.83	−1.26	5.29
02-070	Fly ash	Eastern bituminous	9.98	8.50	−1.48	5.87

[a] Loss on ignition.
[b] Pollution control device.

unreacted sorbent, which is present as calcium hydroxide. Wet nonoxidized FGD materials exhibited near-neutral pHs and did not exhibit changes with time.

4.1.2 Evaluation of CCP–Soil/Sediment Interactions

4.1.2.1 Sample Set 1

During 2007, preliminary sediment attenuation experiments designed to determine the capacity of a CARRC member-submitted sediment to attenuate select trace elements were performed. Batch experiments were set up incorporating two variables: ionic strength of the solution containing the select analytes chosen for inclusion in this research and liquid-to-solid ratio. Select analytes for this set of experiments were arsenic, boron, cadmium, chromium, mercury, lead, nickel, and selenium. The 72-hour batch experiments were carried out in which sediment and the selected solution were mixed using end-over-end agitation to achieve solution equilibrium. The sediment being used for this particular set of experiments contained reactive pyrite and thus formed sulfuric acid upon mixing with oxygenated water.

This process allowed the determination of distribution coefficients (K_d) between the sediment selected and the trace elements used. Although this is a generalization, the overall effect of sediment attenuation is often described as a K_d, although other mechanisms such as selective precipitation may be operating.

In these experiments, pH was important since the sediment being studied contained reactive pyrite, which produced sulfuric acid. The presence of sulfate, bisulfate, and sulfide could have a pronounced effect on the ultimate concentrations of both trace and major/minor constituents. Results of pH measurements at the end of the 72-hour equilibration time are shown in Table 2. The original sediment pH was 4.29 at 10–15 minutes and 4.03 at the end of 24 hours.

Because of the presence of reactive pyrite, it would be expected that the normal mobilization of certain cations might be negated by the presence of sulfide in the sample as indicated by the odor of hydrogen sulfide in the samples.

It can be seen from the results in Table 3 that there is an interesting trend in pH of solutions after a 72-hour equilibration time. The results which have been grouped to show this indicate that samples containing 100 grams of sediment had pH values consistently above those with 50 grams. Although it is not known for certain what caused this, it may be that the presence of excess sediment in the 100-gram examples used up available oxygen-producing sulfuric acid from pyrite while maintaining some acid neutralization capacity, thus maintaining a higher pH.

The trends in trace element attenuation by the sediment are much more difficult to explain because of the reactive nature of the sediment provided. In the formation of sulfuric acid from oxidation of pyrite, iron is first released and, at the pH values reached during the experiments, could form highly sorptive iron oxide–hydroxides. Additionally, the presence of sulfide can play a role in the attenuation of many heavy metals because of the formation of insoluble sulfides. In addition to

Table 2. pH of Samples at End of Equilibration Time (72 hours)

Sample	Unfiltered pH	Filtered pH
50 g/LIS[1]	4.51	4.55
100 g/LIS	4.91	5.39
50 g/HIS[2]	4.75	4.91
100 g/HIS	5.30	5.56

[1] Low ionic strength.
[2] High ionic strength.

Table 3. Results of K_d Determinations

Analyte	Sediment	0 g LIS	50 g LIS	50 g HIS	100 g LIS	100 g HIS
As	ND*	1.66	ND	ND	0.97	ND
B	ND	31.4	30.7	31	30.3	30.9
Cd	ND	5.00	2.85	3.18	3.36	2.68
Cr	ND	2.68	ND	ND	1.00	ND
Pb	ND	3.13	0.09	0.11	1.04	0.02
Ni	0.11	3.00	1.92	2.14	2.91	2.1
Se	0.006	1.200	0.106	0.121	1.030	0.268
pH	5.75		4.55	4.91	5.39	5.56

* Not detected.

the mechanisms described, natural mineralogical properties of the sediments would have played a role in capture of analytes in the attenuation process. These mechanisms were not evaluated because they were beyond the scope of the task.

Arsenic was nearly fully attenuated in all but one of the experiments, which was the 100 g LIS experiment. We have no explanation for this anomaly. In the other experiments, it is likely that the presence of sulfide could have played a role, as may have been true for selenium, which was attenuated to a large extent except in the same experiment. Chromium was highly attenuated except in the 100 g LIS experiment, which continues to produce puzzling results. Lead, which was highly attenuated in all but one of the experiments, was not removed to any extent in the 100 g LIS experiment. Cadmium was removed at 50% and slightly above in all of the experiments, again, possibly due to the formation of cadmium sulfide. Boron remained quite mobile in all experiments and would be expected to except in cases of highly alkaline material or in the presence of sediment or soil containing high amounts of organic material. Neither of these conditions existed in this set of experiments.

4.1.2.2 Sample Set 2

In continuing work in 2008, sediment attenuation experiments were performed using six mine site sediments from two mine sites (three from each site). The sediments were characterized as unconsolidated sediments, sandstone, and massive or fissile shales. The mine sites are located within the U.S. Environmental Protection Agency (EPA) Region 5.

Batch experiments were set up to evaluate trace element attenuation by the CARRC member sediments. Select analytes for this set of experiments were As, B, Cd, Cr, Pb, Ni, and Se. The liquid-to-solid ratios used were 50:1, 100:1, and a blank containing no sediment. The sample containers were rotated at about 30 rpm for 72 hours, allowed to settle for 1 hour, and then filtered through 0.45-µm filters. pH was taken on both filtered as well as unfiltered samples.

Hydrogen peroxide addition to the sediments was used because of its ability to determine the presence of acid-forming pyrite, usually present as framboidal pyrite, while avoiding the normal induction period required by pyrite in oxygenated water. Normally some time may be required before acid mine drainage is indicated while with peroxide this initial formation of sulfuric acid takes place much more rapidly. Results indicated no significant activity that would lead to the production of acidic leachate; thus reactive pyrites were not a consideration in the interpretation of results in these experiments. On treatment with dilute hydrochloric acid, two of the sediment samples appeared grey which was likely due to reduced iron (Fe^{2+}) while the other four were brown, indicating the presence of oxidized iron (Fe^{3+}).

Boron remained quite mobile in all experiments as would be expected except in cases of highly alkaline material or in the presence of sediment or soil containing high amounts of organic material. Neither of these conditions existed in this set of experiments so the lack of attenuation of boron was consistent with the nature of the materials evaluated. Cadmium attenuation was interesting, especially noting the difference between samples from Site 1 and Site 2. In samples from Site 1, the 100:1 loading of sediment produced a lesser attenuation as shown by higher concentrations of analyte, as would be expected. In samples from Site 2, a lower loading of sediment produced a lower concentration of analyte which is contrary to what one would expect. This could be an artifact of pH. These pH differences were not that great but yet could be a factor. Chromium produced the same sort of anomalous behavior as seen in Site 2 for cadmium. Lead concentrations decreased when more sediment was present except for the unconsolidated grey sediment from Site 1. Even in this case, it is difficult to determine what might have happened as the concentrations were quite low in both the high and low sediment loading. In all cases, more than half of the mercury was attenuated. This is consistent with the general affinity of mercury to stick to surfaces and be removed from solution. In these experiments, mercury was likely present in solution as $HgCl_4^{2-}$—the anionic form of Hg^{2+} in aqueous solutions with excess chloride ion. Nickel concentrations were anomalous with respect to the unconsolidated grey sediment from Site 1, but concentrations were higher with a lower sediment loading in all other cases. Selenium concentrations decreased to detection limits or near detection limits with sediments from Site 2 while attenuation with sediments from Site 1 was generally greater than 80% removal.

For this set of sediments, it was noted that all of the sediments provided some retardation or removal of outside analytes as leachate from an outside source moves through them. The chemistry-related mechanisms can vary but include the following:

- Precipitation and coprecipitation
- Sorption
- Ion exchange

In addition to removal through chemical processes, there is also the possibility for changes in concentration in natural systems related to several physical processes:

- Dispersion
- Diffusion
- Dilution

The important factor is that the sediment provided attenuation as determined through reduction of concentration of select analytes after exposure to two levels of each sediment for all of the elements tested with the exception of boron. This was to be expected since unless pH increases high enough (pH 11.5 to 12.5) to incorporate boron into secondary hydrated phases, it will usually remain quite mobile. Organic materials, however, can also attenuate boron, but this sediment contained little if any of this material. All other analytes exhibited significant attenuation of the included analytes. Exact mechanisms are difficult to determine but likely include sorption on amorphous iron oxide hydroxides which are difficult to directly identify but can be present at significant concentrations in brown-colored sediments as determined in previous research.

A paper was prepared for the World of Coal Ash conference scheduled for May 4–7, 2009, in Lexington, Kentucky, and submitted for review by the CARRC DOE Project Manager. The paper will be presented under CARRC 2009 activities.

4.2 Evaluation of Impacts on CCPs from Emission Controls

4.2.1 CO_2 Capture on CCP Management

CARRC researchers assembled references and performed an electronic literature search on the topic of carbon dioxide (CO_2) capture technologies with potential for use by coal-based power plants. CARRC researchers also met with researchers from the EERC Plains CO_2 Reduction (PCOR) Partnership to learn more about current activities related to CO_2 capture and sequestration.

The review of existing CO_2 capture technologies that might be used by coal-based power plants indicated that these technologies generally are not expected to impact fly ash quality. Strategies that might have an impact on fly ash or other CCP production are oxycombustion, the use of biomass fuels, and the selection of gasification over combustion for new electric generating facilities.

Some strategies to reduce CO_2 or facilitate CO_2 capture may have an impact on the characteristics or availability of ash, but it is anticipated that the greatest impact will be to fly ash because of the technical requirements of fly ash for use in high-value utilization as a cement replacement.

Use of oxycombustion to minimize CO_2 production could change the coal conversion, ash formation, and resulting fly ash mineralogy because of the elevated concentration of oxygen present in the combustion system. It is not likely that these changes would have a significant impact on fly ash quality or performance, although the quality and properties of the fly ash would need to be evaluated.

Biomass fuels are already being used by some coal-based power plants and could be used as a strategy to reduce the CO_2 emission impact of a power plant. It is important to note that biomass also produces CO_2 on combustion but that CO_2 is taken up by the plant during its growth, so the combustion of biomass is considered to be carbon-neutral. The utilization of biomass for large-scale power production has numerous issues, and it is not anticipated that coal-based facilities currently producing fly ash for the concrete market will use more than a small percentage of biomass fuels in the future. Both laboratory data and experience with fly ash from full-scale systems burning low percentages of biomass (<10%) indicate that fly ash from the coal–biomass blends has quality similar to that produced with the coal alone.

Coal gasification (integrated gasification combined cycle [IGCC]) may be selected for new electric generating facilities preferentially over combustion. The by-products from gasification generally include a slag, which has been shown to be valuable in cement manufacture, but no published literature has been found to indicate that it could be used in concrete as a supplementary cementitious material.

A CARRC member topical report providing more detailed information was prepared for and submitted to CARRC members and is included in Appendix A.

4.2.2 Mercury Emission Controls on CCP Environmental and Engineering Performance

Experimental work under this task included evaluation of fly ash collected under mercury emission control test conditions to assess the potential performance of the fly ash in concrete as it relates to the level of air voids that would be developed in the concrete. Air voids in concrete are needed to achieve good performance for concrete exposed to freeze–thaw conditions, and a large percentage of concrete placed in the United States is air-entrained. Air entraining is commonly accomplished by addition of chemical admixtures called air-entraining agents (AEA). AEAs can be sorbed onto unburned carbon, AC, and potentially other fly ash additives or sorbents used to capture or enhance capture of mercury. Unburned carbon and activated carbon have been shown to interfere with commercial AEAs, making them unavailable to facilitate the incorporation of air bubbles into the concrete mix. Laboratory foam index testing at the EERC and elsewhere has shown that AC, even in very small percentages, can have a drastic effect on the amount of AEA required to produce sustainable foam in cement–fly ash mixtures, which is indicative of performance in real-world concrete production.

A method to evaluate the performance of fly ash with AEA was developed, based on published literature. The procedure used follows:

- 8 g of cement is placed in a cylindrical weighing bottle.
- 2 g of sample is added to the bottle and mixed with the cement. No fly ash is added for the control.
- 25 mL distilled H_2O is added to the bottle, and the dry materials and water are shaken to blend. The mixture is shaken vigorously for 15 seconds.
- The mixture is observed, and if any foam is present, the stability of the foam is evaluated by its ability to be sustained for 45 seconds. If no foam is present or the foam dissipates prior to 45 seconds, the test is continued.
- AEA solution (10% solution [v/v] AEA-92) is added one drop (50 µL) at a time. Following each AEA addition, the mixture is shaken for 15 seconds, and the sample is observed as noted above. The end point is determined when the foam produced is sustained for at least 45 seconds.
- The control and samples were evaluated in triplicate.

The fly ash samples evaluated were from multiple sources including industry and research groups. Samples ranged from fly ash + AC to fly ash + noncarbon sorbents and sorbent enhancing agents. The specific identification of the materials is proprietary, but generic sample descriptions are included in Table 4 with foam index test results. The results clearly show that some fly ash–sorbent combinations would be suitable for use in concrete where AEAs are required based on comparison

Table 4. Examples of Foam Index Results

Sample	Sample Description	µL AEA (blank subtracted)	µL AEA (blank subtracted)	µL AEA (blank subtracted)	µL AEA (blank subtracted)
		Trial 1	Trial 2	Trial 3	Average
09-001	Fly ash + non-carbon sorbent	0	0	0	0
09-002	Fly ash + non-carbon sorbent	0	0	0	0
09-003	Fly ash + non-carbon sorbent	0	0	0	0
09-004	Baseline fly ash	0	0	0	0
09-005	Fly ash + carbon-based sorbent	100	100	100	100
09-006	Fly ash + carbon-based sorbent	200	200	250	217
09-007	Fly ash + carbon-based sorbent	350	300	350	333

of results from those samples and the baseline fly ash which exhibited behavior typical of fly ash with low unburned carbon content.

For follow-on work in 2009, CARRC researchers will continue to evaluate materials submitted for foam index testing, and as information is released on the sorbents, CARRC researchers will report that to CARRC members.

4.2.3 Sulfur Emission Control Materials

4.2.3.1 A Review of Literature Related to the Use of SDA Material: Production, Characterization, Utilization Applications, Barriers, and Recommendations

As a follow-on to laboratory evaluations of sulfite-rich FGD materials performed previously under CARRC, CARRC researchers completed a special project to assemble information on SDA materials worldwide, including the range of material composition and behavior and utilization applications for SDA materials.

The literature search, interpretation, and information assembly focused on calcium-based SDA materials. It was found that in the United States, SDA systems typically collect fly ash (40%–75%) and sorbent together, taking advantage of the alkalinity of fly ash and its sulfur dioxide sorbent capabilities resulting in compositional variability which was demonstrated by data from the literature review and laboratory work done by CARRC researchers. Physical properties and performance also varied significantly.

In the literature reviewed, a number of current commercial and potential uses of SDA material were identified, including agriculture, binders, cement manufacture, cement replacement in concrete, civil engineering, flowable fill, fixating agent for waste, marine applications, masonry, mineral wool, mining applications, soil stabilization, sulfuric acid production, synthetic aggregate, wallboard, and wet FGD sorbent. Many of the commercial uses are being implemented successfully in Europe but are slower to enter the marketplace in the United States. Potential uses in the research and development stage were rated as high-, moderate-, or low-potential commercial applications. High-potential applications for the U.S. market are estimated to be those that take advantage of the presence of the fly ash component of the SDA material, can tolerate relatively high sulfur content, and have limited susceptibility to expansion or reduce expansion potential in the production process. These applications fall into two categories: 1) cementitious products and 2) mining applications. The need for utilization options of SDA materials in the United States is expected to increase as the use of SDA systems is expected to grow over the next 10 years.

A final report on the project was also submitted in EPRI in September 2007. A topical report entitled "A Review of Literature Related to the Use of Spray Dryer Absorber Material: Production, Characterization, Utilization Applications, Barriers, and Recommendations" was prepared for CARRC members in October 2007. This report in included as Appendix B. A presentation summarizing the results of the EPRI task was made at the World of Coal Ash Conference held in Covington, Kentucky, May 7–10, 2007.

4.3 Construction and Product-Related Activities

4.3.1 Using Class C Fly Ash to Mitigate Alkali–Silica Reactions in Concrete

This project was added to the CARRC® after the original funding from the Combustion Byproducts Recycling Consortium (CBRC) was cut. There are eight contributing members to the alkali–silica reactivity (ASR) consortium: Holcim (US) Inc.; Nebraska Ash Company; Ash Grove Resources; WE Energies; Lafarge North America; Mineral Resources Technologies; Boral Materials Technologies, Inc.; and the Western Region Ash Group. These members have combined to submit 13 fly ashes and two cement sources. Ten of the fly ashes are Class C, and the other three are Class F. The fly ashes will only be referred to as FAC-1 through FAC-10 and FAF-1 through FAF-3. The fly ash blends and cement sources are identified as FABs and CEM, respectively.

The Class C fly ashes were evaluated for ASR, using the mortar bar method ASTM C1567 at cement replacement levels of 15%, 30%, 40%, and 50%. The Class F fly ashes were assessed at replacement levels of 15%, 30%, and 40%. The fly ash blends were tested at 20% and 35% replacement levels. With the second cement source fewer mixtures were developed. For this the Class C fly ashes were evaluated at cement replacement levels of 20%, 30%, and 40%. The Class F fly ashes and FABs were tested at 20% and 35%.

The results indicate that all ten Class C fly ashes helped to reduce the expansion of the mortar mixtures, even at the lowest replacement level of 15%. This was true for both sources of cement. This reduction in expansion continued at the remaining cement replacement levels with smaller reductions seen from the 40% to 50% replacement level. The Class F fly ashes reduced ASR expansion much better than the straight Class C fly ashes, as was expected. The fly ash blends also performed much better than the straight Class C fly ashes at similar replacement levels.

As originally designed, the future concrete work (ASTM C1293) will remain intact and begin after the mortar bar testing. Whether this concrete testing will be assisted with DOE support is not certain at this time. It will be completed with only industry support if necessary. A comparison of concrete ASR expansion to mortar bar ASR expansion was an important part of this project's original objectives.

A poster on this laboratory effort was presented at the 2009 World of Coal Ash Conference in May 2009. The final project report is included in Appendix C.

4.3.2 CCPs in Green Roadbuilding

North Dakota utilizes CCPs in a wide variety of construction and manufacturing applications and is a leader in the United States for its use of fly ash in concrete. The use of fly ash in concrete is one key use of CCPs that has been identified as environmentally sustainable because the replacement of cement with fly ash results in a reduction of CO_2 emissions related to the concrete produced. Environmentally sustainable or "green" construction technologies and products are currently being developed and demonstrated throughout the United States, including for roadbuilding. Green roadbuilding is an area where CCPs can contribute to efforts to preserve and protect the environment by aiding with storm water management, reducing the use of virgin materials, and aiding with conservation and protection of ecosystems.

The objectives of this project were to demonstrate environmentally sustainable (green) roadbuilding using multiple CCP utilization applications and, in the process, to educate North Dakota industry, state agencies, and the public about environmentally sustainable construction.

Working with the Theodore Roosevelt Medora Foundation, CARRC identified two construction sites for potential demonstration activities. These were parking and driving areas in close proximity to a historic hotel in Medora, North Dakota, and parking and driving areas associated with an outdoor amphitheater near Medora, North Dakota. Both sites had the potential to provide opportunities for various roadbuilding applications, including driving/walking surfaces and soil stabilization. Use of bottom ash for surface water runoff control applications such as rain gardens and use of fly ash in flowable fill were also considered, but neither site offered opportunities under existing construction plans for these applications. The amphitheater site was selected as the demonstration site because the construction activities could be completed within the project schedule, which was limited by availability of DOE NETL funding through the EERC with a deadline of March 31, 2009, and because it presented opportunities to perform several different types of CCP utilization.

The first green roadbuilding application selected was a combination of two different high-volume fly ash (HVFA) concrete paving applications. The HVFA concrete mixes selected included 50% and 70% fly ash concrete in walkways requiring 4-inch pavement and for driving and parking areas requiring 6-inch pavement. A plan for placement was developed with the project participants, and work was initiated and completed to prepare the site and place and finish the concrete. EERC representatives and the fly ash marketing company representative visited the site before and during placement and worked with the contractors to ensure the appropriate mixes were placed in the planned locations. The fly ash marketing company representative worked closely with the ready-mix supplier and finishing contractor to make modifications to the mix designs in order to facilitate ease of placement and finishing. Over the duration of the remainder of the project, the concrete surfaces were monitored. Some initial surface cracking was noted but was, in nearly all cases, attributed to physical locations that could not be avoided (pipes or other structures required on-site). One area exhibited cracking that was likely the result of hot, windy weather conditions during the placement and finishing periods. Again, this type of cracking is not necessarily directly attributed to the use of HVFA concrete. Continued monitoring of the noted minor defects indicated that these did not worsen over the duration of the project.

In a second phase of the project, use of fly ash for base and subgrade stabilization for the soils under additional driving and parking areas at the amphitheater was identified for construction to be performed during the 2009 and 2010 construction seasons. Work on engineering design was performed under this project to allow project engineers to become familiar with the use of fly ash in soil stabilization. Information on the use of fly ash was provided to a commercial engineering firm, and EERC staff worked with the firm to facilitate an understanding of equipment needs for placement, blending and compacting of fly ash-soil mixtures, additions of fly ash for various soil types, environmental requirements in the state of North Dakota, fly ash costs, fly ash delivery costs, and soil testing needs. Cost estimates of standard base and subgrade treatments, fly ash–soil stabilization and fly ash–recycled asphalt recycling were made, and results indicated that costs will be very similar for all types of base and subgrade preparation. Evaluations of the sustainability of soil stabilization technologies were performed and indicated that the sustainability of fly ash use is related to the distance of the source of fly ash to the construction site. The final project report is included in Appendix D.

4.4 Technology Transfer and Maintenance Tasks

4.4.1 ASTM Standards Development

The goal of the standards development activity was to enhance and promote the technically sound utilization of coal ash through development of technical standard guides or practices for technically proven ash utilization applications. Industry and government identified the development of standards such as this as a key component of efforts to advance the beneficial use of CCPs in the United States.

In 2007–2009, CARRC participated in the standard development activities of ASTM in ASTM E50 Committee on Sustainable Development and Pollution Prevention and ASTM C9.24 Subcommittee on Supplementary Cementitious Materials.

Under a special project funded by the Utility Solid Waste Activities Group, CARRC researchers worked to modify or develop the following standards within ASTM E50:

- Draft Standard Guide for The Use of Coal Combustion Products for Underground Mine Fill

- Draft Standard Guide for Selection of Appropriate Leaching Procedures for Coal Combustion Products

- Standard Guide for Use of CCPs for Surface Mine Reclamation: Revegetation and Mitigation of Acid Mine Drainage

- Standard Terminology for CCPs

Under a special project funded by Energy Efficient Combustion Technology, CARRC researchers initiated an effort within ASTM C9.24 to modify the definition of fly ash in ASTM C618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. Currently, the definition of fly ash under C618 disallows the addition of pre- and postcombustion additives and alternative fuels by coal-based power plants. This effort was developed to work within the various task groups under C9.24 to work toward acceptance of a definition of fly ash that more correctly reflects combustion practices by coal-based power plants that market fly ash for use in concrete.

Work under both of these special projects will continue separately under contract with the project partners noted.

4.4.2 Review of North Dakota Regulations, Standards, and Practices Related to the Use of CCPs

To better understand the status and development of different CCP utilization profiles across the United States, the EERC conducted a series of state reviews. The first was conducted in Texas in 2004, the second was in Florida in 2005, and the third was in Pennsylvania in 2006. Following the series of three state reviews, a synthesis report was prepared that transfers the findings into a national perspective. These state reviews were funded in part by EPA and DOE. Both agencies encourage other states to follow a similar statement of work to conduct additional state reviews under separate funding mechanisms.

With funding from the North Dakota Industrial Commission, Basin Electric Power Cooperative, Great River Energy, Minnkota Power Cooperative, and DOE NETL through CARRC, a fourth state review was conducted in North Dakota. A copy of the final report for this effort is included in Appendix C, and a summary of study findings is presented here.

CCPs are the largest solid waste stream generated in North Dakota. According to information obtained during the state review interview process, it was estimated that North Dakota coal-based power plants produce in excess of 8000 tons a day of CCPs (or nearly 3 million tons a year). It was further estimated that North Dakota coal-based power plants currently beneficially use about 40% (or 1.2–1.3 million tons) of CCPs produced a year.

Based on information obtained during the North Dakota state review process, the following items were identified as keys to successful CCP utilization in North Dakota and are discussed at greater length in the report:

1. Great River Energy has an established CCP utilization program at Coal Creek Station which sells nearly 500,000 tons of fly ash (~94%–95% of total production) each year. Many would agree that Coal Creek Station produces perhaps the best fly ash in the country with regard to quality and consistency of supply.

2. The North Dakota Department of Transportation (NDDOT) uses fly ash in almost all concrete projects at a replacement rate of 30%. Most DOTs specify a replacement rate between 15%–30% (if they specify fly ash use at all), making NDDOT's specification on the higher end compared to other states.

3. Fly ash is beneficially used as a key cementitious component by the North Dakota Public Service Commission (PSC) Abandoned Mine Land Division for grout filling of abandoned underground mine lands. Since 1995, PSC used 32,000 tons of fly ash in 28 grout applications. Mine grout is the only preapproved beneficial use application for fly ash in North Dakota.

4. Bottom ash is classified as an inert waste by the North Dakota Department of Health which allows it to be used without approval. In North Dakota, bottom ash is typically used in active mines as a road base and for ice control on public and private roads.

5. Boiler slag is also classified as an inert material. A local boiler slag processor and marketer sells about 125,000 tons of boiler slag a year.

The following were identified as barriers that currently hinder increased CCP utilization in North Dakota. Recommended actions are provided for each barrier.

1. All North Dakota coal-based power plants have a system in place or have plans to control sulfur dioxide (SO_2) emissions (Leland Olds Station is currently installing a SO_2 control system, and Milton R. Young Station Unit 1 will install a wet scrubber in 2011). The by-products produced are either SDA material mixed with fly ash or wet sulfite-rich material/sludge. These by-products are difficult to market because they are a low-value material, have limited use potential, and are not located within close proximity to markets. Currently, it is more cost-effective to dispose of the material; however, if high-value and high-volume applications were possible, electric generating companies may be more likely to pursue potential uses.

2. The primary objective of most electric generating companies is to produce electricity, not to make good-quality CCPs and market them (Great River Energy Coal Creek Station has successfully done both, but that is an exception in the state). Electric generating companies should also perform a cost–benefit analysis to determine what resources (i.e., staff, handling equipment) would be needed to improve CCP use to determine if it is a cost-effective ash management solution for the company.

3. The North Dakota Department of Health's *Guideline 11 – Ash Utilization for Soil Stabilization, Fill-In Materials, and Other Engineering Purposes* summarizes the department's approach to CCP utilization. The applicant must reasonably demonstrate

that the proposed use will not adversely impact the environment. Although the North Dakota Department of Health believes Guideline 11 clearly outlines the requirements for use, those requesting beneficial use applications indicated the guideline is too subjective. Potential CCP users should work with the North Dakota Department of Health in defining parameters (i.e., leaching method, pre- and postmonitoring). This collaboration could be facilitated through a state CCP program or consortium whose primary objective was to educate government agencies about CCPs. At a federal level, EPA could provide more guidance on what "beneficial use" is. A clear definition would be helpful to the North Dakota Department of Health in writing new or modifying existing guidelines.

4. NDDOT representatives interviewed did not see a need to explore nonconcrete beneficial use applications such as soil stabilization or flowable fill. Conversely, the ready-mix suppliers interviewed believed flowable fill is a major untapped market in North Dakota. Industry should approach all levels of NDDOT to demonstrate the engineering, environmental, and economic benefits of using CCPs in flowable fill applications. In addition, NDDOT could take a second look at the economics associated with using flowable fills containing CCPs.

5. Many North Dakota coal-based power plants do not have a quality assurance/quality control (QA/QC) plan for their CCPs. The implementation of a strict QA/QC plan is imperative for utilization in a variety of applications, especially concrete.

6. With the exception of Green River Energy's Coal Creek Station, North Dakota coal-based power plants have transportation and distribution infrastructure issues that make it cost-prohibitive and difficult to transport CCPs to major markets outside of the state. Management at coal-based power plants should evaluate the cost–benefit ratio of improving the CCP distribution infrastructure at their plants. Local markets should also be explored.

7. Greenbuilding initiatives have not gained widespread acceptance in North Dakota from a consumer or regulatory standpoint. Since consumers are not yet pulling the greenbuilding market in North Dakota, it is recommended that approaches to push greenbuilding by government be promoted by industry. CCP industry stakeholders should work with state and national building entities to market the benefits of using CCPs in building materials. Government policy makers should also be encouraged to make greenbuilding a priority.

8. The North Dakota Department of Health's primary focus is to ensure solid wastes are properly disposed of. Because the department is focused on disposal, it was believed the North Dakota Department of Health does not have the resources (i.e., time, knowledge) needed to effectively evaluate new CCP beneficial use applications. Also, once a beneficial use rule is in place, the North Dakota Department of Health does not appear to have any mechanisms in place to encourage use. To encourage preapproved CCP beneficial use applications, the North Dakota Department of Health should have a list of preapproved uses on its Web site and provide access to appropriate checklists. An industry-led group could be effective in assisting the North Dakota Department of Health in education and information dissemination.

9. Ready-mix suppliers interviewed indicated the national commercial concrete market is usually the most difficult consumer group to work with to encourage CCP use. Often, the national company would give an overly prescriptive mix design that the ready-mix supplier believed would benefit from a higher percentage of replacement of fly ash, but the national company would want to stick with its design. Education is key to overcoming this barrier.

10. Fly ash use in the local concrete markets is saturated, so other high-value road-building and construction applications should be explored such as flowable fill, backfill, and road base applications.

11. Some coal ashes from coal-fired industrial boilers do not have the cementitious or pozzolanic properties that coal ashes from coal-fired power plants have and, therefore, will not exhibit the same physical performance in applications such as soil stabilization or flowable fill. There have been instances where industrial coal ashes physically failed in an application and subsequently created a public perception problem for coal ashes from coal-based power plants that are well suited for these uses.

The following potential threats were identified that could hinder CCP utilization in North Dakota in the future:

1. Most North Dakota coal-based power plants will meet 2010 mercury emission regulations (Clean Air Mercury Rule) as they currently operate but will likely need to implement new controls to meet 2018 requirements. The North Dakota Department of Health is concerned about how new mercury emission controls will impact CCP utilization and disposal. The North Dakota Department of Health has not evaluated by-products from plants with mercury emission controls; therefore, regulating the materials' use or disposal is new territory (as will be the case for other state health departments).

2. New CO_2 regulations are expected, but the potential for impact on CCPs is not clear.

4.4.3 Workshops and Training Courses

CARRC researchers developed and presented workshops and short courses on specific topics of interest to CARRC membership, government, and related industries.

4.4.3.1 *Coal Ash Professionals Training Course*

In 2008, CARRC organized the third biannual Coal Ash Professionals Training Course (CAPTC). An Introductory Workshop on CCPs was added as an optional component for the first time. CAPTC and the workshop were held in San Antonio, Texas, March 11–13, 2008.

The Introduction to CCP Production Management Workshop was a first for the CAPTC and had an attendance of 24 individuals. This half-day session was designed as a separate workshop for individuals who are new to the industry or have limited knowledge/experience in CCP production and management. A bus tour of CPS Energy's JT Deely and JK Spruce Power Plants was offered as an optional event for those not attending the introductory workshop.

Course instructors for the CAPTC included established ash managers and marketers, industry consultants, members of the academic and research community, and government representatives. The 2008 training course attracted a total of 79 attendees from over 55 organizations, 24 states, Puerto Rico, Canada, and South Africa. Attendees represented the job functions shown in Figure 1. Approximately 85% of the attendees and over 60% of the participating organizations had not attended a previous CAPTC.

Attendees learned:

- How CCPs are viewed from a coal company, electric generating company, marketer, and regulatory perspective.
- Implications of environmental initiatives and emerging specifications on coal ash.
- Updates on the industry's latest hot topics including IGCC by-products and FGD materials.
- Tricks of the trade from those who successfully utilize coal ash.
- Options for recovering disposed coal ash and disposal site development.

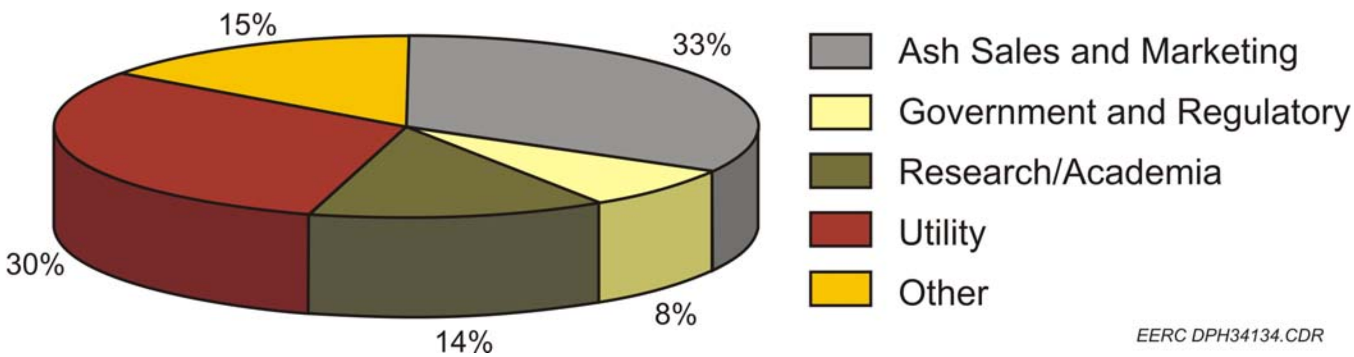

Figure 1. 2008 CAPTC attendee breakdown.

Following the CAPTC, EERC staff prepared CD-ROMs of the meeting materials for distribution to attendees and CARRC members. Discussions were also held with international attendees of CAPTC regarding opportunities to develop a similar course in Europe.

4.4.4 Electronic and Internet-Based Resources

Over the duration of the CARRC program, electronic media have been used as resources for information dissemination. The most recent activities include maintaining the Coal Ash Resource Center Web Site and the CAPD.

4.4.4.1 Coal Ash Resource Center Web Site

Since its original creation, site content has been continually updated with new technical reports, CARRC Annual Progress Reports, and databases including the Buyer's Guide to Coal-Ash Containing Products, the FIRST SEARCH document database, and the ABC Database. The "Ask an Expert" function serves as a point of contact for individuals with inquiries related to CCPs.

4.4.4.2 CAPD

Primarily environmental data from over 550 samples dating back to 1999 is housed in a Microsoft Access CAPD. Recent engineering data have been added to expand the breadth of the database. Additionally, engineering, mineralogical, and environmental data from over 1000 samples dating back to 1981 from the original CAPD are incorporated into a Microsoft Access database. This format allows CARRC researchers to access and manipulate data in a universal program. Querying the data to formulate forms and reports is simple and fast, facilitating CARRC research efforts. Numerous queries have been performed in 2007–2009 for CARRC members, other EERC research efforts, CCP organization members, and CCP industry members.

4.4.5 Research Exchange

CARRC member meetings were held May 9, 2007, and January 28, 2008. Each member meeting included a business meeting for CARRC members and researchers followed by a technical meeting where progress reports were given and information on potential projects were presented. CARRC researchers also kept members informed through quarterly progress reports and topical reports. Additional research exchange included participation in numerous formal and informal meetings and conferences during 2007 and 2008, and CARRC researchers also communicated informally with industry, regulatory groups, and others through telephone discussions and electronic mail. Through the "Ask an Expert" function on the Coal Ash Resource Center Web page, CARRC researchers receive and respond to multiple inquiries annually, which continued during 2007–2009.

4.4.5.1 CARRC Topical Reports

CARRC topical reports were prepared for two CARRC tasks during 2007–2009:

- A Review of Literature Related to the Use of Spray Dryer Absorber Material: Production, Characterization, Utilization Applications, Barriers, and Recommendations
- Impact of Carbon Dioxide Capture on Coal Combustion Products (CCPs)

4.4.5.2 Technology Transfer

The following is a list of technical papers and presentations related to CARRC work by year.

2007

Heebink, L.V.; Buckley, T.D.; Hassett, D.J.; Zacher, E.J.; Pflughoeft-Hassett, D.F.; Dockter, B.A. Current Status of Spray Dryer Absorber Material Characterization and Utilization. Presented at the World of Coal Ash, Covington, KY, May 7–10, 2007.

Buckley, T.D.; Pflughoeft-Hassett, D.F. National Synthesis on Regulations, Standards, and Practices Related to the Use of Coal Combustion Products. Presented at the World of Coal Ash, Covington, KY, May 7–10, 2007.

Hassett, D.J.; Zacher, E.J.; Pflughoeft-Hassett, D.F.; Heebink, L.V. Microbiologically Generated Mercury Vapor and Methylmercury in Soil Applications of CCBs. Presented at the World of Coal Ash, Covington, KY, May 7–10, 2007.

Dockter, B.A.; Eylands, K.E. Using Class C Fly Ash to Mitigate Alkali–Silica Reactions in Concrete. Presented at the World of Coal Ash, Covington, KY, May 7–10, 2007.

Pflughoeft-Hassett, D.F.; Hassett, D.J.; Buckley, T.D.; Heebink, L.V.; Zacher, E.J. Analysis of How Carbon-Based Sorbents Will Impact Fly Ash Utilization and Disposal. Presented at the World of Coal Ash, Covington, KY, May 7–10, 2007.

Buckley, T.D.; Pflughoeft-Hassett, D.F. *National Synthesis Report on Regulations, Standards, and Practices Related to the Use of Coal Combustion Products*; Final Report for U.S. Environmental Protection Agency Contract No. X1-83316201-0 and U.S. Department of Energy Agreement No. DE-AP26-05NT04745, EERC Publication 2007-EERC-12-11, Energy & Environmental Research Center: Grand Forks, ND, Dec 2007.

Buckley, T.D.; Pflughoeft-Hassett, D.F. *Review of Pennsylvania Regulations, Standards, and Practices Related to the Use of Coal Combustion Products*; Final Report for U.S. Environmental Protection Agency Contract No. X1-83275601, U.S. Department of Energy Agreement No. DE-AP26-05NT51864, and American Coal Ash Association; EERC Publication 2007-EERC-03-04; Energy & Environmental Research Center: Grand Forks, ND, March 2007.

Hassett, D. J.; Heebink, L.V.; Pflughoeft-Hassett, D.F.; Buckley, T.D.; Zacher, E.J.; Xin, M; Sexauer, M.; Jung, R. *Mercury and Air Toxic Element Impacts of Coal Combustion By-Product Disposal and Utilization*; Final Report for the Period Jan 23, 2003 – Dec 31, 2006, EERC Publication No. 2007-EERC-10-03, Oct 2007.

Heebink, L.V.; Buckley, T.D.; Pflughoeft-Hassett, D.F.; Hassett, D.J. *A Review of Literature Related to the Use of Spray Dryer Absorber Material: Production, Characterization, Utilization Applications, Barriers, and Recommendations*; Contract No. EP-21586/C10563, Sept 2007.

Pflughoeft-Hassett, D.F. A Comparison of Properties of FGD and Natural Gypsum Products. Presented at the Agricultural & Industrial Uses of FGD Gypsum Workshop, Atlanta, GA, Oct 23–24, 2007.

Pflughoeft-Hassett, D.F.; Buckley, T.D. The Importance of Education and Outreach in Research. *American Coal* **2007**, *1*, 59–60.

Pflughoeft-Hassett, D.F.; Heebink, L.V.; Buckley, T.D.; Hassett, D.J.; Zacher, E.J.; Pavlish, J.H. Activated Carbon for Mercury Control: Implications for Fly Ash Management. In *Proceedings of the 10th Annual Electric Utilities Environmental Conference (EUEC) on Clean Air, Mercury, Global Warming, and Renewable Energy*, Tucson, AZ, Jan 22–24, 2007.

2008

Pflughoeft-Hassett, D.F. Coal Use and Coal Ash Production. Presented at the Coal Ash Professionals Training Course, San Antonio, TX, March 11–13, 2008.

Hassett, D.J. Chemistry of Coal Ash. Presented at the Coal Ash Professionals Training Course, San Antonio, TX, March 11–13, 2008.

Hassett, D.J. What is the Environmental Impact of CCP Use? Presented at the Coal Ash Professionals Training Course, San Antonio, TX, March 11–13, 2008.

Buckley, T.D. CCP Utilization Basics. Presented at the Coal Ash Professionals Training Course, San Antonio, TX, March 11–13, 2008.

Dockter, B.A. Qualifying Coal Ash for Utilization. Presented at the Coal Ash Professionals Training Course, San Antonio, TX, March 11–13, 2008.

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5.0 CONCLUSIONS

Conclusions from individual CARRC tasks/activities were noted in the previous section describing the accomplishments of CARRC from 2007 through 2009. General conclusions drawn from the work performed and interaction with CARRC members, special project sponsors, and other CCP industry stakeholders are:

- Technical challenges related to CCP management remain to be addressed because of changes in fuels, operations, emission controls, and other generation-driven factors. CARRC successfully helped members develop the type of information needed to address these continuing challenges in the areas of impacts of new/changing emission controls, behavior of CCPs in the environment, the contribution of CCP use to sustainable construction, maintaining and expanding markets for CCPs in existing utilization applications, and other areas.

- Technology transfer will facilitate improved management of CCPs, and CARRC offers the flexibility to allow CARRC researchers to communicate to a variety of audiences identified by CARRC members.

- A program like CARRC that has been actively working with CCP issues for more than 24 years can draw from archived information to quickly address member and industry questions and can limit redundancy in the CCP research arena to optimize effectiveness of available research funding.

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APPENDIX A

IMPACT OF CARBON DIOXIDE CAPTURE ON COAL COMBUSTION PRODUCTS (CCPs)

IMPACT OF CARBON DIOXIDE CAPTURE ON COAL COMBUSTION PRODUCTS (CCPs)

Draft Topical Report

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IMPACT OF CARBON DIOXIDE CAPTURE ON COAL COMBUSTION PRODUCTS (CCPs)

INTRODUCTION

In 2008, Coal Ash Resources Research Consortium® (CARRC®) members prioritized research tasks proposed by CARRC researchers. The results indicated that a task to evaluate the potential impacts of carbon dioxide (CO_2) capture technologies on coal combustion products (CCPs) was a high priority to CARRC members. This information gathering and dissemination task was performed primarily during the last two quarters of 2008 and involved the assembly and review of information on CO_2 capture technologies that are either currently commercially available or under development. This CARRC topical report is the result of that effort. The task was accomplished using CARRC member contributions and U.S. Department of Energy National Energy Technology Laboratory (DOE NETL) funds available to CARRC through the EERC Jointly Sponsored Research Program with DOE NETL.

BACKGROUND

Gases that trap heat in the atmosphere are generally referred to as greenhouse gases (GHG). CO_2 is one of several GHGs. CO_2, like some other GHGs, occurs naturally and is emitted to the atmosphere through natural processes and through human activities. Some GHGs are created and emitted solely from human activities. Figure 1 includes information on GHGs from the overview of the U.S. Environmental Protection Agency (EPA) GHG emissions Web site (1).

It is generally agreed that human activity has contributed substantial amounts of GHGs to the atmosphere, and included in the list of human activities that contribute to GHG emissions is the combustion of coal along with other fossil fuels. DOE's Energy Information Administration (EIA) has assembled data on CO_2 concentrations in the atmosphere and CO_2 emissions from 1751 to 2004, and Figure 2 shows that data. EIA data on the amounts of GHGs produced by various human activities (anthropogenic) in the United States are shown in Figure 3. According to the EIA 2006 data, energy-related CO_2 emissions are responsible for more than 80% of the anthropogenic GHGs emitted in the United States. Coal-based power plants produce approximately 50% of electricity in the United States and contribute to the estimated amount of CO_2 emitted from energy-related activities.

The impact of increasing global GHG emissions and potentially associated climate change has been a topic of debate among scientists, governments, and the public. There has even been an award-winning documentary movie made and distributed on the topic. In 1997, before the issue of GHG emissions and climate change became as prominent in the global community as it is currently, DOE NETL initiated research on CO_2 capture and sequestration. DOE NETL's vision for this program area is "to possess the scientific understanding of carbon sequestration options and provide cost-effective, environmentally sound technology options that ultimately lead to a

Some greenhouse gases such as carbon dioxide occur naturally and are emitted to the atmosphere through natural processes and human activities. Other greenhouse gases (e.g., fluorinated gases) are created and emitted solely through human activities. The principal greenhouse gases that enter the atmosphere because of human activities are:

Carbon Dioxide (CO_2): Carbon dioxide enters the atmosphere through the burning of fossil fuels (oil, natural gas, and coal), solid waste, trees and wood products, and also as a result of other chemical reactions (e.g., manufacture of cement). Carbon dioxide is also removed from the atmosphere (or "sequestered") when it is absorbed by plants as part of the biological carbon cycle.
Methane (CH_4): Methane is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock and other agricultural practices and by the decay of organic waste in municipal solid waste landfills.
Nitrous Oxide (N_2O): Nitrous oxide is emitted during agricultural and industrial activities, as well as during combustion of fossil fuels and solid waste.
Fluorinated Gases: Hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride are synthetic, powerful greenhouse gases that are emitted from a variety of industrial processes. Fluorinated gases are sometimes used as substitutes for ozone-depleting substances (i.e., CFCs, HCFCs, and halons). These gases are typically emitted in smaller quantities, but because they are potent greenhouse gases, they are sometimes referred to as High Global Warming Potential gases ("High GWP gases").

Figure 1. Information on GHGs from the overview of EPA GHG emissions Web site (1).

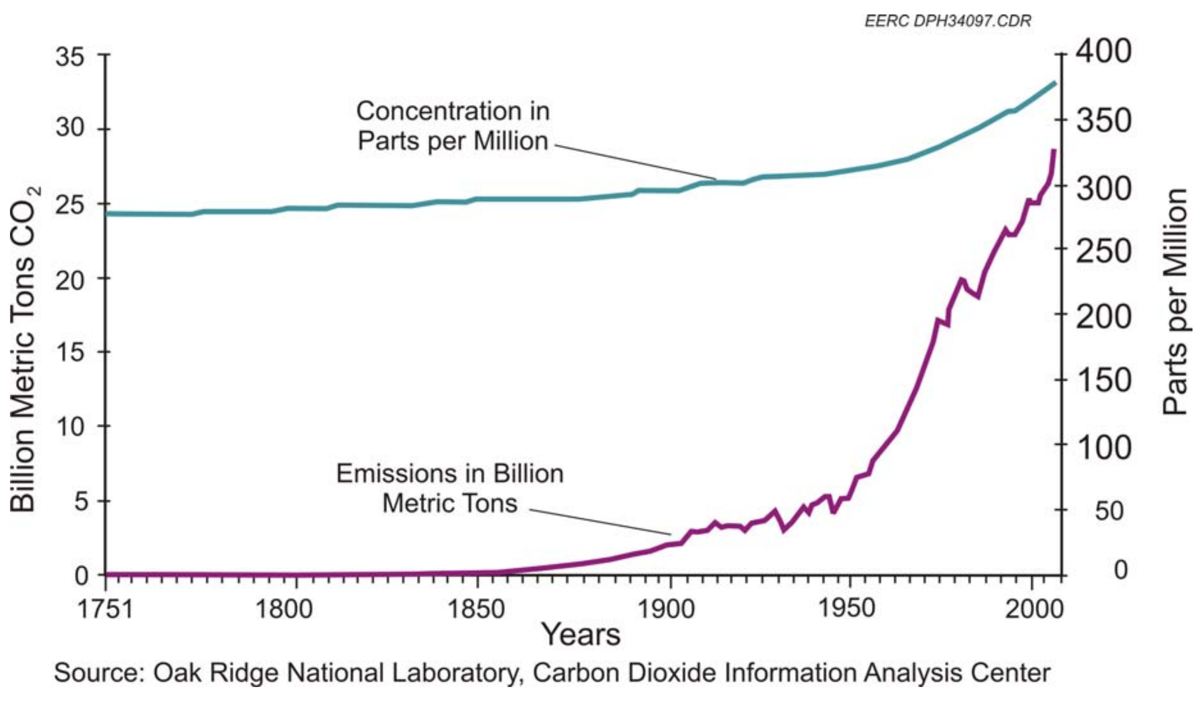

Figure 2. Carbon dioxide emissions and carbon dioxide concentrations (1751–2004) (2).

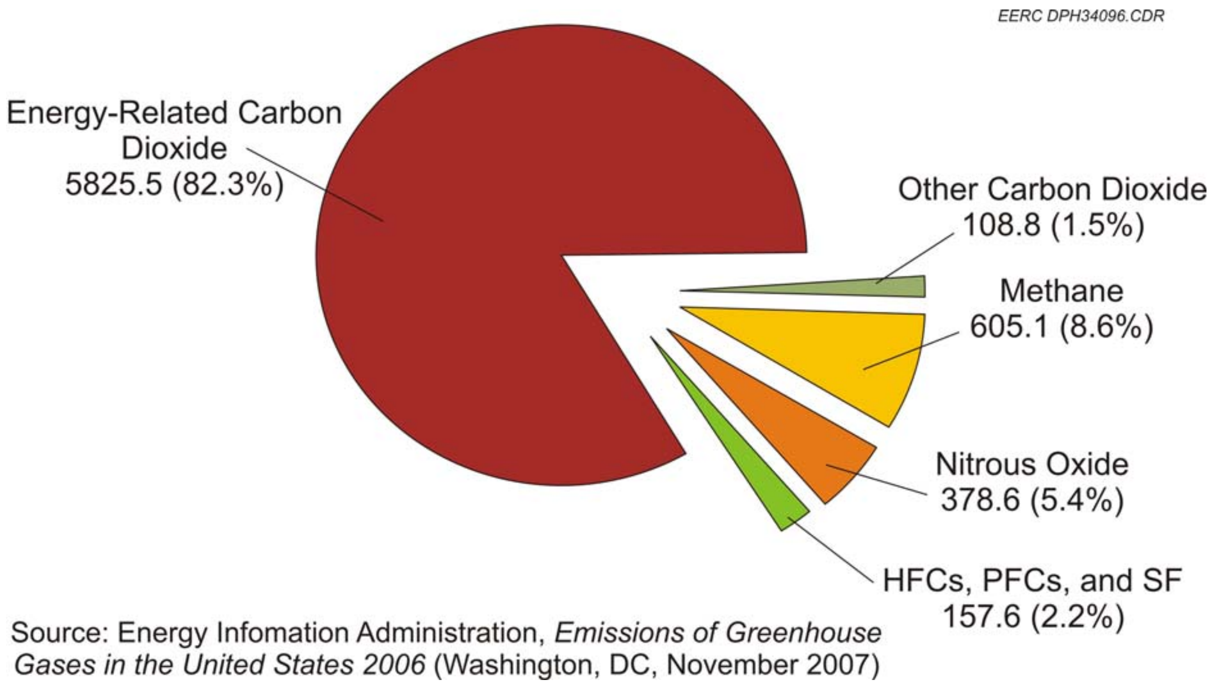

Figure 3. U.S. anthropogenic GHG emissions by gas, 2006 (million metric tons of carbon dioxide equivalent) (2).

reduction in greenhouse gas intensity and stabilization of overall atmospheric CO_2 concentrations (3)."

To achieve this vision, DOE NETL and its partners are working toward a goal of large-scale CO_2 capture and sequestration by 2020. From a regulatory perspective, action toward limiting CO_2 emissions was initiated in March 2008, with the announcement of an Advanced Notice of Proposed Rulemaking. The potential exists for CO_2 emissions from a wide range of sources including coal-based power plants to be restricted by expanding the scope of the 1990 amendment to the Clean Air Act (CAA). The economics of CO_2 capture and sequestration that are currently being evaluated by DOE NETL are expected to be considered by EPA as the potential regulatory process proceeds.

REPORT GOALS AND OBJECTIVES

The coal-based utility industry has been involved with NETL's CO_2 Capture and Sequestration Program through multiple efforts, but one area that has not been addressed is the potential impact of CO_2 capture technologies on CCPs. This CARRC member-prioritized effort was designed to assemble fundamental information to aid in addressing that issue based on the present status of CO_2 capture technology. Specific objectives for the report were to:

- Assemble information on CO_2 capture technologies of the highest potential for use at coal-fired power plants.

- Assess the potential for those technologies to impact common CCP collection, handling, and management.

- Assemble information on the potential non-CCP by-product streams that may be produced from the identified CO_2 capture technologies and any management issues associated with those streams.

METHODOLOGY

Information was assembled from multiple sources and reviewed. Using knowledge of and experience with coal-based electric generating units and the CCPs produced, an assessment of the potential impacts to existing CCPs was made and summarized for the report. The primary source of information was the DOE NETL carbon capture and sequestration program. CARRC researchers also discussed technologies and processes with EERC researchers involved with the industry and DOE NETL-funded Plains CO_2 Reduction (PCOR) Partnership Program.

RESULTS AND DISCUSSION

CO_2 Capture Technologies

CO_2 capture is the term used to describe the separation of CO_2 from emission sources (such as flue gas) or the atmosphere, which must be accomplished before CO_2 can be sequestered. CO_2 capture technologies are categorized as precombustion, postcombustion, and oxycombustion. A summary of each of these categories of CO_2 capture is provided in Figure 4. Figure 5 provides a diagrammatic description of the categories of carbon capture and is useful in understanding the various technology category types.

Current commercial CO_2 capture technologies generally require a relatively pure CO_2 gas stream free of contaminants such as sulfur dioxide, but since flue gas from coal-based power plants has relatively low concentrations of CO_2 and various other components, separation or capture of the CO_2 directly from flue gas is considered challenging.

CO_2 capture must be accomplished before the CO_2 can be sequestered or stored to prevent it from entering the atmosphere. This report does not address issues associated with CO_2 sequestration.

CO_2 is a commodity chemical in the United States and is routinely separated and captured as a by-product of industrial processes such as ammonia production, hydrogen production, and limestone calcination. Unfortunately, the CO_2 capture technologies used for these industries, typically amine absorbers and cryogenic coolers, are not cost-effective when applied to the more dilute CO_2 streams produced at power plants. Current DOE research includes the development of more cost-effective CO_2 capture technologies, which fall into the categories already noted: precombustion, postcombustion, and oxycombustion.

Pre-combustion CO_2 capture relates to gasification plants, where fuel is converted into gaseous components by applying heat under pressure in the presence of steam. CO_2 can be captured from the synthesis gas that emerges from the coal gasification reactor before it is mixed with air in a combustion turbine. Here the CO_2 is relatively concentrated and at a high pressure.

Post-combustion CO_2 capture. Pulverized coal plants, which comprise 99 percent of all coal-fired power plants in the United States, burn coal in air to raise steam. CO_2 is exhausted in the flue gas at atmospheric pressure and a concentration of 10-15 volume percent. This **post-combustion** capture of CO_2 is a challenging application because:

- The low pressure and dilute concentration dictate a high actual volume of gas to be treated.
- Trace impurities in the flue gas tend to reduce the effectiveness of the CO_2 adsorbing processes.
- Compressing captured CO_2 from atmospheric pressure to pipeline pressure (1,200–2,000 pounds per square inch (psi)) represents a large parasitic load.

Oxygen Combustion (oxy-combustion) combusts coal in an enriched oxygen environment using pure oxygen diluted with recycled CO_2 or H_2O. The CO_2 is then captured by condensing the water in the exhaust stream. Oxy-combustion offers several benefits for existing coal-powered plants as determined through large-scale laboratory testing and systems analysis.

Figure 4. DOE summary of CO_2 capture technology categories (4).

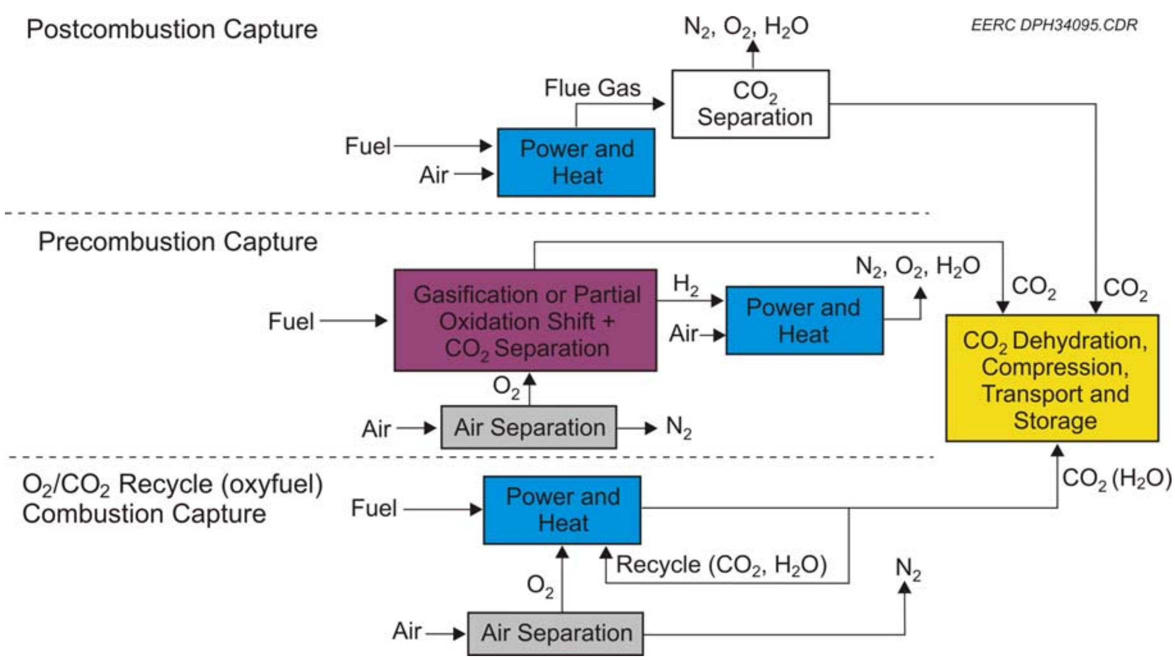

Figure 5. Diagrammatic description of carbon capture technology categories (5).

DOE NETL summarized current state-of-the-art and emerging CO_2 capture technologies (see Figure 6) including an indication of relative cost reduction benefit and estimated time line for commercialization of technologies falling into the categories already noted. The categories of technologies (precombustion, postcombustion, and oxycombustion) are included in Table 1 with general technology descriptions. Table 1 also provides a brief description of the CO_2 capture mechanism and potential impact(s) to existing CCPs. As noted in the table, the only technology that is expected to impact the fly ash quality is oxycombustion.

Impacts of CO_2 Capture Technologies on CCPs

Oxycombustion is the CO_2 capture technology that has the highest potential to impact CCPs when implemented at a coal-based power plant. The presence of increased oxygen in the combustion system has the potential to change the ash formation and the resulting elemental associations, including the minerals formed and associations in the glassy phase. Since many of the reactive components are present in the glassy phase of fly ash as currently produced, it can be speculated that the reactivity of fly ash from an oxycombustion system could be different from ash produced in a conventional system. Characterization of fly ash from oxycombustion is needed in order to quantitate the impacts and understand the potential for associated impacts to management strategies for the fly ash. It is anticipated that the bottom ash would be similarly impacted, but the significance of these impacts to utilization would be expected to be lower because of the generally less stringent technical performance requirements for bottom ash utilization applications. The environmental performance of fly and bottom ash, usually evaluated by use of laboratory leaching tests, might also be expected to change, and materials from specific

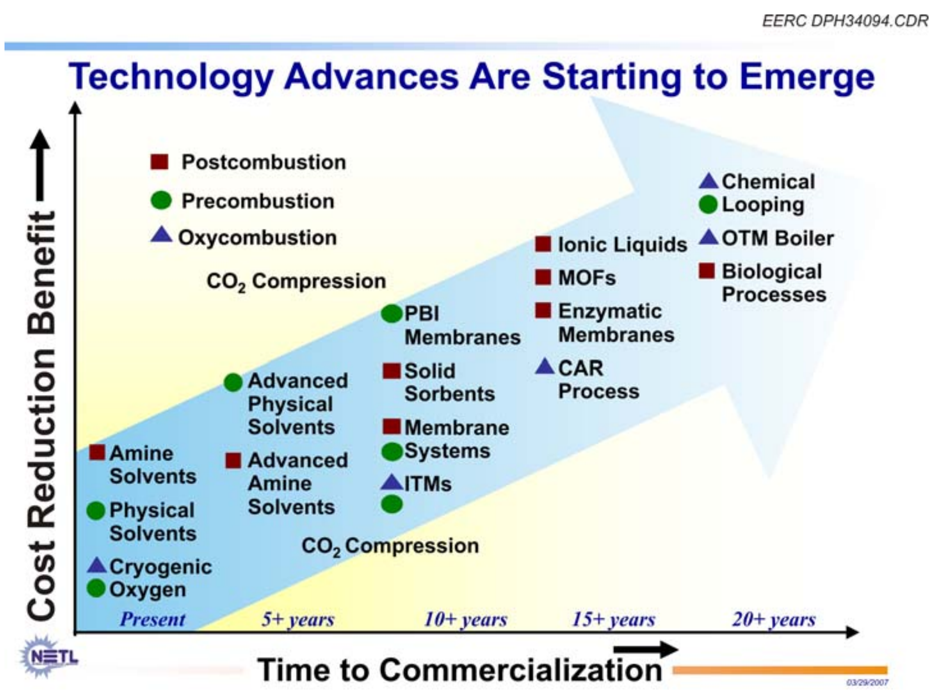

Figure 6. CO_2 capture technologies that are either already commercial or under development (6).

Table 1. CO_2 Capture Technologies

Technology	Technology Category	Example Technology (Figure 6)	How It Works	Ash Impact
Absorption (chemical and physical)	Pre- and postcombustion	Ionic liquids Amine solvents	Reacts with CO_2 and physically dissolves the CO_2	None expected
Adsorption (physical and chemical)	Pre- and postcombustion	MOF[a] process	Physically dissolves CO_2 and chemically reacts with the CO_2	None expected
Low-Temperature Distillation	Pre- and postcombustion	Cryogenic capture	Condenses the CO_2 by cooling the flue gas	None expected
Gas Separation Membranes	Pre- and postcombustion	ITM[b] PBI[c] membranes Enzymatic membranes	Uses partial pressure as the driving force for separation	None expected
Mineralization and Biomineralization	postcombustion	Biological processes	Microbes convert CO_2 into a mineral	None expected
Oxycombustion	Oxycombustion	Chemical looping OTM boiler[d] CAR process[e]	Uses O_2 instead of air for combustion gas producing CO_2-rich flue gas	Expected to alter the mineralogy and elemental phase associations of the fly ash

[a] Metal-organic framework.
[b] Ion transport membrane.
[c] Polybenzimidazole.
[d] Oxygen transport membrane.
[e] Ceramic autothermal recovery.

oxycombustion technologies would require characterization prior to determining management strategies.

Use of Alternative Fuels to Reduce CO_2 Emissions

Another strategy to address CO_2 emissions and that some coal-based electric generating facilities are already using is the addition of carbon-neutral alternative fuels. Biomass fuels such as wood, agricultural wastes, and other biomass materials are considered carbon neutral. The combustion of biomass produces CO_2 just as other carbon-based materials, but biomass fuels are considered carbon-neutral because the carbon present in the material is sequestered from the atmosphere during the growth period of the biomass source (tree, crop, etc.). The addition of any alternative fuel to coal in coal-based power plants has the potential to impact the resulting bottom and fly ash. In research performed at the EERC and elsewhere (7, 8), it has been shown that fly ash from biomass and coal–biomass can exhibit higher levels of alkaline elements, especially potassium. If biomass is combusted at greater than approximately 10%, the impact to the fly ash quality can be significant enough to impact utilization in cementitious applications.

Integrated Gasification Combined Cycle and CO_2 Emissions

Integrated gasification combined cycle (IGCC) is frequently referred to as a CO_2 capture-ready coal conversion technology. Gasification is substoichiometric or reduced air combustion resulting in a synthetic gas (syngas) composed primarily of carbon monoxide (CO) and hydrogen (H_2). Gasifiers are classified into fixed-bed, fluidized-bed, and entrained-bed types. In coal gasification systems, the coal is converted to a combustible gas, volatiles, char, and ash/slag. IGCC systems directly link a gasifier with a gas turbine/steam turbine cycle to achieve high conversion efficiency. The advantage of IGCC for CO_2 capture is that the sulfur is removed prior to the combustion of the gas and the resulting flue gas is relatively clean compared to a typical coal combustion flue gas, hence requiring less cleanup prior to CO_2 capture using the currently available capture technologies. The by-products of IGCC are elemental sulfur or sulfuric acid, char, and slag. For coal-based gasifiers, mercury removal is required. Additional information on IGCC is reported in the EERC report entitled "IGCC and PFBC By-Products: Generation, Characteristics, and Management Practices" (9).

Other Materials-Related Issues Associated with CO_2 Capture

Most CO_2 capture technologies may have low potential to impact CCPs, but the commercial and developing CO_2 capture technologies are expected to provide materials-related issues when implemented. Material-related issues identified in this task can be summarized as follows:

- Solvent-based CO_2 capture technologies (both absorption and adsorption) will require the storage and handling of solvents. Solvent-based technologies are expected to regenerate the solvent for reuse in the system, but as with all regenerable systems, some portion of the solvent will require disposal over the duration of use of the system. Since CO_2 emissions are significant at coal-based power plants, the volumes of solvents requiring storage, handling, and disposal could be significant.

- High-purity oxygen is required to accomplish oxycombustion, and producing that oxygen on-site could include chemical looping which splits combustion into separate oxidation and reduction reactions. A metal (e.g., iron, nickel, copper, or manganese) oxide is used as an oxygen carrier which then releases the oxygen in a reducing atmosphere and the oxygen reacts with the fuel. The metal is then recycled back to the oxidation chamber where the metal oxide is regenerated by contact with air. This is another example of a material that would potentially require disposal.

- Mineralization technologies generally use a biological/microbial process to incorporate CO_2 into minerals. The biological processes would likely require chemical inputs to maintain appropriate conditions for effective mineral formation. These processes are designed to produce a solid material that will require management. Since the goal is to limit release of CO_2 to the atmosphere, the management of this material is expected to require that it remains intact during long-term disposal or storage.

- While IGCC is not a CO_2 capture technology, it does provide advantages for CO_2 separation/capture as noted in the earlier description. As already noted, the resulting solid products of coal gasification in an IGCC system will differ from those produced in coal combustion systems. The by-products of IGCC are elemental sulfur or sulfuric acid, char, and slag. These materials are marketable products as demonstrated by successful marketing programs at two existing U.S. IGCC power plants. Marketing strategies for IGCC by-products from the TECO Polk Power Station in Florida were presented at the 2006 Coal Ash Professionals Training Course (10).

SUMMARY

A review of existing CO_2 capture technologies that might be used by coal-based power plants indicated that these technologies generally are not expected to impact fly ash quality. Strategies that might have an impact on fly ash or other CCP production are oxycombustion, the use of biomass fuels, and the selection of gasification over combustion for new electric generating facilities.

Some strategies to reduce CO_2 or facilitate CO_2 capture may have an impact on the characteristics or availability of ash, but it is anticipated that the greatest impact will be to fly ash because of the technical requirements of fly ash for use in high-value utilization as a cement replacement.

Use of oxycombustion to minimize CO_2 production could change the coal conversion, ash formation, and resulting fly ash mineralogy because of the elevated concentration of oxygen present in the combustion system. It is not likely that these changes would have a significant impact on fly ash quality or performance although the quality and properties of the fly ash would need to be evaluated.

Biomass fuels are already being used by some coal-based power plants and could be used as a strategy to reduce the CO_2 emission impact of a power plant. It is important to note that biomass also produces CO_2 on combustion but that CO_2 is taken up by the plant during its growth, so the combustion of biomass is considered to be carbon-neutral. There are numerous issues with utilization of biomass for large-scale power production, and it is not anticipated that coal-based facilities that currently produce fly ash for the concrete market will use more than a small percentage of biomass fuels in the future. Both laboratory data and experience with fly ash from full-scale systems burning low percentages of biomass (<10%) indicate that fly ash from the coal–biomass blends has quality similar to that produced with the coal alone.

Coal gasification (IGCC) may be preferentially selected for new electric generating facilities over combustion. The by-products from gasification generally include a slag which has been shown to be valuable in cement manufacture; however, no published literature was found to indicate that it could be used in concrete as a supplementary cementitious material.

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APPENDIX B

A REVIEW OF LITERATURE RELATED TO THE USE OF SPRAY DRYER ABSORBER MATERIAL: PRODUCTION, CHARACTERIZATION, UTILIZATION APPLICATIONS, BARRIERS, AND RECOMMENDATIONS

A REVIEW OF LITERATURE RELATED TO THE USE OF SPRAY DRYER ABSORBER MATERIAL: PRODUCTION, CHARACTERIZATION, UTILIZATION APPLICATIONS, BARRIERS, AND RECOMMENDATIONS

CARRC Special Project

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A REVIEW OF LITERATURE RELATED TO THE USE OF SPRAY DRYER ABSORBER MATERIAL: PRODUCTION, CHARACTERIZATION, UTILIZATION APPLICATIONS, BARRIERS, AND RECOMMENDATIONS

PREFACE

The Electric Power Research Institiute funded a special project under the Coal Ash Resources Research Consortium® (CARRC®) to compile and summarize literature on the topic of spray dryer absorber (SDA) material. The goal was to facilitate an understanding of the characteristics, existing and potential utilization applications, and trends for SDA production. The information was collected from multiple sources, and this report summarizes the collected information. CARRC researchers also worked with multiple U.S. SDA producers and drew from research performed under CARRC and other Energy & Environmental Research Center efforts to understand the potential for this material to be utilized rather than disposed of. The input of CARRC members and results of CARRC tasks were invaluable in developing the section on the utilization of SDA materials, which provides an estimation of the best-fit utilization applications for these complex materials. The information assembled and reviewed for the preparation of this report will, in turn, facilitate ongoing and future CARRC technical tasks.

A REVIEW OF LITERATURE RELATED TO THE USE OF SPRAY DRYER ABSORBER MATERIAL: PRODUCTION, CHARACTERIZATION, UTILIZATION APPLICATIONS, BARRIERS, AND RECOMMENDATIONS

ABSTRACT

Coal-fired power plants account for the majority of sulfur dioxide (SO_2) emissions in the United States. Legislative actions in the United States and elsewhere have been responsible for most industrial SO_2 controls, resulting in the installation of flue gas desulfurization (FGD) systems. In the United States, approximately 85% of FGD systems are wet, 12% are spray dryer absorber (SDA) systems, and 3% are dry injection systems. This report is a compilation of an extensive literature review focused on SDA systems and the products they produce.

Most SDA systems collect fly ash (40%–75%) and SDA material together, producing spherical, glassy fly ash particles coated by and intermixed with fine crystals of calcium/sulfur reaction products. SDA materials can vary widely in their physical, chemical, and mineralogical properties depending on their source, and the successful utilization of SDA material is highly dependent on these properties. Characterization data cited in the literature are included in this report.

In the literature reviewed, a number of current commercial and potential uses of SDA material were identified including agriculture, binders, cement manufacture, cement replacement in concrete, civil engineering, flowable fill, fixating agent for waste, marine applications, masonry, mineral wool, mining applications, soil stabilization, sulfuric acid production, synthetic aggregate, wallboard, and wet FGD sorbent. Many of the commercial uses are being implemented successfully in Europe but are slower to enter the marketplace in the United States. Applications currently commercial in the United States include agriculture, concrete, concrete products, flowable fill, mining applications, soil stabilization, structural fills/embankments, and synthetic aggregate. Potential uses in the research and development stage were rated as high-, moderate-, or low-potential commercial applications. High-potential applications for the U.S. market are estimated to be those that take advantage of the presence of the fly ash component of the SDA material, can tolerate relatively high sulfur content, and have limited susceptibility to expansion or reduce expansion potential in the production process. These applications fall into two categories: 1) cementitious products and 2) mining applications.

Barriers prohibiting the use of the material were identified and include:

- Inconsistent terminology used to define the material.
- Lack of understanding of the material.
- Limited data on environmental and health effects.
- Inconsistent guidelines on beneficial ash use.
- Economics.

Based on the information obtained in the research, the EERC recommends the following to maintain existing commercial markets and develop new markets for SDA materials produced in the United States:

- Work within existing organizations such as ASTM International and the American Coal Ash Association to develop and put into use appropriate terminology and definitions for SDA materials.

- Develop an understanding of the impact of compositional variability on the performance characteristics of SDA materials.

- Develop an understanding of the oxidation profiles of SDA materials, and evaluate the impacts of oxidation on product performance.

- Educate potential users, regulatory representatives, and other stakeholders about SDA materials.

- Address quality, compositional, environmental, and performance criteria in research, development, and demonstration efforts.

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NOMENCLATURE

ACAA	American Coal Ash Association
AASHTO	American Association of State Highway and Transportation Officials
AFBC	atmospheric fluidized-bed combustion
$Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$	ettringite
CaCl	calcium chloride
CAIR	Clean Air Interstate Rule
CaO	calcium oxide, lime
$Ca(OH)_2$	calcium hydroxide, hydrated lime, portlandite, unreacted lime
CARRC®	Coal Ash Resources Research Consortium®
$Ca_3Si(CO_3)(SO_4)(OH)_6 \cdot 12H_2O$	thaumasite
$CaSO_3$	calcium sulfite
$CaSO_3 \cdot ½\ H_2O$	hannebachite, calcium sulfite hemihydrate
$CaSO_4$	calcium sulfate, anhydrite
$CaSO_4 \cdot 2\ H_2O$	gypsum, calcium sulfate dihydrate
CCP	coal combustion product
CDF	controlled density fill
CHP	combined heat and power
CLSM	controlled low-strength material
DM	Deutsche Mark
DOE	U.S. Department of Energy
DSI	dry sorbent injection
ECOBA	European Coal Combustion Products Association
EERC	Energy & Environmental Research Center
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ERKOM	"Waste Management of Residues from Coal-Fired Power Plants and Waste Incineration Plants" (known as ERKOM from the German title)
ESP	electrostatic precipitator
EU	European Union
FBC	fluidized-bed combustion
FGD	flue gas desulfurization
FSI	furnace sorbent injection
FSS	fixated scrubber solids
HCl	hydrogen chloride
LIMB	limestone injection multistage burner
LOI	loss-on-ignition
MnDOT	Minnesota Department of Transportation
MW	megawatt
NO_x	nitrogen oxides
NR	not reported
OSU	Ohio State University

OVwG	Oberverwaltungsgericht: Administrative Court of Appeals
RCRA	Resource Conservation and Recovery Act
SCS	Stearns, Conrad and Schmidt
SDA	spray dryer absorber
SEM	scanning electron microscopy
SO_2	sulfur dioxide
SO_3	sulfur trioxide
TCLP	toxicity characteristic leaching procedure
TGA	thermogravimetric analysis
UND	University of North Dakota
VAW	Vereinigte Aluminium-Werke AG, Lünen

A REVIEW OF LITERATURE RELATED TO THE USE OF SPRAY DRYER ABSORBER MATERIAL: PRODUCTION, CHARACTERIZATION, UTILIZATION APPLICATIONS, BARRIERS, AND RECOMMENDATIONS

INTRODUCTION

The use of flue gas desulfurization (FGD) technologies to reduce sulfur dioxide (SO_2) emissions from flue gases at coal-fired power plants gained prominence in the 1980s in the United States. FGD systems are currently used on approximately 22% of U.S. coal-fired power plants. A variety of FGD system types are used globally, and the types of FGD systems used in the United States are summarized in a 2003 Energy & Environmental Research Center (EERC) report [1].

The FGD material that is the focus of this report is termed spray dry absorber material or SDA material. The system is referred to as a spray dry absorber (SDA). An SDA system captures SO_2 from the flue gas by use of slaked lime slurry, which is sprayed into the flue gas, dried by the heat of the flue gas, and collected in a particulate control device. SDA systems may follow a particulate control device that collects the fly ash or the fly ash may intermingle with the lime slurry and be collected in combination with the SDA material. Recycle of the combined solid may be used to improve sorbent utilization. Alkaline fly ash such as that generated from subbituminous coals and some lignite coals will sorb SO_2 gases. As noted by Redinger, the use of fly ash precollection is common in Europe but is not common in the United States. SDA systems are considered efficient and reliable and have a lower capital cost than wet FGD systems [2]. Operating costs for SDA systems are higher than wet FGD systems but the water usage is lower. The resulting product currently has a low utilization rate in the United States.

The product produced from an SDA system is a dry FGD material commonly referred to as SDA material or dry FGD material. Other terms are also used to refer to this material, and a number of these were identified in a previous literature search on the topic of sulfite-rich FGD materials [3]. These terms are noted in Figure 1-1. This report will use the term “SDA material” throughout, except where the generic term “dry FGD material” was used in the review literature. In the United States, SDA material typically contains fly ash, so the authors have elected to note precollection of fly ash or the level of fly ash content when known.

Coal-fired power plants are currently evaluating options to comply with U.S. regulations that will require reductions of emissions of air toxics and acid gases. Responses are expected to result in an increase in SO_2 emission controls and a subsequent increase in the volumes of FGD products produced in the United States. SDA systems, already being used by coal-fired power plants primarily in the western United States, will be one option that power plants may install, especially where water resources are limited. While all types of FGD material production are likely to increase, the potential increase in production volumes of SDA materials is a subject that raises the issue of materials management because of the current low utilization rate in the United States. With goals of 50% utilization of coal combustion products (CCPs) set by the U.S. Department of Energy (DOE) and the American Coal Ash Association (ACAA) to be achieved

- Spray/spray-dry/dryer/drier absorber/atomization/absorption (SDA, SAV) sludge, ash, material, product, byproduct, by-product, end-product, waste, or residue
- Semidry absorber/atomization/absorption (SDA) sludge, ash, material, product, byproduct, by-product, end-product, waste, or residue
- Spray absorption process (SAP) sludge, ash, material, product, byproduct, by-product, end-product, waste, or residue
- Spray dryer (SPD) residue
- Spray dryer by-product (SDB)
- Calcium spray dryer/drier ash, material, product, byproduct, by-product, end-product, waste, or residue
- Lime spray dry/dryer/drier (LSD) ash, material, product, byproduct, by-product, end-product, waste, or residue
- Advanced SO_2 control (ASC) ash, material, product, byproduct, by-product, end-product, waste, or residue
- Sulfite-rich flue has desulfurization sludge, ash, material, product, byproduct, by-product, end-product, waste, or residue
- Sulfite sludge
- Scrubber residue or sludge
- Dry flue gas desulfurization sludge, ash, material, product, byproduct, by-product, end-product, waste, or residue
- Dry scrubber sludge, ash, material, product, byproduct, by-product, end-product, waste, or residue
- Nonoxidized flue gas desulfurization sludge, ash, material, product, byproduct, by-product, end-product waste, or residue
- Flue gas desulfurization sludge, ash material, product, byproduct, by-product, end-product, waste, or residue (with no reference to the FGD process)
- Spent slurry

Figure 1-1. Terms used to refer to SDA material in the literature.

by 2010, additional high-volume production of one or more materials with limited potential for utilization in the current market threatens to offset the great strides to increase CCP utilization in the United States. The first step in determining the best options for utilization of SDA material is to identify current commercial applications and any potential applications that have been investigated or demonstrated.

The goal of the project was to assess the current state of the knowledge regarding the characterization and utilization of SDA material and make recommendations on how to improve the use of the material. The project focused primarily on products produced from SDA systems; however, the report does contain limited information on other FGD processes and products.

This report provides background information on how SDA systems function, descriptions of the variability of SDA materials, and information on the current production and use statistics. This background information provides a framework from which to evaluate the information on utilization applications summarized from the literature.

Background

Development and Status of FGD Systems in the United States

Currently, coal-fired power plants account for the majority of SO_2 emissions in the United States. Health concerns, including breathing difficulty, respiratory illness, and aggravation of existing cardiovascular disease, are associated with exposure to high ambient concentrations of SO_2. The emission of SO_2 from coal-fired power plants can also lead to acid deposition in the environment.

In an effort to address health and environmental concerns related to SO_2 in ambient air, legislation has been enacted to regulate most industrial SO_2 emissions. In the United States, major regulations include the Clean Air Act Amendments of 1970, 1977, and 1990. The 1990 amendment required a permanent 10-million-ton reduction (to almost half the 1980 level) in SO_2 emissions between 1980 and 2010. On March 10, 2005, the U.S. Environmental Protection Agency (EPA) issued the Clean Air Interstate Rule (CAIR), which will permanently cap emissions of SO_2 and nitrogen oxides (NO_x) in the eastern United States. SO_2 emission regulations have also been proposed in many other industrialized nations. Most members of the European Economic Community are regulated, and Canadian laws are similar to those in the United States.

Coal-fired power plants generally employ one of two strategies to control SO_2 emissions: 1) burn compliance fuels or 2) install FGD systems. Compliance fuels can be obtained by burning low-sulfur coal (coals with sulfur content below 2% by weight), blending low- and high-sulfur coals, and washing coal. Most modern power plants, particularly plants built after 1978, are required to have an FGD system. A variety of FGD systems are in use and others are in various stages of development. Commercialized FGD processes include wet, semidry, and completely dry processes. Regardless of type, FGD processes typically use a calcium- or sodium-based alkaline sorbent. The sorbent is injected in the flue gas in a spray chamber/vessel or directly into the duct. The SO_2 is adsorbed, neutralized, and/or oxidized by the alkaline sorbent into a solid compound, either calcium or sodium sulfite or sulfate. The solid is removed from the flue gas stream using downstream equipment.

FGD Systems

For a typical coal-fired power plant, FGD systems will remove ~90% or more of the SO_2 in the flue gas. According to EPA, approximately 85% of the FGD systems installed in the United States are wet, 12% are SDA systems, and 3% are dry injection systems [4]. The following is a brief description of wet and dry FGD systems.

Wet Calcium-Based FGD Systems

In a wet FGD system, flue gas is ducted to a spray chamber/vessel (absorber) where an aqueous solution of sorbent is injected into the flue gas. The most popular type of sorbent used is limestone, but lime can also be used. A portion of the water in the solution is evaporated and the waste gas stream becomes saturated with water vapor. SO_2 dissolves into the solution droplets where it reacts with the alkaline particulates. The resulting wet FGD material falls to the bottom of the spray chamber/vessel, where it is collected [4].

Wet FGD systems are the most popular technology to control SO_2 emissions because they use a widely available and inexpensive sorbent (limestone), can produce FGD gypsum (a usable product) when using forced oxidation, are reliable, and can achieve efficiency up to 99% [1]. Several types of wet FGD processes are available and include limestone-forced oxidation, limestone with natural or inhibited oxidation, lime with or without buffers, lime dual alkali, magnesium-promoted lime, a seawater process, a sodium-scrubbing process, and ammonia scrubbing [1, 5].

Dry and Semidry FGD Systems

There are four types of dry/semidry FGD systems: 1) SDA (semidry) systems; 2) duct sorbent injection (DSI) (dry); 3) furnace sorbent injection (FSI) or limestone injection multistage burner (LIMB) (dry); and 4) fluidized-bed combustion (FBC) (dry). From 1980 to 1992, 7200 megawatts (MW) of dry FGD systems were installed at electric utilities in the United States and have mainly been applied to units burning low-sulfur coals. Of the 43 electric utility dry FGD system installations in the United States, the majority lie west of the Mississippi River [5, 6]. The technology is also used in western Europe.

Dry FGD systems like DSI, FSI, and LIMB inject powdered sorbent directly into the furnace, economizer, or downstream ductwork. The resulting dry product is removed using particulate control equipment such as an electrostatic precipitator (ESP) or baghouse/fabric filter. The flue gas is generally cooled prior to entering the particulate control device. Water can be injected upstream of the absorber to enhance SO_2 removal [4]. Atmospheric fluidized beds use a sorbent such as limestone or dolomite to capture sulfur released by the combustion of coal. Jets of air suspend the mixture of sorbent and burning coal during combustion, converting the mixture into a suspension of red-hot particles that flow like a fluid [7].

The SDA, or semidry, process consists of four operations: sorbent preparation, the spray dryer absorber (also referred to as a chamber or vessel), particulate collection, and product management. An alkaline sorbent is delivered to the power plant in covered railroad cars, trucks, or river barges and then stored in a suitable container to which is it usually pneumatically conveyed. The most popular sorbent is lime (calcium oxide, CaO precalcined) or calcium hydroxide (hydrated lime, $Ca(OH)_2$), but a select number of systems use sodium carbonate. The sorbent is mixed with water, then classified to prevent any large grit particles from going to the spray dryer absorber, where they can cause orifice plugging in the spray nozzles or rotary atomizer. The resulting aqueous slurry is sprayed into the hot flue gas in the spray dryer absorber in a cloud of fine droplets. The residence time is sufficient to allow the SO_2 and other acid gases such as sulfur trioxide (SO_3) and hydrogen chloride (HCl) to react simultaneously with the sorbent and for the water to evaporate. A diagram of the SDA process is shown in Figure 1-2. In this figure, a fly ash precollection ESP is shown as an option. In Europe, fly ash precollection is common for SDA systems, allowing the fly ash stream to be utilized without being mixed with the SDA material. In the United States, it is not common for the fly ash to be precollected, so the fly ash and SDA sorbent combine and pass into the particulate control device as shown in the figure. It is also typical that a portion of the SDA material is recycled back into the SDA, also indicated in the figure.

The resulting material is a dry powder product, which is a calcium sulfite ($CaSO_3 \cdot ½\ H_2O$, or hannebachite) rich material, referred to as SDA material in this report. A small portion of the dry product is collected at the bottom of the absorber, but the bulk of the material is collected in either an ESP or a fabric filter/baghouse. The SDA material may contain up to 75% fly ash by mass, depending on the location of the SDA installation. The distribution of materials collected from the bottom of the absorber and from the particulate control device (ESP or fabric filter/baghouse) in a typical SDA operation is given in Table 1-1 [8]. Since there is a certain amount of unreacted lime in the SDA material, most SDA systems recycle part of their products

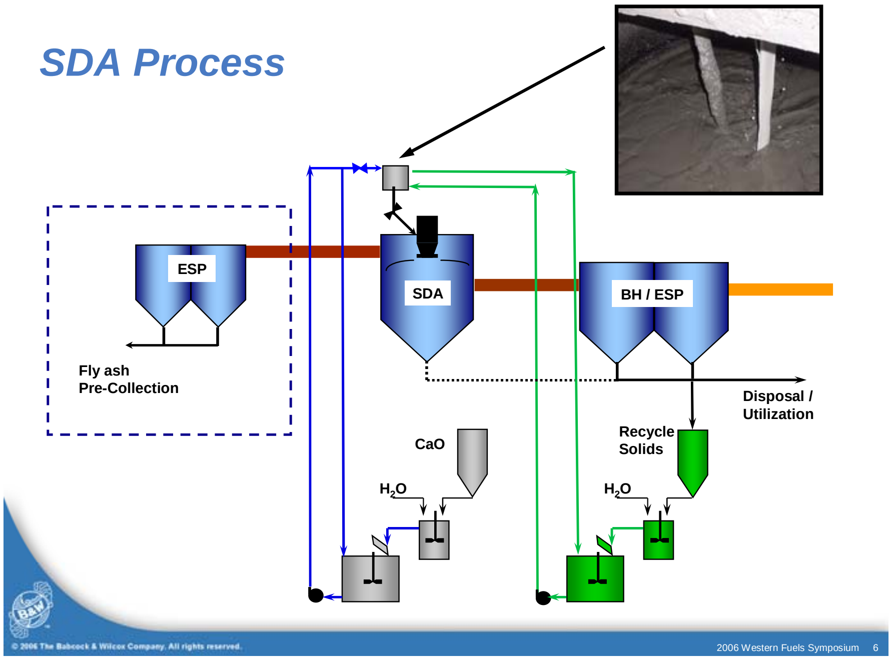

Figure 1-2. Diagram of the SDA process showing the fly ash precollection option and the solids recycle [2].

Table 1-1. Typical SDA Operation Material Distribution [8]

Material	Bottom of Drying Chamber	Particulate Control Device
Fly ash	70%	72%
Calcium sulfite	13%	15%
Calcium sulfate	7%	9%
Unreacted lime	5%	1%
Water	5%	3%

(SDA material and fly ash) back into the feed slurry to increase lime utilization and take advantage of the inherent alkalinity of some fly ashes [9–11].

The advantages of SDA systems over wet scrubbing include:

1. Less costly construction materials typically made of mild steel, thus lower capital costs.
2. Dry products that do not require the use of expensive handling equipment or a wastewater stream.
3. Fewer unit operations requiring less space, making SDA a good choice for retrofit.
4. Flexibility of the feed system, allowing immediate feed control of sorbent to follow boiler load.
5. High reliability.
6. Less sensitive and simpler process chemistry [5, 9, 12, 13].
7. Removal of SO_3 from flue gas.

Perhaps the greatest disadvantage of SDA systems is the higher cost of lime sorbents used in relation to the limestone used for wet scrubbing [9, 12, 13]. In addition, SDA systems produce a product that is difficult to sell and is often disposed of. SDA material is typically disposed of in a manner similar to fly ash.

SDA systems are the second most popular FGD technology. SDA systems are used mostly for relatively small-to-medium-capacity boilers (40–500 MW) that burn low- to medium-sulfur coals. Currently, there are 26 SDA units in operation on coal-fired power plants in the United States. These units are shown in Table 1-2. SDA units in the United States were previously reported by Beidleman and Hilbert [14] and Soud [15]; however, multiple current sources were used to develop this updated table.

In nine European countries, 49 dry FGD plants were reported [16]. The plants are categorized by country in Table 1-3.

Projected Future SDA Installations in the United States

The Babcock & Wilcox Company tracks projected future SDA installations in the United States (see Table 1-4) [18]. Details indicating new capacity versus retrofit installations, generating unit size, coal type, geographic location, and reagent system are provided in Table 1-5. The numbers of projected SDA installations shown in Tables 1-4 and 1-5 are planned projects that have been announced, but many factors could change these planned installations. Additionally, installations of circulating dry scrubber-type systems, producing a product expected to be similar to SDA material, are projected to increase.

Table 1-2. SDA Units in the United States[a]

Utility	Plant and Unit with FGD System	City	State	Nameplate Capacity (MW)		In-Service Date	Design Coal Sulfur (wt%)	Sorbent	Designed SO_2 Removal (% efficiency)	Coal Type
				By Plant	By FGD Unit					
Basin Electric Power Cooperative	Antelope Valley Unit 1	Beulah	ND	900	450	1984	1.20	Lime	Up to 90.0	Lig[b]
	Antelope Valley Unit 2	Beulah	ND	900	450	1986	1.20	Lime	Up to 90.0	Lig
	Laramie River Station Unit 3	Wheatland	WY	1650	550	1982	0.50	Lime/ alkaline fly ash	85.0	Sub[c]
Duke Energy	East Bend Unit 2	Rabbit Hash	KY	669	669	1981	5.20	Lime	99.0	Bit[d]
East Kentucky Power Cooperative, Inc.	H. L. Spurlock Unit 2	Maysville	KY	1118	525	1981	3.60	Lime	90.0	Bit
Grand River Dam Authority	Coal-Fired Complex Unit 2	Chouteau	OK	1,010	520	1986	1.50	Lime/ alkaline fly ash	85.0	Sub
Great River Energy	Stanton Station	Stanton	ND	188	188	1982	0.70	Lime	70.0	Lig
Kansas City Power & Light	Hawthorn Station	Kansas City	MO	594	594	2001	0.33	Lime/ alkaline fly ash	88.0	Sub

Continued . . .

Table 1-2. SDA Units in the United States[a] (continued)

Utility	Plant and Unit with FGD System	City	State	Nameplate Capacity (MW)		In-Service Date	Design Coal Sulfur (wt%)	Sorbent	Designed SO_2 Removal (% efficiency)	Coal Type
				By Plant	By FGD Unit					
Marquette Board of Light and Power	Shiras 3	Marquette	MI	40	40	1983	0.50	Limestone	80.0	Sub
Otter Tail Power Company	Coyote Station	Beulah	ND	400	400	1981	0.80	Lime/ alkaline fly ash	70.0	Lig
PacifiCorp	Wyodak Power Plant	Gillette	WY	365	365	1986	0.80	Lime/ alkaline fly ash	75.2	Sub
Platte River Power Authority	Rawhide Energy Station	Wellington	CO	294	294	1984	0.30	Lime/ alkaline fly ash	80.0	Sub
Sierra Pacific Power Company	Valmy Unit 2	Valmy	NV	521	267	1985	0.50	Lime	70.0	Bit
South Carolina Electric & Gas Company	Cope Station	Cope	SC	430	430	1996	1.90	Lime	Up to 98.0	Bit
Sunflower Electric Power Corporation	Holcomb Unit 1	Holcomb	KS	360	360	1983	1.00	Lime/ alkaline fly ash	80.0	Sub

Continued . . .

Table 1-2. SDA Units in the United States[a] (continued)

Utility	Plant and Unit with FGD System	City	State	Nameplate Capacity (MW)		In-Service Date	Design Coal Sulfur (wt%)	Sorbent	Designed SO_2 Removal (% Efficiency)	Coal Type
				by Plant	by FGD Unit					
Tri-State Generation & Transmission Association, Inc.	Craig Unit 3	Craig	CO	1274	446	1984	0.70	Lime	85.0	Sub
Tucson Electric Power Company	Springerville Unit 1	Springerville	AZ	1560	380	1985	0.70	Lime/ alkaline fly ash	61.3	Sub
	Springerville Unit 2	Springerville	AZ	1560	380	1985	0.70	Lime/ alkaline fly ash	61.3	Sub
	Springerville Unit 3	Springerville	AZ	1560	400	2006	0.70	Lime/ alkaline fly ash	–	Sub
Xcel Energy	Cherokee Unit 3	Denver	CO	715	151	–	0.40	Lime/ alkaline fly ash	70.0	Bit
	Cherokee Unit 4	Denver	CO	715	351	2003	0.40	Lime/ alkaline fly ash	70.0	Bit

Continued . . .

Table 1-2. SDA Units in the United States[a] (continued)

Utility	Plant and Unit with FGD System	City	State	Nameplate Capacity (MW) by Plant	Nameplate Capacity (MW) by FGD Unit	In-Service Date	Design Coal Sulfur (wt%)	Sorbent	Designed SO_2 Removal (% efficiency)	Coal Type
Xcel Energy	Hayden Unit 1	Hayden	CO	446	184	1998	0.40	Lime/ alkaline fly ash	85.0	Bit
	Hayden Unit 2	Hayden	CO	446	262	1999	0.40	Lime/ alkaline fly ash	85.0	Bit
	Sherco Unit 3	Becker	MN	2400	900	1987	0.90	Lime/ alkaline fly ash	72.3	Sub

[a] Multiple current sources were used to develop this updated table.
[b] Lignite.
[c] Subbituminous.
[d] Bituminous.

Current SDA Material Production and Use Rates

ACAA reports the yearly production and use of CCPs in the United States, including statistics on FGD products from wet and dry systems. SDA material is reported with all other products from dry FGD systems, with the exception of FBC systems, in an FGD dry scrubber material category. The ACAA definitions of dry FGD material and FGD dry scrubber material are included in Figure 1-3 [19].

Table 1-3. Dry FGD Plants in Europe [16–17]

Country	Sites with Dry FGD Plants	Dry FGD Production (approx.) (short tons/year)	Year Reported	Percentage of FGD Units Using SDA Process
Austria	4	50,000	1995	41.7% in 1993
Denmark	2	83,200	1997	37.3% in 1993
Czech Republic	8	140,000	1998	NR[a]
Finland	4	32,000	1999	NR
Germany	20	378,000	1996	7.0% in 1993
Italy	1	10,000	2000	NR
Poland	5	500,000–600,000	2000	NR
Spain	1	5000	1999	NR
Sweden	4	10,000	1999	100%

[a] Not reported.

Table 1-4. U.S. SDA Market Projections [18]

Time Horizon	1–5 years (2007–2012)		5–10 years (2013–2017)	
Projected SDA Installations	No. Gen. Units	Gen. Capacity (MW)	No. Gen. Units	Gen. Capacity (MW)
New capacity	14	7050	3	1850
Retrofits	28	11,350	16	7400

The production of dry scrubber FGD material has been reported as a separate category in the annual ACAA CCP Production and Use Survey since the 2002 statistics were released in 2003 [20]. Since then, the reported production has varied from a low of 935,394 short tons in 2002 to a high of 1,829,830 short tons in 2004 [20, 21]. ACAA reported that 1,488,951 short tons of dry FGD material was produced in the United States in 2006. Of that, 136,639 short tons (or 9.18%) was beneficially used, which is the lowest percentage reported by ACAA's survey [22]. Figure 1-4 illustrates the major markets for dry scrubber FGD material in the United States as reported by respondents to the 2006 annual ACAA CCP Production and Use Survey.

Table 1-5. Details of U.S. SDA Market Projections [18]

Time Horizon	1–5 years (2007–2012)		5–10 years (2013–2017)	
	New Capacity	Retrofits	New Capacity	Retrofits
Generating Unit Size (MW)				
>800	2	3		1
500 to 800	7	7	3	6
250 to 500	1	8		8
100 to 250	2	7		1
<100	2	3		
Coal Type (sulfur content, %)				
Lignite	1			
Subbituminous	13	18	3	16
Bituminous – western		3		
Bituminous – eastern		7		
Geographic Location by EPA Region				
1 (ME, NH, VT, MA, RI, CT)		2		
2 (NY, NJ)		3		
3 (PA, WV, VA, MD, DE)		2		
4 (KY, TN, NC, SC, GA, AL, MS, FL)			2	
5 (OH, IN, IL, MI, WI)	1	10		14
6 (AR, LA, OK, TX, NM)	3	2		1
7 (IA, MO, KS, NE)	4	2	1	
8 (CO, UT, WY, MT, ND, SD)	4	7		
9 (CA, NV, AZ)	2			
10 (AK, WA, OR, ID)				
Reagent Stream				
Fly ash recycle	11	26	3	16
Lime only	3	2		

- Dry FGD material – the product that is produced from dry FGD systems and consists primarily of calcium sulfite, fly ash, portlandite ($Ca(OH)_2$), and/or calcite. Lime-based sorbent system dry FGD material main constituents are calcium sulfite and dry fly ash, along with minor quantities of calcium sulfate. Sodium-based sorbent system main constituents are sodium sulfite and dry fly ash along with minor quantities of sodium sulfate. Dry FGD material is being used in construction, engineering, and agricultural applications; however, most of the material is stored in landfills.

- FGD material dry scrubbers – the dry powdered material from dry scrubbers that is collected in a baghouse along with fly ash and consists of a mixture of sulfites, sulfates, and fly ash.

Figure 1-3. ACAA definitions of dry FGD material [19].

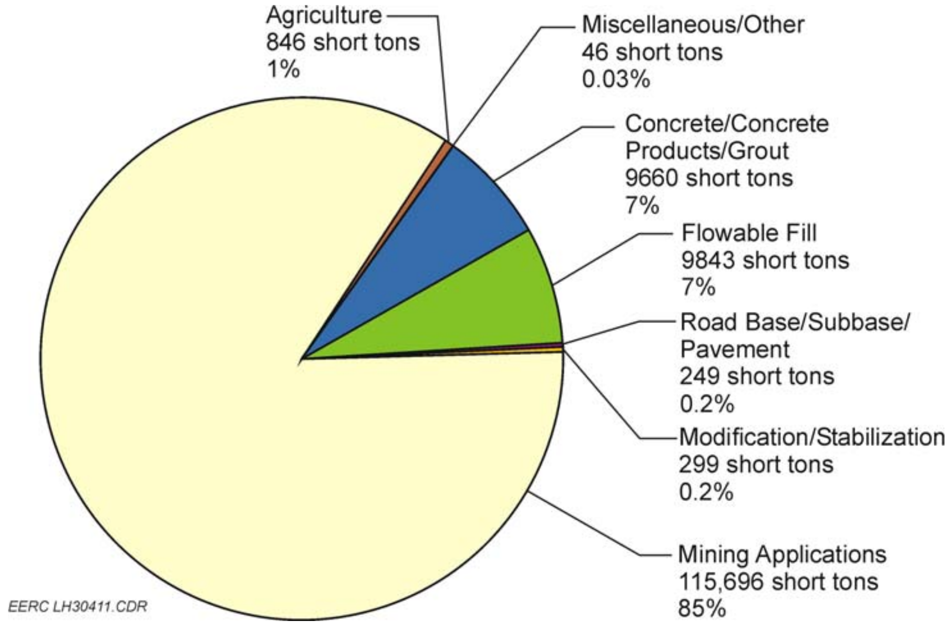

Figure 1-4. Dry scrubber FGD material use in the United States in 2006. Of 1,488,951 short tons produced, 136,639 short tons of dry scrubber FGD material (9.18%) was beneficially used [22].

The use application categories reported for dry scrubber FGD material in the ACAA annual survey since 2002 statistics have included concrete/concrete products/grout, cement/raw feed for clinker, flowable fill, structural fills/embankments, road base/subbase/pavement, soil modification/stabilization, mineral filler in asphalt, mining applications, waste stabilization/ solidification, agriculture, aggregate, and miscellaneous/other. However, the categories vary annually because of variations in respondents to the annual ACAA survey and added SDA units or unit closures (e.g., Xcel Energy's Riverside Unit 7 went out of service in 2004). ACAA typically notes a utility response rate of 54%–60% for its annual Production and Use Survey.

SDA material production and use figures are incorporated into the overall reporting category of dry FGD material by ACAA, and quantities of SDA material produced and used have never been reported separately by ACAA. In addition, although the ACAA survey extrapolates production and use figures for fly ash, bottom ash, FGD gypsum, and wet FGD to account for the actual survey response rate, the figures reported for dry FGD are actual responses and are not extrapolated. Using the 2004–2006 production figures for dry FGD material, and an estimate of sodium-based dry FGD material production based on sodium-based sorbent use predictions for 2007, and taking into consideration the ACAA response rate, the EERC estimated SDA annual production of approximately 3.6 million tons. Using the data in Table 1-2 and production figures provided by several industrial power plants, it was estimated that 350–400 tons of SDA material is produced for each MW of capacity. Using the approximation of 350–400 tons of SDA material produced per MW unit size multiplied by 9556 MW of existing SDA units indicated that ~3.3–3.8 million tons of SDA material is likely produced annually in the United States. The EERC estimate is significantly higher than the ACAA production figures indicate; however, the ACAA statistics are expected to reflect the use profile for dry FGD materials even though not all utilities are responding.

The European Coal Combustion Products Association (ECOBA) reports the production and use of CCPs in Europe (EU 15). EU 15 refers to the fifteen countries that formed the European Union until the end of April 2004. These countries include the United Kingdom, France, Belgium, Luxembourg, the Netherlands, Germany, Italy, the Irish Republic, Denmark, Greece, Portugal, Spain, Sweden, Finland, and Austria. Production of SDA material in 2004 was 463,000 short tons, down from 540,000 in 2003 [23]. Of this, 41% of SDA material produced in 2004 was beneficially used in nonmining applications, which are broken down into general engineering fill, flowable fill, plant nutrition, and other uses. An additional 39% of the SDA material produced was used for mine reclamation and restoration purposes, for a total of 80% SDA product utilization. Therefore, 20% was disposed of [23]. The beneficial use and mine reclamation and restoration applications are compiled in Figure 1-5.

ECOBA lists several specific current uses for SDA material in Europe [24–26]:

- As a component of mining mortar for stabilizing underground cavities
- As an addition in the production of sand–lime bricks
- In the production of cement clinker in a special clinker production method (Müller-Kühne Process)
- As a sorbent in a wet FGD process in power plants
- As a sulfur fertilizer in agriculture

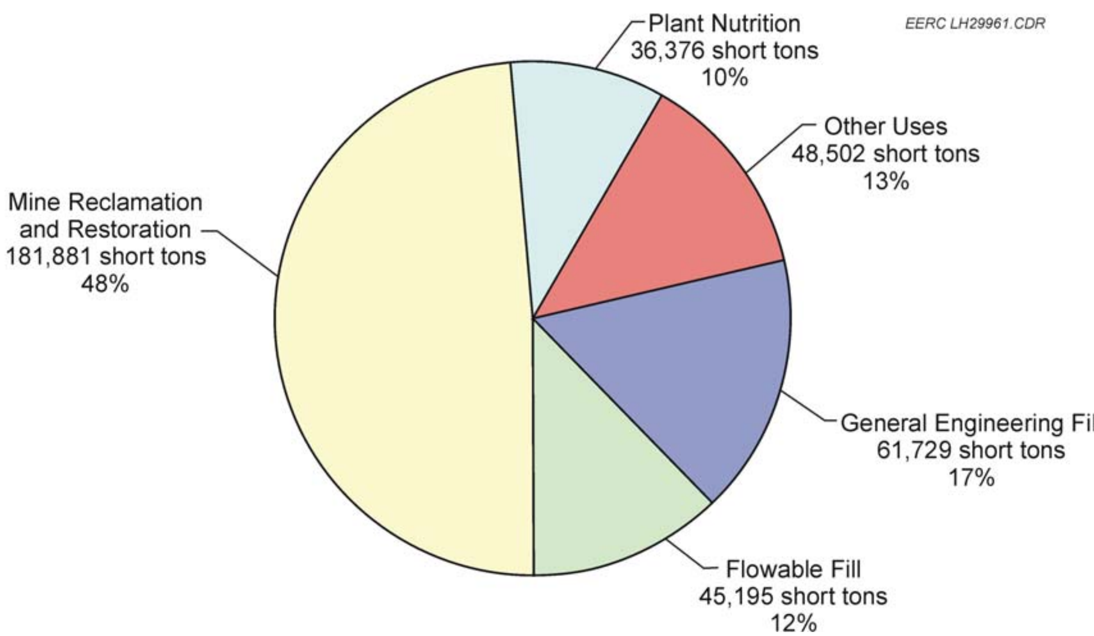

Figure 1-5. Spray dry absorption product use in Europe (EU 15) in 2004. Of 466,278 short tons produced, 373,684 short tons (80.1%) was beneficially used [23].

In May 2004, ten Accession Countries joined the existing EU 15, resulting in an EU comprising 25 member states. The Accession Countries were Cyprus, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, and Slovenia. SDA material is produced in anthracite and lignite coal-fired plants in Poland. From anthracite, 93,304 thousand short tons of SDA material was produced, with 98% utilized in mining and beneficial landfill/land reclamation in 2000. In addition, 1,134,240 thousand short tons of fly ash + SDA material was produced, with a 100% utilization rate. Applications included building materials, bricks and ceramics, roads, and mining. From lignite, 424,389 thousand short tons of fly ash + SDA material was produced, with 100% utilization in beneficial landfill/land reclamation [27].

Projected Future SDA Production in the United States

Based on the current production figures, estimated production rate, and MW of SDA scrubbed units in the United States, it is estimated that up to 7 million tons of additional SDA material could be produced from SDA units installed in the next 5 years, making the total annual production as high as 10 million tons, nearly 300% of the current total, by 2012. With an estimated potential additional 9250 MW of SDA scrubbing added between 2012 and 2017, it is estimated that up to an additional 3.5 million tons of SDA material could be generated annually in that time period. If all the projected SDA units are installed as noted in Tables 1-4 and 1-5, and no existing units are taken off line, the total SDA material production could reach 13–14 million tons annually in 10 years. This estimate reflects an increase of 400%–500%.

RESULTS AND DISCUSSION OF THE LITERATURE REVIEW

Technical reports, journal articles, patents, conference proceedings, book chapters, and news articles were assembled and reviewed to prepare this report. A multitiered search approach was used to obtain literature including sources that were the most readily available and those that required a more in-depth search. The search resulted in a significant number of documents containing references to dry FGD materials including SDA materials. A tiered approach was also used for the review of the literature obtained. EERC researchers used knowledge about these materials to choose the documents for review. The literature reviewed included information on the characteristics of SDA material and commercial and potential utilization applications for SDA material. An effort is under way to add all of the gathered references to the EERC FIRST SEARCH online database located at www.undeerc.org/carrc/firstsearch/.

Definitions of SDA Material

ASTM International [28] and ACAA [19] have developed and published terminology and definitions related to CCPs including FGD materials. These terms and definitions do not currently include SDA system or material definitions; however, the definition of dry FGD material provided by both organizations is inclusive of SDA material that contains fly ash. The ACAA definition of dry FGD material (see Figure 1-3) includes materials that would be produced in dry FGD systems utilizing sodium-based sorbents, but the ASTM International definition (see Figure 1-6) includes only calcium-based materials. SDA systems utilize lime

- Dry FGD material – the product that is produced from dry FGD systems and consists primarily of calcium sulfite, fly ash, portlandite ($Ca(OH)_2$), and/or calcite. ASTM equivalent terms are *dry FGD ash* and *lime spray drier ash.*

- FGD material dry scrubbers – the dry powdered material from dry scrubbers that is collected in a baghouse along with fly ash and consists of a mixture of sulfites, sulfates, and fly ash.

Figure 1-6. ASTM International definitions [28].

slurry, so these materials are calcium-based materials. Strictly applying the ASTM International and ACAA definitions for dry FGD material (which includes fly ash as a component of the material), material from an SDA system using fly ash precollection would not be defined as a dry FGD material; however, the term SDA material is used here to refer to materials that do and do not contain a fly ash component to be consistent with the literature reviewed.

Characterization of SDA Material

SDA materials can vary widely in their physical, chemical, and mineralogical properties, depending on their source. The following factors affect both the quantities and characteristics of SDA material:

- Composition of the coal feedstock (ash content, sulfur content, heating value)
- Combustion conditions
- Sorbent type
- SO_2 uptake efficiency (Ca/S ratio)
- Fly ash collection location and efficiency
- Composition and mineralogy of the fly ash
- Recirculation rate
- Load level
- Stoichiometric (sorbent) ratio

Regardless of the type of process used to scrub the flue gas, all FGD products include spent sorbent as sulfites or sulfates plus unreacted sorbent. The quantity of the sorbent used is usually proportional to the sulfur content of the coal burned but is also a result of the percent of SO_x recovery desired and system operating parameters [29]. The calcium sulfite content is dependent on the SO_2 removal efficiency [17].

Because fly ash commonly makes up a large proportion of the SDA material (40%–75%), the overall physical properties and morphology of most SDA materials are similar to fly ash; therefore, handling properties are similar to fly ash. Most U.S. systems collect the fly ash and SDA material together in an ESP or baghouse/fabric filter, producing spherical glassy fly ash particles coated by and intermixed with fine crystals of calcium/sulfur reaction products [10, 12]. The fly ash particles provide reaction sites for the removal of sulfur and, consequently, become coated with reaction products. The result is a dry, free-flowing powder with particles smaller and finer than fly ash [10]. However, if the SDA material is collected as a separate product stream, then it will appear as a fine, dusty powder with an off-white color. The major difference between

SDA material and conventional fly ash can be attributed to the higher calcium and sulfur content of SDA material. SDA materials are finer and more caustic, have a higher heat of hydration, and produce more alkaline leachate when compared to conventional fly ash [13].

Dry FGD materials from plants that used different types of boilers and burned different types of coal were collected, and it was found that the products had a moderate to wide range of variability in their chemical, physical, and mineralogical properties [30]. The amount of unused sorbent (portlandite, $Ca(OH)_2$) varied the most, by a factor of 14. This variation depended on whether or not the plant recycled its products. This example shows that the physical and chemical properties of dry FGD materials can be highly variable from plant to plant and that an analysis of the material should be conducted prior to beneficial use, particularly when the material has the potential to expand or will contact water.

The following is an analysis of the physical properties, chemical characteristics, and mineralogy of SDA material, based on the literature reviewed. It is important to note that the properties and characteristics of the SDA materials are affected by varying amounts of fly ash present, which was not always reported.

Physical Properties

The physical properties of SDA material are important because they affect storage, handling, disposal, and engineering uses. Uniformity of the material and the ability to pack tightly are especially important for some applications.

SDA materials are generally free-flowing to average-flowing, but higher moisture content can affect flowability and storage problems. Both qualitative and quantitative physical properties can affect transfer and transport. The quantitative physical properties that can affect transfer and transport include particle size, bulk density, specific gravity, and temperature. Disposal is affected by optimum moisture and maximum density, unconfined compressive strength, and permeability [12].

Qualitative Physical Properties

Qualitative physical properties of SDA material include abrasiveness, hygroscopicity, tackiness, corrosivity, and tendency to aerate. The abrasive nature of SDA material has been demonstrated through reported wear on handling equipment. SDA material has also been found to have hygroscopic tendencies due to potential hydration reactions of the lime, calcium sulfate, and calcium sulfite fractions of the material. Evidence of its tacky nature, if it does absorb water, has been demonstrated by solids buildup at the elbows of pneumatic equipment. If wetted, it can stick and build up on mechanical conveyors. When wet, a moderate corrosivity exists. In addition, it has the tendency to aerate and retain air. This makes it easy to convey pneumatically but limits the speed at which it can be conveyed [12, 13].

Particle Size

The particle-size distribution of a material is characterized by the proportion of particle sizes within a series of specific size intervals. Particle-size distribution is important because many engineering parameters are related to the variation of particle size of a material. The fineness of CCPs is also an important characteristic because high-surface-area CCPs are generally more chemically activated which, in turn, may be of importance in evaluating utilization options [31]. The exposed surface area of a given volume will be greater for the smaller CCP particles.

The particle size of SDA material is very fine and tends to be smaller than conventional fly ash. Most SDA materials can be classified as in the silt size range (1/256–1/16 mm, or 3.9–62.5 µm). SDA material particle-size distributions are relatively uniform [13]. Particle sizes depend on both combustion and collection system designs [32].

The particle-size distribution and/or mean mass/particle size of SDA materials have been reported in numerous publications. A compilation is shown in Table 2-1. The reported particle-size distribution ranged from 1 to 400 µm, with 1–70 µm more typical. The reported mean mass/particle size range is 1–45 µm.

Conventional fly ash mean mass/particle size has been reported as 35–55 µm [10], 25–40 µm [36], and a mean of 45 µm at one plant [12, 13].

It was reported that 78%–80% of the SDA material was in the fraction finer than 40 µm, while 57%–78% of conventional fly ash was in this finer fraction [12, 13]. Similarly, four SDA material samples tested had greater than 80% of particles by weight finer than 25 µm, indicating very fine particles [37, 38]. Kolar reported that 85%–100% of the SDA material was less than

Table 2-1. Particle-Size Distribution and Mean Mass/Particle Size of SDA Material Reported in Literature Reviewed, µm

Particle-Size Distribution	Mean Mass/Particle Size	Source (s)
NR	16–45	[2, 30]
NR	13.5	[33]
20–40	NR	[1]
5–60[a]	10–15[a]	[16]
2–74	NR	[29]
1–70	NR	[31,34[b]]
NR	4–30	[17]
NR	2–30	[10]
1–400	7.4–18.0[c]	[35[b]]
NR	20–28	[12[b]]
18–60	24–29	[13]
NR	20–25[c]	[36]

[a] Precollection of fly ash; 3%–10% fly ash content.
[b] Literature review reported within source.
[c] Reported as mean diameter.

60 µm, where 60 µm was the maximum particle size observed with precollection of fly ash [17]. It was reported that the SDA material from Basin Electric Power Cooperative pilot plant was a very fine-grain, powdery material, similar in particle size to the fly ash normally produced at a coal-fired power plant [39].

Early work performed for a University of Tennessee thesis was summarized in another report. The SDA samples tested contained a much smaller percentage of particles less that 2.5 µm in diameter than conventional fly ash. The particle-size distribution analysis also showed that the highest percentage of particles in the SDA material was found to be in the range of 4–10 µm in diameter [40]. The thesis was not available to EERC researchers for review; therefore, the data could not be reviewed in complete context.

Specific Surface Area

The specific surface area of FGD samples tested by the Ohio State University (OSU) corresponded with particle size, indicating mostly nonporous materials [37, 38]. Specific surface area ranges are a function of the fly ash content in the SDA material [17]. The specific surface area of SDA materials reported in the reviewed literature (0.2–16 m^2/g) is shown in Table 2-2.

Bulk Density

Density is defined as the mass (or weight) per unit volume of a material. The reviewed literature had several means of reporting bulk density as compiled in Tables 2-3 and 2-4. Included with bulk density ranges are aerated, poured, packed, and tapped bulk density ranges. Bulk density measurements are used for different purposes, depending on the intended use of the material. Overall, the range of reported bulk density measurements was 400–1760 kg/m^3 (25–110 lb/ft^3).

The fly ash in dry FGD materials has similar particle size, particle density, and morphology to those of conventional fly ashes, but dry FGD materials have lower bulk densities [30]. The difference in bulk density is due to variations in the chemical and mineralogical characteristics of the reacted and unreacted sorbent. The range in bulk density has been attributed to the fly ash content [17]. Contrary to Dawson et al. [30], Klimek et al. indicated that the bulk

Table 2-2. Specific Surface Area of SDA Material Reported in Literature Reviewed, m^2/g

Specific Surface Area	Source (s)
1.64–7.47	[2, 30]
9.49 ± 3.82	[37]
~9.4	[38]
1.6–7.5	[34[a]]
0.2–3.39	[35[a]]
1.5–16	[17]

[a] Literature review reported within source.

Table 2-3. Bulk Density of SDA Material Reported in Literature Reviewed

Bulk Density	Source(s)
630 kg/m^3 (39 lb/ft^3)	[38]
780–1250 kg/m^3 (49–78 lb/ft^3)	[32]
960–1440 kg/m^3 (60–90 lb/ft^3)[a]	[11]
700 kg/m^3 (44 lb/ft^3)[b]	[16]
400–1100 kg/m^3 (25–69 lb/ft^3)	[17]
600 kg/m^3 (37 lb/ft^3)[b, c]	[41, 42]

[a] Reported as density.
[b] Precollection of fly ash; up to 20% fly ash content.
[c] Small portion of fly ash.

Table 2-4. Bulk Density of SDA Material Specified as Aerated or Poured or Loose, Packed or Compacted, and Tapped or Settled Reported in the Literature Reviewed

Aerated or Poured or Loose Bulk Density	Packed or Compacted Bulk Density	Tapped or Settled Bulk Density	Source(s)
480–960 kg/m^3 (30–60 lb/ft^3)	NR	784–1250 kg/m^3 (49–78 lb/ft^3)	[2]
580–960 kg/m^3 (36–60 lb/ft^3)	NR	720–1250 kg/m^3 (45–78 lb/ft^3)	[34[a]]
585–962 kg/m^3 (37–60 lb/ft^3)	784–1250 kg/m^3 (49–78 lb/ft^3)	780–1250 kg/m^3 (49–78 lb/ft^3)	[30]
580–790 kg/m^3 (37–50 lb/ft^3)	780–1020 kg/m^3 (49–64 lb/ft^3)[b]	NR	[12, 13]
550–680 kg/m^3 (34–42 lb/ft^3)	710–760 kg/m^3 (44–47 lb/ft^3)	NR	[13[a]]
480–1040 kg/m^3 (30–65 lb/ft^3)	730–1680 kg/m^3 (45.5–105 lb/ft^3)	640–1040 kg/m^3 (40–65 lb/ft^3)	[35[a]]
980–1460 kg/m^3 (61–91 lb/ft^3)	NR	NR	[31]
480–640 kg/m^3 (30–40 lb/ft^3)	1280–1760 kg/m^3 (80–110 lb/ft^3)	720–1040 kg/m^3 (45–65 lb/ft^3)	[36]

[a] Literature review reported within source.
[b] Refers to packed (tapped) bulk density.

density of SDA material is higher than the bulk density of conventional fly ash because SDA material has a larger fine fraction (78%–80% finer than 40 µm for SDA material vs. 57%–78% for fly ash) [13]. The bulk density of fly ash has been reported as 1000 kg/m^3 (62 lb/ft^3) [41, 42]. The loose, tapped, and compacted bulk densities were similar for fly ash and SDA material containing fly ash ranging from 30–90 lb/ft^3 (480–1440 kg/m^3) overall for the conventional fly ash [36].

Specific Gravity

Specific gravity is defined as the ratio of weight in air of a given volume of solids at a stated temperature to the weight in air of an equal volume of distilled water at the same temperature (usually 20°C). Specific gravity is often used as a method of comparison for engineering materials. This differs from bulk density because only the solid fraction of the material is used; the void fraction is not considered.

Specific gravities reported in the reviewed literature as shown in Table 2-5 range from 2.088 to 2.84. A specific gravity range of 1.5 to 3.1 was reported for fly ash in a previous literature review [31].

Early work performed for a University of Tennessee thesis as summarized in another report indicated that average specific gravities of lignite-fired calcium-based SDA material increased as a function of unreacted sorbent content. The specific gravity of compacted fly ash was 2.52 and for compacted SDA material was 3.14–3.71 [40]. The thesis was not available to EERC researchers for review; therefore, the inconsistency of the data from other available data could not be evaluated.

Table 2-5. Specific Gravity of SDA Material Reported in Literature Reviewed

Specific Gravity	Source(s)
2.29–2.80	[2, 30]
2.088–2.560	[33]
2.3–2.8	[34[a]]
2.29–2.80[b]	[12, 13]
2.48–2.84	[31, 39]
2.50–2.71[c]	[41]

[a] Literature review reported within source.
[b] Used ASTM International D854 (Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer).
[c] Precollection of fly ash; up to 20% fly ash content.

Optimum Moisture Content and Maximum Density

The moisture content of a CCP is a measure of the amount of water present in the voids in the CCP and is expressed as a weight percentage of total dry weight. The natural moisture content is a function of the deposition environment of the CCP and must be determined experimentally for each individual CCP. The natural moisture content of a CCP must be known to calculate the quantity of water that must be added or removed to bring the CCP to its optimum moisture content for compaction.

The optimum moisture content of a CCP is related to the maximum density obtained by compaction in the laboratory. The values of moisture content versus dry density are plotted to form a compaction curve. As indicated by the curve, density is dependent on moisture content. The highest point on the compaction curve corresponds to the maximum dry density and optimum moisture content [31]. Calculations to determine optimum moisture content do not generally allow for the water that will be consumed by the formation of secondary hydrated phases such as ettringite in the use application. Many of these phases contain up to 50% moisture or even higher. The rate of water addition used by engineers in these calculations can lead to incomplete formation of cementitious phases and later expansion caused by delayed ettringite formation. As shown in Table 2-6, the optimum moisture content range reported in the reviewed literature was 10%–63% and the maximum dry density reported in the reviewed literature ranged from 790 to 1860 kg/m^3 (49–116 lb/ft^3).

Table 2-6. Optimum Moisture Content and Maximum Dry Density of SDA Material Reported in Literature Reviewed

Optimum Moisture Content	Maximum Dry Density	Source(s)
40%–68%[a]	833–1056 kg/m^3 (52–66 lb/ft^3)[b]	[38]
28%–63%	790–1300 kg/m^3 (49–81 lb/ft^3)	[43]
16%–60%	880–1630 kg/m^3 (55–102 lb/ft^3)	[34[c]]
16%–38%	1140–1670 kg/m^3 (71–104 lb/ft^3)	[13, 30]
10%–54%	977–1860 kg/m^3 (61–116 lb/ft^3)	[35[c]]
18%–54%	977–1630 kg/m^3 (61–102 lb/ft^3)	[12, 13[c]]
18%–54%	NR	[31]
19%	1610 kg/m^3 (101 lb/ft^3)	[44]
18%–54%	980–1460 kg/m^3 (61–91 lb/ft^3)	[40]
30%–32%[d]	1240–1350 kg/m^3 (77–84 lb/ft^3)[d]	[41]

[a] Weight of water to weight of solids.
[b] Optimum density instead of maximum density.
[c] Literature review reported within source.
[d] Precollection of fly ash; up to 20% fly ash content.

Observations in the literature reviewed include the following:

- Results indicated that the optimum moisture content of the materials increased and the maximum dry density of the compacted material decreased with an increase in the unreacted lime content of the material [40].

- SDA materials had optimum moisture contents higher than the corresponding fly ashes and increased with increasing sulfur content. In contrast, density values at optimum moisture decreased as the sulfur content increased [10].

- Data show that the maximum density is not particularly sensitive to slight variations in the water content in the vicinity of the optimum. Most FGD products can be considered lightweight materials with compacted densities lower than those of a typical natural soil. Lightweight fills impose smaller loads on the natural soils upon which they are placed, resulting in less settlement in the underlying soils and less likelihood that the soils will fail [38].

- Optimum moisture contents of 18%–54%, with an average of 28%, were reported in a previous literature review. Within that same report, the project samples yielded optimum moisture contents of 16%–38%, with an average of 28.5%. These moisture contents represent the amount of moisture added to the dry material even though common practices base the optimum value on moisture content determinations performed after compaction. Moisture content determinations performed during this study used a drying temperature of 110°C, causing hydrated water to be included in the determination. It requires a temperature of over 205°C to dehydrate calcium sulfate completely [13].

The natural moisture content of SDA material has been reported at 1%–5% [31] and with a range of <0.1%–13.2% in previously reviewed literature [35], while the residual moisture of SDA material has been reported to be about 2% [45]. The values reported for optimum moisture content for compaction indicate that a substantial amount of moisture should be added to SDA materials in order to obtain maximum density [12].

Unconfined Compressive Strength

Unconfined compressive strength is usually determined using ASTM International D2166, Unconfined Compressive Strength of Cohesive Soil, or ASTM International D1633, Compressive Strength of Molded Soil–Cement Cylinders. The two procedures are similar except that ASTM International D6133 assumes there is no deformation of the sample during compression and uses its original dimension to calculate unit compressive strength. Results reported in the reviewed literature are summarized in Table 2-7.

Table 2-7. Unconfined Compressive Strength of SDA Material Reported in Literature Reviewed, psi

1-day	7-day	21-day	28-day	56-day	Maximum	Source
NR	NR	NR	51–88	NR	NR	[38]
60[a]	NR	NR	2700	NR	NR	[46]
NR	280–4690	NR	20–790	140–1650	NR	[34]
NR	78–1780	NR	NR	NR	NR	[10]
NR	NR	NR	NR	NR	12–3000	[13[b]]
NR	41–536	81–2250[c]	50–1411	72–1775	NR	[40[b]]

[a] Used ASTM International C109 (Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens).
[b] Literature review reported within source.
[c] Separate sample set.

Typically, the samples continued to gain strength between 28 and 56 days of curing. It was hypothesized that the most probable reason for the wide range of strengths is the difference in chemical composition [13].

It was noted that for low-sulfur SDA materials, a false set may occur as a result of the high calcium and low sulfur content, resulting in disruptive expansion reactions [10]. Strengths were found to increase with curing time, with values being higher after 28 days than after 10 days [38]. The lowest unconfined compressive strength values closely resemble low-strength soil–cement mixtures, and the highest values represent low-strength concrete [40].

Scanning electron microscopy (SEM) confirmed that the presence of unreacted CaO or $Ca(OH)_2$ increases the firmness of the SDA materials. The available moisture dissolves some of the calcium compounds, which then recombine in a pozzolanic reaction with aluminosilicates contained in the fly ash, forming high-specific-volume compounds [40].

Permeability

Permeability is defined as the rate of flow through a material. Permeability coefficients, typically reported in cm/sec, describe flow through a unit area under a unit hydraulic gradient. Hydraulic gradient correlates the forces causing water to flow and the forces resisting flow. A material is considered permeable if it has interconnected pores, cracks, or other passageways through which water or gas can flow. The range of permeability coefficients, or hydraulic conductivities, of fly ash compacted to its maximum dry density is from 10^{-7} to 10^{-4} cm/sec for bituminous fly ashes, 3×10^{-6} to 1×10^{-5} cm/sec for subbituminous ashes, and 1×10^{-7} to 9×10^{-6} cm/sec for lignite ashes [31]. Permeability coefficients for SDA materials from the reviewed literature compiled in Table 2-8 ranged from less than 9×10^{-10} to 6.5×10^{-3} cm/sec.

Table 2-8. Permeability Coefficient of SDA Material Reported in Literature Reviewed, cm/sec

Permeability Coefficient	Source(s)
10^{-9}–10^{-6}	[34[a]]
9×10^{-10}–9.7×10^{-5}	[34]
3.1×10^{-9}–2.7×10^{-7}	[30]
10^{-7}–6.5×10^{-3}	[35]
3.1×10^{-9}–6.8×10^{-7}	[13]
<9×10^{-10}–9.7×10^{-5}	[13[a]]
10^{-7}–10^{-6}	[11, 31, 40]

[a] Literature review reported within source.

Mineralogical and Chemical Composition

Successful engineering applications depend heavily on the mineralogical properties of SDA materials. SDA material has been described as a combination of spherical glassy fly ash particles coated by and intermixed with fine crystals of calcium/sulfur reaction products [13]. Three SDA materials (with up to 20% fly ash) produced in Europe were described as dominated by fine, easily crushed spheres composed of finely aggregated crystals of calcium sulfite hemihydrate [41]. They hypothesized that the spheres were probably formed from the atomized slurry droplets, suggesting rapid water evaporation as the slurry meets the hot SO_2-laden gases. There was also evidence of calcite, gypsum, clay mineral, and quartz, usually coated with a fine layer of sulfite. An SDA material tested consisted of 46% amorphous glassy material, 26.6% hannebachite, 17% mullite, 5.5% hydrated lime, and 3% quartz [47].

The chemical composition of SDA material depends on the sorbent used for desulfurization, the proportion of fly ash collected with the FGD product, coal sulfur content, SO_2 removal, and other factors. Dry FGD materials contain higher concentrations of calcium and sulfur and lower concentrations of silicon, aluminum, and iron than fly ash. The principal reaction product of dry FGD is hannebachite (calcium sulfite hemihydrate):

$$CaO\ (lime) + SO_2\ (g) + \tfrac{1}{2}H_2O = CaSO_3 \cdot \tfrac{1}{2}H_2O \qquad [Eq.\ 1]$$

Under more oxidizing conditions, gypsum (calcium sulfate dihydrate) may also form:

$$CaO\ (lime) + SO_2\ (g) + \tfrac{1}{2}O_2 + 2H_2O = CaSO_4 \cdot 2H_2O \qquad [Eq.\ 2]$$

Sulfite-to-sulfate ratios range from 2:1 to 3:1 [10]. Unreacted sorbent remains as portlandite ($Ca(OH)_2$) in the residuals. At ambient temperature and moist conditions, calcium sulfite ($CaSO_3$) will slowly oxidize to calcium sulfate ($CaSO_4$), and calcium hydroxide will be converted to $CaCO_3$ by CO_2 in the air. SDA material from lime-based systems has similar chemical composition to stabilized wet FGD material [10].

The major constituents of Basin Electric Power Cooperative's pilot SDA material were found to contain 14.6% $CaSO_3$ and 8.9% $CaSO_4$ [39]. The resulting sulfite/sulfate ratio was 1.64. Unreacted lime concentrations were 1.6%, and $CaCO_3$ was 2.1%. Fly ash comprised 71.5% of the material, while the reaction products and unreacted sorbent were the remaining 28.5%.

The weight ratio of fly ash to sorbent-derived material can vary between 0.7 and 8, depending on the composition of the coal [45] and the proportion of the fly ash that is removed before the scrubber. Without precollection, the fly ash proportion will be 70%–85% by weight, producing a spherical grain. When fly ash precollection is utilized, a filter separation efficiency of >80% will produce an SDA material with <30% fly ash, and very good filters (>99%) will produce contents as low as 1%–4% [17]. If fly ash is recovered before the SDA system, then the product consists mainly of irregular clusters of sulfite crystals, forming agglomerates up to 50 µm across [17, 45].

Examples of the composition of SDA material containing fly ash are shown in Table 2-9.

As shown in Tables 2-10 and 2-11, precollection of fly ash does change the composition of the final SDA material. The impact of SO_2 collection efficiency on SDA material composition is shown in Table 2-11.

Chemical Analyses

Bulk chemical compositional data of SDA materials as reported in the reviewed literature are compiled in Appendix A. Conventionally, major/minor components of CCPs are reported as oxides. A typical report may include a weight percent value for SiO_2, Al_2O_3, Fe_2O_3, CaO, SO_3, MgO, Na_2O, K_2O, P_2O_5, TiO_2, BaO, MnO_2, SrO, moisture content, and loss-on-ignition (LOI). These data are summarized in Table 2-12 for SDA material containing fly ash and in Table 2-13 for SDA material with precollection of fly ash.

When reviewing compositional data on CCPs, it is important to understand that reporting of major/minor components as oxides is merely a reporting convention and is not necessarily indicative of the actual chemical forms in the ash. One important example of this is found in the reported calcium oxide concentration. In fly ash or bottom ash, the calcium is usually present as a component of the glassy phase with other elements and is not present as primarily CaO as reported. In FGD materials, calcium is likely associated with sulfur and is present as calcium sulfite or calcium sulfate. When calcium oxide is present as lime in any CCPs and is exposed to water by sluicing or storage in a pond situation, that lime will be converted to calcium hydroxide or hydrated lime. However, the bulk compositional data are useful in evaluating CCPs for various use applications because of the voluminous comparative historical data, empirical evaluations, and comparison with other tests and standards.

Additional chemical parameters were reported as a weight percent of the evaluated SDA material in the reviewed literature. These included $CaSO_3$, $CaSO_3 \cdot ½H_2O$, $CaSO_4$, $CaSO_4 \cdot 2H_2O$, $CaCO_3$, $CaCl_2$, SO_4, organic carbon, total sulfur, free lime, hydroxide, $Ca(OH)_2$, Cl, Ca as available CaO, CO_2, SO_2, SO_3^{-2}, SO_4^{-2}, CO_3^{-2}, Cl^-, loss at 500°C, and loss at 900°C. Loss at

Table 2-9. Typical Composition of SDA Material Containing Fly Ash as Noted in the Reviewed Literature, wt%

Material	From Low-Sulfur Coal	From Low-Sulfur Coal	From High-Sulfur Coal	Five Samples	European Coal
Fly Ash	75	75	40	12–29	20–85
Calcium Sulfite ($CaSO_3 \cdot ½H_2O$)	16	13	38	28–44	9–47
Calcium Sulfate ($CaSO_4$)[a]	6	6	15	6	1.7–17
Unreacted Lime ($Ca(OH)_2$)	2	4	5	10–29	1–15
$CaCO_3$	NR[c]	NR	NR	15–33	4.5–13.7
$CaCl_2$ (calcium chloride)	NR	NR	NR	NR	0.8–6.3
Moisture (free water)	1	2	2	NR	NR
Source(s)	[36]	[10]	[10]	[38, 48]	[49]

[a] Mixed hydrates.
[b] Includes some $CaCO_3$.

Table 2-10. Typical Range of Main Components of SDA Material with Precollection of Fly Ash, wt%

Main Components	Typical Range[a]	Range
Fly Ash/Lime Inerts	3–10	<8
Calcium Sulfite ($CaSO_3$)	55–70	17–68
Calcium Sulfate ($CaSO_4$)	5–15	3.5–29
Unreacted Lime ($Ca[OH]_2$)	2–10	0.5–15
$CaCO_3$	5–15	5–13
$CaCl_2 \cdot n H_2O$	1–4	0.8–9.5[b]
Moisture (free H_2O)	1–3	NR
Source	[16]	[49]

[a] 0.7%–2% sulfur coal and precollection of fly ash with efficient ESP.
[b] Reported as $CaCl_2$.

500°C determines free moisture and moisture of hydration; at 900°C, other compounds such as carbonates decompose to oxides.

The total elemental composition of SDA materials as reported in the reviewed literature is compiled in Appendix B. The highly variable data for SDA material containing fly ash are summarized in Table 2-14.

Table 2-11. Composition (wt%) of SDA Material Overall and as a Function of SO_2 Separation Efficiency. Adapted from Kolar [17].

Main Components	Range with and Without Fly Ash	SO_2 Separation Efficiency[a]				
		90%	85%	80%	75%	70%
Fly Ash/Lime Inerts	0–85	15.4	17.0	19.5	21.0	22.8
Calcium Sulfite ($CaSO_3$)	15–75	33.6	35.8	39.8	40.5	41.5
Calcium Sulfate ($CaSO_4$)	2–30	5.0	5.3	5.9	6.0	6.15
Unreacted Lime ($Ca[OH]_2$)	0–25	38.1	33.4	25.3	22.4	18.8
$CaCO_3$	1–30	NR	NR	NR	NR	NR
$CaCl_2 \cdot 4H_2O$	1–15[b]	4.9	5.5	6.5	7.1	7.75
Moisture (free H_2O)	1–4	3.0	3.0	3.0	3.0	3.0

[a] Prerequisites: SO_2=1600 mg/m^3; fly ash=1000 mg/m^3; and HCl=160 mg/m^3 (all standard temperature and pressure, dry).
[b] Reported as $CaCl_2 \cdot nH_2O$.

Table 2-12. Summary of Bulk Chemical Composition, Reported as Oxides, of SDA Material Containing Fly Ash Reported in Literature Reviewed, wt%

Parameter	Range	Sources
SiO_2	6–46	[2, 14, 30, 31, 33, 34, 35, 40, 44, 49, 50, 51, 52]
Al_2O_3	4–44	[2, 14, 30, 31, 33, 34, 35, 40, 44, 49, 50, 51, 52]
Fe_2O_3	1–44	[2, 14, 30, 31, 33, 34, 35, 40, 44, 49, 50, 51, 52]
CaO	0.2–52	[2, 14, 30, 31, 33, 34, 35, 40, 44, 49, 50, 51, 52]
SO_3	0–32	[2, 14, 33, 34, 35, 40, 44, 49, 50, 51, 52]
MgO	0.1–14	[2, 14, 30, 31, 33, 34, 35, 40, 44, 49, 50, 51, 52]
Na_2O	0.1–46	[2, 14, 30, 31, 33, 34, 35, 40, 44, 49, 50, 51, 52]
K_2O	0.1–6.37	[2, 14, 30, 31, 33, 34, 35, 40, 44, 49, 50, 51, 52]
P_2O_5	0.03–1.2	[2, 14, 31, 33, 35, 40, 44, 50, 51, 52]
TiO_2	0.2–1.19	[2, 14, 30, 33, 35, 40, 44, 49, 50, 51, 52]
BaO	0.39–0.85	[44, 50]
MnO_2	0–0.12	[2,[a] 14, 44, 50]
SrO	0.11–0.46	[2, 44, 50]
Moisture	<0.1–13.2	[31, 33, 35, 40, 44, 50, 51, 52]
LOI or C	0.19–20.5	[14, 31, 35, 44, 50]
Unaccounted	1.7–6.2	[40, 51, 52]

[a] Mn_3O_4

Table 2-13. Summary of Bulk Chemical Composition, Reported as Oxides, of SDA Material with Precollection of Fly Ash Reported in Literature Reviewed, wt%

Parameter	Range	Source(s)
SiO_2	1.4–11.1	[41,[a] 45, 49]
Al_2O_3	0.8–5.4	[41,[a] 45, 49]
Fe_2O_3	0.4–4.4	[41,[a] 45, 49]
CaO	32.9–60	[41,[a] 45, 49]
SO_3	2–30	[41,[a] 49]
MgO	0.4–1.9	[41,[a] 45, 49]
Na_2O	<0.1–0.3	[41,[a] 49]
K_2O	<0.2–0.6	[41,[a] 49]
TiO_2	0–0.2	[45, 49]
LOI or C	1.3–2.1	[45]

[a] May contain up to 20% fly ash content.

The trace metal content of SDA material with precollection of fly ash is, as a rule, lower than that of fly ash and comparable to that of soil [16]. The limited data available in the reviewed literature for SDA material with precollection of fly ash are summarized in Table 2-15. The narrow range of concentrations for each element is within the range for SDA material containing fly ash.

pH

Kost et al. suggest that the pH of dry FGD products depends primarily on the sorbent used and secondarily on the FGD technology [37]. They concluded that the high pH values of most FGD samples were due to the presence of oxides and hydroxides of Ca and Mg. When these products are exposed to water and CO_2, they will convert to carbonates by carbonation reactions and the pH will decrease. The pH values reported in the reviewed literature, shown in Table 2-16, ranged from 9 to 13.

Current and Potential Uses of SDA Material

When SDA material was first produced, there were no obvious uses for it because of the novelty of the process, a lack of applications for the main component calcium sulfite, the undesirable calcium chloride content, a wide range in chemical composition, and the low volume per location [17]. The literature reviewed contained numerous references to current commercial and potential uses of SDA material. Many of the uses have commercial potential but are still in the research and development phase. The following is a summary of current commercial and potential uses of SDA material noted in literature reviewed. It should be noted that this summary is not exhaustive and only represents uses reported in the reviewed literature.

Table 2-14. Summary of Total Elemental Composition of SDA Material Containing Fly Ash Reported in Literature Reviewed, ppm

Element	Range	Source(s)
Aluminum (Al)	10,000–230,000	[12, 13, 30, 31, 35, 37, 46, 53, 54]
Antimony (Sb)	0.8–29	[12, 13, 30, 31, 35, 55, 56]
Arsenic (As)	0.4–1200	[12, 13, 17, 30, 31, 35, 37, 44, 46, 47, 54, 55, 56]
Barium (Ba)	0.76–12,000	[12, 13, 30, 31, 35, 44, 46, 54, 55, 56]
Beryllium (Be)	0.7–63	[12, 13, 30, 31, 35, 37, 46, 54, 55, 56]
Boron (B)	<10–1460	[12, 13, 30, 31, 35, 37, 44, 46, 47, 50, 54, 55, 56]
Bromide (Br)	0.3–21	[31, 35]
Cadmium (Cd)	0.01–70	[12, 13, 17, 30, 31, 35, 37, 44, 46, 49, 54, 55, 56]
Calcium (Ca)	7100–401,000	[12, 13, 30, 35, 37, 46, 53, 54]
Cesium (Cs)	1–22	[35]
Chloride (Cl)	<0.1–10,200	[35]
Chromium (Cr)	3–1000	[12, 13, 30, 31, 35, 37, 44, 46, 49, 54, 55, 56]
Cobalt (Co)	<0.5–172	[12, 13, 17, 30, 31, 35, 37, 46, 54, 55, 56]
Copper (Cu)	3–655	[12, 13, 30, 31, 35, 37, 44, 46, 47, 49, 55]
Fluoride (F)	0.4–1000	[31, 35]
Iodine (I)	0.1–0.6	[35]
Iron (Fe)	6300–367,000	[12, 13, 30, 31, 35, 37, 44, 46, 53, 54, 55, 56]
Lead (Pb)	<0.3–800	[12, 13, 17, 30, 31, 35, 37, 44, 46, 49, 54, 55, 56]
Lithium (Li)	15.1–530	[12, 13, 30, 35, 37, 46, 54]
Magnesium (Mg)	3000–151,300	[12, 13, 30, 31, 35, 37, 46, 53, 54]
Manganese (Mn)	24.5–1432	[12, 13, 30, 31, 35, 37, 46, 47, 54, 55, 56]
Mercury (Hg)	<0.001–10	[12, 13, 17, 30, 31, 35, 44, 46, 49, 55, 56]
Molybdenum (Mo)	<0.018–514	[12, 13, 30, 31, 35, 37, 46, 47, 54, 55, 56]
Nickel (Ni)	1.4–460	[12, 13, 17, 30, 31, 35, 37, 44, 46, 47, 49, 54, 55, 56]
Phosphorus (P)	21–2200	[37, 46, 54]
Potassium (K)	1600–9300	[12, 13, 30, 35, 37, 46, 54]
Rubidium (Rb)	48–530	[35]
Selenium (Se)	<0.4–760	[12, 13, 17, 30, 31, 35, 37, 44, 46, 47, 50, 54, 55, 56]
Silicon (Si)	22,000–157,200	[12, 13, 30, 35, 37, 46, 54]
Silver (Ag)	<0.024–8	[12, 13, 30, 31, 35, 44, 46, 54, 55, 56]
Sodium (Na)	710–240,000	[12, 13, 30, 35, 46]
Strontium (Sr)	30–13,000	[12, 13, 30, 31, 35, 37, 46, 54]
Sulfur (S)	3000–170,000	[37, 53, 54]
Thallium (Tl)	0.1–42	[12, 13, 17, 30, 31, 35, 46, 55, 56]
Tin (Sn)	0.01–962	[12, 13, 30, 31, 35]
Titanium (Ti)	1050–6700	[12, 13, 30, 35, 46]
Uranium (U)	0.8–140	[12, 13, 30, 35]
Vanadium (V)	0.4–950	[12, 13, 30, 31, 35, 37, 46, 44, 54, 55, 56]
Zinc (Zn)	<6–9000	[12, 13, 30, 31, 35, 37, 44, 46, 49, 54, 55, 56]
Rubidium (Rb)	48–530	[35]

Table 2-15. Summary of Total Elemental Composition of SDA Material with Precollection of Fly Ash Reported in Literature Reviewed, ppm

Element	Range	Source(s)
Arsenic (As)	4.8–11	[41[a]]
Barium (Ba)	270–4000	[41[a]]
Boron (B)	100–150	[41[a]]
Cadmium (Cd)	0.9–6.9	[41[a], 49]
Chromium (Cr)	34–60	[41[a], 49]
Copper (Cu)	43–80	[41[a], 49]
Lead (Pb)	28–110	[41[a], 49]
Manganese (Mn)	170–420	[41[a]]
Mercury (Hg)	<0.3	[41[a], 49]
Molybdenum (Mo)	2.7–5.4	[41[a]]
Nickel (Ni)	32–80	[41[a], 49]
Selenium (Se)	3.9–6.5	[41[a]]
Vanadium (V)	60–70	[41[a]]
Zinc (Zn)	94–380	[41[a], 49]

[a] May contain up to 20% fly ash content.

Table 2-16. pH Values of SDA Material Reported in Literature Reviewed

pH	Source(s)
9.7–12.8	[2]
11.8–12.5	[37, 57]
9.3	[47]
9–13	[34[a], 41[b]]
12.4	[53]
11.7–12.4	[39]

[a] Literature review reported within source.
[b] Precollection of fly ash; up to 20% fly ash content.

Agriculture

It is widely know that gypsum ($CaSO_4 \cdot H_2O$) has been used to improve soil conditions for centuries. Gypsum has been shown to improve water retention characteristics, increase infiltration rates, reduce soil crusting, and mitigate salinity and sodicity in alkaline soils or arid and semiarid regions [58]. Studies on the use of FGD gypsum compare it to natural gypsum in terms of the benefits when applied to agriculture soil. Although FGD gypsum is widely used in agriculture, other FGD products, including SDA material, contain very little mineral gypsum; therefore, their suitability for agriculture applications is different and should not be compared to gypsum. ACAA reported 168,190 short tons of FGD gypsum and 846 short tons of dry FGD material were used in agriculture applications in 2006, down drastically from 19,259 short tons in 2005, possibly because of variations in respondents to the ACAA survey [22, 59]. ECOBA reported 36,376 short tons of SDA material used for plant nutrition in 2004 [23]. The low solubility of calcium sulfite ($CaSO_3 \cdot ½H_2O$) in SDA material makes it a poor source of calcium and sulfur for agriculture use. The sulfites may be harmful to plants, by producing hydrogen sulfide gas under anaerobic conditions, unless placed far in advance of planting [60]. However, the substitution of alkaline sulfite-rich dry FGD products for conventional liming materials in agriculture is a potential use for these products, as noted in the research studies summarized below. It is important to note that there are instances in the literature of agricultural use of SDA material in Europe, but the authors focused primarily on literature from the United States.

Calcium sulfite phytotoxicity is a concern when applying SDA material to agriculture soils, as evident below in the literature cited. Strategies for reducing toxicity are also examined. Decreased maize growth was reported in an acid soil when levels of an FGD product containing $CaSO_3$ exceeded 2 g/kg in a soil initially at pH 4.2 [61]. Toxicity from volatile sulfur compounds and increased aluminum toxicity were suspected, but the relative contribution of each could not be quantified. The SO_2^{-3} ion is thermodynamically unstable in the presence of oxygen. It as been reported that rapid $CaSO_3$ oxidation to $CaSO_4$ is expected in the oxidizing atmosphere of most agronomic soils, and additional reactions that generate SO_2 may occur with $CaSO_3$ addition to low-pH media [62]. The oxidation of sulfite to sulfate at near-neutral to alkaline pH values is extremely slow at atmospheric pressure. The fact that oxidation is relatively rapid in soils leads to the conclusion that other mechanisms may play a crucial role. It is likely that in an agricultural soil, fungi, bacteria, and microfauna may aid in the ultimate oxidation of sulfite to sulfate through metabolic processes. Sulfite and SO_2 both are phytotoxic, but toxicity effects may be temporary, subsiding when most SO_2^{-3} has been oxidized to SO_4^{-2} [58]. Research by others indicated that raising the soil pH or allowing oxidation of sulfite to sulfate to occur are two effective strategies for reducing calcium sulfite phytotoxicity [63]. The toxic effects resulting from calcium sulfite use in soils were related to low soil pH and can be considerably diminished by applying an acidity-neutralizing amendment such as hydrated lime. In addition, the oxidation of sulfite to sulfate in water and soil systems can occur in approximately 3–5 weeks. Others also demonstrated that both sulfate and sulfite FGD products can be used to reduce toxicity in acidic subsoil layers. Although short-term phytotoxicity was observed in the sulfite-rich sample, the addition of small amounts achieved the goal of mitigating soil aluminum toxicity and increasing plant growth. This suggests that application of the sulfite-rich sample or similar materials to soils in autumn may improve crop growth the following growing season [58]. The lower toxicity of sulfite in alkaline environments is likely due to the reduced concentrations of bisulfite ions, which are pH-dependent and maximum at below pH 5. Bisulfite combining with atmospheric oxygen is the mechanism used in much of the forced oxidation found in the production of gypsum from sulfite scrubber material.

The impact SDA material has on the environment and plant growth was studied by the University of Georgia and by Argonne National Laboratory. The University of Georgia study showed the incorporation of SDA material into native soils had no impact on germination rates of corn, soybeans, and cotton [47]. Concerning the effect on the elemental composition of plant tissues, arsenic, selenium, molybdenum, boron and, to some extent, calcium increased within all crops grown in Year 1. Tissue concentrations of manganese and sodium decreased, and nickel, lead, iron, and copper levels were not affected. Leachate salinity and soil salinity rose immediately (from 0.2 to 2.9–3.3 dS/m) after the application and remained elevated over the 2 years of the study. The leachate pH was not affected by the application of SDA material, but the application did produce a stable increase in soil pH (from 5.5 to 8.1). Arsenic, selenium, and boron tended to accumulate in the plants. Boron emerged in the leachate, indicating possible impacts to groundwater quality. Plant growth experiments using soil treated with SDA material were conducted at Argonne National Laboratory. Three different soil types and soybean and corn crops were tested, using a combination of SDA material with soil at 0%–4% by weight. For both corn and soybeans, growth decreased as the amount of SDA material increased. Soybeans grown in soil with 4% SDA material exhibited stunted growth when compared to the control crop. For corn, a similar reduction in growth was noticed, although not to the same degree as for soybeans. Boron concentration in the leaves of the corn and soybeans grown in soil treated with SDA material were found to be up to 20 times greater than those found in the leaves of the control grown in soil containing no SDA material [64].

The use of SDA material as a liming agent has been studied. The British Coal Corporation analyzed the use of a European SDA material as a liming agent [41]. Pure limestone has a liming or neutralizing value (calcium oxide content equivalent) of 56, and the SDA material tested had a neutralizing value of 25. The study concluded that if an appropriate amount of the SDA material were added to achieve adequate liming, the recommended upper limits for trace element concentrations in soils after sewage sludge application would not be exceeded. The use of CCPs (including SDA material) as compared to $CaCO_3$ as a liming agent in strongly acidic soils was studied, and it was concluded that CCPs functioned similarly to $CaCO_3$ and that they had very few adverse effects on soil enzyme activities compared with those of $CaCO_3$ [53]. In order of effectiveness for increasing soil pH were FBC ash > LIMB ash > SDA material > fly ash. Because CCPs contain CaO and MgO, the study concluded that it seems likely that the ability of CCPs to act as liming agents may be related to their content of these oxides. For example, the high initial alkalinity associated with the application of CCPs to soil was reduced by conversion of CaO to $CaCO_3$ in soils exposed to atmospheric CO_2. The results of this study also provide information on the use of soil enzyme activities as indicators of soil quality. They clearly demonstrate that caution is required in such use because the relationships between soil qualities are complex and measurements of the changes in enzyme activities without reference to proper controls can be misleading.

Several commercial uses of SDA material in fertilizer applications were identified in Europe; however, the use of SDA material as a fertilizer has not reached the commercial stage in the United States.

Many soils throughout northern Europe are experiencing a growing sulfur deficiency, and therefore, fertilizer companies are increasing the amount of sulfur in commercial fertilizers. The application of SDA material as fertilizer for sulfur deficiency is now permitted in Germany, Denmark, and Austria, as described below [16].

SDA material with low fly ash content has been used as a sulfur fertilizer since 1994 in Denmark, and it has been used as an admixture to and spread with liquid manure. The

Landskontoret for Planteavl (Agricultural Research Institute) has carried out tests that indicate that SDA material, collected without fly ash, is suitable for use on farm soils, and the Danish Ministry of Environmental Protection has given permission for this application, with certain conditions. In commercial applications, the residues are mixed with dolomitic lime to prevent dusting and to allow application of the two materials simultaneously. It is necessary to apply the two materials together because the fertilizing potential of the SDA material is too small to make separate application viable. Dolomitic lime contains magnesium and acts slowly and continuously. The SDA material can also be mixed with liquid manure, agricultural lime, or wastewater sludge [65].

A 3-year VGB Group research project under the "Waste Management of Residues from Coal-Fired Power Plants and Waste Incineration Plants" (known as ERKOM) research program yielded results that gained approval of SDA material as a fertilizer in Germany in 1999 by the Scientific Advisory Board of the Federal Ministry of Agriculture [66, 67]. The minimum sulfur content of a fertilizer of this type is to be 10%, which is achieved by SDA material when the major amount of fly ash is precollected before the SO_2 removal. The German Ministry of Food, Agriculture, and Forestry has specified SDA material as a sulfur–calcium fertilizer in legislation. The SDA material was also licensed in Austria based on the research results in Germany. The total cost of the VGB Group research project of approximately 0.5 million Deutsche Mark (DM) has produced annual savings for the operators in the region of 2.8 million DM [66].

Binders

A novel binder for interior plasters is described in U.S. Patent 5,522,928 using a calcium sulfite component, water, and a finely divided residual material component comprising primarily calcium sulfite. SDA material is called out specifically as the calcium sulfite component [68]. Kolar summarizes a multiphase binder described in German Patent DE 3 82 16 57 C2 [17]. SDA material is mixed with fly ash, and precalcination, oxidation, and calcination are carried out. A salable binder is produced by adding additives and grinding. The use of the product as a flooring binder is considered promising, and other potential applications include use in insulating building materials and raw materials for double floor plates where it may be substituted for cement products. Binder applications have not reached commercialization in the United States.

Cement Manufacture

SDA material has been used commercially to manufacture cement in Germany. A German coal-fired power plant treats SDA material using a fluidized-bed process. Pelletized anhydrite is produced that can be used as a substitute for natural anhydrite in industrial processes such as cement manufacture [69]. Two anhydrite production processes using SDA material are the Fläkt-Dorr-Oliver Process and the Vereinigte Aluminum-Werke AG, Lünen (VAW) Process [17]. Another process used dry FGD material to manufacture cement, once utilized in the Müller-Kühne Process at WSZ Wolfener S.u.Z. in Bitterfeld in Germany [16].

U.S. Patent 4,470,850 claims that a dry FGD material (likely SDA material) can be used in the place of fly ash and gypsum as a solidification regulator in the production of fly ash cement [70]. The essential reaction product in the dry FGD material that functions as the solidification regulator is the calcium sulfite hemihydrate. Although this application appears to be technically feasible, no dry FGD material has been reported as used for cement manufacture in the United States since 2003 [71].

Cement Replacement in Concrete

Research has been conducted on the use of SDA material as a concrete admixture. Below is a summary of the research studies found in the literature reviewed, which consisted primarily of European sources. It is not known if the limited amount of literature pertaining to commercial or demonstrated use of SDA material as a concrete admixture is due to technical constraints or a lack of market development. ACAA reported 9660 short tons of dry scrubber FGD material used in concrete, concrete products, and grout in 2006 [22].

Research carried out at KEMA, Netherlands, has investigated the use of SDA material as a partial replacement for sand and cement in concrete [45, 72]. The SDA materials tested had no precollection of fly ash and contained a mixture of about 70% fly ash and 30% sorbent reaction products. For initial comparative tests, 20% of the portland cement in the concrete was substituted by SDA material. Except for a slight retardation in setting times, concretes in which cement was partly substituted by SDA material, showed strength and durability performances comparable to or superior to reference concretes. No destructive ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$) reactions were observed in tests carried out with an exposure time of 2 years. The presence of chloride was noted in some SDA materials, restricting their application in reinforced concretes [45]. The study concluded that the compositions could be applied successfully to concrete products, but that further verification under real conditions was required. Long-term tests were still being carried out when the report was published.

A demonstration project was carried out by the Technical University of Denmark to assess the use of SDA material as a cement and concrete admixture [73]. Three precast, reinforced concrete front elements containing 20 and 30 wt% SDA material were manufactured. Additives, such as superplasticizers and an air-entraining agent, were added to some specimens. After a period of 1 year, corrosion tests indicated a low probability of corrosion for most of the specimens. The results suggest that when SDA material is used as an admixture in mortar to replace part or all of the usual fly ash, increased compressive strength is achieved. The grain size of the SDA material has some influence on strength. Progressive substitution of cement by SDA material will result in gradually decreasing strength. During this project, it was found that the mineral thaumasite ($Ca_3Si(CO_3)(SO_4)(OH)_6 \cdot 12H_2O$) formed under certain conditions. Because thaumasite greatly reduces the strength of cement and concrete, the project was abandoned.

A review of studies in Europe by Kolar indicated that nonreinforced concrete might be a more suitable application for SDA materials than reinforced concrete [17]. Chloride poses a risk of corrosion of steel reinforcement. Concrete pipes produced containing SDA material in Austria had swelling attributed to the formation of ettringite. Prevention of this was not successful. Additionally, the product was not frost-resistant. It was concluded that these factors limited the use of SDA material-containing concretes in building to solid or hollow bricks for interior walls or backing. Dry storage of the bricks would also be necessary.

The use of dry FGD material as a raw material for cellular or gas concrete was studied in Denmark and Poland [16]. Cellular concrete is made of cement and/or white lime and ground quartz sand and steam-hardened at 180°–200°C (356°–392°F), resulting in a porous structure. There are over 20 factories for the production of cellular concrete in Poland, many of which use fly ash as a raw material. Testing has concluded that the addition of approximately 20% dry FGD material is positive and that it can be used for cellular concrete manufacturing. However, the market incentive is low, and further development work is required. Earlier work in Denmark used up to 30% SDA material, resulting in problems including chlorine corrosion in the autoclaves and thaumasite formation [17].

Two sources of SDA material and one source of limestone FSI product were tested for partial cement replacement in concrete. The products were substituted for 30 wt% Type I cement. Three product concrete mixtures, one fly ash concrete mixture, and one control concrete mixture were prepared. One SDA sample met the ASTM International C618 criteria except for SO_3 content, which was higher than the criterion. The other SDA material and the limestone FSI product did not meet ASTM International C618 criteria for silica, alumina, iron oxides, SO_3, and LOI. However, for all samples, their fineness and pozzolanic activity indices met ASTM International C618 criteria. In addition, the autoclave expansion test results were within the ASTM International C618 limits. The concrete mixtures made with SDA material achieved a higher compressive strength than that of the control mixture at all testing ages (3, 7, 28, and 90 days). The SDA mixtures had longer setting times than the LIMB mixtures and controls [34].

In one project, portland cement concrete incorporated with 10% SDA material was used on a test section of road pavement [46]. Prior to the field placement, laboratory specimens were made using 5% and 10% SDA material. Laboratory and field results indicated that compressive strengths increased with increased percent of SDA material for all test ages (7, 14, 21, and 28 days). A comparison of the laboratory and field concrete mixes shows a similar 28-day compressive strength.

Civil Engineering

Dry FGD material, including SDA material, mixed with fly ash has been used commercially in civil engineering in Europe and has been a topic of study in research projects. Civil engineering applications including landfill construction, embankments, structural fill, and road base have been documented in the literature. ECOBA reported 61,729 short tons of SDA material used for general engineering fill in 2004 [23]. ACAA reported 249 short tons of dry scrubber FGD material used in the road base/subbase/pavement category but no use in the structural fill/embankment category in 2006 [22].

In Nordic countries, there are six blending stations at coal-fired power plants blending dry FGD material and fly ash, sometimes with the addition of cement. These blends are referred to in the literature generically as stabilisate product.[1] An example is Cefill (or Cefyll), produced by the Swedish company Cementa AB, which was developed in the 1980s and has been producing

[1] This is similar to the process used in the United States whereby wet FGD material is mixed with fly ash to produce fixated scrubber solids (FSS) or Pozzotec.

Cefill since at coal-fired combined heat and power (CHP) power plants in Västerås, Sweden. Three qualities of Cefill are typically produced with 30%–70% dry FGD material, 30%–70% fly ash, and 0%–8% cement. Compressive strengths vary from 5 to 30 MPa (725–4350 psi) and water permeabilities vary from 10^{-10} to 10^{-12} cm/sec. A similar stabilisate product called REALIT is produced at coal-fired power plants in Dürnrohr, Austria [16].

A few commercial examples of the use of Cefill and REALIT as a capping material are provided by Bengtsson [16]. Cefill has frequently been used as a bottom- and top-capping material for hazardous waste such as metal ore mine residues and as a vertical seal for preventing horizontal groundwater flow contamination. Many other projects have been carried out in Sweden based on the tight and flexible nature of the cured Cefill material. REALIT was used to seal off a sludge deposit.

The construction of road dams, filling of foundation cavities and cable trenches, and sealing of waste disposal sites using Cefill are applications that have been abandoned in Denmark but are being intensively pursued in Sweden and Finland [17].

In Europe, stabilisate products have been used extensively as a base course material in applications such as storage areas, coal yards, road banks, parking lots, and noise protection walls. An example is a 2-km-long road built at a coal-fired CHP station in Finland using a 1-m-thick layer of a 50% dry FGD material and 50% fly ash without cement addition covered with 0.5–1.5-m fly ash and a 0.24-m layer of crushed stone [16]. This test road has been tested annually for important engineering parameters. Results have been very satisfactory, showing high frost resistance. REALIT was used in the base liner of a squeezed sewage sludge disposal site in Austria [74].

A common European application of stabilisate products is for landscaping and land reclamation [16]. Examples include fill for reclamation of destroyed land and old/closed quarries, fill in an area behind a new quay in a harbor, and reclamation of lignite pit mines. It is common practice to recultivate the top surface of reclaimed land with a layer of soil for planting trees and grass.

In addition, utilization of a stabilisate product is under consideration in the Czech Republic as embankment material for roads and railways.

The fine-grain Dutch SDA material is suitable for use in the stabilized layer of road construction, whereas the artificially prepared grains (lumps) did not meet Dutch standard technical requirements [45]. However, research in Denmark has shown that problems may occur with swelling during application as a foundation material [65]. The expansion of several types of FGD materials was measured, and it was concluded that compacts containing SDA material, alone and in combination with fly ash, expanded by less than 0.2% after a year of exposure, with no evidence of structural deterioration after that time [41].

The use of SDA material in a truck ramp for vehicles to unload trash [57]. Difficulties in achieving uniform conditions during construction were experienced; however, no problems with performance and no evidence of failure were reported.

Dawson et al. evaluated literature on the potential for SDA material to be used as structural fill and concluded that all but the nonreactive SDA material has potential to be used as a structural fill [10]. For reactive SDA material, compressive strengths in excess of 2000 psi can be achieved, whereas low-reactive SDA material strengths greater than 100 psi can be expected.

Swell properties of the material and the strength that can be achieved when compacted are factors in the application of FGD materials for engineering purposes. Swelling primarily occurred in FGD samples containing free lime and occurred in two episodes [38]. The first episode occurred almost immediately upon water addition and is attributed to hydration reactions such as the hydration of lime (CaO) to portlandite ($Ca(OH)_2$) and of anhydrite ($CaSO_4$) to hemihydrate ($CaSO_4 \cdot ½ H_2O$). The second swelling episode usually began after about 10 days and is thought to be a result of the formation of secondary minerals such as ettringite. The strengths achieved varied when FGD samples were compacted at optimum water content.

The use of SDA material for cured compacted products suitable for use as landfill materials, embankments, roadbase compositions, and similar applications is described in U.S. Patent 4,354,876 [8]. It is specifically stated that the material used is obtained from a lime-based dry-scrubbing FGD operation containing fly ash. The material is mixed with water and compacted under sufficient load to achieve at least 70% of the laboratory dry density. The resulting cured compacted products have compressive strengths of at least ~25 psi and permeabilities of less than 1×10^{-5} cm/sec. The process of the invention is designed to take full advantage of the unique self-bonding capabilities of the material. The SDA material may need to be conditioned for this use. Cementitious additives may be required for unreactive to moderately reactive SDA materials.

A test road used SDA material in the pavement layers, the pavement, the subbase, and the embankment [46]. SDA material proved useful; especially as replacement for common earthen borrow material[2] in embankments. The granular and select granular borrow material met or exceeded Minnesota Department of Transportation (MnDOT) specifications. Environmental testing showed the placement had no adverse impact on groundwater quality; however, barium in the SDA material–common borrow mixture slightly exceeded Minnesota drinking water limits. Although the placement was successful from an engineering and environmental standpoint, it did not offer economic advantages because additional costs were incurred for mixing and transporting the SDA material. The SDA material might have an economical advantage if lime or lime kiln dust was required for borrow stabilization.

In Kansas, SDA material (containing about 80% fly ash) has been mixed with dry economizer ash, moistened with water, and used to create a lining layer (~1.25 m thick) for a landfill site. The conditioned SDA material was spread in layers about 0.5–0.75 m thick and compacted to give a layer with a permeability of $<10^{-6}$ cm/sec. Wet boiler slag was brought separately to the landfill and encapsulated in the conditioned SDA material [65].

[2] Earthen borrow is sand, gravel, or other material used for grading.

Flowable Fill

Flowable fill is a material that flows like a liquid, is self-leveling, requires no compaction or vibration to achieve maximum density, and hardens to a predetermined strength [28]. Controlled low-strength material (CLSM), controlled density fill (CDF), and infill are names used to describe flowable fill that comprises a blend of cement, fly ash, sand, and water. ACAA and ECOBA have reported commercial uses for dry scrubber FGD material (9843 short tons in 2006) and SDA material (45,195 short tons in 2004), respectively, in flowable fill applications [22, 23]. Research conducted to date indicates that SDA material can be an effective component in the production of flowable fill.

The potential for SDA material to be used in flowable fill as a replacement for conventional fly ash was examined. The design mixes consisted of varying amounts of SDA material, cement, lime, admixtures, and water. The mixes were tested in the laboratory for flowability, unity weight, moisture content, unconfined compressive strength, erodiblity, set time, penetration, and long-term strength characteristics. Tests were conducted for up to 90 days of curing. The study concluded that flowable fill containing SDA material can be an economical alternative to conventional materials. SDA flowable fill mixtures tested gained good strength (400 psi obtained in 1–2 days for standard flowable fill and 400 psi obtained in 1/3–6 hours for quick-set flowable fill) and had excellent placeability. The authors suggested, especially for high-cementitious-content flowable fill, that long-term strength tests be conducted to estimate the potential for later excavation. Furthermore, chemical reaction and mechanisms that accelerate initial set time need to be studied. Long-term strength tests for more than 1 year are needed, and full-scale field tests would be valuable. Resilient modulus, stress–strain behavior, freeze–thaw, swell potential, and corrosivity characteristics also need to be studied [75].

Others mixed SDA material with an additional fly ash and stabilized the mixture by adding about 3 wt% lime kiln dust [76]. The stabilized product was either used as a flowable fill or left in a storage yard for several years. Samples extracted from these sites were analyzed using x-ray diffraction and scanning electron microscopy. The analytical results show the formation of thaumasite, ettringite, and an intermediate phase with varying chemical composition of calcium, aluminum, silicon, and sulfur. Ettringite and thaumasite are not present in CCPs but are secondary minerals formed from the reaction of the CCPs with water. Most of the thaumasite formed in the system was growing directly from the gypsum matrix. Thaumasite was also growing in the void space. Thaumasite grown in the system occur as short, stubby crystals. Ettringite crystals, on the other hand, grow in isolated pockets when the conditions of a saturated lime environment are available.

Fixating Agent for Waste

SDA material, and other alkaline-rich FGD materials have the potential to solidify or fixate wastes. Alkaline FGD materials may be useful to stabilize metals in acidic hazardous wastes that have reduced solubilities at higher pH, such as cadmium, iron, manganese, zinc, copper, and cobalt [34]. Waste sludge stabilization is similar to soil and road base stabilization; however, since the sludges generally have a high moisture content and low solids content, more FGD material needs to be used to fixate waste. Research studies that have evaluated the use of SDA material as a fixating agent for waste are summarized here.

The great fineness of SDA material, especially with low fly ash content, yields a high water retention capacity, which could be used for the thickening of sewage sludge and river or harbor silt. Some applications have been successful; however, negative experiences have occurred in Denmark because calcium hydroxide appears to cause early hardening [17].

In one study, different waste materials (cadmium and chromium plating precipitation sludges, waste oil digestion sludge, and a sedimentation slurry from an aluminum can reclamation center) were mixed with SDA material [77]. In all mix designs, a ridged structural material evolved as a result of the expansive and pozzolanic reactions occurring from the wetted SDA material. Structural and physical characteristics and leaching were evaluated. The cadmium plating waste–SDA material mix exhibited a 7-day unconfined compressive strength of up to 5.221 MPa (759 psi) and the chromium plating sludge–SDA material mix reached 7.587 MPa (1103 psi). The SDA material mixed with water exhibited a 7-day unconfined compressive strength up to 5.035 MPa (762 psi). The unconfined compressive strength for weak concrete is 10.346 MPa (1504 psi). The raw and waste materials fixated with SDA material were leached with acetic acid and with deionized water. The SDA material did not leach above Resource Conservation and Recovery Act (RCRA) regulations. The cadmium waste and aluminum can-processing waste heavy metal leaching characteristics were reduced from hazardous to nonhazardous by fixation with SDA material, as was chromium plating waste at mass ratios of 1:1, 2:1, and 25:1 (SDA material to dry chromium waste). The oil sludge was not affected by SDA material fixation with regard to inhibiting leaching.

A study on the leachability of SDA material from Argonne National Laboratory concluded that if proper fixation techniques can be developed, SDA material has the potential to be used as an impounding agent in the codisposal of chemical wastes containing lead, cadmium, and other elements whose leachability decreases with increasing pH [64].

A laboratory study conducted at the Western Research Institute evaluated the ability of FGD materials to stabilize the organic and inorganic constituents of hazardous wastes. Two sources of atmospheric fluidized-bed combustion (AFBC) material and two sources of SDA material were used in this study, and four types of hazardous waste streams were obtained including separator sludge, mixed metal oxide–hydroxide waste, metal-plating sludge, and creosote-contaminated soil. Each product was mixed with each hazardous waste, allowed to equilibrate, and then leached using the toxicity characteristic leaching procedure (TCLP). It was found that chromium was leached from both SDA material-stabilized mixtures. However, the products tested can be used to stabilize the cadmium found in the metal oxide–hydroxide hazardous waste. Mineralogy tests were performed on a number of products and hazardous waste mixtures. Quartz and ettringite were the most dominant mineral phases; others included gypsum, portlandite, and calcite [34].

This application has not reached commercialization in the United States.

Marine Applications

It has been suggested that SDA material could be used in marine applications such as artificial reefs and offshore sea defenses, although ACAA does not report this as a separate use application. The literature reviewed, and summarized here, showed positive results when reefs and blocks were prepared using SDA material and placed in a seawater environment. All studies showed that artificial reefs and blocks could provide a favorable habitat for marine life without adverse impacts to the environment. Tests carried out in the United Kingdom by the Coal Research Establishment show that blocks containing SDA material, exposed to both tidal and totally submerged conditions, showed no evidence of surface friability or cracking [41]. Block weights generally increased with time to levels compatible with water adsorption values found in laboratory tests. The strength of blocks containing a proportion of portland cement and fly ash increased compared with those containing only SDA material, but all specimens behaved adequately. Similarly, the Marine Sciences Research Center conducted an investigation on the preparation and evaluation of blocks prepared from a variety of CCPs and placed in a seawater environment. Testing indicated that properly designed reef blocks possessed adequate structural integrity for marine environments, exhibited no adverse environmental effects, and functioned acceptably as habitat for marine life [10, 78]. Dump blocks from SDA material and fly ash mixtures bonded with 7.5% portland cement were produced. It was indicated that the blocks could be used for artificial reef construction. The compressive strength was 5 Nm/m^2, and very low leaching was observed [45].

Masonry

SDA material has shown promise for use as a raw material to manufacture masonry products; however, only one reference to the commercial manufacture of masonry was found in the literature. Based on results by KEMA and on further testing in Germany, considerable amounts of dry FGD material were used in German and Dutch sand–lime brick manufacturing [16]. However, the manufacturing of sand–lime bricks seems to have ceased (as of the writing of that report). Detailed information of the application is limited, both for competitive reasons and because of the risk of unfavorable publicity regarding the use of “waste products” in a high-quality application. ACAA reported 9660 short tons of dry scrubber FGD material used in concrete, concrete products, and grout in 2006 [22].

International patent WO 82/00819 and U.S. Patent 4,377,414 describe a method to use SDA material in the production of shaped cementitious products such as pellets, bricks, tiles, and blocks [79, 80]. The method uses a closely controlled compaction process. First, an SDA material containing fly ash is uniformly contacted with a critical amount of water and then immediately compacted at a critical compaction ratio to provide a manageable green body in which the fly ash particles are positioned with respect to one another so that the interstitial spaces are sufficient to accommodate the volumetric changes in the cementitious materials without any deleterious expansion of the product. The product is then cured in as little as 2 days at 120°–180°F (49°–82°C).

Evaluation of the use of SDA material in sand–lime bricks has been carried out in the Netherlands by KEMA [45, 81]. Sand–lime bricks are made of fine white lime and high-quartz sand molded, pressed, and steam-cured in autoclaves at 175°–214°C (347°–417°F). About 3000 sand–lime bricks were manufactured and tested. The test bricks were manufactured with mixtures of SDA material and fly ash replacing about 20% of the sand in the conventional bricks. The quality of the bricks containing SDA material was satisfactory in comparison to conventional bricks, with higher compressive strength and splitting-tensile strength. The results were good with respect to compressive strength and splitting-tensile strength, porosity, and absorption coefficient with capillary action of water. No efflorescence was found when only moderate amounts of sodium sulfate (<0.4 wt%) or potassium sulfate (<2.2 wt%) were present. The carbon content of the fly ash must be limited to <7 wt%. The oxidation rate of calcium sulfite to calcium sulfate is extremely low, particularly in air. SDA materials have also been used in the manufacture of sand–lime bricks in Germany [69]. It has been noted that laboratory tests showed that the best results were obtained by replacing 50% of the sand with SDA material containing 70% fly ash [17]. For the pressing of solid bricks, it is necessary to reduce the SDA material proportion to 20%.

Mineral Wool

SDA material can be used to manufacture mineral wool used in insulation and ceiling tiles, as described in the research study conducted by the EERC. SDA material with a high level of fly ash was used to prepare mineral wool in a pilot-scale cupola furnace. The SDA material was formed into balls, melted at 2600°–3000°F (1430°–1650°C) in the cupola, and fiberized by means of a compressed airstream. The mineral wool product was easily fabricated and appeared to be comparable in fiber diameter to that of commercial mineral wool [82]. There were no reported commercial uses of this application in the United States, and ACAA does not report this as a separate use application.

Mining Applications

One large-volume use for alkaline, dry FGD material is in reclamation of acidic minespoils. Dry FGD material could be used to neutralize the spoil acidity and reestablish the vegetative cover to stabilize soils and reduce erosion [83]. It has been indicated that SDA material could potentially be used in a grout mix design to fill mine voids [34]. ECOBA reported 181,881 short tons of SDA material used for mine reclamation and restoration in 2004 [23]. Mining applications are the largest reported use of dry scrubber FGD material in the United States. ACAA reported 115,696 short tons of dry scrubber FGD material used in mining applications in 2006 [22].

Brendel et al. summarized the findings from an EPRI study entitled *Advanced SO_2 Control By-Product Utilization: Laboratory Evaluation*, EPRI CS-60443 [34]. In this study, grout mixes were prepared with cement and FGD materials (including SDA material) at various proportions with sufficient water to achieve a flow in the range of 5–35 seconds. Three mix designs were created with SDA material including 3:1, 1:1, and 1:2 (cement to SDA material) ratios. Data show increased strength gain from 7 days [2.3–16.1 MPa (334–2335 psi)] to 28 days [4.5–26.1 MPa (652–3785 psi)]. Data show that more cement does not always improve strength.

SDA material has been used as a mine fill in the United States and Europe. Instances cited in literature are described below.

A former limestone room and pillar mine in Sugar Creek, Missouri, is being stabilized using up to 700 tons of SDA material per day. The SDA material is mixed with water to create a slurry that is injected into the mine through 10-inch-diameter cased boreholes drilled through 160 feet or more of overburden. Because this particular SDA material contains ammonia, ventilation during mine stabilization was provided by constructing steel reinforced shotcrete walls between selected pillars to control airflow. As of September 2002, over 71,000 tons of the SDA material/water slurry had been injected into the mine [84].

In North Dakota, SDA material (containing about 75% fly ash) has been mixed with wet bottom ash to a water content of 20%–25% and used to backfill an old lignite strip mine. The mine was lined with clay (0.5–1.5 m thick) and capped with a clay layer (~1.5 m thick), overburden, and top soil [65].

In Germany and Poland, SDA material has been used successfully in the mining industry as filler in packing and backfill operations and as an additive in mining mortars [16, 69]. SDA material has been used in the backfilling of gravel pits without bottom sealing in Austria. Mining mortar from SDA material and fly ash was used in 1990 in Germany for the construction of underground retaining walls, for backfilling and consolidation, and for special uses. The use of SDA material for filling abandoned tunnels in lime, ore, and coal mines has been officially sanctioned and approved by German court decisions (OVwG (Oberverwaltungsgericht: Administrative Court of Appeals) Saarlouis, File 1-W 125/89; 1 F 17/89) [17].

Soil Stabilization

SDA material has physical and chemical characteristics similar to those of a lime–fly ash mix and, thus, has the potential to be used in soil stabilization. The ability for the SDA material to form ettringite without swelling is key to its engineering performance. It also needs to be durable enough to withstand potential damage due to freezing and thawing and wetting and drying action. ACAA reported 299 short tons of dry scrubber FGD material used in soil modification and stabilization in 2006 [22]. Soil stabilization with SDA material has been documented in only a few laboratory and field demonstration projects.

OSU performed laboratory experiments to characterize the engineering properties of silty clay stabilized with SDA material and FSI products. Tests were conducted to evaluate compressive strength, permeability, swelling potential, compressibility, and leachate composition. These tests were performed on compacted samples of SDA material–soil mixtures at the optimum moisture content. The FGD materials tested substantially improved the strength and stiffness of soil, which was dependent on the mix ratio. All stabilized soil mixtures developed strength of at least 0.69 MPa (100 psi) by 28 days. Generally, the permeability of the stabilized soil decreased with time as a result of the chemical reaction occurring within the mixture. Every sample showed an increase in volume over time due to ettringite formation. Consolidated test results showed low compressibility of stabilized soils. The concentration of heavy metals in the leachate was considerably lower compared to EPA drinking water standards [34].

ICF Northwest Inc. performed tests on a variety of FGD materials, including SDA material, mixed with A-7 clay, with and without additional lime. Soil had a liquid limit of 28.5 and a plastic limit of 24. The mixtures consisted of a) 90% soil, 7% FGD material, and 3% lime; b) 90% soil and 10% FGD material; and c) 90% soil, 7% fly ash, and 3% lime. The 28-day compressive strength of SDA material mixed with lime was 4.34 MPa (630 psi) and without lime was 2.83 MPa (410 psi) [34].

Sulfuric Acid Production

The Müller-Kühne process is based on Müller's tests to produce sulfuric acid from anhydrite and Kühne's idea to produce cement at the same time by adding carbon (coke), clay, and sand. As early as 1985, investigations were started to substitute natural raw materials with products such as SDA material [17]. Dry FGD material was processed into sulfuric acid in the Müller-Kühne Process at WSZ Wolfener S.u.Z. in Bitterfeld in Germany until recently [16]. No information was found to indicate why this process is not currently used.

No instances of sulfuric acid production research in the United States were noted in the reviewed literature, and ACAA does not report this as a separate use application.

Synthetic Aggregate

The production of synthetic aggregate using SDA material has been demonstrated in several countries on a commercial level. However, other commercial attempts have not been as successful or were only demonstrated on a laboratory scale. Production methods tend to use mixtures of fly ash and SDA material, either pelletized or briquetted. Most synthetic aggregates are lighter than natural aggregates, and are suitable for the manufacture of lightweight precast products such as roofing tiles, masonry blocks, or as a concrete and asphalt paving material. Although synthetic aggregate was not reported as an application for SDA material by ACAA in 2006 [22] or ECOBA in 2004 [23], numerous instances of commercial use and research projects were noted in the reviewed literature.

In the United States, a manufacturing plant is being operated at the Birchwood Power Facility by Universal Aggregates, LLC. The plant is turning CCPs, including SDA material, into 1,667,000 tons of lightweight aggregate annually [85]. The process used by Universal Aggregates, LLC, is described in U.S. Patent 6,054,074 [86]. The method mixes a sulfur-containing CCP, recycle fines containing calcium hydroxide, an aluminum-containing material, and water to produce an agglomerated product. This is then combined with curing fines that contain calcium oxide and is cured. The cured material is screened to separate dry fines, which are recycled, and the aggregate, which is used as a product. CCPs used in the method can include wet FGD material with fly ash, dry FGD material such as SDA material, wet lime kiln dust with dry lime kiln dust, or FBC material with fly ash. Specifications are provided for the various materials. Further investigation of the end product is being conducted by the Research and Development Department of CONSOL Energy (CONSOL R&D) with Universal Aggregates, LLC, under a DOE cooperative agreement. The objective is to conduct a systematic study of the durability of manufactured aggregates using a variety of CCPs, including SDA material, with different chemical and physical properties. The manufactured aggregates and aggregate product materials were tested under different freeze–thaw, wet–dry, and long-term natural weathering conditions [33].

Sherburne EnviRock initiated production of manufactured, lightweight aggregate intended for use in the concrete masonry block market in 2001. A year later EcoBlend, a concrete mineral admixture also intended for use in concrete masonry, was added to production. SDA material containing fly ash is used as the primary feedstock [87].

A study performed by ICF Northwest Laboratory to produce synthetic aggregate from five different FGD materials, including SDA material, using two production processes: 1) agglomeration followed by sintering and 2) briquetting followed by CO_2 environment curing. The SDA material and FSI material produced the strongest briquettes, with an average strength of 10.71 and 7.43 MPa (1554 and 1077 psi), respectively [34].

SDA material was used as an aggregate in asphaltic concrete pavement in a test road. Type 31B base course and Type 41A wear course mixes were made in the lab with 5% SDA material and 5.5% or 5.8% asphalt, respectively. The asphalt content needed to be decreased to meet MnDOT air void specifications. However, no conclusions can be drawn from these data, because it was difficult for the batch operators to meter the amount of SDA material and other aggregates used. An addition of 5% of SDA material caused a decrease in both stability and percent air voids compared to the control mixes. It was noted that less compactive effort was required to achieve the 95% of maximum density when using the SDA material containing bituminous material [46].

Synthetic aggregate production using the Aardelite process has been used commercially to manufacture synthetic aggregate. Aardelite is a proprietary technology owned by Danieli Corus but licensed to Aarding Lightweight Granulates B.V. in the Netherlands. The technology and equipment are sold by Aarding Lightweight Granulates B.V. to power plants. To date, four Aardelite plants have been built [88]. To make Aardelite, SDA material can be mixed with water and pelletized [65]. The pellets are then embedded in fly ash, so the final pellet has a core of SDA material surrounded by fly ash. The composite pellets are hardened with steam at 90°C and size-graded by sieving. The four plants use a different embedding material. However, according to a company representative, there are no commercial plants using SDA material in operation [89]. Aardelite pellets can be used as raw material in a variety of building applications including the following [88]:

- Masonry (building) blocks
- Ready mix concrete
- Prefabricated concrete elements
- Concrete piles
- Bitumen-bonded asphalt for road construction
- Paving stones

It has been suggested that these aggregates could also be used in structural concrete. However, research carried out in Denmark by ELSAM indicates that the pellets do not have sufficient strength for this application [65]. When mixed with fly ash, the SDA material can form the mineral thaumasite, which has poor strength characteristics. Low-grade aggregates and pellets may be suitable for use in road base and as filler in asphaltic concrete.

Research initiated in Denmark has examined using the self-hardening properties of SDA material to form pellets [36]. Additives, such as portland cement or hydrated lime, may be added to SDA material with a low reactivity so that the pellets acquire adequate strength and density. Pellets (5–15 mm) were manufactured in the laboratory using a continuous roll mill pelletizing machine, and cured in a water-saturated environment. Despite encouraging results, the demonstration work did not result in the commercial production of aggregates.

It is possible to produce artificial gravel and chippings by mixing SDA material with 10%–20% water and compacting it in a pelletizing plant to a density of 2 t/m^3 and curing. A 5% addition of cement is required for low-fly ash SDA materials. The artificial gravel and chippings can be used as a substitute for natural gravel or chippings for cement or bitumen-bound road surfaces and cement-bound building brick. Development work in Denmark has been discontinued because of long setting times, reduced frost resistance, and an increase in volume due to thaumasite formation [17].

Wallboard

The use of SDA material in wallboard has been demonstrated in Denmark by DURACON ApS [65]. The process uses the same production facilities as other fiber–cement boards that are fire-resistant. The boards consist of a mixture of SDA material (~40%), fly ash (~10%), recycled paper (10%), cement, and additives. The finished panels should be cured in an autoclave. The raw materials are low in cost, minimizing production costs compared with similar wallboards. The panels are strong enough, with sufficient stiffness, for normal handling and working, and fire resistance tests show good performance. The product was undergoing full-scale testing in 1992, with a potential daily production capacity of about 4000 m^2 of board. Instances of this product reaching full commercial implementation were not found.

Kolar also reported that several authors have described the production of wallboard made of SDA material, fly ash, fibers, and portland cement or lime hydrate [17]. The board is autoclaved and dried. The boards are claimed to be suitable for interior applications in residential buildings, hospitals, schools, and industrial buildings.

ACAA has not reported dry scrubber FGD material use in wallboard applications since dry scrubber FGD materials have been categorized.

Wet FGD Sorbent

Dry FGD material is used as a sorbent in the wet FGD process in both Germany and Denmark; although it has not reached commercialization in the United States [16, 22]. The excess alkali in the dry FGD material serves as a sorbent for the SO_2 in the flue gas, and the sulfite in the material is simultaneously converted to commercial-grade gypsum. A prerequisite for this use is a very low fly ash content. It has been reported that the gypsum quality has improved when operating on dry FGD material as compared to using limestone powder and typically contains 98%–99% calcium sulfate dihydrate (gypsum) [16].

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

An extensive literature review was performed that provided information on:

- SDA systems and their operation and the impacts of system components and operation on the SDA material composition.
- The production and use statistics for SDA material produced in the United States and Europe.
- SDA material characteristics.
- Commercial and potential uses of SDA material.

The literature review brought into focus several issues evident to producers and users of SDA material that have an impact on the status of this material in commercial markets. These issues are summarized here and include a list of barriers to the commercial utilization of SDA material.

SDA Production and Material Characteristics

SDA systems have two primary configurations. In the United States, the most common system configuration has the spray dryer chamber located so the flue gas is combined with the sorbent before it is introduced into the primary particulate collection system. In this configuration, the fly ash and dry SDA material are mixed in the spray dryer chamber, and in cases where the fly ash is alkaline, the fly ash actually serves as a sorbent so the fly ash particles are coated with calcium sulfite/sulfate. Recycle of this mixture is frequently used to optimize sorbent utilization. Variables in this system include the amount of fresh lime sorbent that is introduced, the fly ash characteristics, the recycle rate, and the spent sorbent–fly ash ratio.

The typical European SDA system configuration includes a fly ash precollection unit that removes the fly ash from the flue gas before it enters the spray dryer chamber. The variables in this system configuration are fewer resulting in a more consistent material between plants.

The SDA material that results from these two primary system configurations have obvious compositional differences. The systems with fly ash precollection produce an SDA material that is composed primarily of calcium sulfite, calcium sulfate, and other minor calcium-based compounds. The systems that incorporate the fly ash stream into the sorbent stream in the spray dryer chamber produce SDA materials that are composed of these same calcium compounds with fly ash that may or may not be coated with calcium sulfite or sulfate, depending on the alkalinity and composition of the fly ash. Even without accounting for varying chemical composition of the fly ash, it is apparent that SDA materials produced from these two configurations will be significantly different in composition performance. In European literature, SDA materials are frequently referred to as dry FGD material. This term is used more generically in the United States but does include SDA material. Unfortunately, in most of the literature reviewed, the system configuration was not described nor was the percentage of fly ash, if present, noted. However, the variability of the materials investigated and/or used is evident in the results of the literature review by the variability of the composition and properties reported. Wide variability for these materials was documented for every physical property for which literature was found and for the chemical composition to include the trace element concentrations. Although mineralogical characterizations were limited, it is expected that similar crystalline phases would be present in all types of SDA materials, but that those with fly ash present would also contain a significant amorphous phase. On review of the characterization data from the literature review, it was noted that varying conclusions were drawn by individual authors. The variability of samples used in the studies likely contributed to the divergence in conclusions. Another factor that likely played a role in the differences was the methodology used to evaluate specific parameters. This serves as a caution in relating literature data and conclusions as representative of SDA materials without a clear understanding of the specific material(s) referred to in the literature.

Utilization of SDA Material

As described in Section 2 under "Current and Potential Uses of SDA Material," SDA material is commercially used in a variety of applications in the United States and Europe. A review of the ACAA production and use survey results also provides an indication of utilization in the United States. These applications are noted in Table 3-1.

The utilization profiles for SDA material in the United States and Europe are different at least in part because of the different chemical composition resulting from the inclusion of fly ash in the United States, while in Europe, SDA material typically does not include a fly ash component. Additionally, the more stringent European disposal regulations encourage utilization of CCPs, and likely encouraged utilization of SDA materials. Some commercial applications, such as mine fill and wet FGD sorbent, may have less stringent composition or quality control criteria.

Table 3-1. Commercial Applications for SDA Material in the United States and Europe

European Commercial Applications	U.S. Commercial Applications
Agriculture (e.g., sulfur fertilizer)	Agriculture
Flowable Fill	Concrete, concrete products, and flowable fill
Raw Material for Cement Manufacture	Soil stabilization
Raw material for Sulfuric Acid Production	Structural fills/embankments
Wet FGD Sorbent	Synthetic aggregate[a]
	Mining applications

[a] Although not listed in the 2006 ACAA statistics [22], this is a current SDA material use.

Based on the commercial applications reported and research on utilization of SDA material, a list of applications was assembled, ranking applications as having high, moderate, and low potential for the U.S. market relative to the technical achievability of the applications. Key technical issues that were considered in ranking these applications were:

- Variability of SDA materials – Most U.S. current and projected SDA systems incorporate some fly ash into the final SDA material. The level of fly ash present and the specific chemistry of that fly ash results in a variability in the chemical composition of the final SDA material, and that is expected to result in a variability in the physical and engineering performance of the material for many of the use applications noted.

- Sulfur content – Since SDA is used to remove sulfur gases from flue gas, the total sulfur content of SDA materials can be significantly higher than fly ash. For some applications, this elevated concentration of sulfur may limit the use. Additionally, most of the sulfur present in SDA material is present both as sulfite and as sulfate, with sulfite being the prevalent form. For some applications, the potential for oxidation of the sulfite to sulfate could limit use of SDA materials and needs to be considered.

- Potential for expansion – SDA material that contains fly ash has the potential to expand, especially when exposed to water. The composition of SDA materials containing fly ash includes the primary building blocks for ettringite formation, a key secondary hydrated phase that can cause expansion if it forms in finished products or final placements. The pH of SDA material is not considered conducive to ettringite formation, but free lime present in SDA material may provide enough alkalinity to allow ettringite formation to occur. Expansion needs to be considered in any use applications for SDA material. While expansion can be predicted by use of appropriate tests, many tests currently available for determining expansion potential may not be adequate to predict field or full-scale performance. This is due to many factors, but laboratory studies indicated that expansion may be taking place into material voids. A simple test based on density changes of materials that will with great certainty predict expansion under laboratory conditions has been developed by the EERC [90].

Economic feasibility was not used in this ranking process, but in order for any material to be commercially viable in a utilization application, the economics need to be advantageous and should be considered in feasibility investigations. For some applications, the environmental suitability of SDA materials, or any other CCP or industrial resource, may need to be evaluated. Environmental performance of SDA materials was outside the scope of this literature review, but the issues associated with use applications that may result in impacts to human health and the environment are prevalent in public reports and technical literature.

High-Potential Applications

High-potential applications for the U.S. market are estimated to be those that take advantage of the presence of the fly ash component of the SDA material, can tolerate relatively high sulfur content, and have limited susceptibility to expansion or reduce expansion potential in the production process. These applications fall into two categories: 1) cementitious products and 2) mining.

Cementitious Products

ACAA's 2005 utilization rate for dry scrubbing materials in concrete and concrete products was ~14,000 tons, or ~1% of the 2005 U.S. production. It is unlikely that this utilization rate includes significant quantities of sodium-based dry scrubber materials because of the technical and performance issues associated with high levels of available alkali in materials used for formulation of concrete. Therefore, it is assumed that the 2005 1% utilization rate refers almost exclusively to SDA material. Anecdotal evidence suggests that this utilization is likely primarily in concrete products such as masonry. ACAA also reported that nearly 10,000 tons of dry scrubbing materials were used for flowable fill in 2005 (0.7% of the amount produced) [59]. It is also assumed that the bulk of the dry scrubber material reported in flowable fill is also likely SDA material. Literature and anecdotal evidence indicated that some of these cementitious products or applications have specific requirements for the SDA material to be used most effectively. It is predicted that these use applications have high potential for growth as more SDA materials become available. Based on the prediction of 13–14 M tons of SDA material to be produced annually in the United States by 2017, it is estimated that the utilization rate should be maintained at the current approximate 2% level and could reach 5% or higher of production if industry develops technical and performance data and markets the product effectively. This equates to about 260,000 to 700,000 tons annually. Location of material and markets will have a definitive impact on market development and penetration. Much of this growth is anticipated after 2012 as installations increase in number.

Masonry

Although SDA material has been shown to be an effective component of masonry products, most commonly concrete blocks, the SDA material may need to be conditioned prior to use, and cementitious additives may be required for unreactive to moderately reactive SDA materials. Use of alkaline activation and the elevated-temperature curing of these products has been shown to result in good performance of the SDA material in these products.

Flowable Fill

The basic physical and engineering properties (moisture density, compressive strength development, and permeability) of reactive and low-reactivity SDA material indicate that these materials should be able to perform acceptably as flowable fill material. Research conducted to date supports this claim and shows that SDA material can be an economical alternative to conventional materials; however, more research is needed on nonreactive SDA materials. It is recommended that more long-term tests be conducted to test long-term strength, stress–strain behavior, freeze–thaw properties, swell potential, and corrosivity.

Synthetic Aggregate

SDA material is currently being used to manufacture synthetic aggregate in the United States; however, there is also evidence that some synthetic aggregate-manufacturing processes developed to use SDA material have not had commercial success. Successful aggregate production from SDA material indicates the potential for use in concrete block, brick, and other shaped compacted product production. Much like the masonry application, it may be necessary to activate the SDA or use an elevated-temperature curing to facilitate good product performance.

Mining Applications

SDA material has been used commercially as a mine fill. Additionally, SDA material has been shown to be capable of neutralizing the spoil acidity and reestablishing vegetative cover to stabilize soils and reduce erosion. However, excessive application on mine spoils did cause excessively high pH and cementation. The technical issues associated with the use of SDA material in mine applications can be addressed through an understanding of the experience already reported in the literature, characterization of the material, and careful attention to the methods for applications and quantities of material applied. Statistics from 2005 indicate that approximately 8% of dry scrubber materials produced in the United States were used in mining applications [59]. This represented by far the largest current use of dry scrubber materials. It is reasonable to assume that much of the dry scrubber materials included in the 2005 statistics were SDA materials simply because of the very limited number of other dry scrubber systems currently being used as compared to SDA systems reported. Since projected SDA installations are expected to be in the Midwest and western United States, it is likely that mining applications of SDA materials will remain a good utilization candidate and will increase proportionately to the amount of material produced in the western states. Contingent on rules currently under development by the Office of Surface Mining, it is anticipated that the utilization rate of 8% can be readily maintained and could be expected to increase to 15% during the period from 2007 to 2012. During that period, most of the new installations will be in western states, where mine placement is expected to be economically feasible. Between 2012 and 2017, this use application could continue to increase but on a more limited basis because later SDA installations are anticipated to be in the Midwest and the advantage of location is not expected to favor mine reclamation as much as western installations. It is estimated that a maximum utilization rate of 20% could be realized by 2017. This would equate to 2.6–2.8 million tons annually, a more than 10-fold increase over current utilization volumes.

Moderate-Potential Applications

Cement Replacement in Concrete

SDA material should be evaluated for suitability as a cement replacement in concrete, especially as groups like ASTM International and the American Association of State Highway and Transportation Officials (AASHTO) move toward performance-based specifications as opposed to prescriptive specifications. Research has shown that except for retardation in setting times, concrete in which cement was partially substituted by SDA material showed strength and durability performance comparable to superior to traditional concrete. This application is most promising when SDA material and fly ash are collected together with a high percentage of fly ash, as is common in U.S. installations. The technical issues that require some continued evaluation can be readily addressed using protocols similar to the ones developed and used for fly ash and other supplementary cementitious materials. It will be possible to determine the appropriateness and amounts of specific SDA materials for use in concrete, and there is technical evidence that it can offer good performance. Much like fly ash qualification for use in concrete, the producer or potential marketer will need to take the responsibility of evaluating their specific material, developing the market, and educating the users. This process will require time, so although the market has high potential to be technically successful, it is expected to take time to develop that market.

The potential for large volumes of SDA material to be used in this application will likely be dependent on a number of factors, including potential reductions in the availability of fly ash for use in concrete, which is expected to be impacted by the installation of mercury control technologies that use activated carbon and combine the activated carbon with the fly ash stream. If even some of the current concrete-quality fly ash being produced becomes unsuitable for use in concrete, there may be a market need for alternate materials. Of course, if activated carbon is used and mixed with fly ash on a unit or plant where the fly ash is incorporated into the SDA material, the SDA material may not meet the required specifications for use in concrete.

Current data on dry FGD material utilization do not separate use in concrete or concrete products. It is estimated that only very low quantities of SDA material (<0.5%) are currently being used for cement replacement. This utilization rate is not expected to increase significantly, but at the predicted production rate for 2017 (13–14 M tons/year), a use rate of 0.5%, or 65,000–70,000 tons, would be significant for the overall use of the material.

Engineering Applications

SDA material has been used commercially in engineering applications in Europe and with limited success in the United States. ACAA reported 2666 tons of dry FGD material was used for structural fills and embankments in the United States in 2005 [59]. This utilization rate of approximately 2% was likely primarily SDA material and indicates that SDA can be successfully utilized in engineered fills. This utilization rate would be expected to be maintained as additional SDA materials are generated.

Agriculture

In Europe, SDA material is typically collected separately from fly ash, whereas in the United States, SDA material and fly ash are often intermingled. This difference could be the reason that SDA material is used commercially as a sulfur fertilizer in Germany, Denmark, and Austria, but not in the United States. There are unanswered engineering and environmental questions as well. The potential for SDA material to be used as a liming agent or for soil amendment has received mixed results depending on the pH of the soil, crops planted, amount of SDA material used, and whether the SDA material was blended with any other material. The leaching of boron could be a potential environmental concern. ACAA reported ~19,000 tons of dry scrubber material used in agricultural applications in 2005, nearly 1.5% of the total production of ~1.4 million tons [59]. This represents the second largest current use of dry scrubber material. It is likely that the dry scrubber material used in agricultural applications was SDA material because the sodium-based dry scrubber materials have potential detrimental effects on many crops and soil types. An effort is currently under way in the United States to demonstrate the effectiveness of FGD gypsum for use as an agricultural soil amendment. Even though SDA material contains fly ash and calcium sulfite, which makes it different from FGD gypsum, the potential for SDA material to be used in agricultural applications may be enhanced by the current efforts on FGD gypsum use. The agricultural use of calcium sulfite, which is toxic to plants under certain conditions, appears to be less problematic than initially expected. Under normal soil pH and with a limited supply of air for oxidation, it would be expected that the oxidation of sulfite to sulfate, which is not toxic to plants, would be extremely slow. However, in field studies, this conversion occurs rapidly. This anomaly is likely due to microbial transformations of sulfite to sulfate. It has been demonstrated that simply placing the sulfite-rich material in the agricultural soils a few weeks in advance of planting mitigates any detrimental effects of sulfite. There is moderate potential for SDA material to be used in agriculture in the western United States, where FGD gypsum is expected to be less available. The trace element concentrations of SDA materials are likely one technical and regulatory issue that will need to be addressed. Utilization rates are predicted to be maintained at near 1% based on the increased production.

Soil Stabilization

SDA material has physical and chemical characteristics that are similar to a lime–fly ash mix and, thus, has the potential to be used in soil stabilization even though mixed results have been found in the expansion potential of SDA material used as a road foundation. The ability for the SDA material to form ettringite without swelling is key to its engineering performance. It also needs to be durable enough to withstand potential damage due to freezing and thawing and wetting and drying action. Soil stabilization with SDA material has been documented in only a few laboratory and field demonstration projects, and no commercial uses were found in the reviewed literature even though marketers indicated the successful use of specific SDA materials in soil stabilization in certain regions of the United States. There is the potential for the technical issues related to the use of SDA material in soil stabilization to be addressed, so this application has moderate potential. Currently, there is only anecdotal evidence of SDA material being used for soil stabilization in the United States, but if the technical issues are adequately addressed, it is projected that the utilization rate could reach 0.5%–1.0% of the production rate.

Wet FGD Sorbent

Dry FGD material has been used commercially as a sorbent in the wet FGD process in Germany and Denmark. Since there is alkalinity still available in SDA material, it is possible that it could be a good candidate for use in wet FGD systems in the United States, likely in inhibited or natural oxidation systems. The technical issues would need to be addressed, and the actual use would likely be dependent on locations of an SDA producer and wet FGD system. Currently, there is no SDA material being used in this application, but it could reach a utilization rate of up to 1% or greater by 2017. This application warrants investigation to evaluate the impact of the presence of fly ash in the SDA material, and it is likely that this application has the highest potential for a region where an SDA material producer and wet FGD system user are in close proximity.

Low-Potential Applications

The following applications are expected to have low utilization potential. Predictions for utilization rates have not been made.

Binder

SDA material used as a binder for interior plasters was noted in U.S. and German patents. The use of SDA material as a flooring binder is considered promising, and other potential applications include use in insulating building materials and raw materials for double-floor plates where it may be substituted for cement products. This is a promising low-volume, high-value application.

Cement Manufacture

Although SDA material has been used commercially to manufacture cement in Germany, it has not reached the demonstration phase in the United States. A process has been patented in the United States to use dry FGD material in place of fly ash and gypsum in the production of cement; however, it is not anticipated that the process will reach commercialization.

Fixating Agent for Hazardous Waste Sludge

Research has shown that SDA material has the potential to solidify or fixate hazardous wastes if proper fixation techniques can be developed. The mechanism for this is likely due to the excess alkaline materials present in SDA material. Although SDA material particles are generally coated with sulfite and sulfate, the grinding action of a pug mill would likely activate the material by exposing alkaline surfaces through abrasion of particles.

Marine Applications

Research conducted to date has shown that SDA material can be used in marine applications such as artificial reefs and offshore sea defenses. SDA materials exposed to marine environments appear to show no evidence of surface friability or cracking and are a favorable habitat for marine life. The economical and environmental feasibility of this application should be further evaluated.

Mineral Wool

The production of mineral wool from SDA material is technically feasible if the SDA material contains a high percentage of fly ash. However, the market is not demanding this process at this time.

Sulfuric Acid Production

The use of SDA material in the production of sulfuric acid may be technically feasible; however, the authors believe this is not an economical beneficial use option.

Wallboard

Using SDA material as a source of gypsum in traditional wallboard is not a promising utilization option. However, research conducted in Denmark showed that SDA material, when mixed with fly ash, cement, and other additives and cured in an autoclave can produce good-quality fiber–cement board. The economics of this application need to be considered.

Barriers to SDA Material Utilization

The European and U.S. production and utilization statistics for SDA material clearly indicate that SDA materials are currently underutilized, especially in the United States, even though this report summarized a number of commercial applications and several applications that have high potential to become commercial. The literature reviewed brought into focus the barriers that exist and limit the use of SDA material in the United States. The barriers identified by the authors are:

- **Inconsistent Terminology Used to Define the Material –** In the literature reviewed, there was a marked inconsistency with regard to the terms used to describe SDA materials and FGD materials in general. The discrepancies were so broad that, in some cases, the EERC technical staff performing the review could not determine the specific product to which the authors referred. Inconsistent terminology makes it difficult for those in the industry, particularly government entities, to define the material and its potential uses properly. In any area, a well-defined vocabulary is the cornerstone of effective communication, and this is essential in technical fields. This lack of consistent terminology is a barrier to both the commercialization and to the research and development of SDA material utilization.

- **Lack of Understanding of the Material –** The successful management of SDA material requires a thorough understanding of the engineering and chemical properties of the material. Although a number of references were identified that considered the characterization of the material as it relates to potential uses, the engineering and chemical properties of specific materials need to be investigated further. As with other CCPs, it is difficult to generalize the properties of the material because of differences in coal type, combustion system, collection process, and management. As previously noted, SDA materials exhibit a variability that results from the system configuration and the percentage of fly ash present in the final SDA material. Potential uses that apply to one type of material may not be appropriate for others. The natural oxidation of sulfite to sulfate in SDA material is documented and yet the impact of this oxidation process on product performance is not well-defined and needs to be considered in evaluating utilization applications.

- **Limited Data on Environmental and Health Effects –** Although all SDA materials encountered in this literature review meet regulatory limits for classification as nonhazardous wastes, there are still concerns about surface water and groundwater contamination by runoff, seepage, and leachate during disposal or use applications. Many potential uses for SDA material fall under the general category of land application, which raises questions about the potential for the material to affect the environment and/or human health.

- **Inconsistent Guidelines on Beneficial Ash Use –** Many state rules apply to fly ash, bottom ash, and boiler slag utilization; however, products from FGD systems are relatively new in comparison to other products, and specifications have not been written that deal specifically with SDA material. In European countries where regulations have been adopted, most progress has been made with regard to SDA material utilization.

- **Economics –** Economic factors are an overriding issue in utility ash management decisions. Currently, the potential to produce revenue from the sale of SDA material is limited; therefore, most utilities find it more economically feasible to dispose of the material rather than dedicate resources (i.e., employees and infrastructure) to utilize it. The prices received for SDA material are simply too low to justify a large financial commitment to SDA material marketing. In some countries in Europe, increasing landfill taxes have driven the development of SDA material applications.

Conclusions

The literature assembled and reviewed provided a good representative cross section of the technical information available on the utilization of SDA material in the United States and Europe. The following conclusions were developed based on the information assembled from the review:

- SDA materials exhibit a broad variability based on the SDA system configuration, the fly ash content of the SDA material, the composition of the fly ash in the SDA material, and the use of optional sorbent recycle.

- The presence of significant levels of calcium sulfite and the natural oxidation of sulfite to sulfate has the potential to affect the material performance in utilization applications and products.

- European SDA materials, frequently referred to as dry FGD material in the European literature, generally do not incorporate fly ash into the final SDA material, and documented commercial utilization of SDA material in Europe is higher than in the United States.

- U.S. SDA systems typically incorporate fly ash into the final SDA material and are most commonly used in coal-fired units where alkaline ash is produced so the fly ash can also act as an SO_2 sorbent.

- U.S. SDA material utilization rates are lower than European utilization rates, likely because of higher variability of the U.S. material, incorporation of fly ash into the material, and current regulations in Europe that promote industrial resource utilization.

- Numerous utilization applications have high to moderate potential for commercialization in the United States, but technical, environmental, and economic evaluations will likely be needed before these materials can be successfully introduced into the markets identified.

Recommendations

As U.S. coal-fired power plants install additional FGD systems to reduce SO_2 emissions in coming years, it is anticipated that a number of plants will elect to use SDA systems, resulting in an associated increase in the volume of SDA material produced in the United States. Although disposal is currently the predominant management option for SDA material in the United States, the potential exists that viable commercial options can be developed for this material. In order to optimize SDA material use in existing commercial applications and develop the potential commercial options in the United States, technical, environmental, and economic evaluations will be required. The following recommendations present an outline for the CCP industry to maintain existing commercial markets and develop new markets for U.S. SDA materials:

- Work within existing organizations such as ASTM International and ACAA to develop and put into use appropriate terminology and definitions for SDA materials.

- Develop an understanding of the impact of compositional variability on the performance characteristics of SDA materials.

- Develop an understanding of the oxidation profiles of SDA materials and evaluate the impacts of oxidation on product performance.

- Educate potential users, regulatory representatives, and other stakeholders about SDA materials.

- Address quality, compositional, environmental, and performance criteria in research, development, and demonstration efforts.

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APPENDIX A

BULK CHEMICAL COMPOSITION, REPORTED AS OXIDES, OF SDA MATERIAL REPORTED IN LITERATURE REVIEWED

Table A-1. Bulk Chemical Composition of SDA Materials Containing Fly Ash Reported in Literature Reviewed

Source	[2]	[14]	[30]	[31]	[33]	[34]	[35]	[40]	[44]	[49]	[50]	[52]
No. of Samples	3	2–5	7	Unknown	2	Unknown	up to 7 of 24 References for Each	Unknown	1	Unknown	1	1
Units:	wt%, dry basis	wt%, dry basis	wt%	%	wt%, dry basis	%	%	%	wt%	wt%	wt%	wt%, dry basis
SiO_2	38.78–46.26	22.05–33.10	16–26	21.1–32.4	24.05–30.22	16–32	6–68	21.1	26.52	10–40	32.0	21.5
Al_2O_3	17.51–20.57	9.84–18.26	6.3–13	8.5–23	11.52–15.89	6–23	4–44	8.5	8.26	6–15	15.3	10.7
Fe_2O_3	2.83–3.63	2.55–5.82	1.6–7.7	4.2–6.8	2.21–3.79	2–8	1–44	6.8	4.91	1.5–5	3.8	6.4
CaO	13.12–18.34	21.59–29.27	18–31	19.7–32.2	25.66–34.13	18–32	0.2–52	18.1	27.16	20–28	24.1	28.4
SO_3	3.35–10.07	5.96–20.05			7.92–11.98	6–22	0–32	3.4	16.48	1–10	13.0	24.3
MgO	1.34–1.47	2.18–4.33	0.65–4.6	5.8–6.0	0.89–3.90	0.6–6	0.1–14	5.8	4.62	0.5–1.5	2.9	0.73
Na_2O	1.02–1.39	0.49–1.52	0.9–46	2.7–4.7	0.13–1.82	0.9–5	0.2–28	4.7	2.60	0.1–0.4	1.67	0.25
K_2O	0.83–0.97	0.36–0.50	0.2–0.84	0.37–0.5	0.43–1.10	0.2–0.8	0.1–6.37	0.5	0.87	0.5–1.5	0.52	0.81
P_2O_5	0.68–1.18	0.15–1.10		0.4	0.03–1.01		0.2–1.2	0.4	0.09		0.43	0.27
TiO_2	0.54–0.70	0.41–1.16	0.27–0.92		0.57–1.19		0.5–1.0	0.5	0.41	0.2–0.8	0.67	0.45
BaO									0.85		0.39	
MnO_2	0.03[a]	0.00–0.12							0.09		0.10	
SrO	0.11–0.19								0.46		0.44	
Moisture				1–5	1.22–1.71		<0.1–13.2	1.3	1.10		0.55	0.61
LOI or C		0.19–6.90		0.8			0.32–20.5		1.64		1.41	
Unaccounted								1.7				6.2
$CaSO_3$					11.89–17.96[b]			14.6				
$CaSO_3 \cdot ½H_20$							13–59					
$CaSO_4$							6–43	8.9				
$CaCO_3$							2.1	2.1				
$Ca(OH)_2$					8.5–25.0[c]		4–21					
Free Lime								1.6				
Ca as Available CaO							0–5.4					
SO_4			12–22									
SO_2							0.1–20.5			5–25		
CO_2		1.77–7.54					<0.1–15[d]					
Hydroxide			0.45–8.2			0.5–10	<0.1–9.5					
Cl										0.5–4		

[a] Mn_3O_4

[b] Based on total sulfur content in ash

[c] Based on thermogravimetric analysis (TGA) or lime index measurement

[d] Carbonate, as CO_2

Table A-2. Bulk Chemical Composition of SDA Materials with Precollection of Fly Ash Reported in Literature Reviewed

Source	[41]	[45]	[49]
No. of Samples	3[a]	4	Unknown
Units:	wt%, dry basis	wt%	wt%
SiO_2	7.9–10.6	1.4–11.1	<2.5
Al_2O_3	4.1–4.7	0.8–5.4	<1.5
Fe_2O_3	1.9–4.4	0.4–1.8	<0.7
CaO	33.6–37.8	32.9–46.9	35–60
SO_3	17.4–30.0		2–17
MgO	1.0–1.9	0.4–1.7	<0.8
Na_2O	0.2–0.3		<0.1
K_2O	0.3–0.6		<0.2
TiO_2		0.0–0.2	<0.1
LOI or C		1.3–2.1	
Na_2O/K_2O		0.2–0.8	
$CaSO_3 \cdot ½H_20$		50.0–62.0	
$CaSO_4 \cdot 2H_2O$		4.5–10.0	
$CaCO_3$		0.5–12.5	
$CaCl_2$		0.6–7.2	
$Ca(OH)_2$		2.4–18.9	
Free Lime	<0.5–4.0		
SO_4	7.0–24.6		
SO_2			9–40
Total Sulfur	9.3–15.7		
CO_2	10.6–20.1		
C (org.)	0.1–0.2		
SO_3^{-2}		29.7–38.8	
SO_4^{-2}		2.5–6.9	
Cl	0.93–3.0		0.5–6
Cl^-		0.4–4.6	
CO_3^{-2}		0.3–7.5	

[a] May contain up to 20% fly ash.

APPENDIX B

TOTAL ELEMENTAL COMPOSITION OF SDA MATERIAL REPORTED IN LITERATURE REVIEWED

Table B-1. Total Elemental Composition of SDA Materials Containing Fly Ash Reported in Literature Reviewed

Source:	[12, 13]	[17]	[30]	[30]	[31]
No. of Samples:	8	1[a]	8	8 (by AA)	Unknown
Units:	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Aluminum (Al)	33,300–66,700		33,300–66,700		18,000–110,000
Antimony (Sb)	5.6[b]–29		5.6[b]–29		7.5–8
Arsenic (As)	3.6–48	0.4–380	<12–22[b]	3.6–48	14.2–47
Barium (Ba)	190–3090		190–6060		100–2000
Beryllium (Be)	1.4–3.1		0.8–3.1		4–63
Boron (B)	<10–230		<10–230		500
Bromide (Br)					0.3–21
Cadmium (Cd)	0.2[b]–0.63	0.1–5	<0.4–5.8	<0.2–0.63	0.5–70
Calcium (Ca)	14,300–223,000		126,200–223,000		
Cesium (Cs)					
Chloride (Cl)					
Chromium (Cr)	36–210		36–210		27–130
Cobalt (Co)	9.9–26	<0.5–62	9.9–26		4.8–80
Copper (Cu)	20–160		20–160		8.1–170
Fluoride (F)					0.4–1000
Iodine (I)					
Iron (Fe)	10,900–53,700		10,900–53,700		10,000–367,000
Lead (Pb)	<0.3–19	4–550	<16–44[b]	<0.3–14	4.4–150
Lithium (Li)	18–42		18–42		
Magnesium (Mg)	3880–27,700		3880–27,700		
Manganese (Mn)	55–680		55–680		45–630
Mercury (Hg)	<0.05–0.39	<0.1–10		<0.05–0.39	BDL–0.5
Molybdenum (Mo)	2.7–514		2.7–514		0.5–33
Nickel (Ni)	17–110	1.4–125	17–110		13–460
Phosphorus (P)					
Potassium (K)	1760–7020		1760–7020		
Rubidium (Rb)					
Selenium (Se)	<0.4–7.3[b]	3–34	71[b]–283	<0.4–7.3[b]	4.7–20
Silicon (Si)	72,800–120,000		72,800–120,000		
Silver (Ag)	1.6[b]–5.8		1.6[b]–5.8		0.2–0.5
Sodium (Na)	6540–34,000		6540–34,000		
Strontium (Sr)	184–3040		184–3040		84–2500
Sulfur (S)					
Thallium (Tl)	<18	<10	<18		20–30
Tin (Sn)	<19–349		<24–349		30–36
Titanium (Ti)	1610–5360		1610–5360		
Uranium (U)	<5–140		<25–140		
Vanadium (V)	72–180		72–180		0.4–610
Zinc (Zn)	22–110		<6–79		12–330

[a] High fly ash.
[b] Indicates less than 5 times the detection limit.

Continued…

Table B-1. Total Elemental Composition of SDA Materials Containing Fly Ash Reported in Literature Reviewed (continued).

Source:	[35]	[37]	[44]	[46]	[47]	[49]
No. of Samples:	Unknown	13	1	1	1	Frequent Conc.[c]
Units:	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Aluminum (Al)	18,000–230,000	10,000–86,000		92,100		
Antimony (Sb)	0.8–20					
Arsenic (As)	2.3–1200	6.9–165	28.7	4	68.9	
Barium (Ba)	20–12,000		0.76	3200		
Beryllium (Be)	0.94–63	0.7–9.6		3		
Boron (B)	10–1300	292–948	1460	650	42.1	
Bromide (Br)	0.3–21					
Cadmium (Cd)	0.01–70	1.1–40.7	0.88	<4		0.1
Calcium (Ca)	7100–360,000	178,000–401,000		159,400		
Cesium (Cs)	1–22					
Chloride (Cl)	<0.1–10,200					
Chromium (Cr)	3.6–1000	11.4–56.3	14	62 [Cr(VI): <6]		3
Cobalt (Co)	4.8–172	8.0–20.8		<20		
Copper (Cu)	7.1–655	13.3–73.2	30	61	111	3
Fluoride (F)	0.4–1000					
Iodine (I)	0.1–0.6					
Iron (Fe)	6300–367,000	19,000–51,000		29,300		
Lead (Pb)	3.1–800	6.5–139	16.3	<20		5
Lithium (Li)	48–530	15.1–90.5		110		
Magnesium (Mg)	3000–22,000	3800–151,000		17,900		
Manganese (Mn)	24.5–1432	43–501		680	200	
Mercury (Hg)	<0.005–2.5		0.631	<0.02		<0.1
Molybdenum (Mo)	0.5–110	<0.02–50.2		<20	32.8	
Nickel (Ni)	1.8–460	12.4–58.9	13	<20	64.7	2
Phosphorus (P)		21–1752		2200		
Potassium (K)	1700–9300	1600–5000		4700		
Rubidium (Rb)	48–530					
Selenium (Se)	0.6–760	4.9–23.0	5.4	<4	29.2	
Silicon (Si)	70,000–99,000	22,000–137,000		157,200		
Silver (Ag)	0.04–8		0.20	<4		
Sodium (Na)	710–240,000			13,500		
Strontium (Sr)	30–13,000	153–1370		4300		
Sulfur (S)		42,000–163,000				
Thallium (Tl)	0.1–42			<1		
Tin (Sn)	0.01–962					
Titanium (Ti)	1050–6700			3700		
Uranium (U)	0.8–30					
Vanadium (V)	0.4–950	22.5–83.9	49.7	86		
Zinc (Zn)	12–9000	52–266	25	70		15

[c] Multiplying or dividing by 2 can give the range

Continued…

Table B-1. Total Elemental Composition of SDA Materials Containing Fly Ash Reported in Literature Reviewed (continued).

Source:	[50]	[53]	[54]	[55]	[56]
No. of Samples:	1	1	13	1–19	1
Units:	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Aluminum (Al)		24,000	10,000–86,000		
Antimony (Sb)				3.81–6.19	3.8
Arsenic (As)			6.9–165.5	13.9–82.0	13.9
Barium (Ba)			100–2400	139	139
Beryllium (Be)			0.7–9.6	2.19–2.24	2.2
Boron (B)	1352		292–948	982–1329	1329
Bromide (Br)					
Cadmium (Cd)			1.1–40.7	0.55–1.54	0.55
Calcium (Ca)		245,000	178,000–401,000		
Cesium (Cs)					
Chloride (Cl)					
Chromium (Cr)			11.4–56.3	25.3–42.8	35
Cobalt (Co)			8.0–20.8	13.4	13.4
Copper (Cu)			13.3–139.0	71.8	
Fluoride (F)					
Iodine (I)					
Iron (Fe)		36,000	15,000–51,000	24,825	24,825
Lead (Pb)			6.5–139.0	18.6–59.57	21.1
Lithium (Li)			15.1–90.5		
Magnesium (Mg)		11,000	3800–151,300		
Manganese (Mn)			43–501	558	558
Mercury (Hg)				<0.001–2.553	0.015
Molybdenum (Mo)			<0.018–50.2	13.2	13.2
Nickel (Ni)			12.4–58.9	12.9–30.3	27
Phosphorus (P)			21–1752		
Potassium (K)			1600–5000		
Rubidium (Rb)					
Selenium (Se)	7.6		4.9–23.0	9.15–18.2	18.2
Silicon (Si)			22,000–137,000		
Silver (Ag)			<0.024	1.18–1.97	1.18
Sodium (Na)					
Strontium (Sr)			153–3166		
Sulfur (S)		3000	42,000–170,000[d]		
Thallium (Tl)				0.47	0.47
Tin (Sn)					
Titanium (Ti)					
Uranium (U)					
Vanadium (V)			22.5–83.9	56	56
Zinc (Zn)			52–237	48.9–50	50

[d] Combination of LECO and ICP concentrations.

Table B-2. Total Elemental Composition of SDA Materials with Precollection of Fly Ash Reported in Literature Reviewed.

Source:	[41]	[49]
No. of Samples:	3[a]	Frequent Conc.[b]
Units:	mg/kg	mg/kg
Arsenic (As)	4.8–11	
Barium (Ba)	270–4000	
Boron (B)	100–150	
Cadmium (Cd)	0.9–6.9	1
Chromium (Cr)	34–50	60
Copper (Cu)	43–47	80
Lead (Pb)	28–110	100
Manganese (Mn)	170–420	
Mercury (Hg)	<0.3	<0.1
Molybdenum (Mo)	2.7–5.4	
Nickel (Ni)	32–36	80
Selenium (Se)	3.9–6.5	
Vanadium (V)	60–70	
Zinc (Zn)	94–380	120

[a] May contain up to 20% fly ash.
[b] Multiplying or dividing by 2 can give the range.

APPENDIX C

USING CLASS C FLY ASH TO MITIGATE ALKALI–SILICA REACTIONS IN CONCRETE

USING CLASS C FLY ASH TO MITIGATE ALKALI–SILICA REACTIONS IN CONCRETE

Year 2 Final Report

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USING CLASS C FLY ASH TO MITIGATE ALKALI–SILICA REACTIONS IN CONCRETE

ABSTRACT

High-calcium fly ashes, classified as Class C by ASTM International (ASTM) C618 definition, are often excluded as a means to mitigate alkali–silica reactions (ASR) in concrete. This is because a relationship between high calcium content and expansion was often documented when Class C fly ash was used at a 10% to 15% replacement level in concrete. It is generally true that low replacement levels (<15%) of Class C fly ash may not offer ASR mitigation; however, it has been demonstrated that Class C fly ashes can mitigate the effects of ASR at higher replacement levels than specified. For highly reactive aggregates, the required dosage of Class C fly ash may be quite high, resulting in reduced early strengths. In some cases, the amount of Class C fly ash needed to control ASR may exceed specification limits set by state departments of transportation. In these instances, combining Class C fly ash with silica fume, for example, can help to mitigate ASR and improve early strength gain.

The University of North Dakota Energy & Environmental Research Center has completed the second year of a 3-year series of investigations to evaluate the performance of several Class C fly ashes (>10% CaO) using existing predictive ASR test methods. ASTM standard methods were applied to fly ash samples and cast specimens produced using varying levels of Class C fly ashes. The results have confirmed limited and unpublished work that indicates the effectiveness of using higher percentages of Class C fly ash to mitigate ASR when using moderately reactive aggregates.

Results indicate that all the Class C fly ashes submitted for this study helped reduce the expansion of the mortar mixtures, even at the lowest replacement level of 15%. This reduction in expansion continued as the fly ash content increased.

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INTRODUCTION

This project was initially designed as a 3-year study to perform a comprehensive evaluation of assessing the use of Class C fly ash on the effects of alkali–silica reactivity (ASR) in concrete. The intent of the first-year effort was to increase industry sponsorship, perform a literature review on the latest laboratory testing, and set up a laboratory testing matrix using industry-sponsored cement and fly ash samples. The second and third years were designated for all laboratory testing. During the first year of this project, Combustion Byproducts Recycling Consortium (CBRC) funding was rescinded because of changes in the U.S. Department of Energy's focus for funding energy-related research. Efforts for Years 2 and 3 were continued with support from the industry sponsors but with a reduced scope of work from the original CBRC proposal. No laboratory testing was performed during first-year activities. Because of the elimination of CBRC funds, for the last 2 years, the work scope for this project was slightly modified to accommodate budget changes. The second year's activities were added to the Coal Ash Resources Research Consortium after the original funding from CBRC was cut. Year 2 was devoted to mortar bar testing, while Year 3 will be dedicated to concrete testing for ASR. Both of these testing programs will be discussed in detail later in this report.

There are eight contributing members to the ASR consortium: Holcim (US) Inc.; Nebraska Ash Company; Ash Grove Resources; WE Energies; Lafarge North America; Mineral Resources Technologies, Inc.; Boral Materials Technologies, Inc.; and the Western Region Ash Group. All member contacts for this project are listed in Appendix A. These members have combined to submit 13 fly ash and two cement samples. Ten of the fly ashes are Class C, and the other three are Class F. The fly ashes will only be referred to as FAC-1–10 and FAF-1–3. The fly ash blends and cement sources will be identified as FAB and CEM, respectively. All mortar bar testing has been completed, and the results are listed in Tables 1 and 2. The cement sources were evaluated for chemical analyses. These results are given in Table 3.

Three primary ASTM International (ASTM) methods for evaluating expansion as a result of ASR were used. The first, ASTM C1260 entitled "Potential Alkali Reactivity of Aggregates (Mortar Bar Method)," is probably the most widely used test method. Another commonly used test method is ASTM C1293, "Determination of Length Change of Concrete Due to Alkali–Silica Reaction." A more recent specification, ASTM C1567, "Determining the Potential Alkali–Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar Bar Method)," addresses ASR mitigation using supplementary cementitious material such as fly ash.

For the Year 2 laboratory effort, it was decided to use ASTM C1567 for the bulk of the testing. Some of the samples tested under this method will also be evaluated using the concrete method ASTM C1293 for Year 3.

Table 1. Final 14-Day Expansion for All Fly Ash Blends Using CEM-1

Class C Fly Ash Source	FAB-1 FAC-3	FAB-2 FAC-9	FAB-3 FAC-8	FAB-4 FAC-2	FAB-5 FAC-5	FAB-6 FAC-6
Fly Ash C Amount, %	50	60	60	60	75	75
FAF-1 Amount, %	50	40	40	40	25	25
SiO_2, %	42.2	43.3	44.0	41.4	46.1	42.4
Al_2O_3, %	20.2	19.9	19.6	21.3	20.5	19.6
Fe_2O_3, %	10.54	10.01	9.83	10.14	7.87	7.89
Total, %	72.94	73.21	73.43	72.84	74.47	69.89
CaO, %	15.0	15.8	15.8	15.9	14.6	14.3
SO_3, %	2.12	1.63	1.23	1.92	1.47	2.77
MgO, %	3.9	3.71	3.5	3.1	3.51	3.53
Na_2O, %	1.62	1.57	1.57	1.92	1.78	4.89
K_2O, %	1.59	1.37	1.45	1.31	1.26	1.27
Ash Level	CEM-1, 14-day expansion = 0.211%, average of four tests, ASTM C1260-07					
20%	0.113	0.108	0.122	0.119	0.112	0.159
35%	0.035	0.025	0.024	0.026	0.022	0.052

LITERATURE REVIEW

Several test methods have been developed to predict whether or not a particular aggregate or combination of aggregate and cement paste will cause ASR expansion. Expansion caused by a reaction of the alkali contained in cement and the aggregate in concrete has been noted since the early 1940s, primarily in the southwestern United States but also in Kansas, Nebraska, Alabama, and Georgia. Studies of these failed concretes showed that the expansion was because of a reaction between the alkali in the cement and the siliceous aggregates used in the concrete. Since then, many studies have been performed to better understand the mechanisms causing the expansion as a result of ASR and ways to mitigate those reactions.

A review of available literature indicates that no one mechanism has been clearly identified as the cause of expansion because of ASR. A summary of available test methods and advantages and disadvantages was presented by Chang-Seon and others (1) from Texas A&M University. A paper in the American Concrete Institute journal states that Class C fly ash is not recommended for ASR mitigation based on limited studies of low-level Class C fly ash concrete showing failures (2). Dunstan (3) found low replacement rates of high-calcium ashes resulted in expansion, but expansion decreased with increased fly ash additions. Styron and others (4) reported effective ASR mitigation when 25% of high-alkali cement was replaced with Class C fly ash.

Lenke and Malvar (5) report that there are three characteristics of a fly ash that determine its efficiency in preventing ASR: fineness, chemistry, and mineralogy. Several have reported that the finer the fly ash, the better at reducing ASR (6–9). The chemistry of the fly ash has also been used as a predictor for ASR mitigation (5, 10, 11) with success. The mineralogy of fly ash is a bit

Table 2. Final 14-Day Expansion Results for ASTM Test Method C1567-07 (results are for all Class C and Class F fly ashes and two cement sources)

Sample Source	FAC-4	FAC-9	FAC-10	FAC-8	FAC-3	FAC-2	FAC-7	FAC-5	FAC-6	FAC-1	FAF-3	FAF-2	FAF-1
SiO_2, %	33.7	37.9	38.8	38.6	42.0	35.8	42.9	44.0	38.9	46.5	60.7	57.8	51.3
Al_2O_3, %	17.9	18.4	18.2	18.0	18.4	20.4	19.5	20.0	18.6	19.7	18.1	26.5	22.2
Fe_2O_3, %	4.94	5.91	5.35	5.61	5.71	6.3	5.76	5.03	4.94	4.26	4.11	4.28	16.06
Total, %	56.54	62.21	62.35	62.21	66.11	62.50	68.16	69.03	62.44	70.46	82.91	88.58	89.56
CaO, %	26.5	24.2	24.2	24.2	23.7	23.7	20.6	18.6	18.5	18.3	10.9	7.0	3.6
SO_3, %	3.29	2.2	1.44	1.69	1.11	2.61	0.97	1.92	3.62	1.97	0.0	0.0	0.75
MgO, %	6.52	5.23	4.82	4.97	4.23	4.14	4.1	4.16	4.31	3.46	2.38	1.46	1.14
Na_2O, %	2.62	2.1	1.97	2.19	2.16	2.64	1.86	2.1	6.35	0.1	0.95	0.29	0.6
K_2O, %	0.45	0.48	0.6	0.63	0.64	0.45	0.66	0.8	0.75	0.5	0.84	1.03	2.73
Ash Level	CEM-1, 14-day expansion = 0.211%, average of four tests, ASTM C1260-07												
15%	0.155	0.187	0.186	0.189	0.183	0.191	0.119	0.122	0.162	0.174	0.118	0.016	0.063
30%	0.129	0.125	0.122	0.112	0.122	0.102	0.064	0.049	0.113	0.090	0.039	0.015	0.012
40%	0.052	0.086	0.073	0.082	0.087	0.049	0.033	0.034	0.066	0.035	0.022	0.012	0.008
50%	0.043	0.045	0.034	0.049	0.057	0.032	0.016	0.014	0.043	0.028			
Ash Level	CEM-2, 14-day expansion = 0.218%, average of two tests, ASTM C1260-07												
20%	0.180	0.209	0.181	0.197	0.197	0.163	0.152	0.122	0.175	0.148	0.121	0.016	0.052
30%	0.119	0.185	0.144	0.138	0.177	0.123	0.091	0.082	0.123	0.091			
35%											0.019	0.009	0.012
40%	0.052	0.112	0.071	0.073	0.133	0.086	0.047	0.028	0.064	0.029			

Table 3. Chemical Analyses of Cement Sources

Sample Source	Cement Source 1 (CEM–1)	CEM–2
SiO_2, %	22.2	22.2
Al_2O_3, %	4.4	4.3
Fe_2O_3, %	2.90	3.16
Total , %	29.5	29.66
CaO, %	63.6	64.3
SO_3, %	3.82	3.41
MgO, %	1.52	1.47
Na_2O, %	0.0	0.01
K_2O, %	0.62	0.65
Total Alkali, %	0.56	0.51
Water Soluble Alkali, %	0.44	0.37

more difficult to use as a predictor for several reasons but has been shown to be important in many areas of fly ash utilization. Lenke and Malvar (5) and Malvar and Lenice (11) report that high-calcium fly ashes are less effective in binding alkalis; hence, there may be some relation between efficiency because of mineralogy and chemistry, which may be partially captured in a chemical relationship. A chemical index was derived characterizing the fly ash and cement based on their chemical constituents, which was optimized to maximize the correlation with expansion test data.

In order to capture a relationship between chemistry and mineralogy, bulk chemical analyses are used in conjunction with bulk mineral analyses, and any excess amount of a particular element is then often considered to be associated with an amorphous phase. Fly ash mineralogy is very complex, with each individual fly ash sphere representing a precursor mineral from which it formed and whatever inorganic compounds it may have come into contact with during formation. Each individual sphere can represent a completely different precursor mineral and may or may not have reached complete melting during its formation. Some minerals are more heat-resistant than others and are not completely incorporated into any melt (quartz). Others have a very low melting temperature (clay minerals) and are in a liquid phase at some point. The time it takes for a fly ash particle to cool will also have some effect on the outcome of the mineralogy. Just as in huge geologic features, certain minerals will crystallize before others, depleting the availability of some elements in the melt to form other phases.

The mineralogy is often the catalyst for reactivity in fly ashes. Some of the Class C ashes found primarily in the western United States have been found to contain various forms of calcium and aluminum phases that are highly reactive when hydrated. These reactions are often exothermic and can create enough heat to cause more reactions to take place. Knowing these phases are present in a fly ash can make a large difference in the behavior of a material that cannot really be predicted by chemistry alone. The addition of just H_2O will cause a large number of reactions that will completely change the physical properties, appearance, and behavior of the material without changing the chemistry.

There have been numerous research efforts using the three standard test methods: ASTM C1260, C1293, and C1567. Some evaluations were made using only ASTM C1260. McKeen et al. (12) concentrated on evaluating different sources of local aggregates and fly ashes, while Rogers (13) evaluated the procedure itself using a multi-interlaboratory study. Chang-Seon et al. (1) evaluated the procedure using variable water/cement ratios and variable curing times.

In a comparison of ASTM C1260 and C1293, Touma et al. (14) evaluated several sources of aggregates and how their results compared for mortar bars versus concrete prisms. Lenke and Malvar (5) compared Methods C1260 and C1567 to further refine a piecewise linear model to better address the actual behavioral relationship between ASR expansion and the chemical properties of the fly ash–cement blend.

BACKGROUND

Current utilization rates of fly ash (15) are 28 million tons annually, or roughly 40% of what is produced, which still remains a significantly low number. By far the most common application remains the production of portland cement concrete. In order to increase the utilization rate, the need will be to increase the current rate allowable as a partial cement replacement in concrete in addition to finding new uses. Allowing the use of Class C fly ash, and at larger dosages to mitigate ASR, will assist in meeting this objective.

ASR is a reaction between alkali hydroxides in portland cement and siliceous phases present in the admixtures and aggregates composed of SiO_2. Problems with expansion arise when soluble silica reacts with the alkalis, forming an alkali–silica hydrate gel, which exhibits directional growth (swells in one direction) and keeps CaO from entering the complex. CaO in the alkali–silica gel does not expand. In concrete, CaO is associated with silica and forms a nonswelling calcium silicate hydrate gel during hydration as a key reaction related to cementation. It has been proposed that CaO deficiency coupled with high alkali in localized areas, such as on aggregate surfaces, or extremely high concentrations of soluble silica allows the alkalis to react with the silica by "diluting" the CaO, leaving sites open for alkali incorporation. Recently, Lenke and Malvor (5) developed a piecewise linear two-parameter model for predicting the fly ash required, to mitigate ASR based on the chemistry of the fly ash, the chemistry of the cement, and the reactivity of the aggregate. Identifying the susceptibility of an aggregate to the ASR reaction before using it in concrete is one of the most efficient practices for preventing ASR damage (14).

Fly ash is often added to mitigate expansion as a result of ASR. Current thoughts on the leading mechanisms for which fly ash controls expansion are that the fly ash dilutes the alkali content in the cement. Some of the alkalis are removed from the pore solution by binding them into CaO–silica hydrate gels. The fly ash reduces the concrete permeability and diffusivity by the silica reacting with the $Ca(OH)_2$ produced by the hydration of the cement to form calcium silicate hydrate. Since the calcium silicate hydrate takes up more space than the $Ca(OH)_2$, the pore systems become finer and less continuous. The reduced porosity limits the ability of the alkalis to migrate and, therefore, reduces the ability of alkali–silica gel to form (16). Thomas (17) indicated that several fly ash concrete samples show little or no expansion even when the available alkali content is relatively high.

The impact of this technology will be in the area of higher replacement levels of Class C fly ashes in concrete in areas where ASR is problematic. Within the U.S. Department of Defense, 23 Air Force, three Army, and six Navy/Marine airfields have reported ASR problems (18). Several state highway departments have specifications for admixtures to mitigate ASR, as do several federal agencies and state Departments of Transportation. Recent survey studies (19) indicated that often only Class F fly ash is identified as suitable for ASR mitigation. This conclusion is often reached because of the limited research available using Class C fly ashes. Although other nonash materials may also mitigate ASR, they are generally more expensive than fly ash.

While there are data available that show a correlation between ASR and CaO content, the data show that higher replacement levels of high CaO containing fly ashes can also mitigate expansion because of ASR. By providing adequate data on the use of several Class C fly ashes and associated ASR testing, it is expected that it will be shown that higher replacement levels of high-calcium fly ash can be used to effectively mitigate ASR. In turn, it is expected that the end users requiring ASR protection will gain a comfort level in using Class C fly ash in areas where reactive aggregates are commonly used in concrete.

Almost all fly ashes can be used to prevent damaging expansion as a result of alkali–silica reaction provided they are used in sufficient quantity (20). It is not really correct to say that some fly ashes do not work—they just do not work when an insufficient quantity is used. The amount of fly ash required depends on the reactivity of the aggregate, the quantity of alkalis contributed by the portland cement, and the composition of the fly ash.

More than 50% Class C fly ash may be required with some aggregates. The pozzolanic reaction that occurs when fly ash is used with portland cement produces a calcium silicate hydrate (C-S-H) that has a lower Ca/Si ration than the C-S-H produced by the hydration of portland cement. C-S-H with a low Ca/Si ration has a greater capacity to bind alkalis, thereby reducing the alkalis available for reaction with the aggregate. Low-calcium Class F fly ash produces C-S-H with a lower Ca/Si ration than high-calcium fly ash, and consequently, more alkalis are bound when Class F fly ash is used.

Preventing and mitigating alkali–silica reactivity in portland cement concrete pavements and structures is the focus of a new $10 million Federal Highway Administration (21) (FHWA) initiative. The 4-year ASR program was established and funded be the 2005 Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users. FHWA held an ASR Benchmarking Workshop in June 2006 in Chicago, Illinois, to gather stakeholder input on the new ASR program. Workshop attendees discussed the current state of the practice and areas where further development and deployment of ASR prevention, identification, and mitigation techniques are needed. Participants noted, for example, that the field identification of ASR is difficult and that there is a lack of understanding of the extent of the problem, as ASR is not included as part of most regular pavement or bridge inspection programs. Inspectors need a test for easy, fast, and reliable identification. Participants noted the need as well for a fast, reliable test method to identify the potential for ASR to occur in concrete mixtures proposed for transportation structures. Workshop participants also stressed the importance of increasing awareness of ASR among agencies and contractors and improving the decision-making process for preventing ASR in new construction.

EXPERIMENTAL PROCEDURES/METHODOLOGIES

ASTM C1260, “Potential Alkali Reactivity of Aggregates (Mortar Bar Method),” is probably the most widely used test method with equivalents in AASHTO T303 (American Association of State Highway and Transportation Officials) and CSA A23.2-25A (Canadian Standards Association). Recent specifications, ASTM C1567 entitled “Determining the Potential Alkali–Silica Reactivity of Combination of Cementitious Materials and Aggregate (Accelerated Mortar Bar Method),” address ASR mitigation using supplementary cementitious material such as fly ash.

Another commonly used test method is ASTM C1293, “Determination of Length Change of Concrete Due to Alkali–Silica Reaction.” Since a high degree of variability exists in the results of these and several other tests used to predict ASR, admixtures such as fly ash may be deemed acceptable by one test method but not the other and often not by both.

RESULTS

During this second year of activity, all of the fly ashes and fly ash blends were evaluated for ASR using the ASTM C1567 standard test method. Both sources of cement were also used in this evaluation. CEM-1 utilized fly ash replacement levels of 15%, 30%, 40%, and 50% for the Class C fly ashes and 15%, 30%, and 40% replacement levels for Class F fly ashes. Fly ash replacement levels for CEM-2 were 20%, 30%, and 40% for the Class C fly ashes and 20% and 35% for the Class F fly ashes. The results for both cement sources are indicated in Table 1. The samples are arranged by decreasing levels of calcium oxide content. Graphical representation of these data are also presented in Figures 1 and 2.

The expansion results of the fly ash blends are given in Table 2. The goal was to blend one Class C fly ash source from each of the industry sponsors to produce a blended fly ash with the combined CaO content of between 14% and 16%. Each Class C fly ash tested was blended with one single Class F fly ash source labeled as FAF-1. This source of Class F ash had the lowest level of CaO of all the samples submitted.

The expansion of each cement control sample is represented in Table 1. For CEM-1, the average 14-day expansion was 0.211%, while the average expansion for CEM-2 is 0.218%. According to ASTM C1260, the expansion of less than 0.10% at 16 days after casting is indicative of innocuous behavior in most cases. In addition, expansions of more than 0.20% are indicative of potentially deleterious expansion, and expansions between 0.10% and 0.20% include both aggregates that are known to be innocuous and deleterious in field performance. Thus both cement sources produce results that are indicative to potentially deleterious expansion.

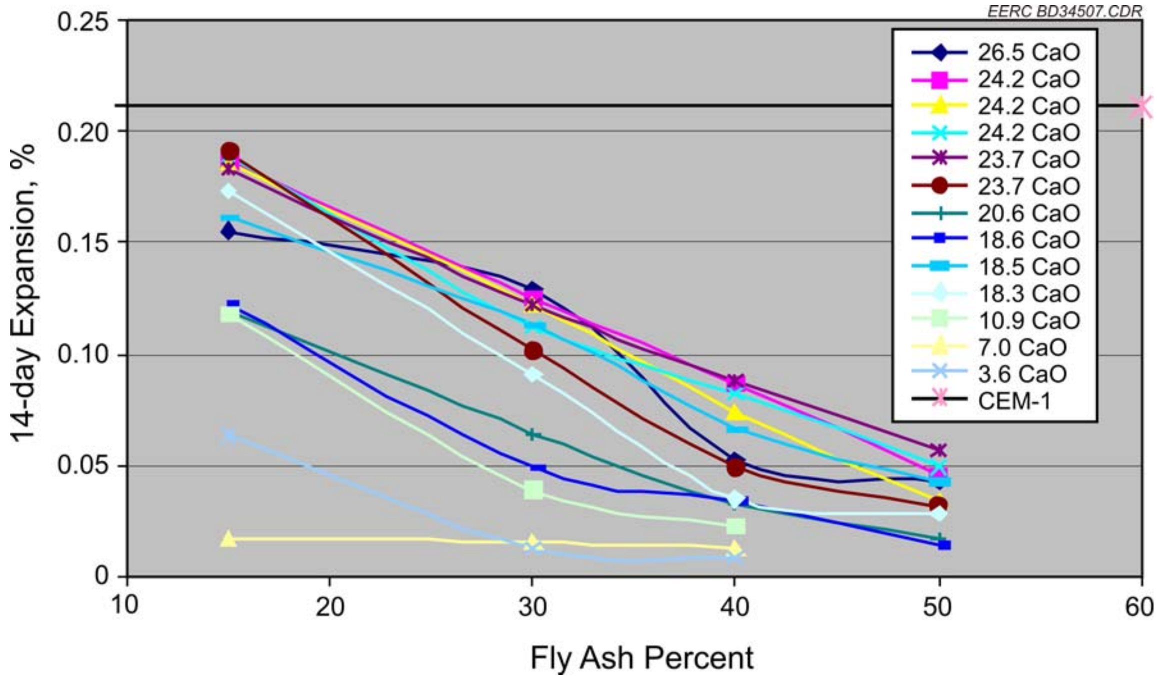

Figure 1. 14-day expansions for all fly ashes using CEM-1.

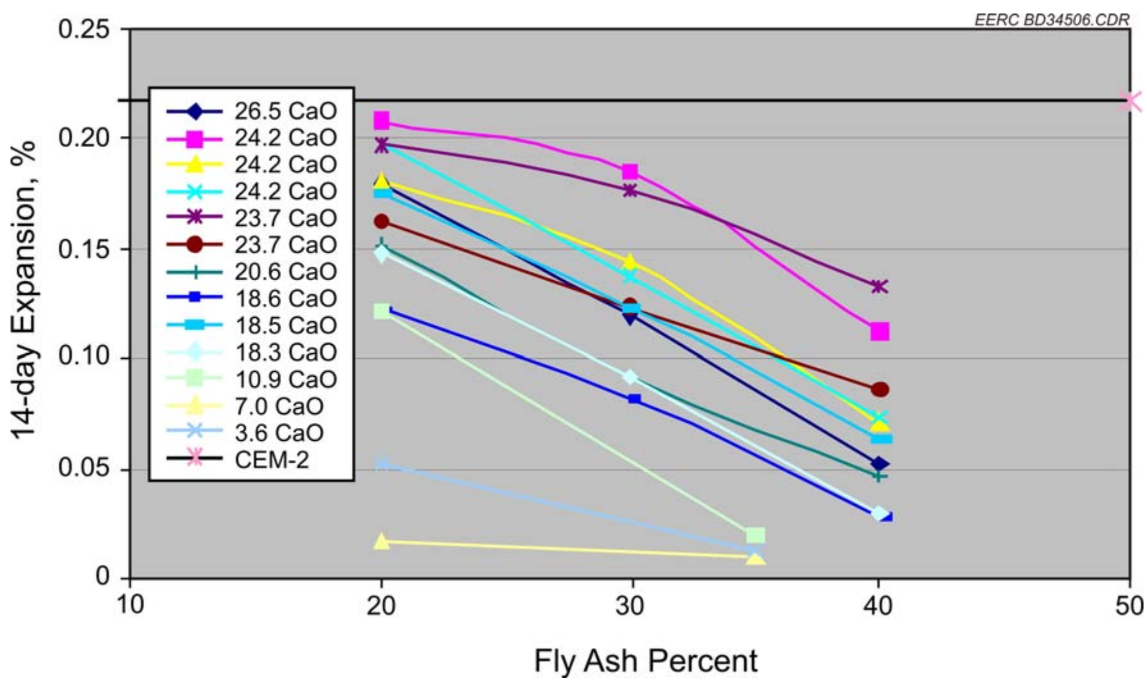

Figure 2. 14-day expansions for all fly ashes using CEM-2.

DISCUSSION AND RECOMMENDATIONS

It is stated in ASTM C1567 that the combination of cement, fly ash, and aggregate that expands less than 0.10% at 16 days after casting is likely to produce acceptable expansions when tested in concrete and have a low risk of deleterious expansion when used in concrete under field conditions.

The expansion results, using CEM-1, indicate that all ten Class C fly ashes helped to reduce the expansion of the mortar mixtures, even at the lowest replacement level of 15%. This reduction in expansion continued at the remaining cement replacement levels, with smaller reductions seen from the 40% to 50% replacement level. In all cases of the Class C fly ashes, tested here using CEM-1, the specimens reached the <0.10% expansion limit at the partial cement replacement level of 40%.

The use of fly ash was not as pronounced in reducing expansion for CEM-2. In some cases (FAC-9 and FAC-3), not all Class C fly ashes reduced the expansion of the mortar mixture at its lowest replacement level of 20%. For these same two Class C fly ashes, the final expansions were not below the 0.10% limit as specified in ASTM C1567. The total alkali contents for CEM-1 and CEM-2 were 0.56% and 0.51%, respectively. There was not much difference between the total alkali contents of the two cement sources.

When testing the fly ash blends, the ashes were only evaluated using cement source CEM-1. The end results were very consistent for all six fly ash blends. Basically, at the 20% ash mixtures with cement, none of the test mixtures had 14-day expansions below the 0.10% limit, while all of the 35% ash mixtures did have expansions below this limit. The highest blend expansion, at 14 days, was FAB-6 at 0.052%.

FUTURE ACTIVITIES

As originally designed, the future concrete work (ASTM C1293) will remain intact and begin after the mortar bar testing. Whether this concrete testing will be financially supported by the U.S. Department of Energy is not certain at this time. It will be completed with only industry support if necessary. A comparison of concrete ASR expansion to mortar bar ASR expansion is an important part of this project's original objectives.

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APPENDIX A

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APPENDIX D

DEMONSTRATION OF COAL COMBUSTION PRODUCTS FOR GREEN ROADBUILDING IN MEDORA, NORTH DAKOTA

DEMONSTRATION OF COAL COMBUSTION PRODUCTS FOR GREEN ROADBUILDING IN MEDORA, NORTH DAKOTA

Final Report

(for the period of February 1, 2008, through March 31, 2009)

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DISCLAIMER

EERC DISCLAIMER

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EXECUTIVE SUMMARY

North Dakota utilizes coal combustion products (CCPs) in a wide variety of construction and manufacturing applications and is a leader in the United States for its use of fly ash in concrete. The use of fly ash in concrete is one key use of CCPs that has been identified as environmentally sustainable because the replacement of cement with fly ash results in a reduction of CO_2 emissions related to the concrete produced. Environmentally sustainable or “green” construction technologies and products are currently being developed and demonstrated throughout the United States, including for roadbuilding. Green roadbuilding is an area where CCPs can contribute to efforts to preserve and protect the environment by aiding with storm water management, reducing the use of virgin materials, and aiding with conservation and protection of ecosystems.

The objectives of this project were to demonstrate environmentally sustainable (green) roadbuilding using multiple CCP utilization applications and, in the process, to educate North Dakota industry, state agencies, and the public about environmentally sustainable construction.

Working with the Theodore Roosevelt Medora Foundation, a construction site was identified for potential demonstration activities. The site was the Burning Hills Amphitheater, which is a location that hosts thousands of visitors annually.

The first green roadbuilding application selected was a combination of two different high-volume fly ash (HVFA) concrete paving applications. The HVFA concrete mixes selected included 50% and 70% fly ash concrete in walkways requiring 4-inch pavement and for driving and parking areas requiring 6-inch pavement. A plan for placement was developed with the project participants, and work was initiated and completed to prepare the site and place and finish the concrete. Energy & Environmental Research Center (EERC) representatives and the fly ash marketing company representative visited the site before and during placement and worked with the contractors to ensure the appropriate mixes were placed in the planned locations. The fly ash marketing company representative worked closely with the ready-mix supplier and finishing contractor to make modifications to the mix designs in order to facilitate ease of placement and finishing. Over the duration of the remainder of the project, the concrete surfaces were monitored. Some initial surface cracking was noted but was, in nearly all cases, attributed to physical locations that could not be avoided (pipes or other structures required on-site). One area exhibited cracking that was likely the result of hot, windy weather conditions during the placement and finishing periods. Again, this type of cracking is not necessarily directly attributed to the use of HVFA concrete. Continued monitoring of the noted minor defects indicated that these did not worsen over the duration of the project. Sustainability of concrete can be estimated based on CO_2 emissions. Production of portland cement produces high levels of CO_2, and since fly ash, when used, replaces cement in the concrete mix, it reduces the amount of CO_2 emissions associated with the concrete. As the percentage of fly ash increases, the sustainability of the concrete based on CO_2 emissions also increases.

In a second phase of the project, use of fly ash for base and subgrade stabilization for the soils under additional driving and parking areas at the amphitheater were identified for construction to be performed during the 2009 and 2010 construction seasons. Work on the engineering design was performed under this project to allow project engineers to become familiar with the use of fly ash in soil stabilization. Information on the use of fly ash was provided to a commercial engineering firm, and EERC staff worked with the firm to facilitate an understanding of equipment needs for placement, blending, and compacting of fly ash–soil mixtures, additions of fly ash for various soil types, environmental requirements in the state of North Dakota, fly ash costs, fly ash delivery costs, and soil testing needs. Preliminary cost estimates of standard base and subgrade treatments, fly ash–soil stabilization, and fly ash–recycled asphalt recycling were made, and results indicated that costs will be very similar for all types of base and subgrade preparation. It was found that no standard sustainability calculations were currently available to aid in determining the sustainability of various subgrade preparation options. A method based on the transportation of materials was developed and applied to a fly ash soil stabilization subgrade preparation and a non-CCP technique based on replacement of native soils with aggregate. For the specific site, the fly ash-stabilized soil subgrade resulted in slightly lower CO_2 emissions based on transport of fly ash from a regional power plant to the site as compared to the technique requiring removal and replacement of native soils. The CO_2 emission values calculated for these techniques reinforced the point that the location of the CCP source is frequently a limiting factor for utilization. Economics frequently impact the potential for CCPs to be used in locations distant from the CCP source; however, the sustainability of CCP is also impacted by the distance of the CCP from the utilization site. In this project, both cost and sustainability were similar, but continued monitoring of the project site will indicate sustainability based on reduced maintenance and replacement schedules.

As a follow-on communication and education activity to this project, a U.S. Environmental Protection Agency Region 8 Resource Conservation Challenge will be held, and representatives of the North Dakota Department of Health will participate, as will other project partners.

DEMONSTRATION OF COAL COMBUSTION PRODUCTS FOR GREEN ROADBUILDING IN MEDORA, NORTH DAKOTA

INTRODUCTION

North Dakota is a leader for coal combustion product (CCP) utilization in the United States (1). As a result of concerted efforts by North Dakota utilities, CCP marketers, members of the North Dakota ready-mixed concrete and construction industries, and researchers, North Dakota utilizes CCPs in a wide variety of construction and manufacturing applications. The percentages of fly ash used in concrete in North Dakota both by the North Dakota Department of Transportation (NDDOT) and commercial applications are among the highest in the United States. Additionally, North Dakota uses fly ash in the filling of underground mine voids to mitigate subsidence; for stabilization of soils in road construction, parking areas, and animal feedlots; and for other applications such as flowable fill and concrete products. These CCP utilization applications and others utilizing bottom ash and boiler slag are examples of environmental stewardship as defined by the U.S. Environmental Protection Agency (EPA): "the responsibility for environmental quality shared by all those whose actions affect the environment (2)." EPA and other federal agencies play important roles in promoting environmental stewardship, and among EPA's current promotional efforts is a joint EPA–Federal Highway Administration–industry effort called the Green Highways Partnership (GHP). The GHP has been working to advance sustainability or "greening" of highway construction, with a focus on storm water management, reuse and recycling, and conservation and ecosystem protection, as noted in Table 1.

The current GHP efforts are focused in the EPA Mid-Atlantic Region 3, but the program could offer value to other regions. One component of the GHP is reuse and recycling of materials in highway construction, and CCPs are a major part of that component. The use of CCPs in various road construction applications is one way for the GHP goals and objectives to be realized in geographic areas outside the EPA Mid-Atlantic Region 3. North Dakota uses CCPs in concrete pavements, but that use has not yet achieved its full potential in North Dakota, primarily because some contractors are not yet familiar and/or comfortable with working with the high-volume fly ash (HVFA) concrete mixes. There are also other roadbuilding applications such as use of fly ash for base and subbase/subgrade stabilization that are relatively new to NDDOT and contractors. This project was designed to demonstrate green roadbuilding applications utilizing North Dakota CCPs in order to showcase the use of multiple CCP utilization applications to improve the final road performance. Table 1 provides examples of roadbuilding technologies that utilize CCPs and address the GHP focus areas. Many of these CCP utilization application examples are currently approved for use in North Dakota but have not been implemented at the full commercial level. Additionally, the understanding of the sustainability of CCP utilization in roadbuilding projects has not been documented in North Dakota. This project was designed and implemented to facilitate the transition of the use of CCPs from the demonstration phase into the full commercial phase by implementing multiple construction applications with CCPs in a single construction project, to work with local contractors to answer questions and allow them to gain full-scale experience with CCPs and the associated construction applications, and to develop cost

Table 1. GHP Focus Areas and Examples of CCP Utilization Applications for Each Focus Area

GHP Focus Area	Examples of CCP Utilization Applications Addressing Issues in the GHP Focus Area
Watershed-Driven Storm Water Management	Pervious fly ash concrete to capture and store runoff, reduce need for deicing salts, reduce hydroplaning. Bottom ash use in rain gardens to capture and store runoff and reduce erosion.
Reuse and Recycling	Fly ash concrete. Fly ash for soil stabilization. Fly ash flowable fill for utility cuts, bridge abutments, and other infrastucture needs. Fly ash use for full-depth in-place recycling of asphalt.
Conservation and Ecosystem Protection	Bottom ash use in rain gardens to encourage growth of native vegetation. Fly ash concrete bridges, culverts, tunnels, or barriers for wildlife crossings.

and sustainability comparisons between standard and sustainable CCP use applications appropriate for public and private road construction projects in North Dakota.

BACKGROUND

In 2007, more than 56 million tons of CCPs were beneficially used in the United States (1), but this was only approximately 43% of the CCPs produced. The U.S. Department of Energy, EPA, and the CCP industry have a goal to increase CCP utilization to 50% by 2011. In order to reach that goal, current commercial CCP utilization applications need to be brought to full commercial potential. CCPs are the largest solid waste stream generated in North Dakota. It was estimated that North Dakota coal-based power plants produce in excess of 8000 tons a day of CCPs (or nearly 3 million tons a year) (1) but that the North Dakota utilization rate is significantly lower than the national average. There is potential to increase the use of North Dakota CCPs and facilitate sustainable construction practices within the state. The opportunities lie in areas already initiated by North Dakota state agencies:

- NDDOT uses fly ash in almost all concrete projects at a replacement rate of 30%. Most DOTs specify a replacement rate between 15%–30% (if they specify fly ash use at all), making NDDOT's specification on the higher end compared to other states.

- Bottom ash is classified as an inert waste by the North Dakota Department of Health (NDDH), which allows it to be used without approval. In North Dakota, bottom ash is typically used in active mines as a road base and for ice control on public and private roads.

- The NDDH has developed a guideline (*Guideline 11 – Ash Utilization for Soil Stabilization, Fill-In Materials, and Other Engineering Purposes*) and more recently instituted a streamlined approval method for the use of CCPs in soil stabilization.

The utilization practices of a state DOT, such as NDDOT's use of up to 30% fly ash concrete, are typically reflected in commercial practices, so a key to increasing CCP utilization is to work with state DOT officials to work toward developing an increased number of CCP utilization applications that are best suited for that state's roadbuilding needs. At the same time, the engineering companies and contractors in a state need to become versed in the utilization of CCPs and the benefits. One of those benefits is sustainability. The U.S. National Environmental Policy Act of 1969 declared as its goal a national policy to "create and maintain conditions under which [humans] and nature can exist in productive harmony and fulfill the social, economic and other requirements of present and future generations of Americans." The most widely quoted definition internationally is the "Brundtland definition" of the 1987 Report of the World Commission on Environment and Development that sustainability means "**meeting the needs of the present without compromising the ability of future generations to meet their own needs**" (3).

North Dakota has little urban or industrial pollution and is home to numerous wildlife refuges and natural settings for hiking, boating, wildlife viewing, and other enjoyment of the North Dakota environment. The concept of sustainable or green construction has the goal of preserving and protecting air and water quality and maintaining environments and ecosystems. North Dakota is an ideal location to work toward implementation of sustainable construction and manufacturing including road construction because of its high-quality air and water and its strong desire to maintain and protect these natural resources. North Dakota has the combination of availability of high-quality CCPs, expertise in CCP utilization, commitment to preserving the environment, and protecting the ecosystem, making North Dakota an ideal place to demonstrate green roadbuilding technologies. North Dakota's commitment to preserving the environment and resources for future generations was probably most eloquently expressed by Governor Art Link in a speech made in October 1973 where he stated "*we simply want to insure the most efficient and environmentally sound method of utilizing our precious coal and water resources for the benefit of the broadest number of people possible*" (4). Demonstrating the use of CCPs in sustainable construction practices can be considered a corollary to Art Link and North Dakota's commitment to stewardship of North Dakota's natural resources. It also allows North Dakota to continue to act as a leader in the utilization of CCPs.

The site selected for this project, Medora, North Dakota, exemplifies the environment that North Dakota is committed to preserving and protecting and provides an opportunity for a model demonstration that will be available to interested parties in construction industries and to representatives of state agencies and to visitors who will be able to see North Dakota's commitment to a clean environment in a very practical way.

The green roadbuilding technologies targeted under this project focus on those employing CCPs, especially fly ash. The Energy & Environmental Research Center (EERC) has worked with industry to develop many of these technologies and applications, including HVFA concrete in pavement applications, fly ash and bottom ash for soil stabilization, fly ash and bottom ash in flowable fills and low-strength concrete, and fly ash in concrete products. It is anticipated that these will be components of the demonstration project. Additional technologies and products are also expected to be incorporated into the demonstration, including the use of bottom ash for rain gardens and pervious fly ash concrete to aid in storm water management. All of these applications are currently used commercially, although not all of them have been used in North Dakota.

OBJECTIVE

The primary objective of this effort was to demonstrate environmentally sustainable (green) roadbuilding using multiple CCP utilization applications. Supporting objectives were as follows:

- To familiarize North Dakota construction contractors with road construction techniques that utilize approved North Dakota CCPs in common construction applications.
- To provide an education opportunity for NDDOT personnel to develop additional technical information to support and encourage the use of CCPs as green construction products.
- To provide a model CCP-based green roadbuilding project for North Dakota and surrounding states and demonstrate the environmental and economic advantages for promotional purposes.

METHODOLOGY

The demonstration of green roadbuilding technologies was accomplished through several tasks in partnership with the Theodore Roosevelt Medora Foundation, Great River Energy, and Headwaters, Inc. The project team also worked with a regional engineering firm and construction contractors to accomplish the demonstration of multiple CCP-based roadbuilding technologies by performing the following tasks.

Selection of Green Roadbuilding Technologies

A list of potential green roadbuilding technologies was developed. Theodore Roosevelt Medora Foundation facilities staff and contractors provided information on the specific requirements of potential construction sites. This information was pooled, and a final list of CCP applications was assembled. Negotiations included construction schedules, site requirements, and considerations of the contractors' experience.

Technical Information on Green Roadbuilding Technologies

The focus of this project was to use commercial and proven technologies and demonstrate their sustainability for roadbuilding in North Dakota and the region. Technical documents were assembled and distributed to staff of Theodore Roosevelt Medora Foundation and the engineering and construction contractors already under contract to the Theodore Roosevelt Medora Foundation. Headwaters, Inc., also provided technical direction and support. Material and construction costs were also estimated in order to determine the best use of project funds in order to allow engineering firms and contractors to gain experience during the project.

Construction Planning and Support

Logistics for acquiring CCPs or products containing CCPs were developed in conjunction with Great River Energy and Headwaters, Inc. Placement/construction activities were negotiated, and continued technical support was provided. During the construction activities, EERC technical staff and Headwaters representatives were on-site to communicate with contractors and workers.

Project Review and Education Activities

The project review was performed through communication with project partners and contractors and included assembly of additional information and data on the green roadbuilding technologies used in the demonstration so that the sustainability of the project could be evaluated. Education activities focused primarily on the project engineers and contractors involved in the project, but communications with NDDOT and NDDH were also included.

PROJECT ACTIVITIES

Selection of Green Roadbuilding Technologies

Two construction sites were identified by the Theodore Roosevelt Medora Foundation staff: the Rough Rider Hotel in the city of Medora and the Burning Hills Amphitheater outside of Medora. The construction requirements for each site are noted in Table 2.

The Rough Rider Hotel parking lot, driveways, and walkways were originally the first choice for the demonstration, but the site presented several technical and scheduling issues. The soils at the site were primarily sandy and well-draining. Sandy soils do not benefit as much as other soil types from stabilization with reactive fly ash such as that available in North Dakota. Additionally, the schedule for work at the available locations on that site fell outside of the required schedule for this project.

The Burning Hills Amphitheater site offered both technical and scheduling advantages. The soil at the site was estimated to be primarily swelling (fat) clay. There was damage to existing asphalt pavement at the site associated with swelling and shrinking commonly observed when base or subbase/subgrade is composed of nonstabilized swelling clay. A large area was available for demonstration of both pavement and soil stabilization applications, and there was the opportunity to demonstrate CCP utilization of both new construction for a planned new

Table 2. Theodore Roosevelt Medora Foundation Construction Sites Considered for Demonstration Activities

Identified Site	Construction Requirements	Site Characteristics	Construction Schedule	Potential CCP Utilization Applications Identified
Rough Rider Hotel	Parking lots, driveways, and pedestrian walkways; only new construction required	Primarily sandy soil; geothermal wells under parking area	Hotel remodeling and construction scheduled to start mid-year 2008 with parking, driving, and walking areas to be constructed in mid-2009.	HVFA concrete pavement, pervious concrete for storm water control, and fly ash-stabilized soil
Burning Hills Amphitheater	Parking lots, driveways, pedestrian walkways, and roadway; new construction required for roadway and refurbishing for other areas	Swelling and nonswelling clay soil below existing wear surfaces; asphalt surfacing suitable for recycling	Flexible schedule with pavement placement in April and May 2008. Other construction in fall 2008 and throughout 2009	HVFA concrete pavement, pervious concrete for storm water control, fly ash-stabilized soil, and fly ash for recycling of asphalt

roadway and refurbishment of existing parking, driving, and pedestrian areas. The schedule for the Burning Hills Amphitheater was also flexible, with pavement activities planned for early 2008.

The Burning Hills Amphitheater site was selected, and the following CCP utilization applications in order of highest to lowest priority were targeted:

- 50% fly ash concrete pavement
- 70% fly ash concrete pavement
- Fly ash–soil stabilization
- Fly ash–recycled asphalt base construction
- Pervious fly ash concrete for pedestrian areas
- Bottom ash to promote drainage
- Controlled low-strength material for bridge or rail approach on roadway

Technical Information on Green Roadbuilding Technologies

Technical information on CCPs and their utilization in various roadbuilding applications was assembled and provided to project partners. A bibliography of the published technical documentation provided to project partners is included in Appendix A.

EERC and Headwaters, Inc., representatives also met with various individuals and groups throughout the project to discuss general information on CCP utilization and site-specific issues. The engineering and construction companies participating in the project were:

- Kadrmas, Lee & Jackson, Inc. – provided engineering design services for concrete pavement.

- Kolling & Kolling, Inc. – performed site preparation for the HVFA concrete work.

- Dickinson Ready Mix – provided the high-volume fly ash concrete and expertise related to mix designs.

- Winn Construction, Inc. – performed finishing on the high-volume fly ash concrete.

- Swenson, Hagen & Co. – provided engineering design services for base and subbase/subgrade stabilization.

Additionally, representatives of Headwaters, Inc., and Theodore Roosevelt Medora Foundation communicated with NDDOT Director Francis Ziegler, P.E., regarding the potential for a demonstration of fly ash soil stabilization in North Dakota and a combined effort for a portion of the road construction planned for the Burning Hills Amphitheater site. NDDOT indicated interest in participating in a demonstration of fly ash soil stabilization, and negotiations continue.

Communications with NDDH were also initiated during the project. Discussions with Scott Radig, Director of the Waste Management Division of NDDH, focused on the expansion of the use of CCPs and especially fly ash for soil stabilization in North Dakota and the surrounding region. Mr. Radig agreed to participate in a regional workshop designed to encourage the utilization of fly ash in roads and other construction activities. He agreed to present information on the proper use of fly ash to ensure maintenance of water quality.

Communications with state agency representatives also provided technical direction and support. Material and construction costs were also estimated in order to determine the best use of project funds in order to allow engineering firms and contractors to gain experience during the project.

Construction Planning and Support

After it was decided to perform the project CCP utilization applications at the Burning Hills Amphitheater, work had already been initiated to construct concrete parking, driving, and pedestrian surfaces in areas near the entrance to the amphitheater. On the diagram of the site shown in Appendix B, it can be seen that the pedestrian areas were designed for 4-in. pavement and the driving and parking areas were designed for 6-in. pavement. It was agreed that 50% and 70% fly ash concrete would be placed in both 4- and 6-in. locations. A diagram of the final placement locations is also included in Appendix B. This demonstration was added to existing construction activities at the site. The base and subbase/subgrade preparation had already been initiated when it was decided to go forward with the HVFA concrete pavement demonstration. For this part of the demonstration, base and subbase/subgrade preparation included the removal of up to 18-in. of the clay soil at the site that was then replaced with a granular fill. It was decided that the fly ash soil stabilization demonstration would have to be performed elsewhere in adjacent parking and driveway areas.

Dickinson Ready Mix representatives were very knowledgeable about fly ash concrete, and since one goal of the project was to focus on commercial applications, it was decided to promote as much communication among participating contractors as possible and to use existing specifications, mix designs, and placement techniques. Dickinson Ready Mix provided the mix designs for the 4000 psi 50% and 70% fly ash concrete that was placed in the first phase of construction demonstration activities. The preliminary mix designs (included in Appendix B) were approved by technical staff at the EERC. Kolling & Kolling, Inc., and Winn Construction, Inc., exhibited less familiarity with HVFA concrete. In fact, Winn Construction indicated a hesitancy to participate in the demonstration activities based on previous poor experience with finishing fly ash concrete. After conversations with representatives of the EERC, Headwaters, and Dickinson Ready Mix, Winn Construction agreed to participate. Initial 50% fly ash concrete was delivered to the site. After Winn Construction employees worked to place and finish the concrete, the mix was modified to produce a delivered product that met the expectations of the finishers, and work with the remaining 50% and 70% fly ash concrete continued. After modification of the mix to reduce the superplasticizer chemical admixture and the associated flowability of the concrete mix, Winn Construction workers indicated that the concrete placement and finishing was essentially the same as 100% portland cement concrete. Figures 1 and 2 are photographs of the HVFA concrete placement and finishing activities.

There was some difficulty finishing one section of concrete near the end of the concrete placement activities because of a relatively high wind condition at the site that resulted in accelerated surface drying of the concrete. Additionally, on completion of the placement and several weeks curing, some minor cracking was noted in various locations at the site. Headwaters and EERC representatives noted that these were primarily in susceptible locations where various structures were present in the location of the concrete pour as shown in Figure 3. One crack was noted in the area where the finishers had noted difficulty on the high wind day of construction and was attributed to accelerated surface drying. No rehabilitation was recommended because the cracks were minor. These cracks will be observed on a regular basis by Theodore Roosevelt Medora Foundation staff throughout the project and beyond.

EERC DPH34526.CDR

Figure 1. Placement of HVFA concrete in parking area.

EERC DPH34524.CDR

Figure 2. Finishing of HVFA concrete in pedestrian area.

EERC DPH34523.CDR

Figure 3. Example of cracking noted in finished HVFA concrete.

On completion of the concrete paving work, the project team initiated evaluation of additional CCP utilization applications at the Burning Hills Amphitheater site. Dakota Ready Mix had experience with mix designs, placement, and maintenance of pervious concrete and provided input on potential placement of this product for walking paths to facilitate improved drainage and associated safety for pedestrians. Dakota Ready Mix recommended against the use of pervious concrete because of the issues associated with particulate matter to hinder the pervious nature of the product, so it was decided to postpone demonstration of fly ash in pervious concrete to a future project with site characteristics more amenable to the product performance.

As already noted, the site exhibited evidence of swelling clay, and swelling clay is one soil type that can be successfully treated with fly ash so that the soil exhibits improved performance for base and subbase/subgrade. After evaluating the other potential utilization applications identified for the site, it was determined that the highest volume utilization and the one with the highest potential to improve the site overall was to use fly ash to stabilize soil for base and subbase/subgrade at the site. As shown in the diagram in Appendix C, the remaining parking and driveway areas at the site were large, with a total of 360,000 ft^2 requiring base and subbase/subgrade preparation before installation of asphalt pavement. Asphalt was selected for the pavement because it is a lower-cost option than concrete. The road from Medora to the Burning Hills Amphitheater was also identified as an opportunity to perform additional CCP base and subbase/subgrade. The Theodore Roosevelt Medora Foundation had planned to build a part of the road with an alternate route to reduce the grade and widen the road to improve safety and traffic flow as well as to better allow emergency vehicles to access the Burning Hills Amphitheater area if required. Design work and soil sampling and testing were performed under this project. Project partners worked together to identify CCP options for soil stabilization at the site. Results of the soil testing are included in Appendix C. Soil test results indicated that the soils were a combination of swelling and nonswelling clays to variable depths across the site. These soil types can be improved through the use of fly ash addition. Since there is also damaged asphalt at the site, the use of cold in-place asphalt recycling that incorporates fly ash was also considered for the parking area; however, after evaluation, it was determined it would be impractical to deploy the needed equipment for that activity in the parking area. The asphalt will be removed and stored for potential use with fly ash in the road construction. Additional asphalt will be accessed from other sources in the area, and the recycled asphalt will need to be placed along with the fly ash and blended with existing soil for road base. The options developed for base and subbase/subgrade for the parking areas are shown in Table 3.

Table 3. Identified Options for Fly Ash–Soil Stabilization for Base and/or Subbase/Subgrade

Section		Structural No.	Cost, $	Comments
1	2½-in. asphalt, 12-in. fly ash-treated subgrade	2.9	641,000	Add $90,000 for purchase and delivery of fly ash
2	3-in. asphalt, 12-in. fly ash-treated subgrade	3.12	733,000	Add $90,000 for purchase and delivery of fly ash
3	2½-in. asphalt, 3-in. gravel, 12-in. fly ash-treated subgrade	±3.2	783,000	Add $90,000 for purchase and delivery of fly ash
4	2½-in. asphalt, 6-in. gravel	1.52	791,000	
5	2½-in. asphalt, 6-in. gravel, 12-in. fly ash-treated subgrade	±3.5	925,000	Add $90,000 for purchase and delivery of fly ash
6	4½-in. asphalt	1.73	856,000	
7	4½-in. asphalt, 12-in. fly ash-treated subgrade	3.78	1,010,000	Add $90,000 for purchase and delivery of fly ash
8	4½-in. asphalt, 6-in. gravel base	2.15	1,150,000	
9	3-in. asphalt, 3-in. gravel, 6-in. fly ash-treated subgrade	2.32	803,000	Add $45,000 for purchase and delivery of fly ash

Since the area requiring base and subgrade preparation was so large, it was recommended that two of the fly ash utilization options be demonstrated so that the long-term performance could be compared. The options recommended were:

- 12-in. fly ash-treated soil subgrade (asphalt would be placed directly on the stabilized soil).

- 12-in. fly ash-treated subgrade with 3 in. of gravel base (asphalt would be placed on the base).

These fly ash soil stabilization applications will be demonstrated at the site separately with funds directly from the Theodore Roosevelt Medora Foundation. In addition, the road construction is expected to go forward with the potential to demonstrate one or both of the above fly ash–soil stabilization applications as well as demonstration of the fly ash–recycled asphalt–soil base. Final options for the road construction activities will be determined based on results of soil tests. Prior to initiation of soil stabilization activities, the contractors will submit a "Coal Combustion Product Confined GeoFill Certification and Approval Form" as required by NDDH. A copy of the form is included in Appendix D.

Project Review and Education Activities

The project review included the following activities:

- Follow-up communication with project contractors.

- Assembly of information on the sustainability of the CCP utilization applications identified for use at the Theodore Roosevelt Medora Foundation site.

The result of follow-up communications with the contractors involved in the HVFA concrete placement demonstration was positive. The ready-mix concrete supplier indicated that it will continue to use the 50% and 70% fly ash concrete mix designs and will potentially incorporate the reduction of superplasticizer as appropriate for the specific project and/or contractor. The supplier also encouraged the use of fly ash concrete in many applications and work on NDDOT projects and provided the state-approved fly ash concrete mixes. Probably the most significant feedback received was from the contractor responsible for placing and finishing the HVFA concrete. That company had a history of not using any fly ash in concrete and felt the fly ash would hinder the concrete placement and finishing process and that the final product quality and performance would be diminished because of the inclusion of fly ash. After working with the ready-mix concrete provider and fly ash marketing representative, the contractor indicated that the company and on-site workers found the final mixes as similar to place and finish as 100% portland cement concrete. The contractor indicated that it would be more amenable to using fly ash concrete in future projects.

Education activities for this project focused on the dissemination of existing information to various project contractors. Information provided to contractors was summarized in an earlier section of the report. In addition to the informal discussions and information dissemination, the project team worked together to develop a project outside of this effort to hold a workshop on Market Development, Education, and Outreach to Encourage Fly Ash Use in Roads, Parking Lots, and Other Construction with a focus on the use of CCP in base/subbase stabilization. The information gained in this project will be presented during that workshop, and several partners in this project will also participate in the workshop. As already noted, the NDDH will participate in the workshop. It is also planned that the workshop will be held in Medora and part of the continuing demonstration of use of fly ash in base/subbase preparation incorporated into the workshop format.

An assessment of the sustainability of the CCP utilization applications was made. According to EPA, the environmental benefits of utilizing CCPs include the following:

- **Greenhouse Gas (GHG) and Energy Benefits**. The reuse of CCPs reduces the emission of GHGs in many ways. The primary way that CCP use reduces GHG emissions is through coal fly ash for it takes the equivalent of 55 gallons of oil to produce a single ton of cement. In addition, chemical reactions that occur during the production of portland cement also produce GHGs. The pozzolanic properties of coal fly ash make it a useful replacement for a portion of the portland cement used in making concrete. Fly ash can typically replace between 15% to 30% of the cement in concrete, with even higher percentages used for mass concrete placements. As an added benefit, it makes the concrete stronger and more durable than concrete made with only portland cement as the binder. Another way that using CCPs in place of virgin materials reduces GHG emissions is by reducing the energy-intensive mining operations needed to generate virgin materials. Reduction in mining energy use leads to reduction in GHG emissions.

- **Benefits from Reducing the Landfilling of CCPs**. Beneficially using CCPs instead of landfilling them also reduces the need for additional landfill space. The United States annually landfills over 73 million tons of CCPs. The landfill space required is the equivalent of placing 26,240 quarter-acre home sites under 8 ft of CCPs. Landfill space in the United States is at a premium, and many energy facilities no longer have adequate storage space for CCPs. Beneficially using CCPs reduces the need to locate and develop new disposal facilities and any adverse environmental or health effects associated with them.

- **Benefits from Reducing the Need to Mine Virgin Materials**. CCPs can be substituted for many virgin materials that would otherwise have to be mined. These include lime to make concrete, natural gypsum for wallboard, and gravel for roofing granules. Using virgin materials for these applications means mining them, which can destroy green fields and wildlife habitats. It makes more sense to use existing materials that would otherwise be disposed of than to mine new ones, while simultaneously reducing waste and environment destruction. Reducing mining of virgin materials also conserves energy.

These benefits relate to the sustainability of using CCPs. For the fly ash concrete applications in this project, sustainability was calculated relative to the 30% fly ash concrete that

NDDOT has indicated it uses in many roadbuilding applications. As noted above, it takes 55 gallons of oil to produce 1 ton of cement. If 1 ton of fly ash were used to replace 1 ton of cement, the GHG benefit can be determined. Table 4 shows the comparison of GHG benefits for a more typical 30% fly ash concrete to the two types of HVFA concrete demonstrated in this project.

As can be seen in the results noted in Table 3, the CO_2 emissions linked to the cementitious content of the concrete are reduced as the percentage of fly ash increases. Some sources indicate that 0.8–1.0 ton of CO_2 emissions is avoided for every ton of fly ash used to replace a ton of cement; however, the results in Table 3 are based on the EPA statement that it requires 55 gallons of oil to produce 1 ton of cement. The transportation contribution to GHG emissions associated with concrete production was not included in these calculations.

The project proposal indicated that an electronic resource would be used to evaluate the sustainability of the utilization applications demonstrated in this project; however, that resource is still not fully available. The University of Washington and CH2M HILL continue to work on Greenroads, which is a rating system designed to evaluate roadbuilding sustainability, distinguishing high-performance, more sustainable, new, reconstructed, or rehabilitated roads. It awards credits for approved sustainable choices/practices and can be used to certify projects based on total point value. A few of the places relevant to this project where points can be awarded are Reduce Fossil Fuel Use, Reduce Equipment Emissions, and Reduce Paving Emissions. The points for reducing emissions are awarded based on the use of hybrid engines and biofuels.

Since that resource was not available, an alternate method of evaluating the sustainability of two types of base/subbase preparation was developed. The goal of this process was to estimate and compare the emissions associated with subgrade preparation options with and without the use of fly ash. For purposes of this calculation, the subgrade preparation without use of fly ash would be removal of 6 in. of native soil and replacement with Class 5 aggregate. Following are the factors taken into consideration for calculating the CO_2 footprint of base/subgrade preparation.

Table 4. Comparison of GHG Benefits for Fly Ash Concrete

Fly Ash Concrete Type	Cement in 1 ton of Cementitious Material, lb	Fly Ash in 1 ton of Cementitious Material, lb	GHGs from the Cement Used/ton of Cementitious Material, lb CO_2	Reduction in Associated CO_2 Emissions Compared with Portland Cement Concrete
Portland Cement Concrete, 0% fly ash	2000	0	1225.4	–
30% Fly Ash Concrete (FAC)	1400	600	857.8	367.6
50%, FAC	1000	1000	612.7	245.1
70%, FAC	600	1400	367.6	490.2

- Assessment of the CO_2 associated with transporting the ash:

  - Average semitruck fuel efficiency estimated and confirmed through personal contact.

  - Distance between construction site and ash source estimated using two directions from Web sites.

  - The amount of ash needed was found using the method outlined in Chapter 7 of *Soil Stabilization and Pavement Recycling with Self-Cementing Coal Fly Ash* and the total area to be stabilized.

  - Number of trips determined by tanker size.

  - CO_2 from diesel calculated by EPA methods (5).

- Assessment of the CO_2 associated with utilizing ash:
  - Equipment fuel efficiency found through contact.
  - Run time estimated by/with help from outside contact.
  - CO_2 from diesel calculated by EPA methods.

- Assessment of the CO_2 associated with removing/replacing existing soil:
  - Volume to be removed was calculated based on customer specifications.
  - Number of trips determined by truck-size fill density and road restrictions.
  - Distance to drop site.
  - Distance to pickup site.

Sample calculations are included in Appendix E, and the calculations were performed assuming that each subgrade preparation would be applied to the entire project area of 360,000 ft^2. In order to simplify the calculation, processes that would be equivalent for any base/subbase preparation techniques were not included in the calculation. Examples of activities not included are the final base grading and final compaction. These activities would be performed regardless of the specific base/subbase preparation. The on-site placement activities were also not included at this time because the equipment run time was not available. For the purposes of this calculation, the transport of materials was the only activity included in the CO_2 emission evaluation.

Results of the CO_2 emissions associated with the fly ash and standard (no fly ash) subgrade preparation are shown in Table 5.

Based on the estimates for transport of materials for the 12-in. fly ash-stabilized subgrade as compared to a replacement of 6 in. of native soil with 6 in. of aggregate, the CO_2 emissions for the fly ash-stabilized soil subgrade are slightly less than that for the aggregate. These values are dependent on the location of the site relative to the sources of fly ash and aggregate and are also influenced by the transportation requirements for any material removed. In this case, the

Table 5. CO_2 Emissions Associated with Transport of Materials for Subgrade Preparation

	12-in. Fly Ash-Stabilized Soil Subgrade	Replacement of 6-in. Soil with 6-in. Aggregate
Amount of Material Removed	Not applicable (NA)	6667 yd^3
Distance from Site to Point of Storage or Use	NA	0.25 miles
CO_2 Emissions from Transport of Removed Material	0	0.36 tons
Amount of Material Delivered to Site	36,000 yd^3 fly ash	6667 yd^3 aggregate
Distance from Supplier to Site	135 miles	37 miles
CO_2 Emissions from Transport of Material from Supplier to Site	49.95 tons	53.69 tons
Total CO_2 Emitted	49.95 tons	53.95 tons

native soil will be used in another construction activity very close to the site so that transport distance is minimal. This is not always the case.

For the construction site at the Theodore Roosevelt Medora Foundation Burning Hills Amphitheater, the use of HVFA concrete and fly ash-stabilized subgrade provided a slight improvement to sustainability measured solely on CO_2 emissions as compared to standard concrete mixes and subgrade preparation techniques. However, additional factors are expected to impact the sustainability of the construction activities and will be monitored by Theodore Roosevelt Medora Foundation staff. These include the performance of the products placed and techniques applied. The life of the HVFA concrete is expected to be longer than asphalt that had been used at the site previously. For the remainder of the site, an asphalt pavement will be placed, and it is expected that the 12-in. fly ash-stabilized subgrade will provide an improved base that will lengthen the life and improve the performance of the asphalt pavement. These items will result in lower maintenance and reduced frequency of replacement that relates to improved sustainability.

CONCLUSIONS

The anticipated impact of this project was to increase the use of green roadbuilding technologies in North Dakota, especially those that incorporate CCPs. The standards of success for this project were:

1. The successful completion of at least four CCP-based green roadbuilding technologies in the construction of the parking and driving areas at the site in Medora, North Dakota. The project will be summarized for inclusion in the Coal Combustion Product Partnership (C2P2) and GHP case studies so that a wider audience becomes aware of the demonstration.

2. The preparation and dissemination of information on technologies or applications that have not previously been used in North Dakota or by the contractors for the project.

3. The determination of the sustainability of the project based on existing rating systems. The rating will be compared to the rating of the project as it would have been performed using standard applications/technologies. This information will be incorporated into reports and shared with contractors and DOT representatives to facilitate a dialogue on and an awareness of the sustainability of specific applications and technologies.

These standards were or will be met. Currently, two types of HVFA concrete pavements are in service at the demonstration site. Two types of fly ash soil stabilization will be demonstrated at the site with funding from the Theodore Roosevelt Medora Foundation. On completion of all construction activities, a summary of the entire demonstration will be prepared for submission to C2P2 and GHP. This can be accomplished under the effort to develop and hold a workshop with funding from the EPA Region 8 Resource Conservation Challenge.

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APPENDIX A

TECHNICAL DOCUMENTATION

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American Coal Ash Association. *Fly Ash Facts for Highway Engineers*; Technical Report Prepared for the Federal Highway Administration, Aurora, CO, June 13, 2003.

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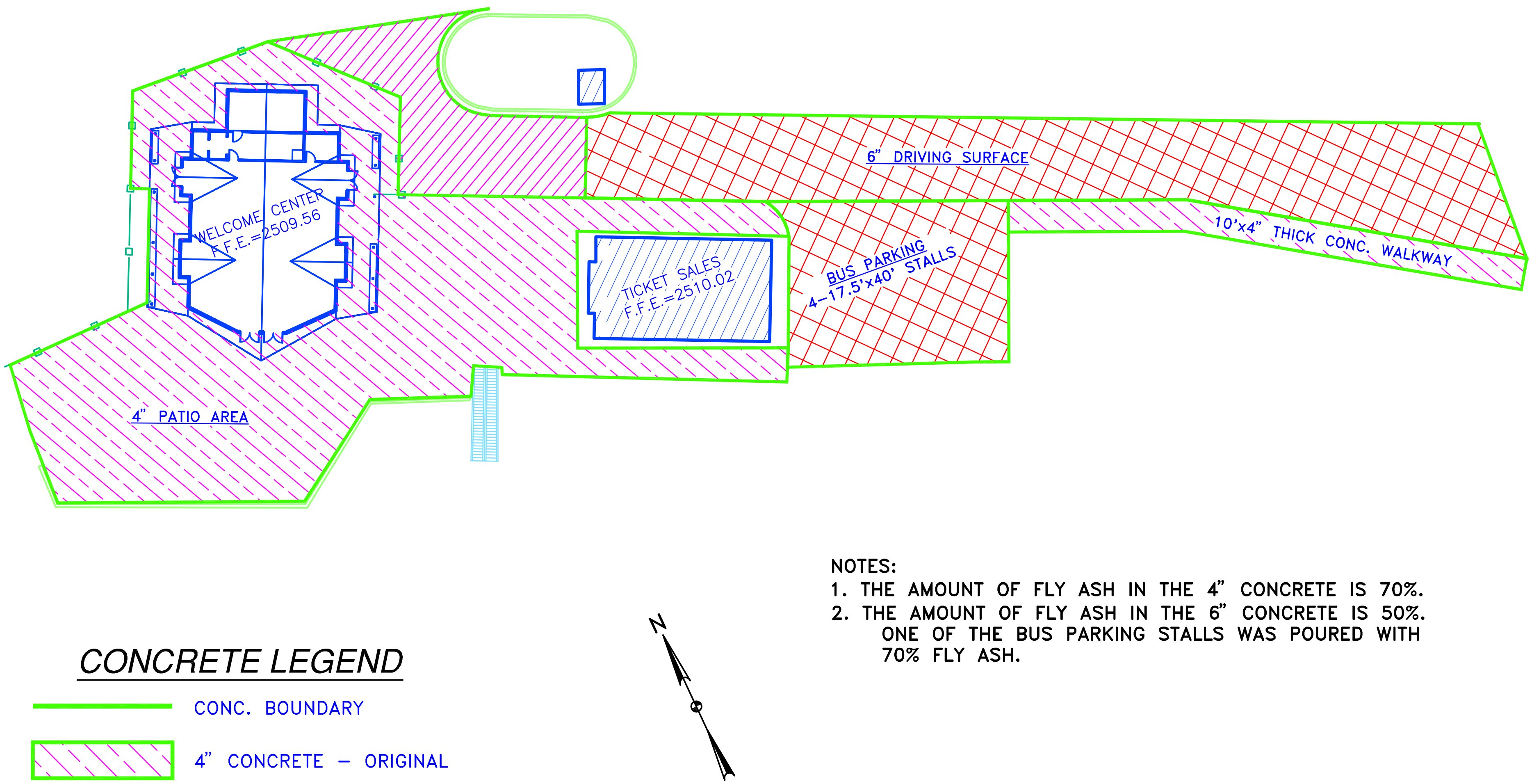
We Energies. Stabilizing Cold In-Place Recycled Asphalt Pavements with Self-Cementing Class ‘C’ Fly Ash: A Field Guide for Owners, Engineers and Contractors; pamphlet.

APPENDIX B

FINAL PLACEMENT LOCATIONS

MEDORA WELCOME VISITOR CENTER CONCRETE AREAS



NOTES:
1. THE AMOUNT OF FLY ASH IN THE 4" CONCRETE IS 70%.
2. THE AMOUNT OF FLY ASH IN THE 6" CONCRETE IS 50%. ONE OF THE BUS PARKING STALLS WAS POURED WITH 70% FLY ASH.

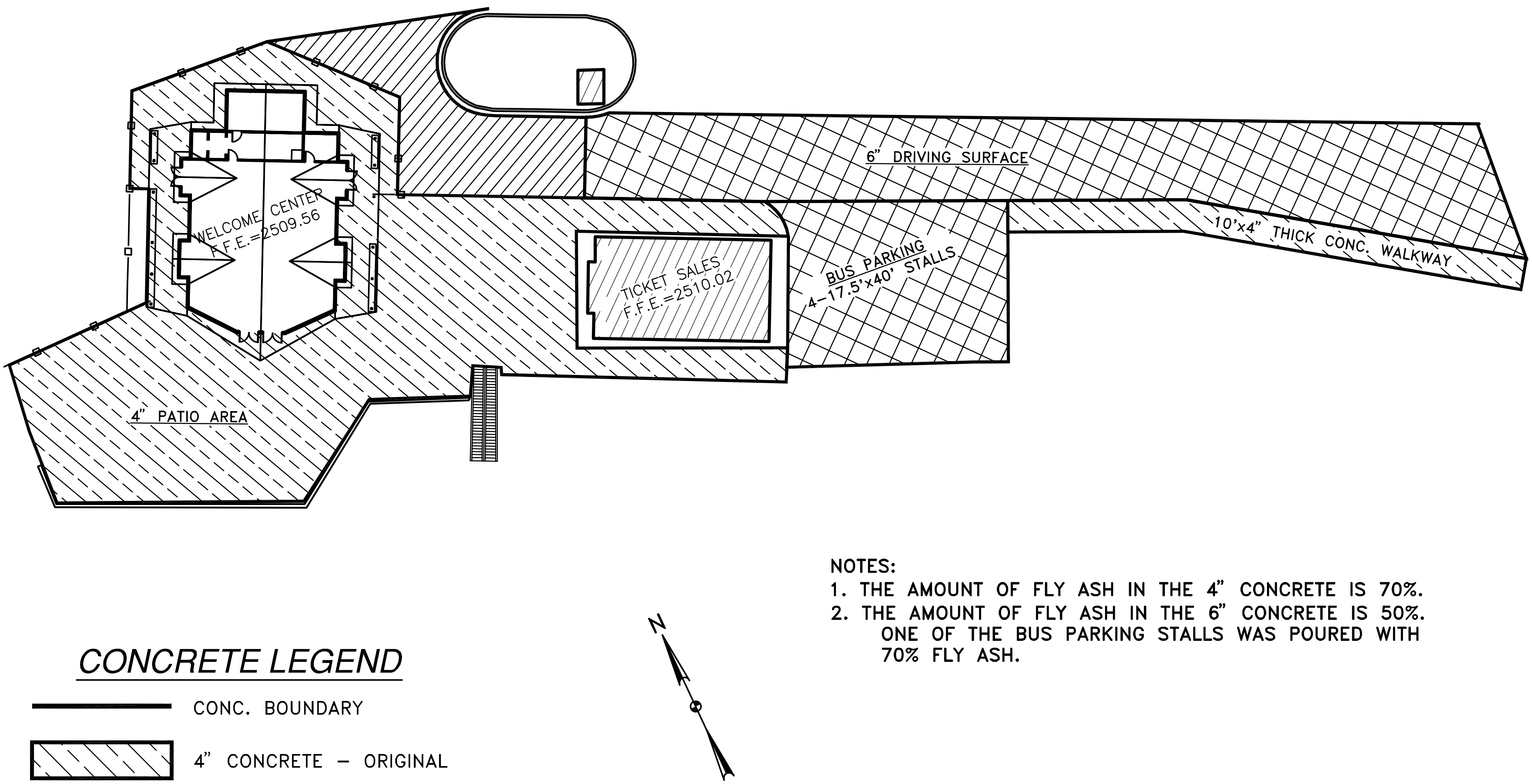
CONCRETE LEGEND

- CONC. BOUNDARY
- 4" CONCRETE – ORIGINAL
- 4" CONCRETE – ADDITIONAL
- 6" CONCRETE – ADDITIONAL

Kadrmas Lee & Jackson
Engineers Surveyors Planners

Mar 31, 2009 – 8:30am – J:\private\3608109\cadd\ep\3608109bas02_Deborah_Hasset_ONLY.DWG

MEDORA WELCOME VISITOR CENTER CONCRETE AREAS



NOTES:

1. THE AMOUNT OF FLY ASH IN THE 4" CONCRETE IS 70%.
2. THE AMOUNT OF FLY ASH IN THE 6" CONCRETE IS 50%. ONE OF THE BUS PARKING STALLS WAS POURED WITH 70% FLY ASH.

CONCRETE LEGEND

- CONC. BOUNDARY
- 4" CONCRETE – ORIGINAL
- 4" CONCRETE – ADDITIONAL
- 6" CONCRETE – ADDITIONAL

Kadrmas Lee & Jackson
Engineers Surveyors Planners

Mar 31, 2009 – 8:30am – J:\private\3608109\cadd\ep\3608109bas02_Deborah_Hasset_ONLY.DWG

Concrete Mix Design
and
Material Cost Estimate

6.5G

Suggested Mix Design (SSD Basis)

6.5 sk / 4000 psi / 50% flyash

Material	Weight *lbs./CY*	Specific Gravity	Abs. Vol. *CF/CY*	Trial Batch *lbs./CF*
Cement (Type II)	306.0	3.15	1.557	11.3
Silica Fume	0.0	2.20	0.000	0.0
Fly Ash	306.0	2.54	1.931	11.3
Coarse Agg.	1800.0	2.65	10.894	66.7
Coarse Agg Free Moisture	0.0	1.00	0.000	Incl in Stone
Coarse Agg #2	0.0	2.63	0.000	0.0
Coarse Agg #2 Free moisture	0.0	1.00	0.000	Incl in Stone
Fine Agg.	1200.0	2.62	7.354	44.4
Fine Agg. Free Moist.	0.0	1.00	0.000	Incl in Fines
Add Water	238.7	1.00	3.825	8.8
Air Content		5.7%	1.540	
Totals =	3850.7		27.1	

w/c =	0.390
Fine Agg Moisture =	0.0%
Coarse Agg Moisture =	0.0%
Coarse Agg 2 Moisture =	0.0%
Fines to total Agg. Ratio =	0.400
Calculated Unit Weight =	142.09
Theoretical Density (air free) =	150.65
Target 28 Day Strength =	

Add Water (Gallons) = 28.65
Absolute Volume = 25.56

Estimated Admixture Dosages

	oz./cwt	oz./CY
AEA =	0.67	4.10
WR =	0	0.00
MRWR =	0	0.00
HRWR =	3	18.36
NCA =	0	0.00
CA =	0	0.00

Mix designs should be tested to confirm expected performance

MIDWEST TESTING LABORATORY

1805 Hancock Dr / P.O. Box 2084 / Bismarck, North Dakota 58502
Phone (701) 258-2833 / Fax (701) 258-2857

REPORT OF: CONCRETE MIX DESIGN

PROJECT: 2007 Plant Test
Dickinson ND

DATE: March 20, 2007

REPORTED TO: Dickinson Ready Mix
PO Box 726
Dickinson, ND 58602

COPIES:

PROJECT NO: B5970

MIX NUMBER: 6.5 Bag, 70% Ash

MATERIALS: 6.54

Cement	Portland cement, Type I/II, conforming to ASTM:C150 specifications, furnished by Lafarge Dakota, Inc. Exshaw, Alberta, Canada
Fly Ash	Class "C" meeting ASTM:C618 specifications, Coal Creek Power Station, Underwood, ND.
Coarse Aggregate	1" - #4 Gravel meeting ASTM:C33 specifications, supplied by Fisher Sand & Gravel, Glendive, Mt.
Fine Aggregate	#4 Down Sand meeting ASTM:C33 specifications, supplied by Fisher Sand & Gravel, Dickinson, ND.
Admixtures	Polyheed 997, mid-range water-reducing admixture conforming to ASTM:C494, Type A, supplied by Master Builders
	MB AE90 air-entraining admixture conforming to ASTM:C260 requirements, supplied by Master Builders

MIX PROPORTIONS USED:

Cement (lbs.)		183
Fly Ash (lbs.)		428
Total Cementitious (sacks)		6.5
Coarse Aggregate 1"-#4 (lbs.)		1870
Fine Aggregate (lbs.)		1130
Admixtures	1. Polyheed 997 (oz.)	18.3
	2. MB AE 90 (oz.)	* 3.7
Water (gallons)		28.0
Water/Cementitious Ratio		0.38
Air Content (%), Calculated		6.0
Slump (inches), Calculated		3

MIX DESCRIPTION: 6.5 bag, 70% ash, air-entrained, 4000 psi @ 56 days

REMARKS:

The weights shown above are based on the aggregate being in an SSD condition and should be increased by the amount of moisture on the aggregate at the time of batching. *The amount of added air entrainment will have to be varied to maintain the specified air content. We would recommend testing the plant produced mix prior to project placement to verify design proportions and strength.

Signed

Concrete Mix Design
and
Material Cost Estimate

6.5F **Suggested Mix Design (SSD Basis)**

6.5 sk / 4000 psi / 70% flyash

Material	Weight *lbs./CY*	Specific Gravity	Abs. Vol. *CF/CY*	Trial Batch *lbs./CF*
Cement (Type II)	183.0	3.15	0.931	6.8
Silica Fume	0.0	2.20	0.000	0.0
Fly Ash	428.0	2.54	2.700	15.9
Coarse Agg.	1870.0	2.65	11.317	69.3
Coarse Agg Free Moisture	0.0	1.00	0.000	Incl in Stone
Coarse Agg #2	0.0	2.63	0.000	0.0
Coarse Agg #2 Free moisture	0.0	1.00	0.000	Incl in Stone
Fine Agg.	1130.0	2.62	6.925	41.9
Fine Agg. Free Moist.	0.0	1.00	0.000	Incl in Fines
Add Water	232.2	1.00	3.721	8.6
Air Content		5.6%	1.506	
Totals =	3843.2		27.1	

w/c =	0.380
Fine Agg Moisture =	0.0%
Coarse Agg Moisture =	0.0%
Coarse Agg 2 Moisture =	0.0%
Fines to total Agg. Ratio =	0.377
Calculated Unit Weight =	141.81
Theoretical Density (air free) =	150.16
Target 28 Day Strength =	

Add Water (Gallons) = 27.87
Absolute Volume = 25.59

Estimated Admixture Dosages

	oz./cwt	oz./CY
AEA =	0.61	3.73
WR =	0	0.00
MRWR =	0	0.00
HRWR =	3	18.33
NCA =	0	0.00
CA =	0	0.00

Mix designs should be tested to confirm expected performance

MIDWEST TESTING LABORATORY

4102 - 7th Ave. N. / P.O. Box 3042 / Fargo, North Dakota 58108
Phone (701) 282-9633 / Fax (701) 282-9635

REPORT OF: TESTS OF CONCRETE CORES

PROJECT: Plant Tests 2007
Pervious Concrete

DATE: December 18, 2007

REPORTED TO: Attn: Scott Olin
Dickinson Ready Mix
P.O. Box 726
Dickinson, ND 58602-0726

COPIES:

PROJECT NO: B5970

MIX PROPORTIONS:

Cement (lbs/yd^3)	495
Fly Ash (lbs/yd^3)	87
5/8" Rock (lbs/yd^3)	2500
Fine Aggregate (lbs/yd^3)	100
MB AE 90 (oz/yd^3)	12.0
Polyheed 997 (oz/yd^3)	25.0
Water (gallons/yd^3)	19.0

SAMPLE I.D.:	01	02	03	04
LOCATION:	Test Panel	Test Panel	Test Panel	Test Panel
ORIGINAL LENGTH (inches):	9.3	9.8	9.4	9.4
DIAMETER (inches):	3.73	3.73	3.73	3.73
DENSITY (lbs/ft^3):	115.2	111.6	113.0	112.2
VOID RATIO (%):	26.1	28.4	27.5	28.0
DATE CAST:	8-21-07	8-21-07	8-21-07	8-21-07
DATE CORED:	8-28-07	8-28-07	8-28-07	8-28-07
DATE TESTED:	9-4-07	9-18-07	9-4-07	9-18-07
AGE OF TEST	14	28	14	28

COMPRESSIVE STRENGTH TEST RESULTS:

Area (square inches)	10.93	10.93	10.93	10.93
L/D Ratio	2.18	2.15	2.17	2.17
Total Loads (lbs.)	11,450	11,500	9,000	10,950
Unit Stress (psi)	1050	1050	825	1000

REMARKS:

Samples were obtained by Midwest Testing Laboratory, Inc. and tested in accordance with ASTM C 42 in a wet condition.

SIGNED Gregory A. Johnson

Gregory A. Johnson, P.E.
Materials Engineer

MIDWEST TESTING LABORATORY

4102 - 7th Ave. N. / P.O. Box 3042 / Fargo, North Dakota 58108
Phone (701) 282-9633 / Fax (701) 282-9635

REPORT OF: TESTS OF CONCRETE CYLINDERS

PROJECT: Plant Tests 2007
Pervious Concrete

DATE: January 9, 2008

REPORTED TO: Attn: Scott Olin
Dickinson Ready Mix
P.O. Box 726
Dickinson, ND 58602-0726

COPIES:

PROJECT NO: B5970

GENERAL DATA

CYLINDER NUMBER	01A	01B	01C	01D
DATE CAST	8/21/2007			
CAST BY (ASTM C31)	Midwest Testing Laboratory, Inc.			
CONCRETE TEMPERATURE (°F) (ASTM C1064)	N.G.			
SLUMP (") (ASTM C143)	N.G.			
VOID CONTENT (%) (ASTM C231)	N.G.			
UNIT WEIGHT (pcf) (ASTM C138)	126.3			
SPECIFIED STRENGTH (At 28 days)	3500			
LOCATION:	Permeable Trial – Rodded			

MIX PROPORTIONS

MIX PROPORTIONS	1
FLY ASH (Lbs.)	87
CEMENT (Lbs.)	495
FINE AGGREGATE (Lbs.)	100
COARSE AGGREGATE (Lbs.)	2500
ADMIXTURE	997 - 25 oz./yd^3, MBAE 90 - 12 oz./yd^3
CONCRETE FURNISHED BY:	Dickinson Ready Mix

COMPRESSIVE STRENGTH DATA (ASTM C39)

LABORATORY NUMBER	2948A	2948B	2948C	2948D
DAYS JOB CURED	3	3	3	3
DIAMETER (inches)	6.00	6.01	6.01	5.98
CROSS-SECTIONAL AREA (in^2)	28.27	28.37	28.37	28.09
AGE OF TEST (Days)	7	28	28	135
LOAD AT FAILURE (Lbs.)	67,720	73,610	64,300	91,130
STRENGTH (P.S.I.)	2400	2600	2270	3240
TYPE OF FRACTURE	4	4	4	4

REMARKS:

Ave. dia. 6.00", ht. 12.04", wt. 24.89 lbs., vol. .197 ft^3.

SIGNED [signature]

MIDWEST TESTING LABORATORY

4102 - 7th Ave. N. / P.O. Box 3042 / Fargo, North Dakota 58108
Phone (701) 282-9633 / Fax (701) 282-9635

REPORT OF: TESTS OF CONCRETE CYLINDERS

PROJECT: Plant Tests 2007
Pervious Concrete

DATE: January 9, 2008

REPORTED TO: Attn: Scott Olin
Dickinson Ready Mix
P.O. Box 726
Dickinson, ND 58602-0726

COPIES:

PROJECT NO: B5970

GENERAL DATA

CYLINDER NUMBER	02A	02B	02C	02D
DATE CAST	8/21/2007			
CAST BY (ASTM C31)	Midwest Testing Laboratory, Inc.			
CONCRETE TEMPERATURE (°F) (ASTM C1064)	N.G.			
SLUMP (") (ASTM C143)	N.G.			
VOID CONTENT (%) (ASTM C231)	N.G.			
UNIT WEIGHT (pcf) (ASTM C138)	120.6			
SPECIFIED STRENGTH (At 28 days)	3500			
LOCATION:	Cylinder Rolled Not Rodded			

MIX PROPORTIONS

MIX PROPORTIONS	1
FLY ASH (Lbs.)	87
CEMENT (Lbs.)	495
FINE AGGREGATE (Lbs.)	100
COARSE AGGREGATE (Lbs.)	2500
ADMIXTURE	997 - 25 oz./yd^3, MBAE 90 - 12 oz./yd^3
CONCRETE FURNISHED BY:	Dickinson Ready Mix

COMPRESSIVE STRENGTH DATA (ASTM C39)

LABORATORY NUMBER	2950A	2950B	2950C	2950D
DAYS JOB CURED	3	3	3	3
DIAMETER (inches)	5.99	6.00	5.99	5.99
CROSS-SECTIONAL AREA (in^2)	28.18	28.27	28.18	28.18
AGE OF TEST (Days)	7	28	28	135
LOAD AT FAILURE (Lbs.)	49,290	65,490	66,810	110,650
STRENGTH (P.S.I.)	1750	2320	2370	3930
TYPE OF FRACTURE	4	4	4	4

REMARKS:

Ave. dia. 5.99", ht. 12.07", wt. 23.74 lbs., vol. .1968 ft^3.

SIGNED

MIDWEST TESTING LABORATORY

4102 - 7th Ave. N. / P.O. Box 3042 / Fargo, North Dakota 58108
Phone (701) 282-9633 / Fax (701) 282-9635

REPORT OF: TESTS OF CONCRETE CORES

PROJECT: Plant Tests 2007
Pervious Concrete

DATE: December 18, 2007

REPORTED TO: Attn: Scott Olin
Dickinson Ready Mix
P.O. Box 726
Dickinson, ND 58602-0726

COPIES:

PROJECT NO: B5970

MIX PROPORTIONS:

Cement (lbs/yd^3)	616
5/8" Rock (lbs/yd^3)	2259
3/8" Rock (lbs/yd^3)	300
Fine Aggregate (lbs/yd^3)	110
MB AE 90 (oz/yd^3)	11.0
Polyheed 997 (oz/yd^3)	30.0
Water (gallons/yd^3)	22.5

SAMPLE I.D.:	05	06	07	08
LOCATION:	N. End	N. End	S. End	S. End
ORIGINAL LENGTH (inches):	11	10.5	10.5	10.4
DIAMETER (inches):	3.75	3.75	3.75	3.75
DENSITY (lbs/ft^3):	126.1	131.0	129.0	126.1
VOID RATIO (%):	13.5	10.6	12.6	13.9
DATE CAST:	9-29-07	9-29-07	9-29-07	9-29-07
DATE CORED:	Not Given			
DATE TESTED:	11-10-07	11-27-07	11-10-07	11-27-07
AGE OF TEST	11	28	11	28

COMPRESSIVE STRENGTH TEST RESULTS:

Area (square inches)	11.04	11.04	11.04	11.04
L/D Ratio	2.07	2.15	2.16	2.15
Total Loads (lbs.)	21,260	22,250	23,450	28,690
Unit Stress (psi)	1930	2015	2130	2600

REMARKS:

Samples were obtained by Midwest Testing Laboratory, Inc. and tested in accordance with ASTM C 42 in a wet condition.

SIGNED Gregory A. Johnson
Gregory A. Johnson, P.E.
Materials Engineer

MIDWEST TESTING LABORATORY

4102 - 7th Ave. N. / P.O. Box 3042 / Fargo, North Dakota 58108
Phone (701) 282-9633 / Fax (701) 282-9635

REPORT OF: TESTS OF CONCRETE CYLINDERS

PROJECT: Plant Tests 2007
Pervious Concrete

DATE: January 9, 2008

REPORTED TO: Attn: Scott Olin
Dickinson Ready Mix
P.O. Box 726
Dickinson, ND 58602-0726

COPIES:

PROJECT NO: B5970

GENERAL DATA

CYLINDER NUMBER	04A	04B	04C	04D
DATE CAST	9/19/2007			
CAST BY (ASTM C31)	Dickinson Ready Mix			
CONCRETE TEMPERATURE (°F) (ASTM C1064)	N.G.			
SLUMP (") (ASTM C143)	N.G.			
VOID CONTENT (%) (ASTM C231)	17.6	20.0		
UNIT WEIGHT (pcf) (ASTM C138)	128.5	124.7		
SPECIFIED STRENGTH (At 28 days)	3500			
LOCATION:	Pervious Rodded			

MIX PROPORTIONS

FLY ASH (Lbs.)	---
CEMENT (Lbs.)	611
FINE AGGREGATE (Lbs.)	100
COARSE AGGREGATE (Lbs.)	2250/300
ADMIXTURE	Poly 997 30 oz./yd^3, MBAE 90 11 oz./yd^3
CONCRETE FURNISHED BY:	Dickinson Ready Mix

COMPRESSIVE STRENGTH DATA (ASTM C39)

LABORATORY NUMBER	4064A	4064B	4064C	4064D
DAYS JOB CURED	3	3	3	3
DIAMETER (inches)	5.99	5.99	5.97	5.96
CROSS-SECTIONAL AREA (in^2)	28.18	28.18	27.99	27.90
AGE OF TEST (Days)	7	7	106	106
LOAD AT FAILURE (Lbs.)	78,370	66,270	90,090	101,500
STRENGTH (P.S.I.)	2780	2350	3220	3640
TYPE OF FRACTURE	3	3	3	3

REMARKS:

SIGNED Gregory [signature]

MIDWEST TESTING LABORATORY
4102 - 7th Ave. N. / P.O. Box 3042 / Fargo, North Dakota 58108
Phone (701) 282-9633 / Fax (701) 282-9635

REPORT OF: TESTS OF CONCRETE CYLINDERS

PROJECT: Plant Tests 2007
Pervious Concrete

DATE: January 9, 2008

REPORTED TO: Attn: Scott Olin
Dickinson Ready Mix
P.O. Box 726
Dickinson, ND 58602-0726

COPIES:

PROJECT NO: B5970

GENERAL DATA

CYLINDER NUMBER	05A	05B	05C	05D
DATE CAST	9/19/2007			
CAST BY (ASTM C31)	Dickinson Ready Mix			
CONCRETE TEMPERATURE (°F) (ASTM C1064)	N.G.			
SLUMP (") (ASTM C143)	N.G.			
VOID CONTENT (%) (ASTM C231)	19.0	18.5		
UNIT WEIGHT (pcf) (ASTM C138)	127.8	128.1		
SPECIFIED STRENGTH (At 28 days)	3500			
LOCATION:	Jigged and Rolled			

MIX PROPORTIONS

FLY ASH (Lbs.)	---
CEMENT (Lbs.)	611
FINE AGGREGATE (Lbs.)	100
COARSE AGGREGATE (Lbs.)	2250/300
ADMIXTURE	Poly 997 30 oz./yd^3, MBAE 90 11 oz./yd^3
CONCRETE FURNISHED BY:	Dickinson Ready Mix

COMPRESSIVE STRENGTH DATA (ASTM C39)

LABORATORY NUMBER	4065A	4065B	4065C	4065D
DAYS JOB CURED	3	3	3	3
DIAMETER (inches)	5.99	5.99	5.99	5.98
CROSS-SECTIONAL AREA (in^2)	28.18	28.18	28.18	28.09
AGE OF TEST (Days)	7	7	106	106
LOAD AT FAILURE (Lbs.)	60,090	69,980	85,660	87,970
STRENGTH (P.S.I.)	2140	2490	3040	3130
TYPE OF FRACTURE	3	3	3	3

REMARKS:

SIGNED Gregory A [signature]

APPENDIX C

REMAINING PARKING AND DRIVEWAY AREAS

Midwest Testing
LABORATORY, INC.

Construction Materials Testing • Geotechnical Engineering Services

April 1, 2009

Mr. Mike Baltzer
Swenson, Hagen & Co, PC
909 Basin Ave
Bismarck, ND 58504-6648

RE: Amphitheatre Parking Lot Renovation
Medora, North Dakota
MTL Project No B9229

Dear Mike:

Enclosed please find the results of the sulfate content tests performed by Minnesota Valley Testing Laboratories. The sample numbers correspond to the boring numbers as shown on the attached drawing. The samples were all obtained at the one foot depth.

If you have any questions, please contact us.

Sincerely,

MIDWEST TESTING LABORATORY

Steven S. Smith, P.E.

SSS/cb

Attachments: MTVL reports (4)
test boring layout

www.midwesttestinglabs.com
Mailing Address: PO Box 2084 Bismarck, ND 58502-2084
1805 Hancock Drive Bismarck, ND 58503 • 701-258-2833 • Fax: 701-258-2857

MINNESOTA VALLEY TESTING LABORATORIES, INC.
1126 N. Front St. ~ New Ulm, MN 56073 ~ 800-782-3557 ~ Fax 507-359-2890
1411 S. 12th St. ~ Bismarck, ND 58502 ~ 800-279-6885 ~ Fax 701-258-9724
51 L Avenue ~ Nevada, IA 50201 ~ 800-362-0855 ~ Fax 515-382-3885
www.mvtl.com

MEMBER ACIL

Report Date: 31 Mar 09
Lab Number: 09-M627
Work Order #:81-322
Account #: 002148
Date Sampled:
Date Received: 20 Mar 09 12:00
PO #: B9229

Steven Smith
Midwest Testing Lab
PO Box 2084
Bismarck ND 58502

Sample Description: Sample 3-1
Sample Site: B9229

	As Received Result		Method RL	Method Reference	Date Analyzed	Analyst
Sulfate	84.9	ug/g	12.5	ASTM D516-02	31 Mar 09 11:30	Morgan

Approved by: O. Zander

RL = Method Reporting Limit

Elevated "Less Than Result" (<): @ = Due to sample matrix
! = Due to sample quantity
= Due to sample concentration
+ = Due to extract volume

CERTIFICATION: MN LAB # 038-999-267 ND # ND-00016

MINNESOTA VALLEY TESTING LABORATORIES, INC.
1126 N. Front St. ~ New Ulm, MN 56073 ~ 800-782-3557 ~ Fax 507-359-2890
1411 S. 12th St. ~ Bismarck, ND 58502 ~ 800-279-6885 ~ Fax 701-258-9724
51 L Avenue ~ Nevada, IA 50201 ~ 800-362-0855 ~ Fax 515-382-3885
www.mvtl.com

MEMBER ACIL

Report Date: 31 Mar 09
Lab Number: 09-M628
Work Order #:81-322
Account #: 002148
Date Sampled:
Date Received: 20 Mar 09 12:00
PO #: B9229

Steven Smith
Midwest Testing Lab
PO Box 2084
Bismarck ND 58502

Sample Description: Sample 5-1
Sample Site: B9229

	As Received Result		Method RL	Method Reference	Date Analyzed	Analyst
Sulfate	111	ug/g	11.8	ASTM D516-02	31 Mar 09 11:30	Morgan

Approved by: O. Zander

RL = Method Reporting Limit

Elevated "Less Than Result" (<): @ = Due to sample matrix
! = Due to sample quantity
= Due to sample concentration
+ = Due to extract volume

CERTIFICATION: MN LAB # 038-999-267 ND # ND-00016

MINNESOTA VALLEY TESTING LABORATORIES, INC.
1126 N. Front St. ~ New Ulm, MN 56073 ~ 800-782-3557 ~ Fax 507-359-2890
1411 S. 12th St. ~ Bismarck, ND 58502 ~ 800-279-6885 ~ Fax 701-258-9724
51 L Avenue ~ Nevada, IA 50201 ~ 800-362-0855 ~ Fax 515-382-3885
www.mvtl.com

MEMBER ACIL

Report Date: 31 Mar 09
Lab Number: 09-M629
Work Order #:81-322
Account #: 002148
Date Sampled:
Date Received: 20 Mar 09 12:00
PO #: B9229

Steven Smith
Midwest Testing Lab
PO Box 2084
Bismarck ND 58502

Sample Description: Sample 8-1
Sample Site: B9229

	As Received Result		Method RL	Method Reference	Date Analyzed	Analyst
Sulfate	12.2	ug/g	12.2	ASTM D516-02	31 Mar 09 11:30	Morgan

Approved by: O. Zander

RL = Method Reporting Limit

Elevated "Less Than Result" (<): @ = Due to sample matrix
! = Due to sample quantity
= Due to sample concentration
+ = Due to extract volume

CERTIFICATION: MN LAB # 038-999-267 ND # ND-00016

MINNESOTA VALLEY TESTING LABORATORIES, INC.

1126 N. Front St. ~ New Ulm, MN 56073 ~ 800-782-3557 ~ Fax 507-359-2890
1411 S. 12th St. ~ Bismarck, ND 58502 ~ 800-279-6885 ~ Fax 701-258-9724
51 L Avenue ~ Nevada, IA 50201 ~ 800-362-0855 ~ Fax 515-382-3885
www.mvtl.com

MEMBER ACIL

Report Date: 31 Mar 09
Lab Number: 09-M630
Work Order #:81-322
Account #: 002148
Date Sampled:
Date Received: 20 Mar 09 12:00
PO #: B9229

Steven Smith
Midwest Testing Lab
PO Box 2084
Bismarck ND 58502

Sample Description: Sample 9-1
Sample Site: B9229

	As Received Result		Method RL	Method Reference	Date Analyzed	Analyst
Sulfate	12.5	ug/g	12.0	ASTM D516-02	31 Mar 09 11:30	Morgan

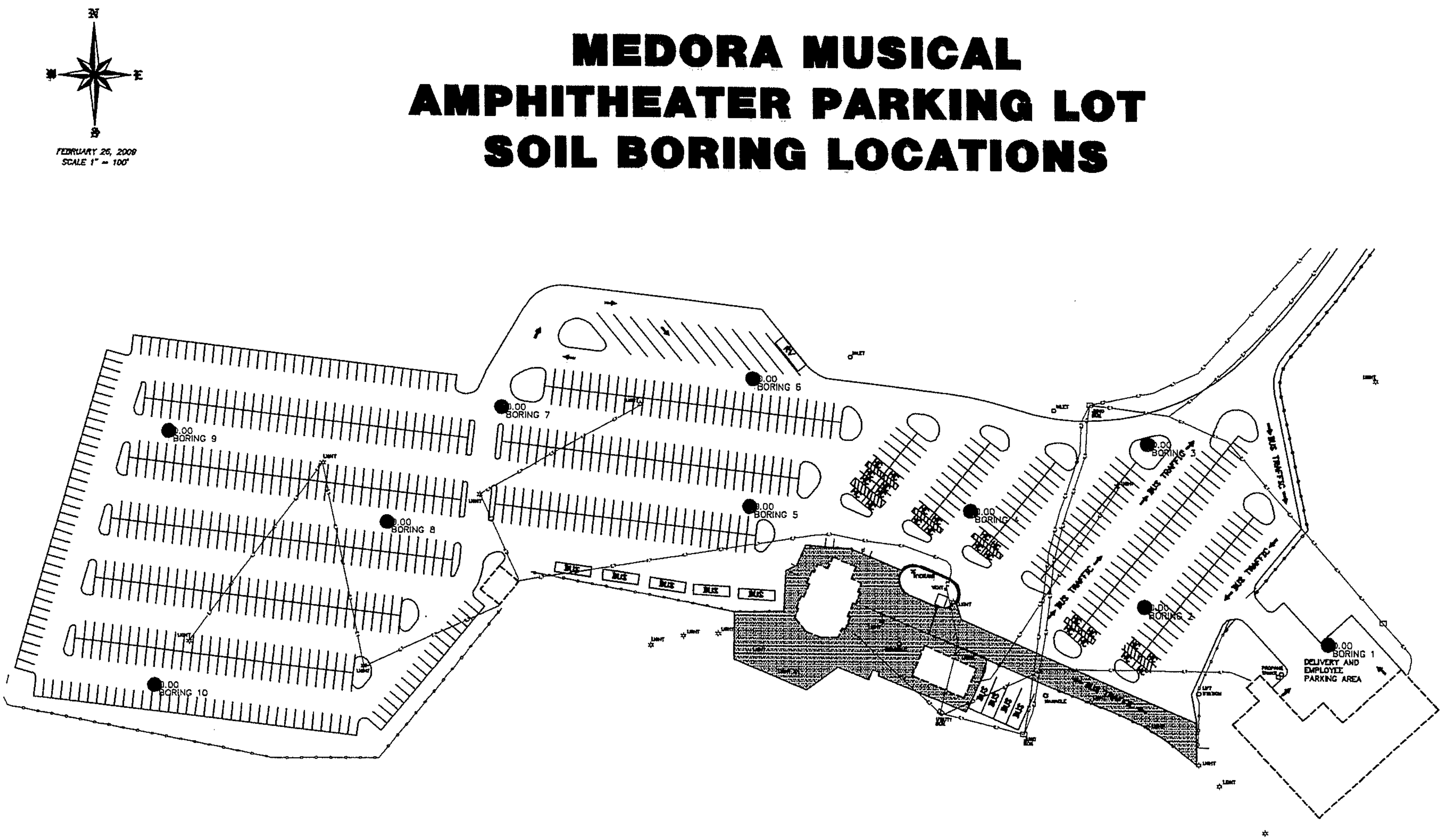
Approved by: D. Zander

RL = Method Reporting Limit

Elevated "Less Than Result" (<): @ = Due to sample matrix
! = Due to sample quantity
= Due to sample concentration
+ = Due to extract volume

CERTIFICATION: MN LAB # 038-999-267 ND # ND-00016

MEDORA MUSICAL
AMPHITHEATER PARKING LOT
SOIL BORING LOCATIONS



SWENSON, HAGEN & COMPANY P.C.
909 Basin Avenue
Bismarck, North Dakota 58504
Phone (701) 223-2600
Fax (701) 223-2606
Surveying
Hydrology
Land Planning
Civil Engineering
Landscape & Site Design
Construction Management

Midwest Testing LABORATORY, INC.

Construction Materials Testing

Geotechnical Engineering Services

Geotechnical Investigation Report

Amphitheatre Parking Lot Renovation
Medora, North Dakota

MTL Project Number B9229

Geotechnical Investigation Report

Amphitheatre Parking Lot Renovation
Medora, North Dakota

Prepared for
Swenson, Hagen & Co, PC

This report was prepared by:

Chad A Cowley

Chad A. Cowley, E.I.T.

STEVEN S. SMITH
REGISTERED
PROFESSIONAL
PE-2863
ENGINEER
NORTH DAKOTA

Date Mar 17, 2009

March 17, 2009

MTL Project Number B9229

Midwest Testing Laboratory, Inc.
P.O. Box 2084
Bismarck, ND 58502-2084
701-258-2833

March 17, 2009

Mr. Mike Baltzer
Swenson, Hagen & Co, PC
909 Basin Ave
Bismarck, ND 58504-6648

RE: Amphitheatre Parking Lot Renovation
Medora, North Dakota
MTL Project No B9229

Dear Mike:

As requested, on March 4, 2009, we advanced 10 soil test borings for the above-referenced project at locations selected by your office. The purpose of these borings was to obtain a general description of the soil conditions at the site and obtain samples for laboratory analysis.

The test borings were advanced using three and one-quarter inch hollow stem auger with split barrel soil samples obtained at regular intervals in accordance with ASTM:D1586, "Test Method for Penetration Test and Split Barrel Sampling of Soils". Soils encountered were visually and manually classified in the field with representative portions returned to the laboratory for verification of the field classifications. Logs of the borings describing soil conditions encountered are attached.

Test borings one, two, seven, and eight initially encountered one to four inches of surface aggregate. Four inches of asphalt pavement followed by two to three inches of aggregate base was identified at test borings three through six. Test borings nine and ten initially encountered two inches of surface vegetation.

Fill material was identified in borings one through four to a depth ranging from two to four feet below grade. The fill consisted of lean clays with sand, sandy lean clays, and clayey sands. Borings five through ten encountered lean clays with sand to a depth of two feet.

Variable soil conditions were identified throughout the remaining depths of our borings. Cohesionless soils consisting primarily of silty sands and sands with silt along with cohesive soils consisting of lean clays and fat clays were all encountered within the parking area. The cohesionless soils had field conditions ranging from loose to medium dense. The cohesive soils had field consistencies ranging from stiff to very stiff. For a complete description of the soil conditions encountered, we refer you to the attached boring logs.

As instructed, we have also determined the moisture-density relationship and supporting characteristics of two major soil types encountered during our investigation. The results of these analyses are included on the attached Tests of Soils reports.

Please note that the moisture-density relationship was determined utilizing ASTM:D698, "Standard Test Methods for Laboratory Compaction Characteristics Using Standard Effort." Supporting characteristics were evaluated utilizing the California Bearing Ratio (CBR), ASTM:D1883, "Standard Test Method for CBR of Laboratory Compacted Soils".

As previously mentioned, the supporting characteristics of two specimens representing the major soil types encountered were evaluated. Review of the results finds CBR values of 5.4 and 7.2 for the clayey sand sample and the sandy lean clay sample, respectively

We recommend excavating all surface vegetation within the limits of the parking lot. Test borings nine and ten indicate approximately two inches of surface vegetation will need to be removed. We further recommend scarifying the top 12 inches of the subgrade and recompacting to 95 percent of the maximum density as determined by the standard proctor, ASTM:D698. The subgrade soils should then be conditioned so that its moisture content at the time of compaction is plus or minus three percent of optimum as determined by this same method. We assume that the future parking lot will be within six inches of the current surface elevations.

With the subgrade soils prepared in the manner described and provided that adequate drainage of the pavement section is maintained, based on results of laboratory testing, it is our opinion that a CBR of six would be available for design of the pavement section.

Should you have any questions or require additional information, please contact us.

Sincerely,

MIDWEST TESTING LABORATORY

Chad A Cowley

Chad A. Cowley, E.I.T.

Steven S. Smith

Steven S. Smith, P.E.

cac/cb

Attachments: test boring logs (10)
tests of soils (2)
moisture-density relationships (2)
soil classification
descriptive terminology
test boring layout

MIDWEST TESTING LABORATORY

JOB NO.: B9229 LOG OR TEST BORING NO.: 1 VERTICAL SCALE: 1"=1'

PROJECT: Amphitheatre Parking Lot Renovation, Medora, North Dakota

DEPTH IN FEET	SOIL DESCRIPTION (SURFACE ELEVATION: **2508.6**)	SAMPLE NO.	SAMPLE TYPE	N	MOISTURE	DENSITY	LL/PL	Qu
	SURFACE AGGREGATE							
4"	FILL-LEAN CLAY WITH SAND-brown, Frost to 3½' (CL) *N value influenced by frost	1	FA	--			32/16	
		2	SS	*70				
4	LEAN CLAY WITH SAND-brown, very stiff (CL)	3	SS	21				
6	END OF BORING **COORDINATES: N 470,005.8; E 1,208,244**							

WATER LEVEL DATA

DATE	TIME	CAVE IN DEPTH	WATER LEVEL
3-4-09	12:05	HSA 4½'	None
3-4-09	12:05	4'	None

BORING DATA

STARTED: 3-4-09 **COMPLETED:** 3-4-09 @ 12:05

METHOD USED: 3¼" ID HSA 0-4½'

CREW CHIEF: M. Roberts

MIDWEST TESTING LABORATORY

JOB NO.: B9229 LOG OR TEST BORING NO.: 2 VERTICAL SCALE: 1"=1'

PROJECT: Amphitheatre Parking Lot Renovation, Medora, North Dakota

DEPTH IN FEET	SOIL DESCRIPTION SURFACE ELEVATION: 2507.3	SAMPLE NO.	SAMPLE TYPE	N	LABORATORY TESTS MOISTURE	DENSITY	LL/PL	Qu
	SURFACE AGGREGATE							
2"	FILL-SANDY LEAN CLAY-brown, trace of gravel, moist, Frost (CL)	1	FA	--				P200 55
2	FILL-CLAYEY SAND-brown, fine to medium-grained, medium dense, dry, Frost (SC) *N value influenced by frost	2	SS	*18				
3	SILTY SAND-light brown, fine to coarse-grained, trace of gravel (SM)							
4½	FAT CLAY-olive brown, very stiff (CH)	3	SS	23				
6	END OF BORING **COORDINATES: N 470,041.3; E 1,208,062**							

WATER LEVEL DATA

DATE	TIME	CAVE IN DEPTH	WATER LEVEL
3-4-09	11:25	HSA 4½'	None
3-4-09	11:25	3'	None

BORING DATA

STARTED: 3-4-09 **COMPLETED:** 3-4-09 @ 11:25

METHOD USED: 3¼" ID HSA 0-4½'

CREW CHIEF: M. Roberts

MIDWEST TESTING LABORATORY

JOB NO.: B9229 LOG OR TEST BORING NO.: 3 VERTICAL SCALE: 1"=1'

PROJECT: Amphitheatre Parking Lot Renovation, Medora, North Dakota

DEPTH IN FEET	SOIL DESCRIPTION — SURFACE ELEVATION: **2506.4**	SAMPLE NO.	SAMPLE TYPE	N	MOISTURE	DENSITY	LL/PL	Qu
	ASPHALT							
4"	AGGREGATE BASE							
6"	FILL-LEAN CLAY WITH SAND-brown, moist, Frost (CL)	1	FA	--				
2	FILL-SANDY LEAN CLAY-light brown, trace of gravel, dry, Frost (CL) *N value influenced by frost	2	SS	*43				
3	SAND WITH SILT-light brown, fine to coarse-grained, trace of gravel (SP-SM)	3	SS	18				
5	SILTY SAND-light brown, fine to medium-grained, dense (SM)							
6	END OF BORING **COORDINATES: N 470,204.5; E 1,208,066**							

WATER LEVEL DATA

DATE	TIME	CAVE IN DEPTH	WATER LEVEL
3-4-09	9:40	HSA 4½'	None
3-4-09	9:40	3'	None

BORING DATA

STARTED: 3-4-09 **COMPLETED:** 3-4-09 @ 9:40

METHOD USED: 3¼" ID HSA 0-4½'

CREW CHIEF: M. Roberts

MIDWEST TESTING LABORATORY

JOB NO.: B9229 LOG OR TEST BORING NO.: 4 VERTICAL SCALE: 1"=1'

PROJECT: Amphitheatre Parking Lot Renovation, Medora, North Dakota

DEPTH IN FEET	SOIL DESCRIPTION SURFACE ELEVATION: 2506.9	SAMPLE NO.	SAMPLE TYPE	N	MOISTURE	DENSITY	LL/PL	Qu
	ASPHALT							
4"	AGGREGATE BASE							
6"	FILL-LEAN CLAY WITH SAND-brown, moist, Frost (CL)	1	FA	--	24		32/16	
2	FILL-SANDY LEAN CLAY-brown, trace of gravel, dry, Frost (CL) *N value influenced by frost	2	SS	*28				
3	SILTY SAND-light brown, fine to medium-grained (SM)							
4½	FAT CLAY-olive brown, very stiff (CH)	3	SS	18				
6	END OF BORING **COORDINATES: N 470,136.1; E 1,207,890**							

WATER LEVEL DATA

DATE	TIME	CAVE IN DEPTH	WATER LEVEL
3-4-09	10:00	HSA 4½'	None
3-4-09	10:00	3'	None

BORING DATA

STARTED: 3-4-09 **COMPLETED:** 3-4-09 @ 10:00

METHOD USED: 3¼" ID HSA 0-4½'

CREW CHIEF: M. Roberts

MIDWEST TESTING LABORATORY

JOB NO.: B9229 LOG OR TEST BORING NO.: 5 VERTICAL SCALE: 1"=1'

PROJECT: Amphitheatre Parking Lot Renovation, Medora, North Dakota

DEPTH IN FEET	SOIL DESCRIPTION SURFACE ELEVATION: **2507.2**	SAMPLE NO.	SAMPLE TYPE	N	MOISTURE	DENSITY	LL/PL	Qu
	ASPHALT							
4"	AGGREGATE BASE							
6"	LEAN CLAY WITH SAND-brown, moist, Frost (CL)	1	FA	--				
2	SAND WITH SILT-brown, fine to coarse-grained, Frost (SP-SM) *N value influenced by frost	2	SS	*44				
3	FAT CLAY-olive brown, very stiff (CH)	3	SS	25				
6	END OF BORING **COORDINATES: N 470,139.5; E 1,207,670**							

WATER LEVEL DATA

DATE	TIME	CAVE IN DEPTH	WATER LEVEL
3-4-09	10:20	HSA 4½'	None
3-4-09	10:20	3½'	None

BORING DATA

STARTED: 3-4-09 **COMPLETED:** 3-4-09 @ 10:20

METHOD USED: 3¼" ID HSA 0-4½'

CREW CHIEF: M. Roberts

MIDWEST TESTING LABORATORY

JOB NO.: B9229 LOG OR TEST BORING NO.: 6 VERTICAL SCALE: 1"=1'

PROJECT: Amphitheatre Parking Lot Renovation, Medora, North Dakota

DEPTH IN FEET	SOIL DESCRIPTION — SURFACE ELEVATION: **2506.0**	SAMPLE NO.	SAMPLE TYPE	N	LABORATORY TESTS: MOISTURE	DENSITY	LL/PL	Qu
	ASPHALT							
4"	AGGREGATE BASE							
7"	LEAN CLAY WITH SAND-brown, moist, Frost (CL)	1	FA	--				
2	FAT CLAY-light grayish brown mottled, very stiff, moist, silt seams, Frost to 3½' (CH)	2	SS	*25				
	*N value influenced by frost							
		3	SS	20				
6	END OF BORING							
	COORDINATES: N 470,268; E 1,207,674							

WATER LEVEL DATA

DATE	TIME	CAVE IN DEPTH	WATER LEVEL
3-4-09	10:35	HSA 4½'	None
3-4-09	10:35	4'	None

BORING DATA

STARTED: 3-4-09 **COMPLETED:** 3-4-09 @ 10:35

METHOD USED: 3¼" ID HSA 0-4½'

CREW CHIEF: M. Roberts

MIDWEST TESTING LABORATORY

JOB NO.: B9229 LOG OR TEST BORING NO.: 7 VERTICAL SCALE: 1"=1'

PROJECT: Amphitheatre Parking Lot Renovation, Medora, North Dakota

DEPTH IN FEET	SOIL DESCRIPTION (SURFACE ELEVATION: **2509.2**)	SAMPLE NO.	SAMPLE TYPE	N	MOISTURE	DENSITY	LL/PL	Qu
	SURFACE AGGREGATE							
2"	LEAN CLAY WITH SAND-light grayish brown, moist, Frost (CL)	1	FA	--			29/18	
2	SAND WITH SILT-light brown, fine to medium-grained, Frost to 3½' (SP-SM) *N value influenced by frost	2	SS	*22				
4½	FAT CLAY-light grayish brown, stiff (CH)	3	SS	15				
6	END OF BORING **COORDINATES: N 470,237.1; E 1,207,454**							

WATER LEVEL DATA

DATE	TIME	CAVE IN DEPTH	WATER LEVEL
3-4-09	10:55	HSA 4½'	None
3-4-09	10:55	2½'	None

BORING DATA

STARTED: 3-4-09 **COMPLETED:** 3-4-09 @ 10:55

METHOD USED: 3¼" ID HSA 0-4½'

CREW CHIEF: M. Roberts

MIDWEST TESTING LABORATORY

JOB NO.: B9229 LOG OR TEST BORING NO.: 8 VERTICAL SCALE: 1"=1'

PROJECT: Amphitheatre Parking Lot Renovation, Medora, North Dakota

DEPTH IN FEET	SOIL DESCRIPTION SURFACE ELEVATION: **2509.7**	SAMPLE NO.	SAMPLE TYPE	N	MOISTURE	DENSITY	LL/PL	Qu
	GRAVEL-brown							
1"	LEAN CLAY WITH SAND-brown, moist, Frost (CL)	1	FA	--				
2	SAND WITH SILT-light brown, fine to medium-grained, medium dense, Frost to 3' (SP-SM) *N value influenced by frost	2	SS	*42				
		3	SS	15				
6	END OF BORING **COORDINATES: N 470,120.7; E 1,207,309**							

WATER LEVEL DATA

DATE	TIME	CAVE IN DEPTH	WATER LEVEL
3-4-09	11:10	HSA 4½'	None
3-4-09	11:10	2½'	None

BORING DATA

STARTED: 3-4-09 **COMPLETED:** 3-4-09 @ 11:10

METHOD USED: 3¼" ID HSA 0-4½'

CREW CHIEF: M. Roberts

MIDWEST TESTING LABORATORY

JOB NO.: B9229 LOG OR TEST BORING NO.: 9 VERTICAL SCALE: 1"=1'

PROJECT: Amphitheatre Parking Lot Renovation, Medora, North Dakota

DEPTH IN FEET	SOIL DESCRIPTION SURFACE ELEVATION: **2511.4**	SAMPLE		N	LABORATORY TESTS			
		NO.	TYPE		MOISTURE	DENSITY	LL/PL	Qu
	LEAN CLAY WITH SAND-dark brown to brown, surface vegetation in upper 2", moist, Frost (CL)	1	FA	--				
2	SILTY SAND-light brown, fine to medium-grained, medium dense, Frost to 2½' (SM)	2	SS	12				
4½	SAND WITH SILT-light brown, fine to medium-grained, loose (SP-SM)	3	SS	8				
6	END OF BORING **COORDINATES: N 470,210.2; E 1,207,092**							

WATER LEVEL DATA

DATE	TIME	CAVE IN DEPTH	WATER LEVEL
3-4-09	11:50	HSA 4½'	None
3-4-09	11:50	2½'	None

BORING DATA

STARTED: 3-4-09 **COMPLETED:** 3-4-09 @ 11:50

METHOD USED: 3¼" ID HSA 0-4½'

CREW CHIEF: M. Roberts

MIDWEST TESTING LABORATORY

JOB NO.: B9229 LOG OR TEST BORING NO.: 10 VERTICAL SCALE: 1"=1'

PROJECT: Amphitheatre Parking Lot Renovation, Medora, North Dakota

DEPTH IN FEET	SOIL DESCRIPTION SURFACE ELEVATION: **2512.6**	SAMPLE NO.	SAMPLE TYPE	N	MOISTURE	DENSITY	LL/PL	Qu
	LEAN CLAY WITH SAND-dark brown to brown, surface vegetation in upper 2", moist, Frost (CL)	1	FA	--	22		35/19	
2	SILTY SAND-light brown, fine to medium-grained, Frost to 3' (SM) *N value influenced by frost	2	SS	*25				
4½	SAND WITH SILT-light brown, fine to medium-grained, medium dense (SP-SM)	3	SS	14				
6	END OF BORING **COORDINATES: N 469,956.3; E 1,207,076**							

WATER LEVEL DATA

DATE	TIME	CAVE IN DEPTH	WATER LEVEL
3-4-09	11:35	HSA 4½'	None
3-4-09	11:35	3'	None

BORING DATA

STARTED: 3-4-09 **COMPLETED:** 3-4-09 @ 11:35

METHOD USED: 3¼" ID HSA 0-4½'

CREW CHIEF: M. Roberts

MIDWEST TESTING LABORATORY

1805 Hancock Dr / PO Box 2084 / Bismarck, North Dakota 58502
Telephone (701) 258-2833 / Fax (701) 258-2857

REPORT OF: TESTS OF SOILS

PROJECT: Amphitheatre Parking Lot Renovation, Medora, North Dakota

DATE: March 17, 2009

REPORTED TO: Swenson, Hagen & Co, PC
Attn: Mike Baltzer
909 Basin Ave
Bismarck, ND 58504-6648

COPIES:

PROJECT NO: B9229

SAMPLE NUMBER:	1	2
LOCATION:	Test boring 3, depth 1/2-4 1/2′	Test boring 6, depth 1/2-4 1/2′
CLASSIFICATION:	CLAYEY SAND (SC)	SANDY LEAN CLAY (CL)
COLOR:	brown	brown
PARTICLE DISTRIBUTION:		
Gravel (%)	6	2
Sand (%)	45	29
Fines (%)	49	69
ATTERBERG LIMITS:		
Liquid Limit	30	33
Plastic Limit	17	16
Plasticity Index	13	17
LABORATORY MOISTURE-DENSITY RELATIONS (see attached curves):		
Method	Standard Proctor, ASTM:D698, Method "A"	
Optimum Moisture (%)	13.8	14.1
Maximum Density (pcf)	117.3	118.7
CALIFORNIA BEARING RATIO (CBR):		
Specimen Density (pcf)	111.5	112.9
Percent Compaction (%)	95	95
Remolded Moisture Content (%)	13.8	14.1
Surcharge Load (lbs)	10.0	10.0
Percent Swell – 96 hours	0.3	0.2
Final Moisture Content (%)	15.8	16.1
Final Moisture (Top 1") (%)	15.2	15.6
CBR @ 0.1" Penetration	7.2	5.4

REMARKS: Material as represented by the above samples were remolded at 95 percent of the maximum dry density and at optimum moisture content. Samples were soaked 96 hours prior to testing.

MIDWEST TESTING LABORATORY

1805 Hancock Dr. / P.O. Box 2084 / Bismarck, North Dakota 58502
Phone (701) 258-2833 / Fax (701) 258-2857

REPORT OF: MOISTURE-DENSITY RELATIONS OF SOIL

PROJECT: Amphitheatre Parking Lot Renovation, Medora, North Dakota

DATE: March 17, 2009

REPORTED TO: Swenson, Hagen & Co, PC
Attn: Mike Baltzer
909 Basin Ave
Bismarck, ND 58504-6648

COPIES:

PROJECT NO: B9229

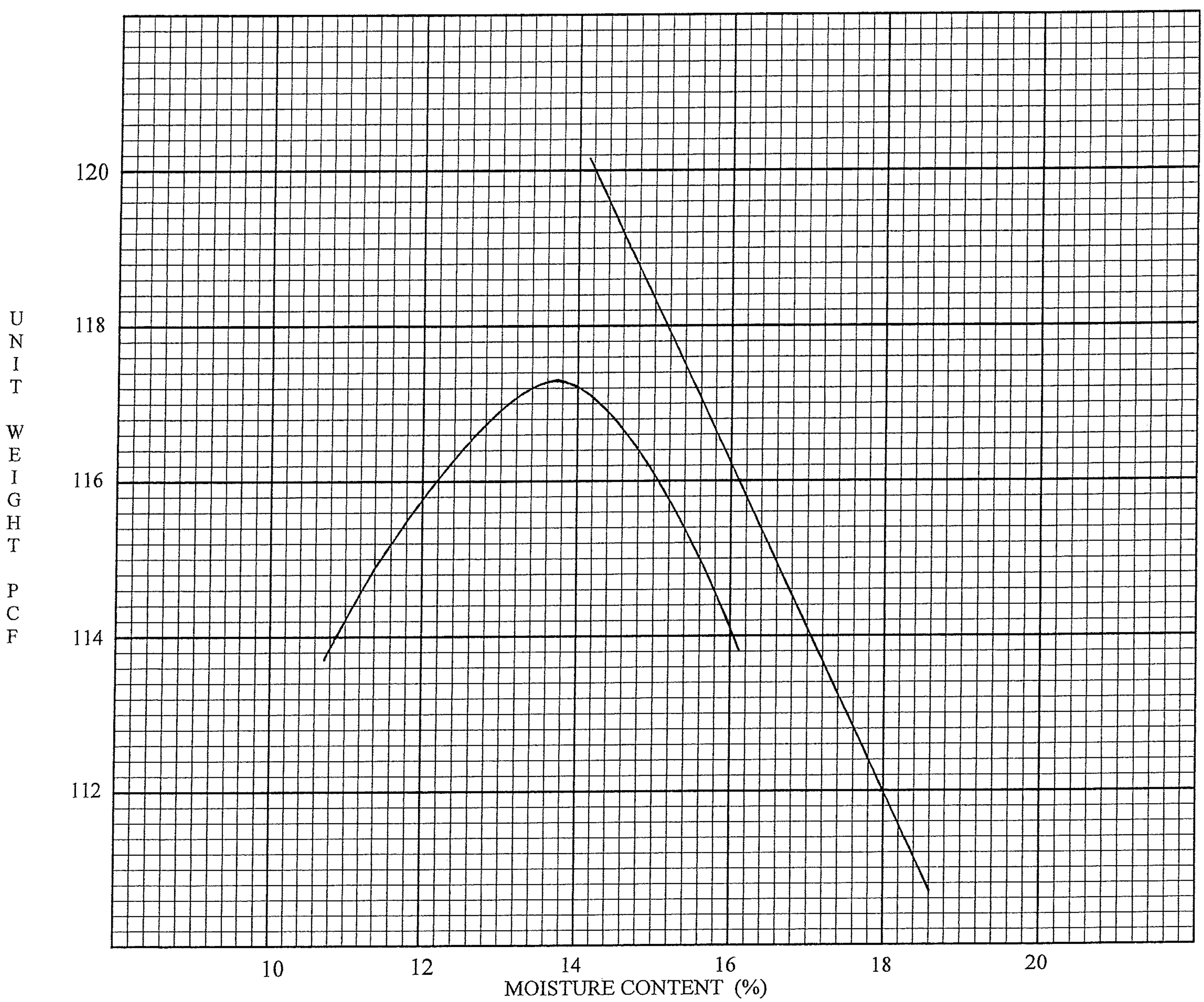
SAMPLE NUMBER: 1 (Test boring 3, depth 1/2-41/2')

METHOD: Standard proctor, ASTM:D698, Method "A"

MAXIMUM DENSITY: 117.3 pcf

SOIL TYPE: CLAYEY SAND- brown (SC)

OPTIMUM MOISTURE: 13.8%



MIDWEST TESTING LABORATORY

1805 Hancock Dr. / P.O. Box 2084 / Bismarck, North Dakota 58502
Phone (701) 258-2833 / Fax (701) 258-2857

REPORT OF: MOISTURE-DENSITY RELATIONS OF SOIL

PROJECT: Amphitheatre Parking Lot Renovation
Medora, North Dakota

DATE: March 17, 2009

REPORTED TO: Swenson, Hagen & Co, PC
Attn: Mike Baltzer
909 Basin Ave
Bismarck, ND 58504-6648

COPIES:

PROJECT NO: B9229

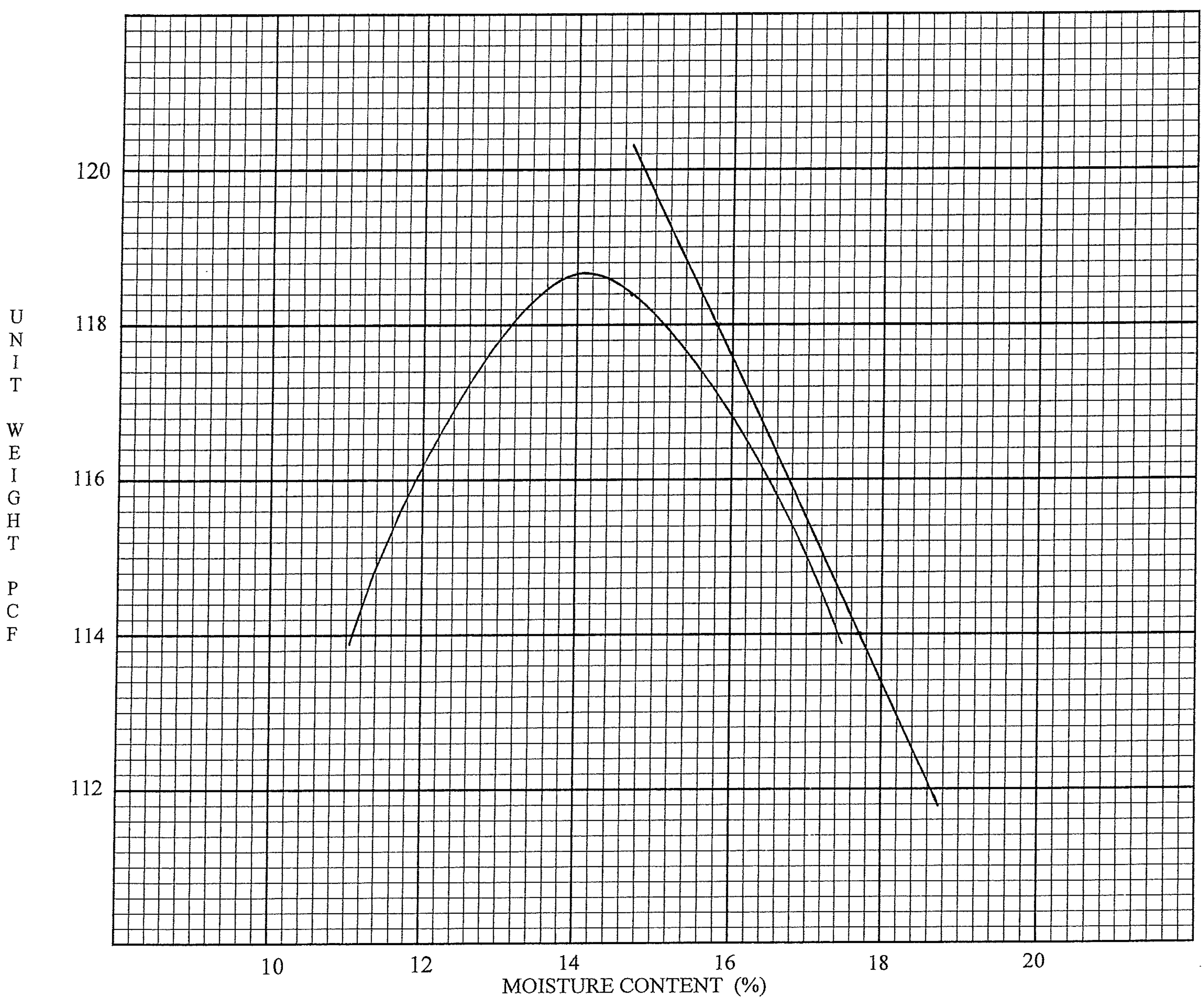
SAMPLE NUMBER: 2 (Test boring 6, depth 1/2-41/2')

METHOD: Standard proctor, ASTM:D698, Method "A"

MAXIMUM DENSITY: 118.7 pcf

SOIL TYPE: SANDY LEAN CLAY- brown (CL)

OPTIMUM MOISTURE: 14.1%



Classification of Soils For Engineering Purposes

ASTM:D 2487-98

Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests[A]				Soil Classification: Group Symbol	Soil Classification: Group Name[B]
Coarse-Grained Soils More than 50% retained on No. 200 Sieve	Gravels More than 50% coarse fraction retained on No. 4 Sieve	Clean Gravels Less than 5% fines[C]	Cu≥4 and 1≤Cc≤ 3[E]	GW	Well graded gravel[F]
			Cu<4 and/or 1>Cc>3[E]	GP	Poorly graded gravel[F]
		Gravels with Fines More than 12% fines[C]	Fines classify as ML or MH	GM	Silty gravel[F,G,H]
			Fines classify as CL or CH	GC	Clayey gravel[F,G,H]
	Sands 50% or more of coarse fraction passes No. 4 Sieve	Clean Sands Less than 5% fines	Cu≥6 and 1≤Cc≤3[E]	SW	Well-graded sand[I]
			Cu<6 and/or 1>Cc>3[E]	SP	Poorly graded sand[I]
		Sands with Fines More than 12% fines[D]	Fines classify as ML or MH	SM	Silty sand[G,H,I]
			Fines classify as CL or CH	SC	Clayey sand[G,H,I]
Fine-Grained Soils 50% or more passes the No. 200 Sieve	Silts and Clays Liquid limit less than 50	Inorganic	PI> 7 and plots on or above "A" line[J]	CL	Lean clay[K,L,M]
			PI<4 or plots below "A" line[J]	ML	Silt[K,L,M]
		Organic	(Liquid limit - oven dried) / (Liquid limit - not dried) <0.75	OL	Organic clay[K,L,M,N]
					Organic silt[K,L,M,O]
	Silts and Clays Liquid limit 50 or more	Inorganic	PI plots on or above "A" line	CH	Fat clay[K,L,M]
			PI plots below "A" line	MH	Elastic silt[K,L,M]
		Organic	(Liquid limit - oven dried) / (Liquid limit - not dried) <0.75	OH	Organic clay[K,L,M,P]
					Organic silt[K,L,M,Q]
Highly organic soils Fibric Peat > 67% Fiber	Primary organic matter, dark in color, and organic odor Hemic Peat 33%-67% Fibers			PT	Peat Sapric Peat < 33% Fibers

[A]Based on the material passing the 3-in. (75mm) sieve.

[B]If field sample contained cobbles or boulders, or both, add "with cobbles or boulders, or both" to group name.

[C]Gravels with 5 to 12% fines require dual symbols:
- GW-GM well-graded with silt
- GW-GC well-graded gravel with clay
- GP-GM poorly graded gravel with silt
- GP-GC poorly graded gravel with clay

[D]Sands with 5 to 12% fines require dual symbols:
- SW-SM well-graded sand with silt
- SW-SC well-graded sand with clay
- SP-SM poorly graded sand with silt
- SP-SC poorly graded sand with clay

[E] $Cu = D_{60} / D_{10}$ $\quad Cc = \frac{(D_{30})^2}{D_{10} \times D_{60}}$

[F]If soil contains ≥15% sand, add "with sand" to group name.

[G]If fines classify as CL-ML, use dual symbol GC-GM, or SC-SM.

[H]If fines, are organic, add " with organic fines" to group name.

[I]If soil contains ≥ 15% gravel, add "with gravel" to group name.

[J]If Atterberg limits plot in hatched area, soil is CL-ML, silty clay.

[K]If soil contains 15 to 29% plus No. 200, add "with sand" or "with gravel", whichever is predominant.

[L]If soil contains ≥ 30% plus no. 200, predominantly sand, add "sandy" to group name.

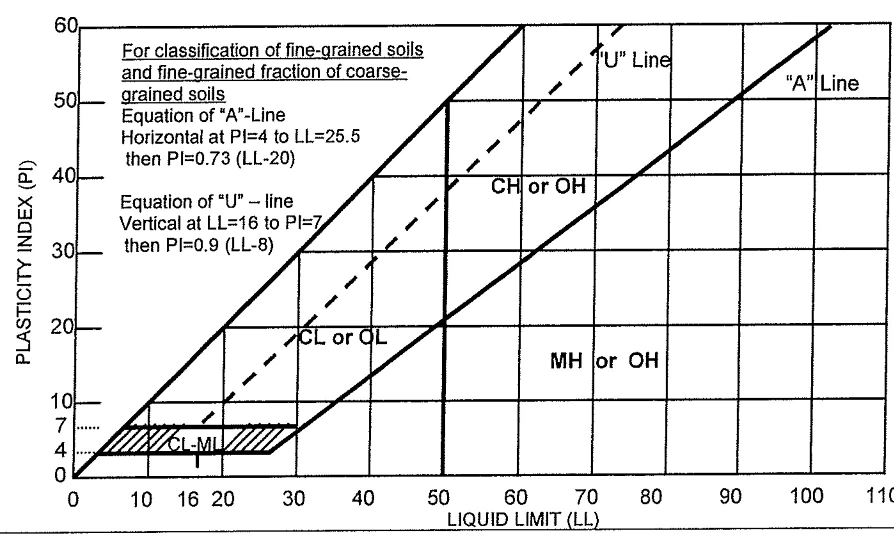
[M]If soil contains ≥ 30% plus no. 200, predominantly gravel, add "gravelly" to group name.

[N]PI≥ 4 and plots on or above "A"line.

[O]PI<4 or plots below "A" line.

[P]PI plots on or above "A" line.

[Q]PI plots below "A" line.



DESCRIPTIVE TERMINOLOGY

RELATIVE DENSITY

Term	"N" Value
Very Loose	0-4
Loose	5 – 9
Medium Dense	10 – 30
Dense	31 – 50
Very Dense	Greater than 50

THICKNESS OF SOIL INTRUSIONS

Term	Range
Lense / Lamination	0 – 1/8"
Seam	1/8" – 1"
Layer	1" – 12"

CONSISTENCY OF COHESIVE SOILS

Term	"N" Value
Very soft	Less than 2
Soft	2 – 4
Medium stiff	5 – 8
Stiff	9 – 15
Very Stiff	16 – 30
Hard	Greater than 30

RELATIVE PROPORTIONS

Term	Range
Trace	0 – 5%
A Little	5 – 15%
With	15 – 50%

PARTICLES SIZES

Term	Range
Boulders	Over 12"
Cobbles	3"– 12"
Gravel	
Coarse	3/4" – 3"
Fine	#4 – 3/4"
Sand	
Coarse	#4 - #10
Medium	#10 - #40
Fine	#40 - #200
Silt	#200 – 0.005 mm
Clay	Less than 0.005 mm

Note: Sieve sizes shown are U.S. Standard

DRILLING & SAMPLING SYMBOLS

Symbol	Definition
FA	Flight Auger
SS	Split Spoon
TW	Thin-Walled Tube
HSA	Hollow Stem Auger
N	Penetration Resistance: blows required to drive a two-inch OD split spoon sampler one foot by means of a 140-pound hammer falling 30 inches

LABORATORY TEST SYMBOLS

Symbols	Definition
LL	Liquid Limit, %
PL	Plastic Limit, %
Q_u	Unconfined Compressive Strength, psf

Additional insertions in Q_u column

Symbols	Definition
G	Specific Gravity
SL	Shrinkage Limit, %
pH	Hydrogen Ion Content-Meter Method
O	Organic Content, % - Combustion Method
M.A.	Grain Size Analysis - Mechanical Method
Hyd.	Grain Size Analysis - Hydrometer Method
C	One-Dimensional Consolidation
Q_c	Triaxial Compression
K	Coefficient of Permeability

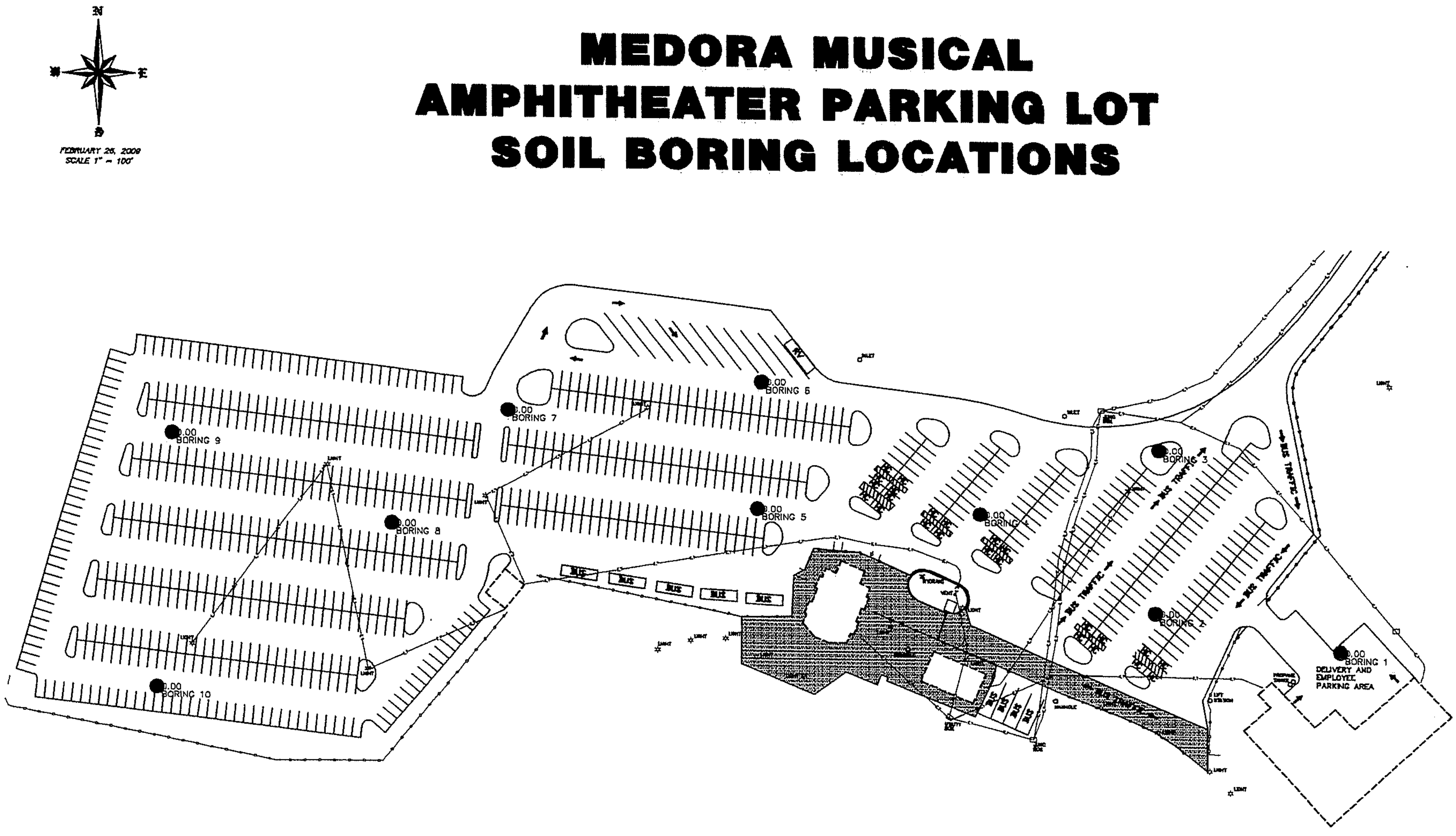
WATER LEVEL INFORMATION

Water levels shown on the boring logs are levels measured in the borings at the time and under the conditions noted. In sand, the indicated levels can be considered reliable. In clay soil, it is not possible to determine the ground water level within the normal scope of a test boring investigation, except where lenses or layers of more pervious water-bearing soils are present. Even then, a long period of time may be necessary to reach equilibrium. Therefore, the position of the water level noted on the boring logs for cohesive or mixed-texture soils may not indicate the true level of the ground water table.

SOIL STRATIFICATION BOUNDARIES

The soil stratification lines shown on the boring logs indicate the approximate boundary between different soil types. In the field, the transition between soil types may be gradual.

MEDORA MUSICAL
AMPHITHEATER PARKING LOT
SOIL BORING LOCATIONS



Reliable Service

Midwest Testing
LABORATORY, INC.

Construction Materials Testing
Geotechnical Engineering Services

Fargo
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PO Box 3042
Fargo, ND 58108-3042
Phone: 701-282-9633
Fax: 701-282-9635

Jamestown
609 2nd St SE
PO Box 1021
Jamestown, ND 58402-1021
Phone: 701-252-9485
Fax: 701-252-0407

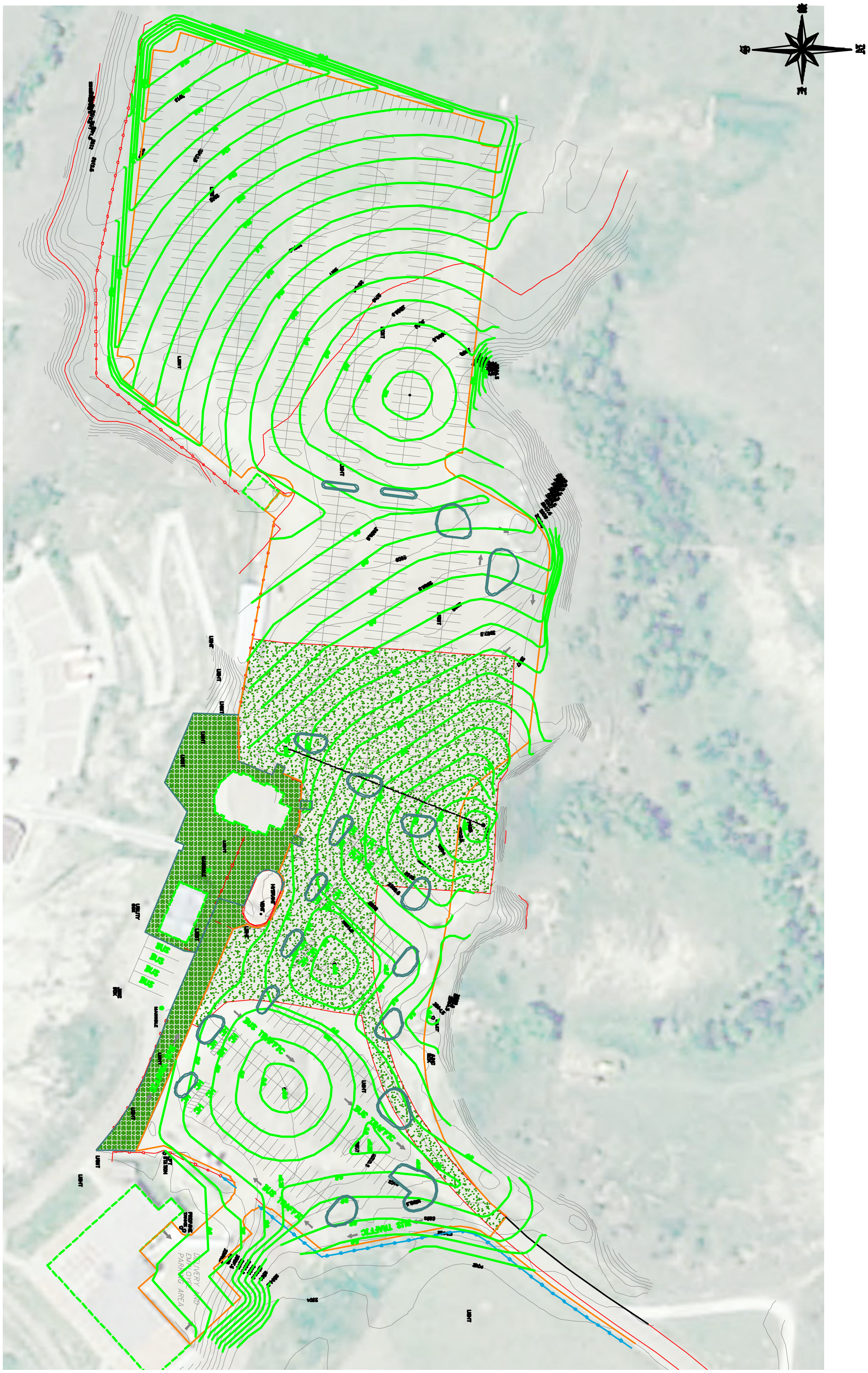
Grand Forks
1555 N 42nd St, Unit B
Grand Forks, ND 58203-0809
Phone: 701-772-2832
Fax: 701-772-2633

Bismarck
1805 Hancock Drive
PO Box 2084
Bismarck, ND 58502-2084
Phone: 701-258-2833
Fax: 701-258-2857

Dickinson
1463 West Villard
PO Box 467
Dickinson, ND 58602-0467
Phone: 701-227-8701
Fax: 701-227-4450

www.midwesttestinglabs.com

BURNING HILLS AMPHITHEATER
MEDORA, NORTH DAKOTA



SWENSON, HAGEN & COMPANY P.C.
Surveying
Hydrology
Land Planning
Civil Engineering
Landscape & Site Design
Construction Management
909 Basin Avenue
Bismarck, North Dakota 58504
Phone (701) 223-2600
Fax (701) 223-2606

APPENDIX D

NORTH DAKOTA DEPARTMENT OF HEALTH COAL COMBUSTION PRODUCT CONFINED GEOFILL CERTIFICATION AND APPROVAL FORM

Coal Combustion Product Confined GeoFill Certification and Approval Form

Section I - GENERAL INFORMATION

Contractor Name or Lead Agency, Address, Phone No. -
Contractor or Agency Contact Person -
Hauler Name, Address, and Phone No. (if different from contractor or Agency) -
Project Identifier (State No., Contractor , etc.) -
Detailed Project Location (intersection or street address) -
Project Description (road base, parking lot, building foundation, etc.) -
Type and Quantity CCP Used / Surface Area -

Section II - SUPPORTING DOCUMENTATION

Map enclosed Yes ☐ No ☐ Dust Control Plan Enclosed Yes ☐ No ☐ MSDS Enclosed Yes ☐ No ☐

North Dakota Groundwater Sensitivity database checked and map of project area enclosed. Yes ☐ No ☐

Section III - ENVIRONMENTAL PROTECTION DOCUMENTATION

If Answers to 1 - 5 are not "No" and 6-7 "Yes", contact NDDH Solid Waste Division for further instructions - Ph. 701-328-5166	**Yes**	**No**
1. Will CCPs be placed in surface waters?		
2. Will CCPs be placed in the groundwater table?		
3. Will CCPs be placed in wetlands?		
4. Will the percentage of fly ash used to stabilize the soil exceed 20% of the final stabilized volume?		
5. Will the ash-stabilized soil extend beyond the boundary of the confined geofill cover (asphalt, concrete and/or compacted gravel)?		
6. If the project is on private property, is the property owner aware that CCPs will be placed on his/her property?		
7. Is the project in compliance with all local ordinances, and all other agency approvals?		

Additional Information - Use the space below and additional sheets, if necessary, to provide NDDH-required additional information

I certify, based on reasonable inquiry and my professional knowledge, that the information provided herein is true, accurate, and complete. I also certify that this project will incorporate best engineering and management practices related to environmental protection. I have been provided with the fugitive dust plan and MSDS attached to this notification and am familiar with their information and will implement the plan and follow MSDS guidance during this project.

Name and Title

Signature and Date

APPENDIX E

SUSTAINABILITY CALCULATIONS

CALCULATIONS FOR CO_2 EMISSIONS ASSOCIATED WITH SUBGRADE PREPARATION

Distribution Calculation

$$(Distribution\ Ratio) = (Depth\ Stabilized) * (1\ ft/12\ in.) * (Standard\ Proctor\ Density) * (Ash\ Content)$$

$$(Distribution\ Ratio) = (12\ in.) * (1\ ft/12\ in.) * (100\ lb/ft^3) * (Ash\ Content) = (10.00\ lb/ft^2)$$

$$\text{(Aria Covered/Truck Load)} = \frac{\text{(Load Size)} * \text{(2000 lb/ton)}}{\text{(Distribution Ratio)}}$$

$$(Aria\ Covered/Truck\ Load) = \frac{(18\ ton/truck\ load) * (2000\ lb/ton)}{(10.00\ lb/ft^2)} = (3600\ ft^2/truck\ load)$$

CO_2 Generated From Hauling Ash

$$\text{(Number of Loads Needed)} = \frac{\text{(Area Stabilized)}}{\text{(Aria Covered/Truck Load)}}$$

$$\text{(Number of Loads Needed)} = \frac{(360{,}000\ \text{ft}^2)}{(3600\ \text{ft}^2\text{/truck load})} = \text{(100 loads)}$$

$$(CO_2\ Generated) = \frac{(Truck\ Loads\ Needed) * (two\ trips/load) * (Distance\ Hauled)}{(Fuel\ Economy)} * CO_2\ Generated\ from\ Burning\ Diesel$$

$$(CO_2\ Generated) = \frac{(100\ loads) * (two\ trips/load) * (135\ mil)}{(6\ mi/gal)} * (22.2\ lb\ CO_2/gal) = (49.95\ tons\ of\ CO_2)$$

CO_2 Generated From Hauling Aggregate/ Existing Fill

$$(Volume\ to\ Be\ Hauled) = (Depth) * (1\ ft/12\ in.) * (Aria) * (1\ yd^3/27 ft^3)$$

$$(Volume\ to\ Be\ Hauled) = (6\ in.) * (1\ ft/12\ in.) * (360{,}000\ ft^2) * (1\ yd^3/27\ ft^3) = (6667\ yd^3)$$

$$\text{(Number of Loads Needed)} = \frac{\text{(Volume to be Hauled)}}{\text{(Size of Truck Load)}}$$

$$(Number\ of\ Loads\ Needed) = \frac{(20{,}000\ yd^3)}{(17\ yd^3)} = (1176\ loads)$$

$$(CO_2\ Generated) = \frac{(Truck\ Loads\ Needed) * (two\ trips/load) * (Distance\ Hauled)}{(Fuel\ Economy)} * CO_2\ Generated\ from\ Burning\ Diesel$$

$$(CO_2\ Generated) = \frac{(1176\ loads) * (two\ trips/load) * (37\ mi)}{(6\ mi/gal)} * (22.2\ lb\ CO^2/gal) = (161.06\ tons)$$

Distribution Calculation*	
Specified Ash Content	10%
Standard Proctor Density	100 lb/ft^3
Depth of Stabilized	12 in.
Rate of Ash Distribution	10.00 lb/ft^2
Weight of Ash	18 ton/truck load
Aria to Be Covered by Truck Load of Ash	3600 ft^2/truck load

* Soil Stabilization and Pavement Recycling with Self-Cementing Fly Ash, American Coal Ash Association Educational Foundation, January 2008.

CO_2 Generated from Hauling Ash	
Area Stabilized	360,000 ft^2
Truck Loads Needed	100 loads
Distance from Ash Source	135 miles
Semitruck Average Fuel Economy	6 mi/gal
CO_2 Generated from Burning Diesel	22.2 lb CO_2/gal
CO_2 Generated	49.95 tons of CO_2

CO_2 Generated from Hauling Aggregate	
Depth of Aggregate	6 in.
Area Covered	360,000 ft^2
Volume of Aggregate Needed	6667 yd^3
Size of Truck Load	17 yd^3
Number of Loads Needed	392
Distance from Aggregate Pit	37 mi
Truck Fuel Economy	6 mi/gal
CO_2 Generated from Burning Diesel	22.2 lb CO_2/gal
CO_2 Generated	53.69 tons

CO_2 Generated from Hauling Existing Fill	
Depth of Aggregate	6 in
Area Covered	360,000 ft^2
Volume of Aggregate Needed	6667 yd^3
Size of Truck Load	17 yd^3
Distance from Aggregate Pit	37 mi
Number of Loads Needed	392
Truck Fuel Economy	6 mi/gal
CO_2 Generated from Burning Diesel	22.2 lb CO_2/gal
CO_2 Generated	0.36 tons

United States Environmental Protection Agency
Office of Transportation and Air Quality
EPA420-F-05-001
February 2005

Emission Facts

Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel

The U.S. Environmental Protection Agency (EPA) developed this series of four fact sheets to facilitate consistency of assumptions and practices in the calculation of emissions of greenhouse gases from transportation and mobile sources. They are intended as a reference for anyone estimating emissions benefits of mobile sources air pollution control programs.

Carbon content in motor vehicle fuels

One of the primary determinants of carbon dioxide (CO_2) emissions from mobile sources is the amount of carbon in the fuel. Carbon content varies, but typically we use average carbon content values to estimate CO_2 emissions.

The Code of Federal Regulations (40 CFR 600.113) provides values for carbon content per gallon of gasoline and diesel fuel which EPA uses in calculating the fuel economy of vehicles:

Gasoline carbon content per gallon:	2,421 grams
Diesel carbon content per gallon:	2,778 grams

Note that for the "Inventory of U.S. Greenhouse Gas Emissions and Sinks," EPA estimates CO_2 emissions from fuel from the heat content of the fuel and carbon content coefficients in terms of carbon content per quadrillion BTU (QBTU), using data from the Energy Information Administration (EIA). EIA's numbers are derived from carbon content by mass, and equate to roughly the same carbon content per gallon of fuel as the values provided in 40 CFR 600.113. EPA uses heat content data from Energy Information Administration's (EIA) "Annual Energy Outlook 2003" and carbon content from EIA's "Emissions of Greenhouse Gases in the United States, 2000."

Note also that these estimates are based only on an average carbon content of conventional gasoline and diesel fuel, and do not specifically address the impact of fuel additives such as ethanol or methyl tertiary-butyl ether (MTBE) that may depend on the feedstock.

Calculating CO_2 emissions

The Intergovernmental Panel on Climate Change (IPCC) guidelines for calculating emissions inventories require that an oxidation factor be applied to the carbon content to account for a small portion of the fuel that is not oxidized into CO_2. For all oil and oil products, the oxidation factor used is 0.99 (99 percent of the carbon in the fuel is eventually oxidized, while 1 percent remains un-oxidized.)[1]

Finally, to calculate the CO_2 emissions from a gallon of fuel, the carbon emissions are multiplied by the ratio of the molecular weight of CO_2 (m.w. 44) to the molecular weight of carbon (m.w.12): 44/12.

CO_2 emissions from a gallon of gasoline = 2,421 grams x 0.99 x (44/12) = 8,788 grams = 8.8 kg/gallon = 19.4 pounds/gallon

CO_2 emissions from a gallon of diesel = 2,778 grams x 0.99 x (44/12) = 10,084 grams = 10.1 kg/gallon = 22.2 pounds/gallon

Note: These calculations and the supporting data have associated variation and uncertainty. EPA may use other values in certain circumstances, and in some cases it may be appropriate to use a range of values.

[1] Based on emissions data, EPA's Office of Transportation and Air Quality (OTAQ) is currently examining whether this fraction is higher (closer to 100 percent) for gasoline.

For More Information

You can access documents on greenhouse gas emissions on the Office of Transportation and Air Quality Web site at:

www.epa.gov/otaq/greenhousegases.htm

For further information on calculating emissions of greenhouse gases, please contact Ed Coe at:

U. S. Environmental Protection Agency
Office of Transportation and Air Quality
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APPENDIX E

REVIEW OF NORTH DAKOTA REGULATIONS, STANDARDS, AND PRACTICES RELATED TO THE USE OF COAL COMBUSTION PRODUCTS

REVIEW OF NORTH DAKOTA REGULATIONS, STANDARDS, AND PRACTICES RELATED TO THE USE OF COAL COMBUSTION PRODUCTS

Final Report

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The EERC would also like to express its appreciation to the many individuals who participated voluntarily in the information-gathering process of the review. Those individuals are named in the participant list located in Appendix A of this report.

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LIST OF ACRONYMS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASTSWMO	Association of State and Territorial Solid Waste Management Officials
AC	activated carbon
ACAA	American Coal Ash Association
AML	abandoned mine land
AMLD	Abandoned Mine Land Division
ASTM	American Society for Testing and Materials
AVS	Antelope Valley Station
C^2P^2	Coal Combustion Products Partnership
CAMR	Clean Air Mercury Rule
CARRC®	Coal Ash Resources Research Consortium®
CCP	coal combustion product
CCS	Coal Creek Station
DOE	U.S. Department of Energy
DOT	Department of Transportation
EERC	Energy & Environmental Research Center
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
FGD	flue gas desulfurization
GRE	Great River Energy
LEED®	Leadership in Energy and Environmental Design
LOI	loss-on-ignition
LOS	Leland Olds Station
MDU	Montana–Dakota Utilities Co.
MW	megawatt
NDDH	North Dakota Department of Health
NDDOT	North Dakota Department of Transportation
OTPC	Otter Tail Power Company
PSC	Public Service Commission
QA/QC	quality assurance/quality control
SDA	spray dryer absorber
SO_2	sulfur dioxide
SWOT	strengths, weaknesses, opportunities, threats
UND	University of North Dakota
USGBC	U.S. Green Building Council

REVIEW OF NORTH DAKOTA REGULATIONS, STANDARDS, AND PRACTICES RELATED TO THE USE OF COAL COMBUSTION PRODUCTS

EXECUTIVE SUMMARY

Over 54 million tons of coal combustion products (CCPs) are beneficially used in the United States each year, but over 70 million tons, or 57%, are still being disposed of in landfills or surface impoundments (American Coal Ash Association [ACAA], 2006). The U.S. Department of Energy (DOE) and the U.S. Environmental Protection Agency (EPA) set goals to increase CCP utilization to 50% by 2011. As 2011 draws near, this goal appears to be more difficult to attain, particularly as new emission regulations are implemented, resulting in larger quantities and changing qualities of CCPs produced.

To better understand the status and development of different CCP utilization profiles across the United States, the University of North Dakota Energy & Environmental Research Center (EERC) is conducting a series of state reviews. The first was conducted in Texas in 2004, the second was in Florida in 2005, and the third was in Pennsylvania in 2006. Following the series of three state reviews, a synthesis report was prepared that transfers the findings into a national perspective. These state reviews were funded in part by EPA and DOE. Both agencies encourage other states to follow a similar statement of work to conduct additional state reviews under separate funding mechanisms.

The EERC, with funding from the North Dakota Industrial Commission, Basin Electric Power Cooperative, Great River Energy, Minnkota Power Cooperative, and DOE's Coal Ash Resources Research Consortium® (CARRC®), conducted a fourth state review in North Dakota.

CCPs are the largest solid waste stream generated in North Dakota. According to information obtained during the state review interview process, the authors estimate that North Dakota coal-based power plants produce in excess of 8000 tons per day of CCPs (or nearly 3 million tons per year). They further estimate that North Dakota coal-based power plants currently beneficially use about 40% (or 1.2–1.3 million tons) of CCPs produced per year.

Based on information obtained during the North Dakota state review process, the following items were identified as keys to successful CCP utilization in North Dakota and are discussed at greater length in this report:

1. Great River Energy (GRE) has an established CCP utilization program at Coal Creek Station (CCS) which sells nearly 500,000 tons of fly ash (~94%–95% of total production) each year. Many would agree that CCS produces perhaps the best fly ash in the country with regard to quality and consistency of supply.

2. The North Dakota Department of Transportation (NDDOT) uses fly ash in almost all concrete projects at a replacement rate of 30%. Most DOT's specify a replacement rate between 15%–30% (if they specify fly ash use at all), making NDDOT's specification on the higher end compared to other states.

3. Fly ash is beneficially used as a key cementitious component by the North Dakota Public Service Commission Abandoned Mine Land Division for grout filling of abandoned underground mine lands. Since 1995, PSC used 32,000 tons of fly ash in 28 grout applications. Mine grout is the only preapproved beneficial use application for fly ash in North Dakota.

4. Bottom ash is classified as an inert waste by the North Dakota Department of Health (NDDH) which allows it to be used without approval. In North Dakota, bottom ash is typically used in active mines as a road base and for ice control on public and private roads.

5. Boiler slag is also classified as an inert material. A local boiler slag processor and marketer sells about 125,000 tons of boiler slag per year.

The following were identified as barriers that currently hinder increased CCP utilization in North Dakota. Recommended actions are provided for each barrier.

1. All North Dakota coal-based power plants have a system in place or have plans to control sulfur dioxide (SO_2) emissions (Leland Olds Station is currently installing a SO_2 control system, and Milton R. Young Station Unit 1 will install a wet scrubber in 2011). The by-products produced are either spray dryer absorber material mixed with fly ash or wet sulfite-rich material/sludge. These by-products are difficult to market because they are a low-value material, have limited use potential, and are not located within close proximity to markets. Currently, it is more cost-effective to dispose of the material; however, if high-value and high-volume applications were possible, electric generating companies may be more likely to pursue potential uses.

2. The primary objective of most electric generating companies is to produce electricity, not to make good-quality CCPs and market them. (GRE CCS has successfully done both, but that is an exception in the state.) Electric generating companies should also perform a cost–benefit analysis to determine what resources (i.e., staff, handling equipment) would be needed to improve CCP use and determine if it is a cost-effective ash management solution for the company.

3. NDDH's *Guideline 11 – Ash Utilization for Soil Stabilization, Fill-In Materials, and Other Engineering Purposes* summarizes the department's approach to CCP utilization. The applicant must reasonably demonstrate that the proposed use will not adversely impact the environment. Although NDDH believes Guideline 11 clearly outlines the requirements for use, those requesting beneficial use applications indicated the guideline is too subjective. Potential CCP users should work with NDDH in defining parameters (i.e., leaching method, pre- and postmonitoring). This collaboration could be facilitated through a state CCP program or consortium whose primary objective was to educate government agencies about CCPs. At a federal level, EPA could provide more guidance on what a "beneficial use" is. A clear definition would be helpful to NDDH in writing new or modifying existing guidelines.

4. NDDOT representatives interviewed did not see a need to explore nonconcrete beneficial use applications such as soil stabilization or flowable fill. Conversely, the ready-mix suppliers interviewed believed flowable fill is a major untapped market in North Dakota. Industry should approach all levels of NDDOT to demonstrate the engineering, environmental, and economic benefits of using CCPs in flowable fill applications. In addition, NDDOT could take a second look at the economics associated with using flowable fills containing CCPs.

5. Many North Dakota coal-based power plants do not have a quality assurance/quality control (QA/QC) plan for their CCPs. The implementation of a strict QA/QC plan is imperative for utilization in a variety of applications, especially concrete.

6. With the exception of GRE's CCS, North Dakota coal-based power plants have transportation and distribution infrastructure issues that make it cost-prohibitive and difficult to transport CCPs to major markets outside of the state. Management at coal-based power plants should evaluate the cost–benefit ratio of improving the CCP distribution infrastructure at their plants. Local markets should also be explored.

7. Green building initiatives have not gained widespread acceptance in North Dakota from a consumer or regulatory standpoint. Since consumers are not yet pulling the green building market in North Dakota, it is recommended that approaches to push green building by government be promoted by industry. CCP industry stakeholders should work with state and national building entities to market the benefits of using CCPs in building materials. Government policy makers should also be encouraged to make green building a priority.

8. NDDH's primary focus is to ensure solid wastes are properly disposed of. Because the department is focused on disposal, the authors believe NDDH does not have the resources (i.e., time, knowledge) needed to effectively evaluate new CCP beneficial use applications. Also, once a beneficial use rule is in place, NDDH does not appear to have any mechanisms in place to encourage use. To encourage preapproved CCP beneficial use applications, NDDH should have a list of preapproved uses on its Web site and provide access to appropriate checklists. An industry-led group could be effective in assisting NDDH in education and information dissemination.

9. Ready-mix suppliers interviewed indicated the national commercial concrete market is usually the most difficult consumer group to work with to encourage CCP use. Often, the national company would give an overly prescriptive mix design that the ready-mix supplier believed would benefit from a higher percentage of replacement of fly ash, but the national company would want to stick with its design. Education is key to overcoming this barrier.

10. Fly ash use in the local concrete markets is saturated, so other high-value road-building and construction applications should be explored such as flowable fill, backfill, and road base applications.

11. Some coal ashes from coal-fired industrial boilers do not have the cementitious or pozzolanic properties that coal ashes from coal-fired power plants have and, therefore, will not exhibit the same physical performance in applications such as soil stabilization or flowable fill. There have been instances where industrial coal ashes physically failed in an application and subsequently created a public perception problem for coal ashes from coal-based power plants that are well suited for these uses.

The following potential threats were identified that could hinder CCP utilization in North Dakota in the future:

1. Most North Dakota coal-based power plants will meet 2010 mercury emission regulations (Clean Air Mercury Rule) as they currently operate but will likely need to implement new controls to meet 2018 requirements. NDDH is concerned about how new mercury emission controls will impact CCP utilization and disposal. NDDH has not evaluated by-products from plants with mercury emission controls; therefore, regulating the materials' use or disposal is new territory (as will be the case for other state health departments).

2. New CO_2 regulations are expected, but the potential for impact on CCPs is not clear.

REVIEW OF NORTH DAKOTA REGULATIONS, STANDARDS, AND PRACTICES RELATED TO THE USE OF COAL COMBUSTION PRODUCTS

BACKGROUND

Over 54 million tons of coal combustion products (CCPs) are beneficially used in the United States each year, but over 70 million tons, or 57%, are still being disposed of in landfills or surface impoundments. The overall CCP utilization rate is gradually rising, from 40.08% in 2004, to 40.29% in 2005, to 43.43% in 2006 (American Coal Ash Association [ACAA], 2006). The U.S. Department of Energy (DOE) and the U.S. Environmental Protection Agency (EPA) set goals to increase CCP utilization to 50% by 2011. As 2011 draws near, this goal appears to be more difficult to attain, particularly as new air emission regulations are implemented, resulting in larger quantities and changing qualities of CCPs produced. Given these challenges, both agencies are committed to reaching their utilization goals and are conducting research studies and working together to create and support programs that encourage CCP use. Such programs include EPA's Industrial Materials Recycling Program under the Resource Conservation Challenge (RCC), the Coal Combustion Products Partnership (C^2P^2), the Green Highways Partnership, and the U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED®) Program. Other programs such as the newly formed Industrial Resources Council bring together industry associations (CCPs, foundry sand, construction and demolition debris, and rubber) to achieve similar goals.

Many of the technical barriers associated with CCP utilization have been addressed, but social and knowledge barriers still exist. One of the key nontechnical barriers is the broad range of state laws, regulations, policies, and guidelines regarding the use of CCPs (American Coal Ash Association, 1998; Pflughoeft-Hassett et al., 1999; Dockter and Jagiella, 2005). Some states have worked to develop progressive and effective guidance for CCP utilization that helps to increase CCP utilization while being protective of the environment. Conversely, some states still lack the resources and information to feel comfortable with the environmental appropriateness of using CCPs in certain applications, particularly with nontraditional applications. In addition, changing state laws, regulations, policies, and guidelines can be a lengthy process, taking a number of years to come to fruition, which often frustrates CCP industry stakeholders.

To better understand the status and development of different CCP utilization profiles across the United States, the University of North Dakota (UND) Energy & Environmental Research Center (EERC) was given a grant by EPA and Headwaters Resources, LLC, to conduct a pilot review of state regulations, standards, and practices related to the use of CCPs. Texas was selected as the pilot state because of its progressive approach to CCP utilization. A subsequent grant was awarded to the EERC by EPA and DOE to conduct a second state review. Florida was selected as the second state to review, primarily because it was undergoing changes to its CCP regulations. The EERC subsequently received a grant from EPA, DOE, and ACAA to perform a review in a third state that exhibited a different CCP use scenario and geographic area than the previous two states. Pennsylvania was ultimately chosen as the third state. The final reports from the series of state reviews can be accessed online at www.undeerc.org/carrc/html/review.html. Following the completion of the series of three state reviews, a synthesis report was prepared that translates the results from the three in-depth state reviews into a national perspective. The preparation of the synthesis report was funded by EPA and DOE.

The EERC, with funding from the North Dakota Industrial Commission, Basin Electric Power Cooperative, Great River Energy (GRE), Minnkota Power Cooperative, the DOE National Energy Technology Laboratory Coal Ash Resources Research Consortium® (CARRC®), conducted a fourth state review in North Dakota. This report contains an in-depth analysis of how coal ash is being used in North Dakota, describes what is being done to promote coal ash utilization, lists barriers and threats that hinder use, and recommends actions that can be taken to overcome barriers.

GOAL

The primary objective of this effort is to assess activities in North Dakota that have resulted in encouraging or prohibiting the use of CCPs in an environmentally appropriate manner. The specific goals are to 1) evaluate factors related to the use of CCPs in North Dakota; 2) summarize North Dakota's successes, barriers, and threats; and 3) develop recommendations (action items) that may help North Dakota and other states increase the use of CCPs in an environmentally sound manner.

STATE REVIEW PROCESS

The following tasks outline the steps taken to conduct this review. Experience with previous state reviews showed that the most effective method for conducting the review was to conduct a multiday site visit in a central location within the state. Panels of key stakeholders were assembled and interviewed during the course of this site visit which took place August 27–29, 2007, in Bismarck, North Dakota. Information provided during the interviews was compiled and summarized in this report. The following sections describe each step of the review process in more detail. Tasks are listed in order; however, many tasks were implemented concurrently.

Task 1: Establish an Administrative Team

A project administrative team was established to perform the majority of the administrative work, including organizing the review, compiling findings, and writing reports. Ms. Tera Buckley, EERC Marketing Research Specialist, acted as team leader, with input from Ms. Debra Pflughoeft-Hassett, EERC Senior Research Advisor.

Task 2: Form an Advisory Board

A second team, the project advisory board, was formed to provide input to interviewee selection, assist in the development of a standard questionnaire, and review findings. Advisory board members included Mr. John Sager, EPA; Mr. David Goss, ACAA; and Ms. Kendra Morrison, EPA Region 8. Associated contact information is listed in the project participant list in Appendix A.

Task 3: Assemble a Review Team

A select group of individuals comprised the review team. The primary role of the review team was to administer the meetings at the review. Review team members were Ms. Tera Buckley, EERC; Ms. Debra Pflughoeft-Hassett, EERC; Mr. John Sager, EPA; and Mr. Shane Vasbinder, Basin Electric Power Cooperative. Associated contact information for review team members is listed in Appendix A.

Task 4: Create a Review Guide

A review guide was developed for North Dakota interviewees that included an agenda, background information, and targeted questionnaires for each discussion group (see Appendix B). To facilitate appropriate discussions, the following four discussion groups were formed to answer questions posed by the review team:

- Government agencies – directors and other key personnel of state transportation and health departments

- CCP generators – coal-based electric generating company environmental and ash managers

- Concrete and other engineering applications – CCP marketers and ready-mix concrete suppliers

- Mining – key personnel at the North Dakota Public Service Commission (PSC)

Task 5: Develop a List of Interviewees

With input from the advisory board, the administrative team developed a list of potential interviewees for each of the discussion groups identified in Task 4. The final participant list for the review is included in Appendix A. Those on the participant list attended a discussion session, submitted written comments, or participated in a telephone interview.

Task 6: Prepare Final Report and Disseminate Information

The primary objective of this task was to prepare a final report that could be used to encourage CCP use in North Dakota and other states. Target audiences for the final report include CCP industry representatives and users, personnel at the state government agencies, members of the American Association of State Highway and Transportation Officials (AASHTO), Association of State and Territorial Solid Waste Management Officials (ASTSWMO), and other state and federal agency groups and individuals.

The results of the report are organized into keys, barriers, threats, and actions. These sections were modeled after a SWOT (strengths, weaknesses, opportunities, threats) analysis commonly used by marketing professionals to audit an organization and the environment in which it operates. It is the first stage of planning and helps identify key issues. The SWOT terms were modified to reflect terms that the authors felt were more applicable to the CCP industry.

STATUS OF CCP PRODUCTION AND UTILIZATION IN NORTH DAKOTA

North Dakota currently has four active surface lignite mines that supply coal to all coal-based power plants in the state:

- BNI Coal Ltd. (a subsidiary of ALLETE), Center Mine
- Coteau Properties Company (a subsidiary of the North American Coal Corporation), Freedom Mine
- Dakota Westmoreland Corporation (a subsidiary of Westmoreland Mining LLC), Beulah Mine
- Falkirk Mining Company (a subsidiary of North American Coal Corporation), Falkirk Mine

North Dakota's mines produced 30.3 million short tons of lignite coal in 2006. Since 1988, North Dakota's lignite production has consistently been near the 30-million-ton-per-year range, which makes it one of 15 major coal-producing states in the United States (Lignite Energy Council, 2007a).

North Dakota has seven coal-based power plants. These plants and their megawatt (MW) capacities are listed in Table 1. The total annual generating capacity for all North Dakota coal-based power plants is over 4000 MW.

In addition to the coal-based power plants listed in Table 1, Basin Electric Power Cooperative, through its for-profit subsidiary, Dakota Gasification Company, owns and operates the Great Plains Synfuels Plant northwest of Beulah, North Dakota. The synfuels plant is the only commercial-scale coal gasification plant in the United States that manufactures natural gas.

Table 1. North Dakota Coal-Based Power Plant Annual Generation Capacity

Owner	Station	Capacity, MW
Basin Electric Power Cooperative	Antelope Valley	900
Basin Electric Power Cooperative	Leland Olds	669
Great River Energy	Coal Creek	1200
Great River Energy	Stanton	188
Minnkota Power Cooperative Inc.	Milton R. Young	744
Montana–Dakota Utilities Co.	R.M. Heskett	86
Otter Tail Power Company	Coyote*	420

* Coyote Station is owned by Montana–Dakota Utilities Co. (25%), NorthWestern Public Service (10%), Northern Municipal Power Agency (30%), and Otter Tail Power Company (35%).

The plant produces an array of by-products including ammonium sulfate, anhydrous ammonia, carbon dioxide, dephenolized cresylic acid, krypton and xenon gases, liquid nitrogen, naphtha, and phenol (Basin Electric Power Cooperative, 2007). These by-products are not considered traditional CCPs and, therefore, will not be considered in this review.

CCPs are the largest solid waste stream generated in North Dakota. The North Dakota Department of Health (NDDH) estimates that approximately 9900 tons per day of CCPs are generated compared to about 1400 tons per day of municipal solid waste, 100 tons per day of industrial waste, and about 6 tons per day of hazardous waste (Tillotson, 2007). However, according to information obtained during the state review interview process, the authors' estimate was lower than NDDH at just over 8000 tons per day of CCPs (or nearly 3 million tons per year). The authors further estimate that North Dakota coal-based power plants currently beneficially use about 40% (or 1.2–1.3 million tons) of CCPs produced each year. The basis for these production and use estimates is described by station below.

Antelope Valley Station

Antelope Valley Station (AVS) is located near Beulah, North Dakota, and is owned and operated by Basin Electric Power Cooperative. It is the newest coal-based power plant in North Dakota and is considered a minemouth facility, receiving its coal from the nearby Freedom Mine.

It is estimated that AVS produces approximately 775,250 tons of CCPs per year. About 87% (~675,250 tons) of this material is landfilled each year. AVS has one landfill for all of its CCPs.

AVS has a spray dryer absorber (SDA) system for sulfur dioxide (SO_2) control.[1] The fly ash and SDA material are collected together. About 50,000 tons of AVS fly ash/SDA material is used in area oil fields to solidify waste pits and for mine subsidence each year. An additional 50,000 tons per year is used at the Freedom Mine in soil stabilization applications and for haul roads. AVS provides the fly ash/SDA material to the mine at no charge. AVS recently began working with Headwaters Resources to market its fly ash/SDA material in geotechnical applications.

In February 2007, Basin Electric Power Cooperative approved installing an air-jigging system with a price of more than $25 million at AVS to further reduce SO_2 emissions. The air-jigging system consists of two different components. One involves pulsating air through the coal stream, and the second involves a vibrating slide. In combination, these two processes separate the heavier products in the coal which typically contain the higher percentages of sulfur, mercury, pyrites, and clay in the lignite. Construction of the air jig is expected to start in 2008, with the system becoming operational in mid-2009 (Lignite Energy Council, 2007b).

[1] SDA material is a dry powder product, which is a calcium sulfite ($CaSO_3 \cdot ½ H_2O$, or hannebachite)-rich material. SDA material and fly ash are often collected together in a particulate control device.

Coal Creek Station

Coal Creek Station (CCS) is North Dakota's largest coal-based power plant and is owned and operated by GRE. The plant is located near Underwood, North Dakota. The adjoining Falkirk Mine supplies CCS with coal.

CCS produces about 520,000 tons of fly ash per year, with an outstanding beneficial use rate of 94%–96%. CCS fly ash is used primarily as a cement replacement in concrete and is sold to ready-mix suppliers in North Dakota, South Dakota, Minnesota, Wisconsin, and Iowa and in Manitoba, and Saskatchewan, Canada, through its marketer, Headwaters Resources. GRE estimates that North Dakota uses about 120,000 tons of CCS fly ash in concrete each year. CCS is the state's only fly ash source for concrete. CCS produces 300,000 tons of bottom ash per year, and the majority is used as aggregate, sand-blasting grit, in roofing shingles, and for ice control. CCS produces 125,000 tons of wet flue gas desulfurization (FGD) material,[2] and all of that material is landfilled. CCS is considering installing a forced-oxidized FGD system that will produce a marketable by-product (FGD gypsum) and is exploring its use in agriculture applications.

Coyote Station

Coyote Station, located near Beulah, North Dakota, has multiple owners including Otter Tail Power Company (OTPC) (35%), Montana–Dakota Utilities Co. (MDU) (25%), NorthWestern Public Service (10%), and Northern Municipal Power Agency (30%). The station receives its coal from nearby Beulah Mine. Coyote Station produced approximately 106,000 tons each of dry FGD material[3] and boiler slag in 2006. All of the dry FGD material is landfilled. It sells about 20% (21,200 tons) of its boiler slag for use in roofing shingles and sand-blasting grit. In addition, 4% (4240 tons) of the boiler slag is used for ice control on mining and public roads. The remaining 76% (80,560 tons) of the boiler slag is disposed of in a landfill. The fly ash produced is mixed with lime and recycled back into the dry FGD system. All of the resulting material is landfilled because it is not reactive.

Leland Olds Station

Leland Olds Station (LOS) is located near Stanton, North Dakota, and is owned and operated by Basin Electric Power Cooperative. It receives coal from Freedom Mine.

LOS has a landfill for its fly ash and a separate sluice pond for its bottom ash. LOS produces about 150,000 tons of fly ash, and all of it is landfilled. It produces about 210,000 tons of bottom ash per year and sells ~29% (60,000 tons) for sand blasting under the brand name Black Beauty®. LOS is installing a wet FGD system which will require the landfill to double in size.

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[2] Wet FGD material is also commonly known as scrubber sludge. It is a material produced from a wet unoxidized system to control SO_2. The material is generally a mixture of calcium sulfate, calcium sulfite, and fly ash.

[3] Dry FGD material is a dry powder material that is generally a calcium sulfate-rich material.

Milton R. Young Station

Milton R. Young Station (MRYS) is a coal-based power plant located near Center, North Dakota, owned and operated by Minnkota Power Cooperative, Inc. It is a minemouth plant, receiving its coal from the nearby Center Mine. It has two units, and both are cyclone-fired. MRYS produces 180,000 tons of bottom ash per year, and it is anticipated that 80%–90% will be recycled in 2008 and continue thereafter. MRYS produces 175,000 tons of fly ash per year and uses 60% (105,000 tons) of its fly ash as a reagent in its wet FGD system. All fly ash not used as a reagent is disposed of dry. The plant also produces 240,000 tons of wet FGD material per year, and all is disposed of. In 2010, MRYS will have a new lime system, and all fly ash will be disposed of dry; in 2011, a wet scrubber will be operational for Unit 1, producing a wet FGD material/sludge.

R.M. Heskett Station

Montana–Dakota Utilities Co.'s R.M. Heskett Station (RMHS) is a bubbling fluidized-bed combustor designed to operate with river sand as its bed material. The plant is located north of Mandan, North Dakota, and receives its coal from the Beulah Mine. In 2006, RMHS produced 35,970 tons of fly ash, and all of that material was disposed of. It also produced 4782 of bottom ash and used 17% (800 tons) in road base/subbase applications.

Stanton Station

Stanton Station (SS) was named for its proximity to Stanton, North Dakota. SS has an SDA system in place for sulfur control which produces about 15,000 tons of fly ash/SDA material per year. That material is currently being marketed in the soil stabilization market. The plant also produces between 20,000 and 29,000 tons of bottom ash, which is landfilled.

KEYS TO SUCCESSFUL CCP UTILIZATION IN NORTH DAKOTA

Based on the information obtained at the North Dakota state review discussion group sessions, the authors believe the following are the keys to successful CCP utilization in North Dakota. The keys highlight "strengths" or positive aspects. The keys are listed in order of importance. The measure of importance is based on the volume of CCPs beneficially used.

Key 1: GRE CCS Has One of the Best Fly Ash Utilization Programs in the Nation

In the 1980s, GRE's CCS landfilled a vast majority of CCPs it produced. In 1995, GRE came to realize that CCP utilization is an environmentally responsible effort that could reduce landfill disposal costs and generate a significant revenue stream for the company. To make CCP utilization a priority at CCS, GRE formed an internal process improvement team representing all areas and levels of the company (i.e., upper management, plant operators, and maintenance). This multifaceted team approach gave people ownership over their areas and created a working environment focused on utilization. At the time the internal process improvements team was created, CCP utilization at CCS was 90,000 tons per year.

During the past decade, GRE's CCS established what many would agree is the premier fly ash utilization program in the country, beneficially using 94%–96% of the fly ash it produces. CCS takes great care to ensure that fly ash quality is not impaired by fuel changes, plant outages, or new emission control technologies. CCS has strict quality assurance/quality control (QA/QC) measures in place that supersede all other electric generating companies in the state and, perhaps, the nation. CCS fly ash is used primarily as a cement replacement in concrete and is sold to ready-mix suppliers in North Dakota, South Dakota, Minnesota, Colorado, Wisconsin, and Iowa and in Manitoba and Saskatchewan, Canada.

GRE's commitment to CCP utilization has taken considerable staff effort and monetary resources. GRE invests in research to explore new beneficial use applications for its CCPs and is very involved in CCP utilization programs and associations across the country. For example, GRE's ash manager is the Chairperson for ACAA. It also supports education and outreach efforts that encourage CCP utilization on a local, regional, and national scale. GRE hosted a workshop, "*CCP Beneficial Use Training*," in March 2006 to educate government representatives and end users about the use of fly ash in North Dakota. GRE has also been a long-time supporter of education and outreach activities organized through the EERC's Coal Ash Research Center including the Coal Ash Professionals Training Course. All of these activities allow GRE to remain on the forefront of CCP utilization and help pave the way for others.

As part of their commitment to CCP utilization, GRE and its ash marketer Headwaters Resources, LLC, have invested over $27 million in infrastructure at CCS. Today, CCS has two weight scales for trucks, 200 private rail cars, and an 85,000-ton fly ash storage dome. It loads/unloads 30 rail cars a day and can load up to 150 trucks per day. It also has a method for dealing with overloading trucks. GRE has fly ash terminals in Minnesota and Colorado. After seeing the positive effects of infrastructure at CCS, GRE is in the process of updating loading facilities at SS as well.

With its investment in distribution infrastructure and dedicated to quality control, the price of CCS fly ash went from $0 in 1996 to $35 FOB in 2007. Considering that CCS sold about 494,000 tons of fly ash in 2006, this represents a revenue stream of over $17 million and a significant savings in disposal costs.

Key 2: North Dakota Department of Transportation Allows 30% Fly Ash Replacement in Concrete

According to the North Dakota Department of Transportation (NDDOT) *Standard Specifications for Road and Bridge Construction* (Section 820) adopted in 2002, fly ash must meet the following specification for the specific type of work:

- Portland cement replacement in concrete – AASHTO M295
- Lime fly ash-treated subgrade – ASTM (American Society for Testing and Materials) International C593
- Econocrete – AASHTO M295

- Aggregate base – ASTM C593

The regulation also stipulates that the fly ash shall be from an electric generating plant using a single coal source. This is generally a nonissue for North Dakota coal-based power plants because they are minemouth plants or use only one coal source. However, from a functional perspective, there is no compelling reason why stations that burn more than one coal cannot produce fly ash that is perfectly suitable for use in concrete. An additional stipulation is that fly ash produced at plants where the limestone injection process is used for controlling air pollutants will be considered unacceptable for use in portland cement concrete. The maximum loss-on-ignition (LOI) of 2.0% is based on AASHTO M295.

Fly ash replacement of cement is allowed on a 1:1 ratio, up to a maximum of 30% by weight for standard concrete projects. NDDOT uses fly ash in almost all concrete projects at a replacement rate of 30%. Most DOTs specify a replacement rate between 15% and 30% (if they specify fly ash use at all), making NDDOT's specification on the higher end compared to other states. For mass pours, a replacement rate of 40% is allowed and is more typical. Fly ash is not allowed as a cement substitute when high-early-strength concrete is used. Lime or lime–fly ash mixtures may be used in the top layer of stabilized subgrade.

Fly ash suppliers, with support from contractors, drove the current fly ash regulations. As an example, prior to the specifications mentioned above, NDDOT specified that 20% of fly ash would replace 15% of cement in concrete. NDDOT was approached by fly ash suppliers to change this specification, subsequently, it performed its own research and looked at what other states were doing and modified the specification to the current 1:1 ratio. NDDOT also specified that, after September 15, a contractor would have to ask to use fly ash in a project because NDDOT was concerned about cold weather placement. NDDOT performed freeze–thaw testing with UND and determined that concern was not an issue and removed the time constraint.

Fly ash suppliers are continuing to approach NDDOT to get more fly ash used in DOT projects. Recently, fly ash suppliers requested higher fly ash percent replacement and are providing test data to NDDOT to support this request. If the data look promising, NDDOT will try a higher percentage in one or two demonstration projects before modifying the specification.

Key 3: Mine Grout to Fill Underground Mine Voids Is the Only Preapproved Beneficial Use for Fly Ash in North Dakota

The North Dakota Abandoned Mine Land Reclamation Program operates under the guidelines of the Surface Mining Control and Reclamation Act, the approved State Reclamation Plan, the Federal Assistance Manual, and associated rules, regulations, and policy decisions. The state program is administered by the Abandoned Mine Land Division (AMLD) of the PSC. Oversight of the program is conducted by the Casper Field Office of the Office of Surface Mining.

Fly ash is beneficially used as a partial replacement for cement by AMLD for grout filling of underground abandoned mine lands (AMLs). North Dakota has 600 documented underground AMLs, but the PSC estimates North Dakota actually has between 1000 and 2000 AMLs. About half of the mines are dry and the other half are wet. Since 1995, PSC used 32,000 tons of fly ash in 28 grout applications. More fly ash could be used, but the PSC has limited funding. Program funding comes from a $0.10 per ton production tax on lignite coal mined within the state. For the last 15 years, PSC operated on a budget of $1.5 million per year; however, in 2007, with the passing of Senate Bill S.2616, the budget will be raised to $3 million per year and the program extended until 2021.

In designing its grout mix design, PSC wanted a very flowable and strong material that did not segregate. PSC prefers using fly ash in the mix because it does not flash set like cement and will gain strength for a year or more after placement. Although PSC has no state laws or administrative rules specifying grout mix design for AML underground mine-grouting projects, the grout specifications in PSC Invitations for Bids require that the grout consist of:

- Portland cement: 100 pounds per cubic yard.
- Fly ash: 600 pounds per cubic yard.
- Aggregate: as required to achieve a yield of 27 cubic feet per cubic yard.
- Superplasticizer: (high-range water reducer) 70 ounces per cubic yard.
- Water: as required to achieve the specified slump range. Slumps will be measured 5 minutes after superplasticizer has been mixed into the grout.

This grout formulation has been reviewed and approved by NDDH for use in underground mine-grouting projects. Although quantities of aggregate and water may vary, a typical grout includes approximately 2500 lb of aggregate and 50 gallons of water (in addition to cement, fly ash and superplasticizer) per cubic yard. The grout is required to achieve a minimum unconfined compressive strength of 150 psi within 28 days. The PSC requires material testing (under separate contract) to ensure that the grout and all components meet specifications.

From an environmental standpoint, PSC and NDDH were concerned about the leachate of elements contained in fly ash. On a laboratory scale, PSC used aquariums to simulate a mine leachate scenario. PSC is not required to install groundwater-monitoring wells for all AML underground mine-grouting projects. The need for groundwater monitoring and establishment of groundwater-monitoring programs is site specific and, therefore, determined and developed on a site-by-site basis. Some circumstances that may determine the usefulness of groundwater monitoring include:

- Whether the underground mine contains water.

- Whether there are domestic wells, stock ponds, seeps, or natural water bodies that could potentially be affected by grouting. These would need to be near the project area and associated in some way with water in the mine or the mined coal seam.

Groundwater-monitoring programs for AML grouting projects may include placing monitor wells in the mined coal seam, especially downgradient from the project area. It may also include monitoring private domestic wells, screened in or near the mined coal, near the project area. Groundwater monitoring is usually conducted in consultation with a groundwater hydrologist and includes measurements of water quantity and quality regularly over a period of months or years. PSC also consults with NDDH regarding grouting projects and groundwater monitoring. Most environmental impacts are highly localized near the entry hole and are short-term (seen within 3 days of placement). Once the grout sets, it is very stable and of little environmental concern from a leachate standpoint.

Mine grout to fill underground mine voids is the only preapproved beneficial use application for fly ash in North Dakota. Once fly ash sources are approved for this application, they do not need to get consent from NDDH for each application. In order for a fly ash source to be approved, an electric generating company must request approval from PSC, which approves the physical performance of the fly ash source and works with NDDH to ensure it is an environmentally appropriate material. Approved fly ash sources include CCS, AVS, and LOS. CCS fly ash is preferred by PSC contractors because CCS has an excellent infrastructure at the plant to obtain the fly ash (i.e., ease of loading), although AVS fly ash makes a harder grout and is less costly. PSC has not used AVS fly ash since 2002. However, CCS fly ash is becoming more expensive as it is marketed outside of the state for concrete applications, and PSC suspects AVS fly ash will become a more attractive option. But, even at the higher cost for CCS fly ash, PSC is seeing an 18% reduction in grout cost by using fly ash in place of cement and believes the grout is actually leaching fewer elements because it is denser with fly ash.

When mine reclamation is conducted in North Dakota cities, it can often disrupt the citizens' lifestyles. AMLD is careful to establish relationships with city officials and holds several public meetings to keep citizens informed on the process. From a public relations standpoint, PSC believes the general public accepts the use of fly ash in mine grouts because they prefer to have the AMLs filled and stable. The general public also seems to think it is a good idea to return material back to where it came from.

Key 4: Bottom Ash Is Classified as an Inert Material by NDDH

In North Dakota, all bottom ash generated from coal-based electric generating companies is classified as an inert material by NDDH. The designation allows bottom ash to be used in beneficial use applications without seeking consent from NDDH. Bottom ash is used in active mines as a road base and for ice control on public and private roads. Inadequate information was gleaned from the discussion group sessions and supplemental materials to estimate the amount of bottom ash beneficially used.

Key 5: Boiler Slag Is a Commodity and Is Classified as an Inert Material by NDDH

Like bottom ash, boiler slag is also classified as an inert material by NDDH. Boiler slag is only produced in systems with cyclone furnaces, and since there are limited power plants with cyclone furnace designs, a relatively competitive market for boiler slag has developed in the United States. Slag is used for sand blasting, ice control, manufacture of roofing shingles, and for base on mine roads or drainage media. The market for sand blasting, in particular, has increased.

Most of the boiler slag used in North Dakota is used by Abrasives Inc., a fully integrated manufacturer, processor, and marketer of boiler slag products located in Glen Ullin, North Dakota. The company distributes product in North Dakota, Montana, Wyoming, South Dakota, New Mexico, Arizona, Colorado, and Utah as well as in Canada. Abrasives Inc. sells its product under the brand name Black Magic®, which is packaged in supersacks weighing approximately 3800 lb, 50-lb bags, or 80-lb bags. Abrasives Inc. indicated that it sold approximately 125,000 tons of boiler slag from North Dakota coal-based power plants in 2007 and expects to sell much larger quantities in coming years (Roth, 2007). The slag market for sand-blasting grit is increasing. Even with the transportation issues that had previously limited the use of North Dakota slag, another national boiler slag distributor, Reed Minerals, has been making inquiries on material availability in North Dakota.

REPORTED BARRIERS AND RECOMMENDED ACTIONS THAT COULD INCREASE CCP USE IN NORTH DAKOTA

The following barriers were identified during the North Dakota state review process. The barriers or "weaknesses" detract from a CCP stakeholder's ability to increase CCP utilization. Following each barrier is the recommended action that could be taken to overcome the barrier and, thus, increase CCP utilization. The proposed actions could be implemented by a variety of CCP stakeholders, including government at the federal, state, and local level; electric generating companies; ash marketers; ready-mix producers; academia; and industry groups. The authors believe the barriers are listed in order of significance. Significance was determined by the quantity of CCPs impacted by the barrier.

Barrier 1: North Dakota Coal-Based Power Plants Produce Large Quantities of FGD Material with Limited Market Potential

All North Dakota coal-based power plants have a system in place or have plans to control SO_2 emissions (LOS is currently installing a SO_2 control system, and MYRS Unit 1 will install a wet scrubber in 2011). The specific FGD technologies employed in North Dakota produce by--products that are difficult to market because they are a low-value material, have limited use potential, and are not located within close proximity to markets.

Two North Dakota coal-based power plants (AVS and SS) have SDA systems for SO_2 control and produce a fly ash that is mixed with SDA material. At AVS, fly ash is used as part of the SDA sorbent, while at SS, the fly ash and SDA material are combined after the SDA system. Approximately 78,000–104,000 tons of fly ash/SDA material is used per year in oil field waste sludge (drilling mud mixed with oil) solidification applications in North Dakota. The sludge is put into lined pits and mixed with about 300–500 tons of fly ash/SDA material per pit. However, horizontal drilling is decreasing the amount used because less sludge is created with this new drilling technique. AVS has successfully marketed 13% of its fly ash/SDA material to solidify oil field waste sludge and for soil stabilization in mines. AVS fly ash/SDA material is also approved for use in grout applications in mines; however, contractors prefer to use CCS fly ash because of the ease of loading the material at the plant. Stanton only produces 15,000 tons of fly ash/SDA material per year, and that material is currently being marketed into the soil stabilization market.

Other plants with dry or wet FGD systems in place also produce an FGD material that is not readily marketed because of quality issues with the material and cost issues related to transportation. Most electric generating companies appeared to favor the disposal of FGD materials in the near future. To get FGD materials beneficially used may require a research and development expense that many are not willing to spend.

CCS is considering installing a wet forced-oxidation system that would produce a usable FGD gypsum by-product. FGD gypsum is typically sold to the wallboard market; however, because there are no wallboard manufacturers in or near North Dakota, other beneficial uses must be explored. GRE funded a study conducted by the Electric Power Research Institute (EPRI), North Dakota State University, and Ohio State University to evaluate the use of FGD gypsum as a soil conditioner for agriculture applications which would soften the soil and allow water to be adsorbed more readily. The experiment involves FGD gypsum being applied at 1, 5, and 10 tons per acre to wheat fields in Dickinson, North Dakota. NDDH indicated it would need to evaluate this new proposed beneficial use.

Recommended Actions for Barrier 1

A literature review conducted by the EERC (Heebink et al., 2007) indicated that applications for fly ash/SDA material use in the United States with the highest potential included cementitious products, masonry, flowable fill, synthetic aggregate, and mining applications. Fly ash/SDA material has the most potential to be used in applications that take advantage of the fly ash component of the SDA material, can tolerate relatively high sulfur content, and have limited susceptibility to expansion or reduced expansion potential in the production process.

Agriculture applications have a moderate potential for SDA/fly ash material produced in North Dakota because there is currently no competing FGD gypsum produced in the state. The northwest part of the state has sodic soils and could benefit from the use of FGD material as a soil conditioner. It is possible that SDA material or sulfite-rich FGD material could be used for agriculture crops, especially nonfood crops such as energy crops (i.e., corn, switchgrass).

Investments in research and development will be needed to explore these potential applications. Currently, it is more cost-effective to dispose of FGD material produced in North Dakota; however, if high-value and high-volume applications were possible, electric generating companies may be more likely to research potential uses. Because North Dakota is an agriculture-rich state, the U.S. Department of Agriculture could be engaged to explore potential uses for FGD material.

Barrier 2: CCP Utilization Is Not a Priority at Many North Dakota Coal-Based Power Plants

The primary objective of most electric generating companies is to produce electricity, not to make good-quality CCPs and market them. GRE CCS has successfully done both, but that is an exception in the state. CCP utilization is not a major focus for most North Dakota electric generating companies because there is not an immediate need or clear monetary benefit for using the material. Disposal costs are relatively inexpensive (estimated cost is $15/ton), and landfills have space for more material.

Recommended Actions for Barrier 2

Electric generating companies should also perform a cost–benefit analysis to determine what resources (i.e., staff, handling equipment) would be needed to improve CCP use and determine if it is a cost-effective ash management solution for the company. It is determined that utilization could be a cost-effective solution to ash management; the electric generating company may want to consider working with an ash-marketing company to help facilitate utilization. Ash-marketing companies have expertise in ash handling, storage, and distribution as well as industry insight into what beneficial use applications would garner the greatest economic return.

Barrier 3: NDDH Has a Subjective Guideline for Beneficial Use

The NDDH Division of Waste Management Solid Waste Program administers the disposal and utilization of CCPs. The North Dakota Solid Waste Management Rules, Chapter 33–20 of the North Dakota Administrative Code, written pursuant to North Dakota Century Code Chapter 23–29, include standards for various types and sources of solid waste. CCPs are called "special waste" which is defined in the state law as follows:

> "Special waste means solid waste that is not a hazardous waste regulated under Chapter 33-20.3 and includes waste generated from energy conversion facilities; waste from crude oil and natural gas exploration and production; waste from mineral and ore mining, beneficiation, and extraction; and waste generated by surface coal-mining operations. The term does not include municipal waste or industrial waste."

North Dakota has developed modern standards and facilities for management of solid waste, including CCPs. NDDH's disposal requirements address location restrictions, operating criteria, facility design, groundwater monitoring and corrective action, closure and postclosure care, and financial assurance (Tillotson, 2007). NDDH's disposal requirements exceed EPA recommendations, and the electric generating companies generally agreed the disposal requirements are appropriate.

In addition to disposal, NDDH has worked with a number of energy companies as well as with some food processors using coal as a fuel to develop beneficial uses for CCPs. *Guideline 11 – Ash Utilization for Soil Stabilization, Fill-In Materials and Other Engineering Purposes* (see Appendix C) summarizes NDDH's approach to CCP utilization. In essence, the proposed uses for CCPs must reasonably demonstrate that the proposed use will not adversely impact the environment. The project's potential impact to surface water, groundwater, air, and soil quality should be evaluated. Background information on the source, quality, and quantity of ash as well as appropriate analysis must be provided (Tillotson, 2007).

Although NDDH believes Guideline 11 clearly outlines the requirements for CCP beneficial use, those requesting beneficial use applications indicated the guideline is too subjective. For example, what NDDH considers "reasonably demonstrate" tends to vary depending on the application and who is requesting the application. In addition, those interviewed indicated that they do not know what standard they will be measured against for each application. For some applications, the leachate must meet drinking water standards, and for others, it must meet groundwater standards. In addition to the leachate standard, the leachate method is also variable. NDDH believes some leaching methods are more appropriate than others, depending on the proposed use. NDDH said the acceptable leachate standard and method will vary depending on the application and that the guideline needs to be flexible.

The subjectivity of Guideline 11 is a barrier to electric generating companies in the state because they are reluctant to request a beneficial use. They are not sure how much time and money it will take to reasonably demonstrate a potential beneficial use to NDDH or if it is even possible to meet NDDH's requirements. Those interviewed noted instances where they could have used CCPs in a beneficial use application but did not want to hassle with the approval process, so they disposed of the material instead.

Recommended Actions for Barrier 3

NDDH should consider revising its Guideline 11 to define what it means to reasonably demonstrate a potential use. Requestors need to know in advance what the parameters of the proposed use in order to know if they should go forward with the request. To make the guideline less subjective, a specific leachate method should be defined, the parameters the leachate must meet (i.e., ground water or drinking water standards) should be listed, and any pre- or postmonitoring should be mentioned. Making Guideline 11 more explicit would take a considerable dedicated amount of time and resources upfront on behalf of NDDH, but it is believed that the approval process would be smoother for all parties involved in the long term.

To assist NDDH in the revision or development of new guidelines and/or regulations, potential CCP users could work with NDDH to help lessen its workload (i.e., assemble existing data) and educate them about potential beneficial use applications (i.e., provide case studies on beneficial use). This collaboration could be facilitated through a state CCP program or consortium whose primary objective was to educate government agencies about CCPs. In previous state reviews, the states had an industry group whose membership consisted primarily of the state's electric generating companies – Texas was represented by the Texas Coal Ash Utilization Group; Florida by the Florida Electric Power Coordinating Group, Inc.; and Pennsylvania by the Electric Power Generation Association. These groups were extremely effective in promoting the use of CCPs and addressing barriers prohibiting utilization, such as the lack of regulations allowing the beneficial use of CCPs. Organized industry-led groups can be effective in working with government agencies and state legislators because each one represents a unified voice on behalf of its members and allows industry to pool its collective knowledge base and monetary resources to address key issues. North Dakota does not have an industry group similar to the past states reviewed. The North Dakota Industrial Commission does offer funding for research; however, its primary objective is not to educate government and influence policy.

At the federal level, EPA could provide guidance on the definition of "beneficial use." EPA has a definition for waste but not for beneficial use of CCPs. EPA's Industrial Materials

Recycling Program defines industrial materials recycling, also referred to as beneficial use, as a means for reusing or recycling by-product materials generated from industrial processes. These materials can be used as substitutions for raw materials in the manufacture of consumer products, roads, bridges, buildings, and other construction projects (U.S. Environmental Protection Agency, 2008). A clear definition for the beneficial use of CCPs would be helpful to NDDH in writing new or modifying existing guidelines. In addition, Toxic Release Inventory reporting could be modified to exempt beneficially reused material and only require reporting of material that is sent to a disposal site.

Barrier 4: NDDOT Is Not Exploring Other Beneficial Uses

Although NDDOT is comfortable with using fly ash in concrete and appeared to have a clear understanding of the benefits of using fly ash in concrete, it did not appear to be interested in exploring other beneficial use applications such as soil stabilization or flowable fill. NDDOT uses soil stabilization techniques with reactive clays to dry wet soil; however, it indicated that this practice is expensive because it takes a lot of labor to mix fly ash 6 inches into the soil or base. NDDOT indicated that flowable fill has been used in urban utility trenches and referenced an instance when the city of Fargo used flowable fill in pipes and bridge approaches. NDDOT believes existing dirt at the site is usually used instead of flowable fill so that material does not have to be hauled away and did not see a need to use an engineered fill material.

Contrary to the NDDOT representatives interviewed, the ready-mix suppliers believed flowable fill is a major untapped market in North Dakota. Just in the repair market alone, flowable fill could be used for a quick fix during winter months. Those interviewed said that oftentimes the existing dirt (i.e., clay) is not a good fill material and needs to be mixed with gravel and sand.

It is important to note that in 1996, the EERC conducted a research study to evaluate eleven CCPs produced at North Dakota coal-based power plants for use in road-building applications including concrete, flowable fill, soil stabilization, and permeable base course. All fly ashes examined were likely candidates for flowable fill applications (Pflughoeft-Hassett et al., 1996).

Although flowable fill is a large potential market, it is important to note that Montana–Dakota Utilities Co. did have a flowable fill plant that is no longer in operation because of product acceptance issues among city engineers. Some city engineers simply do no want to use flowable fill and, in some instances, do not want to use flowable fill material that contains CCPs. Instances were noted where city engineers believed that the use of CCPs in cementing applications, including flowable fill, could hurt product performance and cause environmental problems such as the leaching of trace metals.

Recommended Actions to Barrier 4

CCP generators should approach potential users of flowable fill material, including all levels of NDDOT, to demonstrate the engineering, environmental, and economic benefits of using CCPs in flowable fill applications. This can be accomplished by hosting a workshop and inviting industry and NDDH representatives to learn about flowable fill. CCP generators could also use flowable fill containing CCPs for their own use (i.e., fill gas or water lines). It would be most effective if the workshop included visiting an in-state demonstration using CCP-containing flowable fill. North Dakota Ready Mix Association (NDRMA) has hosted lunch box seminars for private engineers on flowable fill.

NDDOT could take a second look at the economics associated with using flowable fills containing CCPs. Perhaps it may find that, in the long-term, engineered materials such as flowable fills are more cost-effective.

Barrier 5: Many Fly Ashes Are Not Managed in a Way that Produces a Consistent Quality Product

QA/QC is an important factor that greatly influences the marketability of CCPs. Quality control involves continuous measure of process and products to determine performance and consistency of supply. Quality assurance provides assurance that the customer is receiving material that meets specifications and performance expectations. Factors important to a QA/QC plan include consistency of fuel, utility plant process, stable combustion conditions, and CCP handling and storage practices. Most QA/QC plans for fly ash include testing for carbon content (LOI), fineness, moisture, color, specific gravity, and a full ASTM C 618 analysis (Majors, 2004).

Many North Dakota coal-based power plants do not have a QA/QC plan for their CCPs. Fly ash has to be more closely monitored for optimal performance in concrete. In some instances, if measures were taken to control the variability of carbon content (LOI) in fly ashes, it would be suitable for use in concrete.

In addition to QA/QC plans, fly ashes produced at plants with SDA systems are mixed with the SDA residues. The fly ash–SDA material blend has little potential for use in concrete applications. These materials could be collected separately.

Recommended Actions for Barrier 5

The implementation of a strict QA/QC plan is imperative for fly ash to be used in concrete. This could be facilitated through an ash marketer with experience in developing and executing QA/QC plans for utilities. Also, fly ash and SDA material could be collected separately so that the fly ash is not contaminated by the SDA material.

Barrier 6: Transportation and Distribution Infrastructure Can Be Cost-Prohibitive

North Dakota is a landlocked state and is not located near major metropolitan areas, so transportation is necessary to get CCPs to major markets. No plants have access to waterways and some do not have rail access, so trucking is the only mode of transportation available for some North Dakota coal-based power plants. This limits the distance the material can be shipped and still be cost-competitive. With the exception of CCS fly ash, it is cost-prohibitive to transport CCPs to major markets outside of the state.

Again with the exception of CCS, North Dakota coal-based power plants lack distribution infrastructure needed to load CCPs into trucks or rail cars. The ready-mix suppliers and NDDOT representatives indicated that they would rather pay a premium price for CCS fly ash because it is so easy to load the material.

Recommended Actions to Barrier 6

Because high-value (i.e., concrete) markets are not locally available to take significant quantities of CCPs and it is not cost-effective to transport the material to these markets, local markets for low-quality/low-value materials should be explored. Agriculture, mining, and oil field applications already use some CCPs in North Dakota, and continued evaluation and marketing in these areas may result in increased opportunity for use.

Management at coal-based power plants should evaluate the cost/benefit ratio of improving the CCP distribution infrastructure at the plants. CCS made a significant up-front investment in its infrastructure; however, it is expected to be economically beneficial through increased sales in fly ash, avoided costs for disposal, and for CO_2 credits associated with the use of fly ash as a cement replacement.

Barrier 7: Limited Green Movement in the State

There are several products that contain CCPs that could be more widely used in green construction practices (see Buyer's Guide to Coal Ash-Containing Products for more information at www.undeerc.org/carrc/BuyersGuide/default.asp), but the USGBC's LEED program and other green initiatives have not gained widespread acceptance in North Dakota. There are beginning to be more green commercial buildings in North Dakota; however, these buildings are certainly not the norm. Those interviewed indicated that, in general, North Dakotans view green building as too expensive, and the benefits of green building are not well understood.

In addition, the architectural and building industries in North Dakota are slow to accept green building practices that could incorporate CCP-containing products. As an example, the North Dakota Ready-Mix Association hosted a green concrete workshop for architects and contractors, and only four architects attended.

From a regulatory standpoint, NDDH also has not encouraged green building practices. In addition, there has been no initiative by the state legislature to encourage state government agencies to promote CCP recycling or the benefits of using CCPs.

Recommended Actions for Barrier 7

Since many consumers are not yet supporting the green building market in North Dakota, it is recommended that approaches to push green building by government be promoted by industry. Government policy makers in North Dakota could be encouraged by electric generating companies, green advocacy groups (i.e., Green Cities), and other entities to develop tax incentives, mandates, regulations, or policies that promote green building. The potential CO_2 savings associated with using CCPs should be a major focus of lobbying efforts. Other environmental benefits such as saving landfill space and saving virgin resources should also be considered.

Other states have been successful in getting government policy makers to encourage CCP use. For example, the California DOT requires that mineral admixtures like fly ash comprise at least 25% of the cementitious material in any concrete used in state-funded paving projects. Montana provides tax incentives for companies that install equipment to begin utilizing material like fly ash.

CCP industry stakeholders should work with state building entities such as the North Dakota Association of Builders and national entities such as the USGBC LEED program and the National Home Builders Association to market the benefits of using CCPs in building materials. This can be accomplished by speaking or exhibiting at events, working with board members to develop legislative language, serving on association boards, or providing outreach materials.

Barrier 8: NDDH Solid Waste Program Focuses on Disposal Not Utilization

The NDDH Solid Waste Program works with publicly and privately owned and operated landfills in the state to ensure that all land disposal operations are conducted in accordance with state regulations. NDDH's primary focus is to ensure solid wastes are properly disposed of; nondisposal uses are not a priority. Because the department is focused on disposal, the authors believe NDDH does not have the resources (i.e., time, knowledge) needed to effectively evaluate new CCP beneficial use applications. Also, once a beneficial use rule is in place, NDDH does not appear to have any mechanisms in place to encourage the use.

To illustrate the disposal focus of NDDH, consider the following examples brought forth during the discussion group sessions. NDDH was approached by electric generating companies in the state to approve the use of CCPs in road and feedlot soil stabilization applications. After extensive reviews of each application, NDDH approved the use of preapproved CCPs in road and feedlot soil stabilization applications. For CCPs to be used in either application, one must complete a checklist (see Appendix X for checklists), and the form must be submitted and kept on file at NDDH. NDDH does not promote these uses and leaves it up to the electric generating company to provide access to the forms and encourage the use. OTPC indicated it tried to obtain the soil stabilization checklist from NDDH, but NDDH said it would have to get the checklist from a CCP supplier. OTPC then had to identify who the CCP supplier was and the appropriate contact person. As another example, NDDH indicated that use of CCPs in surface mine reclamation would not be considered a beneficial use (although CCP use in grout mixtures used in underground abandoned mines is a preapproved beneficial use) and that disposal facilities are currently being managed in at least one North Dakota surface mine.

Recommended Actions to Barrier 8

To encourage preapproved CCP beneficial use applications, NDDH should have a list of preapproved applications and materials on its Web site and provide access to appropriate checklists.

As previously mentioned in Recommended Actions for Barrier 3, an industry-led group could be effective in assisting NDDH in the distribution of information. It could also assist in educating NDDH about CCP utilization.

Barrier 9: The National Commercial Concrete Market Has Misconceptions About CCPs

Ready-mix suppliers interviewed indicated that they classify their customers into three different classes which each perceive concrete mix designs differently:

1. National commercial market – large national companies (i.e., Menards and Wal-Mart) provide a prescriptive mix design based on company policy to the local ready-mix supplier. The prescriptive mix designs are standard and do not take into account local availability of virgin materials, climate, or fly ash quality. These designs typically do not favor a higher percentage of fly ash and, in some instances, require that no fly ash be used in the mix design.

2. Local commercial market – local commercial projects typically specify performance criteria and allow the ready-mix supplier to come up with a mix design to meet that need. This provides the opportunity for ready-mix suppliers to create a design that could potentially use up to 70% fly ash; however, 25% is most common.

3. Residential market – the residential market is driven by price, and performance is a secondary consideration. Most consumers in the residential classification do not know or care if their concrete contains CCPs.

The national commercial market is usually the most difficult consumer group for ready-mix suppliers to work with to encourage CCP use. Often the national company would give an overly prescriptive mix design that the ready-mix supplier believed would benefit from a higher percentage of replacement of fly ash, but the national company would want to stick with its design.

Recommended Actions for Barrier 9

Education is key to overcoming this barrier. Education is typically most effective if done on a case-by-case basis directly between the ready-mix supplier and/or fly ash marketer and the end user and may take several attempts. However, indirect education efforts such as workshops and online courses for engineers and specifiers are also an option for reaching larger audiences. Previous successful outreach to this audience is described below:

- ACAA, with industry stakeholders, made advances with Wal-Mart to get fly ash used in all concrete poured in the construction of new Wal-Mart stores.

- NDRMA is having lunch box seminars for private engineers.

- Colleges could be encouraged to offer more education to engineers about the benefits of using CCPs.

Barrier 10: Local Concrete Market Saturated

In 2006, about 1.2 million cubic yards of concrete was poured in North Dakota, with an average fly ash replacement rate of about 25%. The demand for concrete is expected to remain about the same in the coming years because the population of the state is not growing (population decreased 1% from 2000 to 2006 [U.S. Census, 2007]) and the building industry is stable. The fly ash percent replacement rate is also expected to remain about the same, resulting in very little increase in fly ash use in concrete in the state. However, with recent concerns about bridge safety, it is possible that North Dakota could find additional bridge replacements and repair needs that could increase concrete demand.

Recommended Actions for Barrier 10

Other high-value road-building and construction applications should be explored such as flowable fill, backfill, and road base applications. Workshops for contractors, architects, city engineers, and government agencies would be helpful to educate them on CCP use in nonconcrete applications. GRE hosted a workshop on soil stabilization in which NDDH participated, and it was successful. It may be beneficial to engage the American Public Works Association and Associated General Contractors of North Dakota in future educational efforts.

Barrier 11: Industrial Boiler By-Products Are Becoming a Public Perception Problem

Coal ashes from coal-fired industrial boilers (i.e., sugar beet plants, University boilers) have been used in soil stabilization applications in North Dakota. Some applications were approved by NDDH, but others were done without NDDH knowing they occurred and, therefore, were done without NDDH approval. The authors are unaware of an instance when NDDH has taken a corrective action toward those who conducted unapproved uses of industrial boiler coal ash in a soil stabilization application. Coal ash from industrial boilers is typically not well suited for soil stabilization because it frequently does not have the same cementitious reactivity as coal ashes from electric coal-based power plants.

Industrial boilers are typically stokers, so they do not pulverize the coal prior to combustion, and the resulting ash is generally coarser, exhibiting lower reactivity. Some industrial operators also sluice the ash which further reduces the reactivity because reactions occur before the ash is incorporated into the soil stabilization application. Stokers may also result in incomplete combustion of the coal because of the larger size of the coal going through the combustion zone.

When coal ash from an industrial boiler is used in an application and physically fails, this creates a public perception problem for utility coal ashes that may be better-suited for these uses. Often end users and NDDH do not distinguish between coal ashes from an industrial versus a utility boiler. Beneficial use of these ashes can produce very different environmental and engineering results.

Recommended Actions to Barrier 11

Industrial boilers producing coal ash may be unaware that their ash is different than ash produced from coal-fired power plants. An educational effort could be implemented by NDDH in order to inform industrial CCP generators of what testing and permissions would be needed to get their ashes used. This effort could take place in the form of sending them fact sheets on proper protocol.

POTENTIAL THREATS THAT COULD IMPACT FUTURE CCP UTILIZATION IN NORTH DAKOTA

The following potential threats could hinder the future of CCP beneficial use in North Dakota. For the purpose of this report, a threat is defined as an external challenge that could negatively impact the use of CCPs. Because threats are external, CCP stakeholders have no direct control over them but may benefit by having contingency plans to address them should they occur. The threats are based on information gathered at the discussion groups, and the authors believe the threats are listed in the order of importance.

Threat 1: Mercury Control Will Be a Concern for Utilization

At the time this state review was conducted in August 2007, the Clean Air Mercury Rule (CAMR) was calling for coal-based power plants to meet certain air emission standards for mercury. Most North Dakota coal-based power plants would have met the 2010 mercury emission regulations under CAMR as they currently operate but would have likely needed to implement new controls to meet 2018 requirements. Options for meeting those requirements include injecting activated carbon (AC), using an oxidized catalyst as a sorbent, installing a COHPAC™/TOXECON™ system (EPRI-licensed technologies), purchasing allowances, or coal drying.[4] Each of these options, with the exception of purchasing allowances, has different impacts on the CCPs.

On February 8, 2008, the courts vacated CAMR. EPA will develop a new rule regarding mercury emissions from coal-based power plants. It is unclear what EPA will do next or what the states should do regarding their own mercury rules. North Dakota does not have its own mercury rule and was planning to follow regulations set forth under CAMR.

Regardless of what rule comes to fruition and when those regulations need to be met, mercury is still expected to be regulated. NDDH is concerned about how new mercury emission controls will impact CCP utilization and disposal. NDDH has not evaluated by-products

[4] Coal drying is a process that uses low-grade heat rejected from the steam condenser and waste heat from the flue gas leaving the boiler to evaporate a portion of the fuel moisture from the lignite feedstock in a fluidized-bed dryer. This process was developed in the United States by a team led by GRE, with funding from DOE (DOE Award Number: DE-CF26-04NT41763) (Bullinger and Sarunac, 2007).

resulting from coal-based power plants with mercury emission controls; therefore, regulating material use or disposal is new territory (as will be the case in other state health departments). During the NDDH discussion group session, EERC representatives indicated that NDDH should not be concerned about total mercury concentrations but should evaluate mercury mobility. The EERC further noted that mobility of mercury from CCPs generated with mercury emission controls has been shown to be very low and is not expected to impact disposal requirements (Hassett et al., 2007).

Threat 2: New CO_2 Regulations Are Expected, but the Impact to CCPs Is Not Clear

At present, there is a voluntary program for utilities to reduce the production of greenhouse gases, especially CO_2. In the future, it is anticipated that the reduction of CO_2 will be required, and coal-based electric generating power plants will need to employ CO_2 capture and sequestration technologies.

Aqueous amines are the state-of-the-art technology for pulverized-coal (pc) power plants to reduce CO_2. While this technology is not expected to directly impact CCP quantity or quality, one of the requirements for CO_2 capture using aqueous amines is that the gas stream must have very low particulate matter present. It is not currently known how the by-products from additional gas cleaning will be managed at power plants, but those particulates could either be managed with the by-products of the amine process or with other CCP streams.

Oxycombustion is another approach to producing a clean CO_2 stream for CO_2 capture. If oxycombustion is implemented at an existing power plant, it is possible that the resulting ash characteristics could be different from the materials produced using standard pc combustion.

Each coal-based power plant station will need to determine the best strategy for reducing CO_2 emissions in the future, which could include trading of CO_2 credits. At this time, it is important for coal-based power plants to keep abreast of CO_2 capture and sequestration technologies and for impacts to CCPs to be evaluated as part of the only research in this area.

CONCLUSIONS/SUMMARY

It is estimated that North Dakota coal-based power plants produce nearly 3 million tons of CCPs per year. Of that amount, 40% (or 1.2–1.3 million tons) is beneficially used. The following is a summary of highlights brought forth during the state review process and presented in this report.

Most North Dakota Coal-Based Power Plants Dispose Fly Ash – With the exception of GRE’s CCS, North Dakota coal-based power plants generally dispose of the fly ash they produce. Possible reasons for disposal include the following:

1. Some fly ash is not suitable for use in concrete (i.e., high LOI, inconsistent supply, and quality).

2. Plant owners do not place a priority on utilization.

3. Two plants mix fly ash with SDA material, limiting its use potential.

4. CCS fly ash has saturated the market.

5. Plants lack the distribution infrastructure needed to supply the material.

Most Concrete Poured in North Dakota Contains CCS Fly Ash – The fly ash used in North Dakota concrete projects is predominantly supplied by GRE CCS. NDDOT uses fly ash in almost all concrete projects at a replacement rate of 30%. Ready-mix suppliers generally use a replacement rate of 25%.

Inert Classifications Allow Beneficial Use – Bottom ash and boiler slag produced by North Dakota coal-based power plants are classified as inert materials by NDDH. This allows the materials to be used without prior approval from NDDH.

Underground Mine Grout Fill Is Considered a Beneficial Use – In some states, using fly ash to fill underground AMLs is not considered a beneficial use; however, in North Dakota, it is the only preapproved beneficial use application for fly ash. North Dakota's mine reclamation program could serve as a model for other states.

Currently Produced FGD Materials Are Difficult to Utilize –All North Dakota coal-based power plants have a system in place to control SO_2 emissions (LOS is currently installing a wet FGD system) and produce a subsequent by-product. These by-products are difficult to market because they are a low-value material, have limited use potential, and are not located within close proximity to markets. Applications for fly ash/SDA material with the highest potential included cementitious products, masonry, flowable fill, synthetic aggregate, and mining applications. Agriculture applications are the most promising for other FGD materials.

Flowable Fill Is a Promising Untapped Market – Because the local concrete market is already saturated by CCS fly ash, those wishing to use fly ash will likely need to explore other markets, and flowable fill appears to be the best immediate option with the greatest demand. Barriers to overcome to enter this market include obtaining NDDH approval, getting NDDOT acceptance, and educating contractors/engineers about the use.

The Establishment of an Industry Group Focused on CCPs Would Be Beneficial – Organized industry-led groups can be effective in working with government agencies and state legislators because they represent a unified voice on behalf of their members and allow industry to pool its collective knowledge base and monetary resources to address key issues. Issues that a North Dakota industry-led group could address include working with NDDH to clarify Guideline 11, educating NDDOT on nonconcrete uses, and educating commercial concrete users (i.e., contractors, engineers, and architects) about the benefits of CCPs.

Mercury and CO_2 Emission Regulations Are of Minimal Concern – Pending mercury regulations and expected CO_2 restrictions will impact fly ash characteristics. However, because no power plants, aside from GRE CCS, are currently selling large volumes of fly ash, the impact may be minimal. Because fly ash sales are a significant revenue stream for CCS, it will take all necessary precautions to select emission control technologies that will not negatively impact the quality of the fly ash. Emission controls are not expected to impact disposal.

The Green Movement Needs a Push – Green building has not gained widespread acceptance in North Dakota from a consumer or regulatory standpoint. Opportunities exist to work with government policy makers to encourage legislation that would offer incentives for using green materials (i.e., CCP-containing materials).

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APPENDIX A

PARTICIPANT LIST

REVIEW OF NORTH DAKOTA REGULATIONS, STANDARDS, AND PRACTICES RELATED TO THE USE OF COAL COMBUSTION PRODUCTS

Bismarck, North Dakota
August 27–29, 2007

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APPENDIX B

REVIEW GUIDE

REVIEW OF NORTH DAKOTA REGULATIONS, STANDARDS, AND PRACTICES RELATED TO THE USE OF COAL COMBUSTION PRODUCTS
Review Guide
August 27–29, 2007
Bismarck, North Dakota

Background
The University of North Dakota Energy & Environmental Research Center (EERC) is conducting a review of North Dakota regulations, standards, and practices related to the use of coal combustion products (CCPs). Funding is provided by the North Dakota Lignite Research Council; Basin Electric Power Cooperative; Great River Energy; Minnkota Power Cooperative, Inc.; and the U.S. Department of Energy's Coal Ash Resources Research Consortium.

Previous reviews were conducted in Texas, Florida, and Pennsylvania. The final report from those reviews can be accessed online at **www.undeerc.org/carrc/html/review.html**. A national synthesis report from these individual state reviews is in preparation and will be published in 2007.

Objectives
- Highlight successes to CCP utilization
- Identify barriers to increased CCP utilization
- Develop recommendations that may help North Dakota and other states increase the use of CCPs

Process
A review team will pose a list of predetermined questions to key stakeholders involved in CCP utilization. The following discussion groups will be formed:

- Government agencies – directors and other key personnel of state transportation and health departments
- CCP generators – coal-fired electric generating company environmental and ash managers
- Concrete and other engineering applications – CCP marketers, ready-mix concrete suppliers
- Mining – North Dakota Public Service Commission, mining companies

Separate telephone interviews or e-mail correspondence may also take place with individuals unable to attend their scheduled session or those who have expertise outside of the major discussion groups.

Instructions
Please come to the review prepared to answer the following list of questions and assemble all applicable information prior to the review. Answer the questions as completely as is reasonably possible without stating proprietary information. Written responses to the questions are greatly appreciated but not expected. Any written documentation you can provide will ensure that exact citations are included in the final report. Please provide written comments to Tera Buckley at tbuckley@undeerc.org.

Reporting
A draft final report will be prepared and distributed to all interviewees. You will be given a 30-day review period to review the report and provide comments to the EERC. A final report will be published on or before December 31, 2007.

AGENDA

Monday, August 27, 2007

1:30 – 4:00 p.m. North Dakota Public Service Commission

Tuesday, August 28, 2007

9:00 – 11:30 a.m. Electric Generating Companies*

1:30 – 4:00 p.m. North Dakota Department of Transportation

Wednesday, August 29, 2007

9:00 – 11:30 a.m. North Dakota Department of Health

1:00 – 3:30 p.m. Concrete and Other Engineering Applications*

*Meeting will be held at the Fort Totten meeting room in the state capitol building on the ground floor, west end.

If you are unable to attend your scheduled session, please contact Tera Buckley at (701) 777-5296 or tbuckley@undeerc.org.

GOVERNMENT AGENCIES

1. What is your agency's role in the management (use and/or disposal) of coal combustion products (CCPs)?

2. What type of infrastructure (i.e., employees, programs) has your agency dedicated to CCP management? How does the state headquarters interact with local, regional, and federal offices?

3. For which of the following CCPs does your agency have guidelines, guidance documents, material specifications, regulations, orders, or statutes? How were they developed and adopted? If applicable, provide references for, and dates of, the specific guidelines, guidance documents, material specifications, regulations, orders, or statutes related to CCPs.

   a. Fly ash

   b. Bottom ash

   c. Flue gas desulfurization material

   d. Boiler slag

   e. Other _______________

4. How would changes to the chemical or physical composition of CCPs impact your agency's role in the management of CCPs? For example, new air pollution control requirements may increase the carbon and mercury content of CCPs.

5. Are there any plans to implement any new policies, rules, or regulations regarding CCPs currently in process or expected in the near future?

6. What process does your agency undergo to make changes to its policies, rules, or regulations? Has this process ever changed over time?

7. Please list and explain any successful projects/applications using CCPs. Why were they successful?

8. Please list and explain any problematic projects/applications using CCPs. Explain the problems encountered and any instances where the use of CCPs was precluded in a project.

9. Please list and explain any cases in North Dakota where the use of CCPs has caused environmental damage or resulted in violations of environmental requirements. Describe any corrective actions, monitoring, and follow-up employed to address the issues.

10. In your opinion, what are the biggest obstacles hindering the increased use of CCPs in North Dakota? How could these obstacles be addressed?

11. Which of the following sources of information does your agency rely on in approving the use of CCPs in particular applications?

a. Surveys of current practices (federal or state)

b. Demonstration projects

c. Internal (agency) testing and evaluations

d. Technical reports submitted by qualified consultants

e. Research projects or reports by other agencies, research institutions, or consultants

f. Other ________________________________

12. What further research, laboratory work, or policy initiatives would be necessary to assist your agency in overcoming barriers?

13. In general, how do you perceive the position that North Dakota has taken toward CCP use in comparison to other states?

COAL COMBUSTION PRODUCT (CCP) GENERATORS

1. Please describe or provide written documentation on the type, amount, and current management practices employed for all CCPs produced at your facility.

2. Provide a general description of the CCP market in North Dakota, including supply and demand, and identify the major use applications. Are any CCPs being imported or exported?

3. How is coal ash utilization handled and perceived at your company? For example, at some electric generating companies, CCP utilization is a priority for upper management but not for plant operators.

4. What types of quality assurance/quality control procedures are employed at your company with regard to CCPs? Are efforts taken to ensure a consistent-quality product?

5. How would changes to the chemical or physical properties of CCPs impact your company's role in the generation, use, or disposal of CCPs? For example, new air pollution control requirements may increase the carbon and mercury content of CCPs. Do you foresee beneficiation technologies as a new trend to deal with these changes?

6. Please indicate your thoughts on the current CCP specifications or guidelines that you are aware of in North Dakota. Are there any environmental policies, permits, regulations, or statutes that impact the way you process and handle CCPs? What specifications or guidelines do you feel promote or restrict CCP utilization? What changes would you like to see made to the current specifications and guidelines?

7. Are you or your CCP users (marketers/contractors) provided with the flexibility to make the decision to utilize CCPs when the material meets standard specification requirements, or does the state require additional approvals and testing?

8. Please list and explain any successful projects/applications using CCPs. Why were they successful?

9. Please list and explain any problematic projects/applications using CCPs. Explain the problems encountered and any instances where the use of CCPs was precluded in a project. Describe any corrective actions, monitoring, and follow-up employed to address the issues.

10. Provide details of any ongoing or completed research and demonstration projects regarding CCPs.

11. In your opinion, what are the biggest obstacles hindering the increased use of CCPs in North Dakota? How could these obstacles be addressed? Would any changes to state or federal regulations help you address these obstacles?

12. What barriers has your company overcome to increase the use of CCPs? How?

13. What further research, laboratory work, or policy initiatives would be necessary to assist your company in overcoming barriers?

14. In general, how do you perceive the position that North Dakota has taken toward CCP use in comparison to other states?

CONCRETE AND OTHER ENGINEERING APPLICATIONS

1. Provide a general description of the coal combustion product (CCP) market in North Dakota, including supply and demand, and identify the major use applications. Are any CCPs being imported or exported? How much concrete is being used in various segments of the market (i.e., residential, commercial, highway construction)?

2. What is the general feeling toward CCPs in your industry? How would you describe the competition between fly ash and portland cement? Are there any product acceptance issues among consumers with concrete containing fly ash?

3. Please indicate your thoughts on the current specifications or guidelines that you are aware of in North Dakota related to CCPs. Are there any environmental policies, permits, regulations, or statutes that impact the way you process and handle CCPs? What specifications or guidelines do you feel promote or restrict CCP utilization? What changes would you like to see made to the current specifications and guidelines?

4. Please list and explain any successful projects/applications using CCPs. Why were they successful?

5. Please list and explain any problematic projects/applications using CCPs. Explain the problem encountered and any instances where the use of CCPs was precluded in a project. Describe any corrective actions, monitoring, and follow-up employed to address the issues.

6. What role do other alternative materials (i.e., natural aggregate) play in your business?

7. How would changes to the chemical or physical composition of CCPs impact your company's role in the use of CCPs? For example, new air pollution control requirements may increase the carbon and mercury content of CCPs. Do you foresee beneficiation technologies as a new trend to deal with these changes?

8. In your opinion, what are the biggest obstacles hindering the increased use of CCPs in North Dakota? How could these obstacles be addressed? Would any changes to state or federal regulations help you address these obstacles? Could coal-fired power plants do something to overcome these obstacles?

9. What further research or laboratory work would be necessary to overcome barriers to CCP utilization?

10. In general, how do you perceive the position North Dakota has taken toward CCPs in comparison to other states?

NORTH DAKOTA PUBLIC SERVICE COMMISSION

1. What is your agency's role in the management (use and/or disposal) of coal combustion products (CCPs)?

2. What type of infrastructure (i.e., employees, programs) has your agency dedicated to CCP use in mining applications? How does the state headquarters interact with district, regional, and federal offices?

3. For which of the following CCPs does your agency have guidelines, guidance documents, material specifications, regulations, orders, or statutes? How were they developed and adopted? If applicable, provide references for, and dates of, the specific guidelines, guidance documents, material specifications, regulations, orders, or statutes related to CCPs.

   a. Fly ash

   b. Bottom ash

   c. Flue gas desulfurization material

   d. Other ______________

4. Would changes to the chemical or physical composition of CCPs impact the requirements for CCP use in mining applications? For example, new air pollution control requirements may increase the carbon and mercury content of CCPs.

5. Are there any plans to implement any new policies, rules, or regulations regarding CCPs currently in process or expected in the near future?

6. What process does your agency undergo to make changes to its policies, rules, or regulations? Has this process ever changed over time?

7. Please list and explain any successful projects/applications using CCPs. Why were they successful?

8. Please list and explain any problematic projects/applications using CCPs. Explain the problems encountered and any instances where the use of CCPs was precluded in a project.

9. The National Academy of Sciences recently published a report entitled "Managing Coal Combustion Residues in Mines." What is your opinion of that report? Do you think the report will have an impact on the way CCPs are used in mines in North Dakota?

10. How does the general public perceive CCP use in mining applications?

11. In your opinion, what are the biggest obstacles hindering the increased use of CCPs in North Dakota? How could these obstacles be addressed?

12. Which of the following sources of information does your agency rely on in approving the use of CCPs in particular applications?

    a. Surveys of current practices (federal or state)

    b. Demonstration projects

    c. Internal (agency) testing and evaluations

    d. Technical reports submitted by qualified consultants

    e. Research projects or reports by other agencies, research institutions, or consultants

    f. Other ______________________________

13. What further research, laboratory work, or policy initiatives would be necessary to assist your agency in overcoming barriers?

14. In general, how do you perceive the position that North Dakota has taken toward CCP use in mining applications in comparison to other states?

APPENDIX C

GUIDELINE 11 – ASH UTILIZATION FOR SOIL STABILIZATION, FILL-IN MATERIALS AND OTHER ENGINEERING PURPOSES

GUIDELINE 11 - ASH UTILIZATION FOR SOIL STABILIZATION, FILLER MATERIALS AND OTHER ENGINEERING USES

North Dakota Department of Health - Division of Waste Management
Telephone 701-328-5166 • Fax 701-328-5200 • Website
www.health.state.nd.us
Rev: 04/01

Attachment: Parameters and Methods for Assessing Leachability* of Fly Ash and Runoff from Fly Ash Utilization Sites in North Dakota (Parameters may be reduced based upon review.)

North Dakota Department of Health is working with a number of power plants, coal-fined boiler operators, coal mines, and other entities wishing to utilize waste materials such as coal-fired fly ash and/or bottom ash for engineering purposes. Some projects such as road stabilization, underground mine stabilization, controlled strength flowable fill, and other uses have been reviewed and approved by the Department based on an evaluation of the material's engineering and environmental properties. Persons proposing use of waste materials for beneficial reuse need to demonstrate that the material will be beneficially used without adversely impacting the environment.

Beneficial reuse must be carefully considered to ensure it is not simply *"use constituting disposal"* or *"sham recycling."* Proposers should be familiar with the state's environmental laws and rules, including the North Dakota Solid Waste Law, Chapter 23-29 North Dakota Century Code (NDCC); the North Dakota Solid Waste Management Rules, Article 33-20 North Dakota Administrative Code (NDAC); as well as the state's Water Pollution laws, Chapter 61-28 NDCC, which includes Section 61-28-06 which states in part:

"It shall be unlawful for any person:

a. To cause pollution in any waters of the state or to place or cause to be placed any waters in a location where they are likely to cause pollution of any waters of the state . . ."

The Department needs to review important aspects of any proposal, including, but not limited to, the ash quality and quantity, the proposed use of the ash, site characteristics, potential receptors, how the material will be handled, contingency plans in case adverse environmental conditions arise, how the site will be monitored to ensure environmental protection, what will be done when use of the material is completed, any local health or zoning issues, site closure and reclamation, etc. At a minimum, any proposal should address the following:

1. **Background information on the source, quality, and quantity of the ash** including the generator of the ash; the type of facility, the boilers, the pollution control equipment, etc., used in generating and collecting the ash; the source and the type of fuel used in the process; the variability of the ash; whether it is a mixture of other materials or waste streams, how it is stored and handled prior to any disposal or use, and any other information necessary.

2. **Analysis of the ash,** including both existing information and, as necessary, some leach analysis. Information that might be provided would include mineralogical properties and total analysis plus an assessment of the environmental leachability of the ash materials. At a minimum, an ash leach test on one or more representative samples utilizing either: (1) a

modified EPA Synthetic Precipitation Leaching Procedure (SPLP) Method 1312, with a *solution to solid ratio 4:1*, or (2) A modified ASTM D-3987 procedure with a *solution to solid ratio of 4:1*. A list of chemical parameters is attached to this memorandum. The detection limits for analysis must be substantially below the safe drinking water standards.

3. **A discussion and details on the proposed use of the ash**, including any admixtures, fill materials, soil, etc., should be provided. Information that is essential for review includes a description of the actual beneficial use; the mix ratio and design lift thickness; type and quality of fill materials, moisture levels, compaction, and engineering properties (including the strength and durability of materials), and what the material will be covered with, assessment of weathering, material breakup, etc., should be provided.

4. **A laboratory simulation** of the environmental properties of the proposed use should be addressed. Laboratory simulation testing to replicate field conditions determine leachability of the material as-placed should be provided. Upon discussion with the Department, a field simulation test should be agreed upon that will be adequate to determine any impact on the environment from initial waste placement, and any impact through continued weathering, mechanical abrasion, erosion, field runoff, etc. Various simulation tests have been approved by the Department, including kinetic tests simulating infiltration of water through fill materials.

   One publication that has been utilized for evaluating ash utilization in a mine setting is the publication *"Draft Guidelines and Recommended Methods for the Prediction of Metal Leaching and Acid Rock Drainage at Mine Sites in British Columbia"* by Dr. William A. Price, Reclamation Section, Energy and Minerals Division, Ministry of Employment and Investment, Bag 5000, Smithers, British Columbia, V0J2N0. Other information is available in Departmental files or may be proposed by the applicant based on the conceptual field application. Laboratory simulation of the field application methods might also entail testing of the materials due to its fate in the environment through weathering, breakup, erosion, abrasion, excavation, etc.

5. **The site characteristics**, including soils, topography, geology, hydrogeology, groundwater quality, surface water conditions and flow, vegetation, etc.

6. **Potential receptors**, including nearby communities, residences, parks, natural areas, neighboring land use, waterways, site drainage, groundwater conditions and quality groundwater wells, and any other information necessary to assess potential impacts to health and the environment.

7. **Description of the material handling and conceptual construction**, including transport and storage of materials, placement of materials, equipment, construction techniques, moisture application and monitoring, mixing, testing, etc., as well as controls and monitoring of windblown dust, stormwater and/or any ponded water must be described.

8. **The proposal should address reasonable contingencies** such as discontinuance of the application methods, cleanup of the site should environmental damage occur, final disposal of placed materials after the life of the project, etc.

9. **Approval by any local health, environmental, and permitting authorities** must be obtained before the project is conducted. Any Departmental approval is contingent upon and does not supersede compliance with all local environmental, health, and building code requirements.

10. **Monitoring of surface, groundwater, air, and soil** may be required.

11. The proposer should provide routine reports on construction and operation progress, monitoring results, final construction details and, for ongoing projects, periodic re-analysis of the ash material on an annual basis or, more often, under the following circumstances:

    a. The process generating that waste changes, such as the installation of different boilers, burners, pollution control equipment, or any other process change which might influence the character of the waste being utilized;

    b. In the event that the raw material or type of fuel changes; and

    c. Any other changes or variances which may influence the characteristics of the ash/product or the mixture used in the construction project.

This outline is provided for guidance purposes only. Additional requirements or conditions may be stipulated by the Department, dependent on the particular application, site characteristics, or other regulatory requirements.

Should you have any questions regarding these matters, please feel free to contact the Department at (701) 328-5166. More information on the state's environmental laws and rules are available at our Website www.state.nd.us

North Dakota Department of Health - Division of Waste Management

Parameters and Methods for Assessing Leachability* of Fly Ash and Runoff from Fly Ash Utilization Sites in North Dakota (parameters may be reduced based upon review)

a. Basic water parameters:

(1) Appearance (including color, foaming, and odor)
(2) pH[1]
(3) Specific conductance[2]
(4) Temperature

b. General geochemical parameters:

(1) Ammonia nitrogen
(2) Total hardness
(3) Iron
(4) Calcium
(5) Magnesium
(6) Manganese
(7) Potassium
(8) Total alkalinity
(9) Bicarbonate
(10) Carbonate
(11) Chloride
(12) Fluoride
(13) Nitrate + Nitrite, as N
(14) Total phosphorus
(15) Sulfate
(16) Sodium
(17) Total dissolved solids (TDS)
(18) Total suspended solids (TSS)
(19) Cation/anion balance
(20) Sodium Adsorption Ratio SAR)

c. Heavy Metals:

Group A:

(1) Arsenic
(2) Barium
(3) Boron
(4) Cadmium
(5) Chromium
(6) Lead
(7) Mercury
(8) Selenium
(9) Silver

Group B:

(10) Antimony
(11) Beryllium
(12) Cobalt
(13) Copper
(14) Nickel
(15) Thallium
(16) Vanadium
(17) Zinc

d. For Fly Ash waste analysis, naturally occurring radionuclides:

(1) Gross Alpha Particle Radioactivity (pCi/1)
(2) Radium 226 and 228 (pCi/1)
(3) Uranium

*Ash leach test on one or more representative sample(s) using a **modified** EPA Synthetic Precipitation Leaching Procedure (SPLP) method 1312 with a **solution to solid ratio of 4:1. A modified ASTM D-3987 procedure with a solution to solid ratio of 4:1 may also be used.** Laboratory detection limits must be substantially below the level of any state or federal drinking water standard or goal.

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