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Characterization of Spray Dryer Absorber Products for Use in Cement and Concrete Applications

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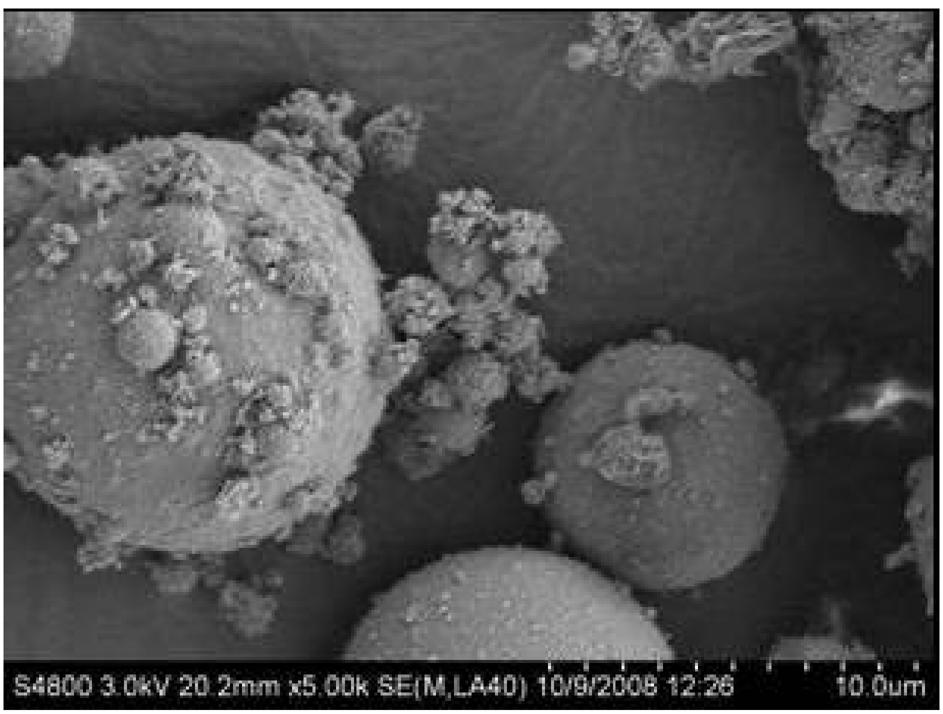

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Technical Update, November 2009

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REPORT SUMMARY

Spray dryer absorber (SDA) products currently account for about 3.5 million tons of coal combustion products (CCPs) generated annually in the United States, and that volume is expected to double over the next ten years. The utilization rate for SDA products is low; most are currently disposed of in landfills. The goal of this project is to develop information and technologies to increase the utilization of SDA products, particularly in concrete and other cement-based construction materials applications. This report summarizes characterization data for SDA product samples to evaluate their suitability for use in concrete applications.

Background

Spray dryer absorbers use a slurry, most often lime or limestone slurry, sprayed as a finely atomized mist into the flue gas in an absorbing tower (dryer) where the atomized slurry reacts with SO_2 from the flue gases and forms calcium sulfite and calcium sulfate. The heat from the flue gases evaporates the liquid from the slurry, leaving a solid, dry residue. In the majority of SDA systems currently operating in the United States, the calcium sulfite/sulfate are then captured with the fly ash in a baghouse or electrostatic precipitator as a combined SDA product. Total SDA product generation in the United States in 2007 was about 3.5 million tons; and the utilization rate of these products is less than 10% of the amount produced.

Objectives

To determine the physical and chemical properties of SDA products from a variety of power plants and to evaluate their potential use in cement and concrete products

Approach

The project team collected SDA product samples from eight operating power plants and designed a test program to measure their physical, chemical, and mineralogical properties. Characterization tests included particle size, specific gravity, mineralogy, and elemental analysis. In addition, the team tested the samples for physical and chemical properties contained in the ASTM C 618 specification for use of fly ash in portland cement concrete. These tests included moisture content, fineness, cement activity index, water requirement, pozzolanic activity index, soundness, drying shrinkage, and loss on ignition (LOI). The team used scanning electron microscopy to help understand the character and morphology of the particles of the products as they relate to use options.

Results

- X-ray diffraction analysis indicated the SDA product samples were made up largely of amorphous phases. Crystalline phases identified at greater than 5% in at least one sample were hannebachite, ettringite, bassanite, calcite, gypsum, calcium aluminate (monoclinic C3A), mullite, portlandite, and quartz.
- The SiO_2+Al_2O_3+ Fe_2O_3 contents of the samples ranged from 30 to 65%: in addition, two samples met the minimum ASTM C 618 requirement for Class C fly ash of 50%.
- Sulfur trioxide ranged from 9 to 21%; all samples were above the C 618 requirement of 5% for Class C and F fly ashes.

- LOI ranged from 3 to 13%; six of the eight samples met the C 618 requirement of less than 6% for Class C and F fly ashes.
- All samples met the C 618 requirements for fineness (<34% retained on #325 sieve), moisture content (<3%), and cement activity test (>75% of control).
- Water requirement ranged from 95 to 107% of the control; six of the eight samples met the C 618 requirement of 105% maximum for Class C and F fly ashes.
- Drying shrinkage ranged from 0.02 to 0.04%; one of the eight samples did not meet the C 618 requirement of 0.03%.
- Available alkalis, as Na_2O equivalent, ranged from 2 to 14%. This meets an optional requirement of ASTM C 618 for alkali silica reaction (ASR) minimization.

These results suggest that some of the SDA products show promise for use in cement and concrete applications.

EPRI Perspective

Maintaining and increasing the utilization rate of coal combustion products is a primary strategic goal of EPRI's CCP Use research program. Because SDA materials currently have a low utilization rate and their volume is expected to significantly increase over the next ten years, developing viable utilization options is a key component of EPRI's overall CCP use research strategy. Understanding the characteristics of SDA materials is an important initial step in this process.

Keywords

Flue gas desulfurization products
Spray dryer absorber
Coal combustion products
Utilization
Cement
Concrete

CONTENTS

1
INTRODUCTION

Flue gas desulfurization (FGD) is the technology used for removing sulfur dioxide (SO_2) from the exhaust flue gases in power plants that burn coal. The emission of SO_2 has decreased under the Clean Air Act Amendments of 1990 and state guidelines, which may impose stricter limits on such emissions in the future. There are several technologies for the removal of SO_2 from the flue gases, including wet lime/limestone absorbers, furnace lime or limestone injection, duct sodium sorbent injection, atmospheric or pressurized fluidized bed combustion (FBC) technologies, and other similar technologies. One of the technologies used by the electric utilities for the control of SO_2 is spray dryer absorbers (SDA).

Spray dryer absorbers are also called semi-dry scrubbers or spray dryers. SDA technology uses a slurry, most often lime or limestone slurry, sprayed as a finely atomized mist into the flue gas in an absorbing tower (dryer) where the atomized slurry reacts with SO_2 from the flue gases and forms calcium sulfite ($CaSO_3$). The heat from the flue gases evaporates the liquid from the slurry, leaving a solid, dry residue. A portion of the calcium sulfite is oxidized to calcium sulfate ($CaSO_4$). The sulfite to sulfate ratios generally range from 2:1 to 3:1. There may be pre-collection of fly ash prior to reaching the spray dryer absorber. However, the majority of the systems in the U.S. use a combined collection system such that both the fly ash and the SDA products are collected together. In the combined collection system, the sulfite and sulfate formed are deposited on the surface of the fly ash particles, which are then collected in an electrostatic precipitator or a baghouse.

The process of the SO_2 removal moves the sulfur compounds from the gas phase into a solid paste or dry powder form. If useful recycling options for the SDA products are not implemented, they must be either contained or buried in landfills. The American Coal Ash Association (ACAA) reported that the combined utilization rate of FGD materials (including SDA products) was about 31% in 2007. The utilization rate is very low for spray dryer products, less than 10%.

A recent EPRI report reviewed use options available for SDA products (EPRI, 2007). This report identified several applications for SDA products that were rated as "high potential applications." Included with these high-potential use options are cement replacement in concrete (with or without other pozzolanic materials such as Class F or C fly ash, slag, or silica fume), flowable fill, dry-cast masonry products (such as bricks, blocks, and paving stones), and synthetic aggregates. Barriers to implementing various uses included a lack of knowledge of potential uses, and information gaps on the characteristics and variability of the SDA products.

Based on feasibility tests and previous research conducted at the University of Wisconsin – Milwaukee Center for By-Products Utilization (UWM-CBU) (Naik et al., 1991), there are a number of high-potential applications consistent with the recommendations and conclusions in EPRI (2007). Therefore, it is believed that there is a high probability of success for the following applications for recycling of SDA products:

- Cement replacement in concrete and dry-cast concrete products
- Artificial aggregates

- Controlled low-strength materials (CLSM, flowable fill)
- Porous concrete
- Reduced- or non-shrinkage concrete

A first step in the process for developing any applications is to establish the range of physical and chemical characteristics of various sources of the SDA products and determine the variability of these characteristics. The objectives of this project were to document physical and chemical properties of SDA products from eight power plants, particularly as the properties relate to use in concrete products.

2
MATERIALS

SDA products from eight power plants were received and identified as 204, 205, 206, 207, 208, 209, 210, and 221. The background information for these SDA products is provided in Table 2-1.

Before beginning any quantitative testing, the general physical appearance of the as-received SDA products was evaluated (Table 2-2). Two of the samples (204 and 209) had agglomeration visible. Three samples were either tan or light tan in color (204, 205, and 206); three samples were white or off-white in color (208, 209, and 221); and two samples were gray in color (207 and 210). The color could be an indication of the type of coal being burned, if there are significant amounts of fly ash combined with the spray dryer material, and/or the amount of carbon remaining in the SDA product sample.

In order to evaluate the potential of the SDA products for various uses as a construction material, or as a substitute for cement in manufacturing concrete, several tests were conducted based upon the test protocol for ash use in construction materials, developed at UWM-CBU in the late 1980s (Naik, et al., 1991) . The American Society for Testing and Materials (ASTM) provides standard specifications for coal fly ash utilization in concrete (ASTM C 618). To judge the suitability of the SDA products for potential use as a mineral admixture in cement-based materials, tests were performed as described in the following sections. Results obtained were compared to the requirements as specified in ASTM C 618 where applicable.

Table 2-1
Background Information for SDA Products

Information	EPRI Source Number			
	204	**205**	**206**	**207**
Plant ID	16190	34188	25134	06232
Boiler/Unit Number	1	10	5A	5
Make of Boiler	Babcock & Wilcox	Combustion Engineering	Babcock & Wilcox	Combustion Engineering
Type of Boiler	Pulverized Coal	Pulverized Coal	Pulverized Coal	Pulverized Coal
Age of Boiler	25 years	26 years	18 years	44 years
Type of Fuel	Sub-bituminous Coal	Sub-bituminous Coal	Sub-bituminous Coal	Colorado Bituminous Coal
Amount of Fuel Used Per Year (thousand tons)	1,710	760	2,000 – 2,500	600
Burning Temperature	2,400˚F	Not Available	2,200˚F	2,400˚F
Type of Energy	Power	Power	Power	Power
Amount of Energy	360 MW	68 MW	510 MW	186 MW
Wet or Dry Ash Collection	Dry	Dry	Dry	Dry
Amount of Bottom Ash (tons/year)	17,000	9,000	20,000 – 25,000	80,000
Amount of Fly Ash* **(**tons/year)	66,000	Not Available	89,000 – 97,000	58,500
Type of FGD System and Age	Spray Dryer (25 years)	Spray Dryer (26 years)	Spray Dryer (8 years)	Spray Dryer (5 years)
Type of FGD Sorbent	Lime	Lime	Lime	Lime
Coal Sulfur Content	< 0.5%	< 0.5%	0.3 – 0.4%	0.5%
SO_2 Removal Efficiency	80%	70%	94%	85%
Separate or Combined SDA/Ash Collection	Combined	Combined	Combined	Combined
Amount of FGD Materials Generated Annually	96,000	30,000	110,000 – 120,000	90,000
Other Notes	Wyoming Coal, 1980s Vintage Low-NOx Burner	Montana (PRB) Coal, Over-Fire Air NOx Control	Southern PRB Coal, SCR Using Ammonia	Colorado Bituminous Coal, Low-NOx Burner with Over-Fire Air

* Because these are combined collection facilities, a direct measure of the volume of Fly Ash vs. SDA material was not available, the volumes of Fly Ash reported in this table are estimates provided by each facility

Table 2-1 (continued)
Background Information for SDA Products

Information	EPRI Source Number			
	208	**209**	**210**	**221**
Plant ID	23223	03630	06191	50213
Boiler/Unit Number	3	3	3	4
Make of Boiler	Babcock & Wilcox	Foster Wheeler	Babcock & Wilcox	Babcock & Wilcox
Type of Boiler	Pulverized Coal	Pulverized Coal	Pulverized Coal	Pulverized Coal
Age of Boiler	22 years	3 years	25 years	1 year
Type of Fuel	Montana Sub-bituminous	PRB Sub-bituminous	Western Sub-bituminous (Colorado-Wyoming mine)	PRB Sub-bituminous
Amount of Fuel Used Per Year (thousand tons)	4,000	1,700	1,600	1,700
Burning Temperature	3,200˚F	Not Provided	2,800˚F – 3,500˚F	2,200 ˚F
Type of Energy	Power	Power	Power	Power
Amount of Energy	859 MW	450 MW	418 MW	530 MW
Wet or Dry Ash Collection	Dry	Dry	Dry	Dry
Amount of Bottom Ash (tons/year)	80,000	23,000	21,000	31,000
Amount of Fly Ash* **(**tons/year)	294,000	512,000	101,000	97,600
Type of FGD System and Age	Spray Dryer (21 years)	Spray Dryer (3 years)	Spray Dryer (25 years)	Spray Dryer (1 year)
Type of FGD Sorbent	Lime	Slaked Lime	Lime	Lime
Coal Sulfur Content	0.6%	0.2%	0.38%	<0.5%
SO_2 Removal Efficiency	72%	61%	85%	90% - 92%
Separate or Combined SDA/Ash Collection	Combined	Combined	Combined	Combined
Amount of FGD Materials Generated Annually	420,000	Not Available	150,000	122,000
Other Notes	Montana Subbituminous Coal, First Generation - Dual Register Burners	Low-NOx burner with SCR (ammonia). PRB coal. Alstom absorber (2006)	No NOx controls, Colorado Coal, B&W Absorber	Wyoming (PRB) coal, Low NOx burner with SCR (ammonia), Mercury control: Powder Activated Carbon

* Because these are combined collection facilities, a direct measure of the volume of Fly Ash vs. SDA material was not available, the volumes of Fly Ash reported in this table are estimates provided by each facility

Table 2-2
Description of Individual Samples

Source Number	Sample Date, Received Date, Sample Description
204	Sample Date: 4-18-2008 Received: 5-7-2008 Sample Weight: 75 lbs. +/- Sample Description: Very fine ash, tan in color, consistency of typical fly ash. Some agglomeration visible (clumps up to 1”).
205	Sample Date: 4-23-2008 Received: 5-7-2008 Sample Weight: 75 lbs. +/- Sample Description: Very fine ash, light tan in color, consistency of typical fly ash. No agglomeration visible.
206	Sample Date: 6-24-2008 Received: 7-30-2008 Sample Weight: 75 lbs. +/- Sample Description: Very fine, tan in color, consistency of typical fly ash. No agglomeration visible.
207	Sample Date: 8-1-08 Received: 9-12-2008 Sample Weight: 75 lbs. +/- Sample Description: Very fine, gray in color, consistency of typical fly ash. No agglomeration visible.
208	Sample Date: 5-9-2008 Received: 5-23-2008 Sample Weight: 75 lbs. +/- Sample Description: Very fine ash, white in overall color, consistency of typical fly ash. No agglomeration visible.
209	Sample Date: 7-9-2008 Received: 7-30-2008* Sample Weight: 75 lbs. +/- Sample Description: Very fine, off-white in color, consistency of typical fly ash. Numerous agglomerated clumps visible (1/4” +).
210	Sample Date: 7-3-2008 Received: 7-30-2008 Sample Weight: 75 lbs. +/- Sample Description: Very fine, gray in color, consistency of typical fly ash. No agglomeration visible.
221	Sample Date: 8-2-2008 Received: 1-28-2009* Sample Weight: 75 lbs. +/- Sample Description: Very fine, off-white in color, consistency of typical fly ash. No agglomeration visible.

3
METHODS AND RESULTS

A test program was designed to measure physical, chemical, and mineralogical properties of the SDA products. The methods used and the results of the tests completed are reported in the following sections.

Physical Properties

As-Received Moisture Content

As-received moisture content (MC) of the SDA products was determined in accordance with the ASTM Test Designation C 311. Table 3-1 provides the test data for each source. The results show that the SDA products had a moisture content that ranged from 0.4% to 6.6% by weight of the oven-dry sample. Two (Sources 204 and 209) of the four SDA products (Sources 204, 206, 209, and 211) that had moisture contents greater than 1.0% also had agglomeration visible in the sample. All sources of SDA products, except Source 204 (MC = 6.6%), met ASTM C 618 requirements for moisture content for a typical coal fly ash (3% maximum).

There are some significant negative attributes associated with moisture in any such products, such as:

1. Moisture/water content leads to increased cost of shipping water along with the product to the potential end-user of the material.
2. If the moisture content is not controlled, then the variation leads to quality control challenges for the user. A typical manufacturer of cement-based materials is equipped very well to handle dry or relatively dry materials. Therefore, wet or variable moisture content SDA products make it harder to implement beneficial use options of the SDA product for reuse/recycle purposes for cement-based construction materials.
3. The water content is a critical parameter for manufacturing cement-based products. Therefore, for SDA product used in cement-based materials, water content must be controlled in a narrow range to control the quality of such cement-based materials.
4. Wetting the ash or soaking it in water could destroy any potential cementitious ability of the product.
5. Variability of the moisture content between individual shipments of SDA product may necessitate some additional pre-processing of the SDA product before it can be beneficially used.

It is important to have a predictable level of moisture content when these materials would be used in manufacturing cement-based construction materials. Therefore, producers of SDA materials should implement a process such that SDA materials are produced with consistently low levels of moisture content.

Table 3-1
As-Received Moisture Content of SDA Products

Source	Moisture Content, % (As-Received Sample)	
	Actual*	Average
204	6.7	6.6
	7.2	
	5.8	
205	0.4	0.4
	0.3	
	0.4	
206	1.8	1.3
	0.7	
	1.3	
207	0.7	0.7
	0.6	
	0.7	
208	0.6	0.6
	0.6	
	0.6	
209	2.7	1.6
	1.0	
	1.0	
210	0.4	0.4
	0.4	
	0.4	
221	1.9	1.7
	1.5	
	1.7	

$$\text{* Moisture Content, \%} = \frac{(\text{as-received sample weight} - \text{oven-dry sample weight}) \times 100}{\text{Oven-dry sample weight}}$$

Fineness

SDA product samples were first oven-dried at 105°C ± 5°C and then tested for fineness using a 325 sieve (45 μm) per ASTM Test Designation C 311 and C 430. The fineness of the SDA product can have an impact on the reactivity of the SDA product. For SDA products with a similar composition, a finer SDA product would be more reactive. ASTM C 618 for coal fly ash specifies a maximum value of 34% retained on the No. 325 sieve as satisfactory for use in concrete. Results of the fineness test for SDA products are given in Table 3-2. All of the SDA sources met this requirement. The sources with the highest moisture content (204, 206, and 209) also had the highest amount of material retained on the No. 325 sieve, most likely due to agglomeration. Based upon this fineness testing, Samples 205, 207, 210, and 221 would be more reactive (faster and more efficient) when used with portland cement compared with Samples 204 and 209. Samples 206 and 208 are considered reactive also but not as good as Samples 205, 207, 210, and 221. Samples 204 and 209 pass ASTM specification. Therefore, they should work well also with portland cement. In general, all samples should have excellent to satisfactory reactivity for use in cement-based construction materials. For typical Class C and F fly ashes, the amount retained on #325 sieve is about 20% or less.

Table 3-2
Fineness (Tests Conducted per ASTM C 311/C 430)

Source	Amount Retained on #325 Sieve (%)	ASTM C 618 Specifications		
		Class C	Class F	Class N
204	31.7	34 max	34 max	34 max
205	6.1			
206	18.5			
207	5.8			
208	14.6			
209	28.5			
210	9.6			
221	9.5			

Particle Size Distribution by Laser Light Scattering Method

The particle size distribution was determined using the laser scattering method. It was performed on the eight SDA products in lieu of the particle size distribution performed by the sedimentation test using a hydrometer. Results are given in Table 3-3. Results show that 90% of SDA product particles were finer than about 48+/- μm in size for Samples 205, 206, 207, 208, 210, and 221. Samples 204 and 209 have more coarse particles; the 90% cutoff was about 156 and 133 μm respectively. However, all samples have quite similar fractions below 50% of the material. As previously noted, it is well accepted that finer CCP particles are more reactive in the presence of portland cement and water in creating cementitious products.

Table 3-3
Particle Size Distribution

Source	90% Finer Than Diameter (µm)	50% Finer Than Diameter (µm)	10% Finer Than Diameter (µm)
204	156.4	13.7	1.8
205	26.5	5.5	1.4
206	44.0	5.9	1.3
207	39.8	8.8	1.5
208	48.1	6.5	1.1
209	132.8	16.9	1.8
210	40.2	5.3	1.3
221	32.6	5.1	0.9

Unit Weight

Unit weight (i.e., bulk density) of the SDA product was determined in accordance with the ASTM Test Designation C 29. Table 3-4 provides the test results. Bulk density of the SDA products varied from 40.3 to 66.2 lb/ft^3. Determining the bulk density value is necessary for calculations for establishing and modifying cement-based construction materials mixture proportioning. Percentages of voids, also given in Table 3-4, indicate the amount of free space available for packing of other materials in making cement-based materials. The higher the percent voids, the higher the amount of other materials necessary for making cement-based materials. Void space of 56.7% to 74.6% was present in the SDA products tested in dried condition. Typical concrete contains between 60 and 80 percent, by volume, of sand (fine aggregates) plus stone (coarse aggregates). This level of void space is, therefore, satisfactory to pack the material with the least expensive materials (i.e., sand and stone) in concrete. These levels of void space are in a similar range as levels in typical Class C and F fly ashes.

Specific Gravity

Specific gravity tests for the SDA products were conducted in accordance with the ASTM Test Designation C 311 and C 188. Results are given in Table 3-5. The specific gravity for the SDA product ranged from 2.24 to 2.60.

The specific gravity of the SDA products is in the range of what would be expected if the sample was composed of coal fly ash alone. The specific gravity of typical Class F fly ash is approximately 2.50 and the specific gravity of typical Class C fly ash is approximately 2.60. For comparison, the specific gravity of typical natural sand is about 2.70. Specific gravity value is necessary for determining relative substitution rate for the SDA products versus amount of cement replaced in a concrete mixture, and also for calculations for establishing and modifying other types of cement-based construction materials mixture proportions.

Table 3-4
Unit Weight and Voids (Tests Conducted on Dried Samples per ASTM C 29)

Source	Unit Weight (lbs/ft^3)		Voids (%)	
	Actual	Average	Actual	Average
204	65.1	66.2	57.4	56.7
	66.6		56.4	
	67		56.2	
205	40.1	40.3	74.7	74.6
	40.4		74.5	
	40.4		74.5	
206	59.2	58.5	63.4	63.8
	58.4		63.9	
	58		64.1	
207	47.2	46.5	66.2	66.7
	46		67.1	
	46.2		66.9	
208	56	54.9	63.4	64.1
	54.2		64.5	
	54.6		64.3	
209	51	51.3	67.4	67.2
	51.6		67.1	
	51.4		67.2	
210	63	60.9	56.1	57.6
	60.2		58.1	
	59.4		58.6	
221	49.9	49.5	69.2	69.5
	49.4		69.6	
	49.2		69.7	

Table 3-5
Specific Gravity (Tests Conducted per ASTM C 311/C 188)

Source	Specific Gravity
204	2.45
205	2.54
206	2.59
207	2.24
208	2.45
209	2.51
210	2.30
221	2.60

ASTM C 618 Tests

Physical Properties per ASTM C 618

ASTM C 618 provides standard specifications for coal fly ash and natural pozzolans for use in concrete. A similar standard specification for SDA products currently does not exist. Therefore, ASTM C 618 was used to judge the suitability of the SDA products for potential use as a mineral admixture in cement-based materials. Physical properties tests were performed as described below in accordance with ASTM C 618. Table 3-6 shows physical properties requirements for coal fly ash and natural pozzolans in accordance with ASTM C 618. SDA products were tested for moisture content, fineness by sieving to determine percent retained on No. 325 sieve, unit weight, and specific gravity. The following additional physical properties of the SDA products were determined: (1) Strength Activity Index with Cement; (2) Water Requirement; (3) Activity Index with Lime; (4) Autoclave Expansion (soundness); and, (5) Increase of Drying Shrinkage of Mortar Bars.

Table 3-6
Physical Test Requirements of Coal Fly Ash per ASTM C 618

Test	ASTM C 618 Specifications		
	Class C	**Class F**	**Class N**
Retained on No. 325 Sieve (%)	34 max	34 max	34 max
Strength Activity Index with Cement at 7 or 28 Days (% of Control)	75 min	75 min	75 min
Water Requirement (% of Control)	105 max	105 max	115 max
Autoclave Expansion (%)	±0.8	±0.8	±0.8
Increase of Drying Shrinkage of Mortar Bars at 28 Days (%)	0.03 max	0.03 max	0.03 max
Specific Gravity	-	-	-
Variation from Mean (%) Fineness Specific Gravity	 5 max 5 max	 5 max 5 max	 5 max 5 max

Strength Activity Index

Strength activity index testing for the SDA products was performed in accordance with the ASTM Test Designation C 311/C 109. Two-inch mortar cubes were made in the manner prescribed in ASTM C 109 using a mixture of cement, sand, and water, without any SDA product (Control Mixture). Compressive strength tests were conducted at the ages of 7 and 28 days for the mixtures. Strength test results are reported in Table 3-7 for the test specimens made from Control Mixture. Additional test mixtures were prepared using 80% cement and 20% SDA product, by weight in accordance with ASTM C 618. Results for these test mixtures (80 + 20 mixtures) are also reported in Table 3-7.

Table 3-7
Mortar Cube Compressive Strength (Tests Conducted per ASTM C 311/C 109)

Source	Compressive Strength (psi)			
	7-Day		28-Day	
	Actual	Average	Actual	Average
Control	4900	4770	5950	5800
	4750		5900	
	4650		5750	
204	4050	4070	5380	5370
	4150		5350	
	4000		5300	
205	3900	3970	4800	4880
	4000		4950	
	4000		4900	
206	4200	4260	5800	5780
	4325		5930	
	4250		5800	
207	4100	4175	5650	5900
	4175		6000	
	4250		--	
208	4750	4800	6300	6320
	4800		6200	
	4850		6450	
209	3950	3975	4800	4950
	4000		4950	
	3975		5100	
210	4300	4220	6050	5820
	4150		5800	
	4200		5600	
221	4750	4750	6380	6430
	4850		6400	
	4650		6500	

Comparison of the compressive strength for mixtures with and without the SDA product is reported in Table 3-8. These results are designated as Strength Activity Index with Cement. In this comparison, Control Mixture was assigned a value of 100, at each age, and all other compressive strength values were scaled from this reference datum.

The compressive strength test results for SDA product mixtures were generally lower than that for Control Mixture without SDA product, with the exception of Source 208 at the 7-day age and Sources 207, 208, 210, and 221 at the 28-day age. Furthermore, SDA product mixtures for Source 221 at the 7-day age and Source 206 at the 28-day age were essentially the same as Control Mixture without SDA product. Therefore, mixtures with SDA Sources 208 and 221 at the age of 7 days and mixtures with SDA Sources 206, 207, 208, 210, and 221 at the age of 28 days performed equal to or better than Control Mixture without SDA product. Overall, both at the early age and later age SDA Sources 208 and 221 performed very well compared to Control Mixture without SDA product.

Table 3-8
Strength Activity Index with Cement* (Tests Conducted per ASTM C 311/C 109)

Source	7-Day Test %	28-Day Test %
Control	100.0	100.0
204	87.0	92.2
205	84.8	84.3
206	91.0	99.8
207	89.3	101.9
208	102.6	109.2
209	85.0	85.5
210	90.2	100.5
221	98.5	107.7

* Results obtained from the mortar cube compressive strength, Table 3-7.

Activity Index with Cement for the SDA products at the age of 7 days ranged from 85 to 103 and at the age of 28 days it ranged from 84 to 109. Test results for all SDA sources were higher than the minimum 75 required by ASTM C 618 for mortar containing 80% cement and 20% coal ash at either the 7- or 28-day age, compared with Control Mixture without SDA product at the same ages. Based upon the data in Tables 3-7 and 3-8, overall it can be concluded that with respect to these two strength tests all SDA products are suitable for partial replacement of cement with SDA product for typical concrete and other cement-based construction materials applications. These applications include structural concrete; lightweight concrete for insulation, noise, and vibration isolation; low-strength concrete mixtures, CLSM; and base course and/or sub-base course for pavement of highways, roadways, runways, driveways, parking lots, and other similar construction applications.

In summary, ASTM C 618 classifies a value at a 7-day or 28-day age of 75 or above for the Strength Activity Index with Cement for coal fly ash as passing. Based upon this ASTM criterion only, all SDA products met the ASTM C 618 requirement.

Water Requirement

Water requirement tests for the SDA products were performed in accordance with the ASTM Test Designation C 311. This test determines the relative amount of water that may be required for mixture proportioning of cement-based construction materials. It is well established that the lower the water required for a desired value of workability for the cement-based material, the higher the overall quality of the product. Test data for water requirement for the SDA products are reported in Table 3-9. The results show that the values for water requirement for the SDA products were generally lower than the maximum value specified in ASTM C 618. ASTM specifies a maximum value of 105%, for Type F or C fly ash. With the exception of Sources 205 and 210, the water requirement of the SDA products ranged from 95% to 99%. It is concluded, therefore, that with the exception of Sources 205 and 210, all other mixtures with SDA product would require slightly less water for the same workability, as that in a mixture without SDA product. Source 205 required 107% (slightly more than the value of 105% specified in ASTM) and Source 210 required 105% (at the limit of ASTM). Mixtures for concrete and other cement-based construction materials made with SDA Sources 205 and 210 may, therefore, require use of ordinary chemical admixtures to manage water demand.

Table 3-9
Water Requirement* (Tests Conducted per ASTM C 311)

Source	Water Requirement (% of Control)	ASTM C 618 Specifications		
		Class C	Class F	Class N
204	97.1	105 max	105 max	115 max
205	107.4			
206	99.2			
207	99.2			
208	95.0			
209	95.0			
210	105.4			
221	97.1			

* Results obtained from the mortar cube mixtures.

Lime Activity Index

The lime activity index test was performed in accordance with 1992 ASTM test requirements. Although not currently a part of ASTM C 618 test procedures for requirements for coal fly ash (Class C and F) and natural pozzolans (such as volcanic ash), the test was performed to obtain additional information on these eight SDA materials regarding their pozzolanic ability. The test was performed to evaluate these SDA materials because the test does show behavior of CCPs in presence of portland cement and water (the actual reaction is due to CCPs and calcium hydroxide ($Ca(OH)_2$) produced by cement and water). Similar to fly ash and pozzolans, SDA material does react with $Ca(OH)_2$, which is also produced by the reaction of lime in presence of water. It is believed that the lime activity index provides some insight into the behavior of SDA materials. This activity index provides an indication of the potential long-term reactivity of CCPs and the ability of the CCP to form cementitious products without cement. Based upon the 1992 ASTM Standard, test procedure C 311/C 109 was followed for testing the SDA products. Three 2-inch mortar cubes were made in a prescribed manner using a mixture of lime, sand, water, and SDA products. Cubes were cured for 24 hours at room temperature (73° +/- 2° F) and then for six days at 130° +/- 5° F. Compressive strength tests were conducted at the age of 7 days. Actual strength test results are reported in Table 3-10 for the mortar cube test specimens. Compressive strength of mortar mixtures containing the SDA products ranged from 55 psi at the age of 7 days for Source 204, to over 1000 psi for Source 208. Such a range/spread of strength data shows that SDA products vary in characteristic such as fineness, moisture content, chemistry of compounds formed, and other similar properties. The 1992 ASTM C 618 specified a minimum requirement of 800 psi for a typical coal ash. Only Source 208 met this requirement. Sources 205, 207, and 210 also developed very good values of compressive strength, 400 to 745 psi, especially considering that cement was not used in these mixtures. Sources 206 and 209 developed marginal strength values with lime (145 and 285 psi, respectively). The fact that six of the SDA products developed generally adequate compressive strength values without using any portland cement shows that SDA products generally exhibited pozzolanic ability, even though all sources did not meet the (old) ASTM C 618 requirement of Class C, F, or Class N pozzolans. Sources 205, 208, and 210 (compressive strength at the 7-day age of 800 +/- 200 psi) could be used for making typical structural-grade concrete. Sources 207 and 209 could be readily used for many types of structural concrete, especially in conjunction with ASTM-grade Class C or F fly ashes. These two sources could also be used for making bricks, blocks, and paving stones. Sources 204, 206, and 221 could be readily used for flowable slurry without using portland cement; and/or, for mixtures with portland cement, at appropriately late-age, these three sources could also be crushed into making aggregates for base course and sub-base course for pavements for highways, roadways, and airfields, parking lots, and storage yards.

Table 3-10
Pozzolanic Activity with Lime* (Tests Conducted per ASTM C 311/C 109)

Source	Compressive Strength (psi)	ASTM C 618 Specification*		
	7-Day	Class C	Class F	Class N
204	55	---	800 min.	800 min.
205	745			
206	145			
207	400			
208	1005			
209	285			
210	605			
221	60			

* Not Part of Current ASTM C 618 Requirements

Autoclave Expansion (Soundness)

Soundness tests (as indicated by the change in length after test specimens are subject to autoclave curing) for the SDA products were performed in accordance with the ASTM Test Designation C 311. This test indicates if periclase (MgO) or free lime (CaO) exists in sufficient quantities to potentially cause expansion problems in concrete and other cement-based construction materials, especially at later ages beyond 28 days. Test results for the eight SDA product sources are given in Table 3-11. ASTM C 618 specifies a maximum limit on the change in length of +/- 0.8 percent due to autoclave expansion. All SDA sources met this requirement and, in fact, had length decrease rather than the increase that is normally the case with cement, coal fly ashes, and natural pozzolans. Sources 204, 206, 207, and 210 exhibited the greatest decrease in length, 0.06% to 0.08%, but were well below the ASTM limit, and, therefore, should not pose any late-age expansion challenges.

Table 3-11
Soundness (Autoclave Expansion) (Tests Conducted per ASTM C 311/C 109)

Source	Change in Length (%)	ASTM C 618 Specification		
		Class C	Class F	Class N
204	-0.07	+/- 0.8	+/- 0.8	+/- 0.8
205	-0.03			
206	-0.06			
207	-0.08			
208	-0.03			
209	-0.03			
210	-0.07			
221	-0.05			

Drying Shrinkage of Mortar

The test for drying shrinkage of mortar bars containing the SDA sources was performed in accordance with the ASTM Test Designation C 311. Results of this test are given in Table 3-12. The drying shrinkage is an optional requirement of ASTM C 618 since some pozzolans have been shown to significantly increase drying shrinkage. Use of most sources of fly ashes meeting ASTM standard in concrete and other cement-based construction materials decreases the amount of drying shrinkage. The ASTM C 618 specification has a limit of 0.03% drying shrinkage of mortar containing a pozzolan. All sources with the exception of SDA Source 209 met this requirement. Source 209 exceeded the requirement (0.04% vs. the 0.03% ASTM specified limit). It is believed that most SDA products would be an excellent choice for use in concrete where minimum (or, reduced) shrinkage is desired. Shrinkage of concrete means cracking, and cracking means poor serviceability and reduced durability. Therefore, normally reduction in shrinkage is achieved by using expensive shrinkage compensating cement (such as Type K cement) or using expensive shrinkage reducing admixtures, or both. Therefore, the best use of SDA products is in production of durable concrete without using an expensive, special type of cement or a special category of very expensive admixture. A blend of SDA product with portland cement can be readily produced to be equivalent to shrinkage compensating cement, such as Type K. The market price of Type K cement is indeed much higher than the market price for ordinary portland cement.

Table 3-12
Drying Shrinkage of Mortar Bars (Tests Conducted per ASTM C 311/C 109)

Source	Change in Length at 28-day Age (%)	ASTM C 618 Specification		
		Class C	Class F	Class N
204	0.02	0.03 max.	0.03 max.	0.03 max.
205	0.02			
206	0.02			
207	--			
208	0.02			
209	0.04			
210	0.02			
221	0.03			

Chemical Properties in Accordance with ASTM C 618

Chemical analysis tests were conducted to determine oxides present in the SDA products. X-ray fluorescence (XRF) technique was used to detect the presence of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), titanium oxide (TiO_2), potassium oxide (K_2O), and sodium oxide (Na_2O). In this method, ignited samples were fused in a 4:1 ratio of lithium carbonate to lithium tetraborate flux and cast into pellets in platinum molds. The XRF technique for measuring sulfur trioxide (SO_3) involves grinding the ash sample and manufacturing a compressed pellet with boric acid. A double dilution method using 4:1 and 10:1 ratio with boric acid was used to correct for matrix effects. These pellets were used to measure XRF intensities for the desired element, in accordance with standard practice for cementitious materials, using an automated Philips PW1410 x-ray spectrometer. The percentages of each element were derived from the measured intensities through a standardized computer program based on a procedure outlined for low-dilution fusion. This is a standard practice for detecting oxides in cementitious compounds, including coal fly ash. Chemical requirements of coal fly ash and natural pozzolans are given in Table 3-13.

Table 3-13
Chemical Test Requirements of Coal Fly Ash per ASTM C 618

Test	ASTM C 618 Specifications		
	Class C	Class F	Class N
Silicon Dioxide plus Aluminum Oxide plus Iron Oxide ($SiO_2 + Al_2O_3 + Fe_2O_3$)	50 min	70 min	70 min
Sulfur Trioxide (SO_3)	5.0 max	5.0 max	4.0 max
Moisture Content	3.0 max	3.0 max	3.0 max
Loss on Ignition	6.0 max	6.0 max*	10.0 max

* Class F fly ash may contain up to 12% LOI if the performance records or laboratory results are acceptable.

Chemical analysis of SDA sources along with loss on ignition (LOI) and moisture content for the SDA sources is reported in Table 3-14. In terms of the oxides analysis, none of the SDA products meet all of the ASTM C 618 Class C or Class F requirements for coal ash. However, Sources 207 and 210 meet Class C chemical analysis requirements except for the sulfur trioxide (SO_3) content. The limit specified in ASTM C 618 for SO_3 is 5.0% for a Class C or F ash and 4.0% for a Class N ash. The SO_3 content of the SDA products ranged from 9.2% (Source 207) to 21.0% (Source 205). This was expected since the products were obtained from a flue gas desulfurization process. The high SO_3 content of the SDA products may make concrete or cementitious products more susceptible to internal sulfate attack. Additional testing of the SDA products for sulfate resistance is necessary in the future. The magnesium oxide values are low (less than 5%) and should, therefore, not create soundness/durability related problems due to the presence of MgO. All but two SDA Sources, 207 and 209, meet the ASTM C 618 requirements for loss on ignition (LOI). The LOI for Sources 207 and 209 (7.0 and 13.0%, respectively) exceeds the value permitted (maximum 6%) by ASTM C 618 for coal fly ash. This requirement is used for air entrained concrete applications, where the preferred LOI value is typically 2% or less. Under certain circumstances, up to 12% maximum LOI is permitted by ASTM C 618. Research shows that high-LOI coal ash can be effectively used for concrete with micro-fibers, as well as for no-fines concrete, roller compacted concrete pavements, and in a permeable concrete road base (Naik et al., 2001; Naik and Kraus, 2002; Naik et al., 2005). Current practice in Wisconsin and elsewhere also shows that high-LOI fly ash would perform satisfactorily for CLSM. Ashes containing a high- or variable-carbon content affect the use of air-entraining agent used in concrete to make the concrete resistant to a freezing and thawing environment.

Table 3-14
Chemical Analysis (Oxides, LOI, Moisture Content, Available Alkali)

Analysis Parameter	Sample Number							
	204	205	206	207	208	209	210	221
Silicon Dioxide, SiO_2 (%)	27.2	15.6	25.7	42.9	27.0	16.5	43.5	21.9
Aluminum Oxide, Al_2O_3 (%)	13.2	11.0	13.5	19.4	15.9	7.6	16.5	13.3
Iron Oxide, Fe_2O_3 (%)	4.7	3.3	5.2	2.8	3.7	2.7	2.8	5.5
SiO_2 + Al_2O_3 + Fe_2O_3 (%)	45.1	29.9	44.4	65.1	46.6	26.8	62.8	40.7
Calcium Oxide, CaO (%)	24.9	31.1	28.8	11.5	28.2	36.0	17.4	31.4
Magnesium Oxide, MgO (%)	4.0	2.9	3.5	1.0	3.0	2.7	1.6	4.1
Titanium Oxide, TiO_2 (%)	1.1	0.8	1.1	0.7	0.6	0.6	0.6	1.1
Potassium Oxide, K_2O (%)	0.4	0.3	0.3	1.4	0.4	0.3	1.3	0.3
Sodium Oxide, Na_2O (%)	1.8	6.8	1.2	0.8	0.9	2.5	0.7	1.5
Sulfur Trioxide, SO_3 (%)	12.7	21.0	14.5	9.2	16.3	10.5	10.9	16.1
Loss on Ignition, LOI * (@ 750 C) (%)	2.7	4.4	3.6	7.0	3.6	13.0	2.9	3.1
Moisture Content, (%)	5.8	1.4	1.4	0.5	1.1	2.0	0.5	1.1
Available Alkali, Na_2O Equivalent** (ASTM C-311) (%)	3.4	13.9	2.1	1.7	4.9	1.5	2.2	1.1

* Under certain circumstances, up to 12.0% max. LOI may be allowed.

** Optional Requirement of 1.5% for ASR Minimization.

pH of SDA Product Mixtures

The pH of a mixture containing SDA products is of interest since the products are intended to be used as a cement replacement in concrete, similar to the way that a typical fly ash is used. The effect of the pH of the cementitious paste with SDA products and the potential for affecting the protection of reinforcing bars is needed to understand if the SDA materials would be readily accepted for use in reinforced concrete elements. The pH was measured on a slurry of the SDA product with distilled water. The concentration of SDA products in the slurry mixture was established as 10 percent by mass. The ASTM standard is not applicable to this test. The slurry was mixed with distilled water for 10 minutes using a magnetic stirring platform. The pH measurements were then taken at the following ages: 15 min., 1 hr., 2 hrs, 1 day, and 3 days. Results of the pH tests are shown in Table 3-15. Typically, there was not a significant change in the pH of the slurry made with a given source of SDA product at various ages up to the age of three days. Table 3-15 also shows the pH of the slurry with SDA product to be quite similar to the pH of typical Class C fly ash. Overall, based on the pH values obtained from the slurry mixtures, the SDA products when used in a cementitious mixture should not adversely affect the resistance to corrosion of reinforcing bars.

Table 3-15
pH Measurement of Slurry Mixtures

Source Number	pH of 10% Slurry Mixture				
	Age				
	15 min.	1 hr.	2 hrs.	1 day	3 days
204	8.14	7.97	8.04	8.14	8.23
205	10.01	9.95	10.06	10.11	10.30
206	9.74	9.81	9.76	9.44	9.14
207	9.89	9.93	10.17	9.95	10.00
208	9.87	9.97	10.20	9.94	9.94
209	9.99	10.02	10.09	9.88	9.83
210	9.95	10.01	10.05	10.00	10.05
221	8.60	8.50	8.57	8.74	9.03

Chemical Composition (Mineralogy)

The mineral analysis for the SDA products was conducted using the X-ray diffraction (XRD) method. Results of the chemical composition are shown in Table 3-16. Amorphous content shows that these SDA product samples have significant amounts of non-reactive materials. These non-reactive materials are useful as very fine filler in a matrix of mortar or concrete, leading to increased compaction of the overall matrix and decreased potential for ingress of harmful chemicals.

Table 3-16
Mineralogy of SDA Products

Mineralogy (% by Weight)								
Analysis Parameter	**204**	**205**	**206**	**207**	**208**	**209**	**210**	**221**
Amorphous	77.5	75.0	75.0	63.3	86.8	61.5	68.0	60.0
Anhydrite ($CaSO_4$)	--	--	--	--	--	1.9	--	--
Bassanite ($CaSO_4 \cdot 0.5H_2O$)	--	6.2	--	--	--	9.0	--	--
Calcite ($CaCO_3$)	3.3	1.8	2.1	--	--	18.2	--	--
Merwinite ($Ca_3Mg(Sio_4)_2$)	--	--	--	--	--	--	--	18.0
C3A (monoclinic) ($Ca_3Al_2O_6$)	--	5.1	--	--	--	--	--	--
Ettringite ($(Ca_6Al_2(SO_4)_3 \cdot 26H_2O$)	6.3	--	7.1	1.8	--	--	--	--
Gypsum ($CaSO_4 \cdot 2H_2O$)	8.6	--	--	--	1.6	3.8	--	--
Hannebachite ($CaSO_3 \cdot 0.5H_20$)	--	--	--	5.1	7.1	--	7.4	16.0
Lime (CaO)	--	--	--	--	1.4	--	--	--
Mullite (Al_2O_3:SiO_2=1.92)	--	--	11.0	19.3	--	--	9.7	--
Portlandite ($Ca(0H)_2$)	--	9.7	--	2.8	3.2	2.4	6.0	--
NasulfateIII (Na_2SO_4)	--	3.8	--	--	--	--	--	--
Quartz (SiO_2)	4.2	--	4.8	7.7	--	3.2	8.8	5.0

There are various sulfite and sulfate compounds that were detected in these SDA sources. These include anhydrite ($CaSO_4$), bassanite ($CaSO_4 \cdot 0.5H_2O$), ettringite ($Ca_6Al_2(SO_4)_3 \cdot 26H_2O$), gypsum ($CaSO_4 \cdot 2H_2O$), hannebachite ($CaSO_3 \cdot 0.5H_20$), and sodium sulfate ($Na_2SO_4$). Anhydrite is formed from the reaction of SO_2, CaO, and O_2. Anhydrite is commonly found in Class C fly ashes and also in some Class F ashes. Anhydrite also reacts with C3A (-calcium aluminate, $3CaO.Al_2O_3$, a compound that is typically present in portland cement and helps concrete gain strength at an early age) to form ettringite. Formation of ettringite immediately after adding water adds to the self-cementing ability found in Class C fly ash. Bassanite, also referred to as hemihydrate, is formed from the partial decomposition of gypsum at high temperatures, and is the intermediate form between gypsum and anhydrite. Hannebachite is a sulfite phase that is typically produced from the desulfurization process, but unlike gypsum, it is insoluble. Limited uses have been found for materials containing hannebachite. Three sources of SDA product were found to contain hannebachite: 207, 208, and 210. The gypsum, sodium sulfate, and anhydrite found in the SDA products may provide some benefits when used in concrete and other cement-based materials since these minerals have been shown to "activate" or increase the early-age strength in cement-fly ash systems. Source 209 exhibited a large amount of calcite ($CaCO_3$), 18.2%, possibly indicating inadequate absorption of limestone in the process. Source 205 had a significant amount of C3A present (5.1%). As noted above, C3A is desirable to develop early age strength of cement-based materials. Mullite (aluminosilicate mineral) was also present in amounts ranging from 9.7% to 19.3% in Sources 206, 207, and 210.

Elemental Analysis

The SDA products were analyzed for total chemical composition by instrumental neutron activation analysis (INAA). The results of the elemental analysis are reported in Table 3-17. The SDA products contained the following elements in significant concentrations (approximately 5,000 ppm or higher): aluminum, barium, calcium, iron, magnesium, potassium, sodium, and titanium. Sulfur and silica were not measured by INAA.

Scanning Electron Microscopy (SEM)

A scanning electron microscope was employed for this part of the investigation. SEM pictures (photomicrographs) for the SDA products are provided in Figures 3-1 through 3-8. These SEM pictures are an important part of understanding the character and morphology of the particles of the products being evaluated for considering their constructive use options. For example, studying the morphology allows judgments to be made regarding the physical and/or mechanical bond that might be possible for the SDA product in creating new construction materials. Also, an unreactive particle with a smooth surface could provide lower mechanical bond in the mortar fraction of a concrete matrix than particles with a rough surface. In addition, photomicrographs allow an opportunity to study the contours of the particles and how they may help in mixing and manufacturing new types of construction materials. The particle morphology also helps in understanding the level of completeness of combustion and microstructure of burned, partially burned, or unburned particles. This evaluation of level of combustion, and particle size and distribution, also helps in judging the water demand when making cement-based materials from such SDA products.

The general appearance of all samples is quite similar. There appear to be a number of fly ash particles (spherical shaped particles) visible. There are also irregular-shaped particles in the samples, both adhering to the fly ash particles and also in groups. There is a differing degree of agglomeration visible in these SDA product samples.

Sources 204 and 205 have a fair amount of spherical particles present, with deposit of some fine materials on them. Source 205 has more such fine materials on them than Source 204 (i.e., Source 204 particles are cleaner than Source 205 particles). This may indicate that water demand for manufacturing cement-based materials would be lower for Source 204 than Source 205, leading to higher quality (strength and durability) of such materials made from Source 204.

Table 3-17
Elemental Analysis (As-Received Sample)

Elemental (Bulk Chemical) Analysis (Average of two samples unless noted otherwise)								
Element	**Material (ppm)**							
	204	**205**	**206**	**207**	**208**	**209**	**210**	**221**
Aluminum (Al)	70425.0	64280.0	74250.0	100120.0	86670.0	39675.0	81850.0	63590.0
Antimony (Sb)	< 1.0	< 1.1	< 1.2	3.5	2.2	< 0.5	4.9	1.9
Arsenic (As)	15.7	27.6	14.9	10.2	7.0	5.2	8.7	10.9
Barium (Ba)	4454.5	10910.0	3807.0	1719.5	3628.5	2846.5	3601.5	3728.0
Bromine (Br)	98.9	5.4	6.5	10.1	10.6	1.8	4.0	152.2
Cadmium (Cd)	< 4.4	< 5.6	< 4.3	< 4.1	< 3.5	< 3.1	< 3.6	<4.1
Calcium (Ca)	< 54751.0	< 64031.0	< 60918.0	42870.0	91650.0	115300.0	< 28604.5	101335.0
Cerium (Ce)	116.7	67.2	116.4	131.5	73.6	56.9	96.3	109.6
Cesium (Cs)	1.2	< 1.3	1.4	6.4	1.5	0.9	8.7	1.2
Chlorine (Cl)	1233.5	< 268.6	< 170.2	2004.5	< 271.8	2382.0	< 161.3	<149.2
Chromium (Cr)	60.3	40.2	65.6	49.3	32.1	25.2	54.8	56.7
Cobalt (Co)	24.5	11.6	20.4	13.3	7.5	10.4	13.4	25.1
Copper (Cu)	< 192.4	< 372.9	< 187.1	< 215.7	< 206.3	< 180.5	< 157.9	<187.0
Dysprosium (Dy)	< 42.6	< 72.1	< 48.0	< 41.4	< 51.1	< 31.1	< 33.9	8.4
Europium (Eu)	2.3	0.8	2.2	2.0	0.7	1.0	1.4	2.4
Gallium (Ga)	< 341.8	< 553.5	< 314.9	< 312.1	< 411.9	< 257.5	< 278.3	<265.7
Hafnium (Hf)	6.6	6.3	8.2	11.8	9.7	6.1	7.5	8.7
Holmium (Ho)	< 3.6	< 5.1	< 3.2	< 3.6	< 3.0	< 3.0	< 3.1	<3.2
Indium (In)	< 0.2	< 0.4	< 0.3	< 0.3	< 0.3	< 0.2	< 0.2	<0.2
Iodine (I)	< 5.5	< 8.6	< 4.9	< 5.5	< 6.1	< 4.0	< 4.5	<7.0
Iridium (Ir)	< 0.0	< 0.0	< 0.0	< 0.0	< 0.0	< 0.0	< 0.0	<0.0

* Detection Limit Indicated by "<"

Table 3-17 (continued)
Elemental Analysis (As-Received Sample)

Elemental (Bulk Chemical) Analysis (Average of two samples unless noted otherwise)								
Element	**Material (ppm)**							
	204	**205**	**206**	**207**	**208**	**209**	**210**	**221**
Iron (Fe)	32505.0	23775.0	35260.0	19090.0	24320.0	17185.0	17730.0	35630.0
Lanthanum (La)	52.5	31.7	57.2	57.6	36.4	28.0	44.7	53.4
Lutetium (Lu)	0.6	0.4	0.6	0.5	0.4	0.3	0.6	0.6
Magnesium (Mg)	5783.0	3821.0	5312.0	2854.5	5416.0	3877.5	3742.5	5782.5
Manganese (Mn)	194.0	223.5	191.1	63.5	633.6	84.5	164.0	71.5
Mercury (Hg)	0.11	0.17	0.13	0.12	0.13	0.07	0.12	<0.80
Molybdenum (Mo)	< 28.5	< 37.6	< 26.6	< 29.3	< 25.0	< 24.3	< 25.6	<22.7
Neodymium (Nd)	20.3	16.8	30.6	23.4	14.1	11.3	17.4	39.2
Nickel (Ni)	< 124.2	< 154.0	< 115.7	125.7	< 49.5	< 51.3	< 95.2	<57.5
Palladium (Pd)	< 42175.0	< 77095.0	< 42245.0	< 42300.0	< 56045.0	< 36765.0	< 33075.0	0.0
Potassium (K)	< 2267.0	< 4221.0	< 2064.5	12210.0	< 2458.5	< 4612.0	14125.0	<5000.5
Praseodymium (Pr)	< 16.8	< 37.4	< 15.2	< 17.1	< 16.0	< 17.7	< 15.7	<23.3
Rhenium (Re)	< 47.1	< 71.7	< 54.4	< 65.2	< 55.7	< 57.7	< 61.7	<94.0
Rubidium (Rb)	< 8.9	< 17.7	16.1	58.1	< 6.4	< 6.1	65.8	<7.5
Ruthenium (Ru)	118.1	288.6	113.1	48.9	85.4	67.5	90.1	121.7
Samarium (Sm)	8.8	5.3	10.3	8.4	5.2	4.4	6.9	10.2
Scandium (Sc)	20.0	15.5	19.6	13.8	9.4	9.5	14.0	18.6
Selenium (Se)	< 3.8	< 5.1	< 6.1	< 3.2	< 3.0	< 2.7	< 2.7	9.6
Silver (Ag)	9.0	9.2	5.5	4.1	2.3	1.7	2.2	2.9
Sodium (Na)	14750.0	53185.0	8251.0	5759.0	8275.0	10215.0	5075.5	9740.0
Strontium (Sr)	1723.6	5544.5	1098.0	478.6	2473.0	537.4	458.7	3506.0
Tantalum (Ta)	0.9	< 0.7	1.1	1.5	2.0	1.5	1.3	2.0

* Detection Limit Indicated by "<"

Table 3-17 (continued)
Elemental Analysis (As-Received Sample)

Elemental (Bulk Chemical) Analysis (Average of two samples unless noted otherwise)								
Element	**Material (ppm)**							
	204	**205**	**206**	**207**	**208**	**209**	**210**	**221**
Tellurium (Te)	< 4.6	10.7	< 4.6	5.9	6.8	< 2.9	5.6	3.4
Terbidium (Tb)	< 0.7	< 1.0	< 0.6	< 0.8	< 0.4	< 0.4	< 0.3	<0.4
Thorium (Th)	18.6	9.1	19.1	20.5	16.0	11.2	16.2	18.2
Thulium (Tm)	< 0.9	< 2.5	< 0.8	< 0.8	< 0.7	< 0.6	< 0.7	<0.4
Tin (Sn)	< 236.8	< 238.6	< 180.0	< 142.4	< 129.8	< 109.7	< 113.7	<91.8
Titanium (Ti)	6812.0	5125.5	6500.0	4322.0	3401.5	3293.5	3279.5	5786.5
Tungsten (W)	< 2.2	< 2.9	< 1.7	3.7	4.0	< 1.2	< 2.8	<2.2
Uranium (U)	6.7	9.2	7.1	7.6	8.4	3.9	7.6	6.6
Vanadium (V)	187.2	155.6	188.6	107.6	51.9	77.8	118.9	156.7
Ytterbium (Yb)	3.7	2.4	4.1	3.8	2.4	1.9	3.4	4.0
Zinc (Zn)	< 72.4	< 98.0	< 70.9	< 68.7	< 57.6	< 55.9	< 61.2	<39.6
Zirconium (Zr)	322.2	< 291.7	< 239.0	334.7	242.4	< 147.3	< 201.2	185.6

* Detection Limit Indicated by "<"

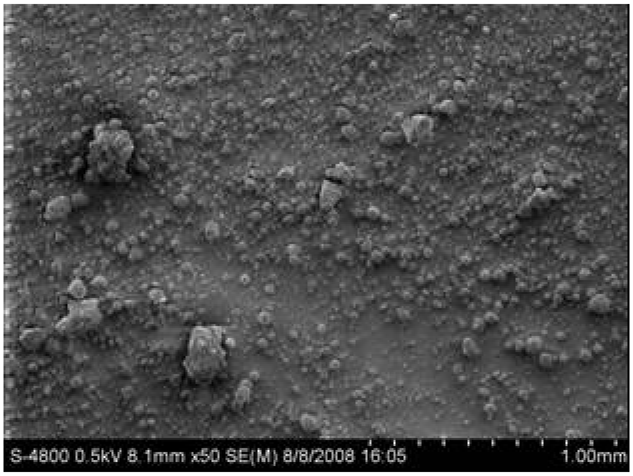
Sources 206 and 208 do not have as many spherical particles as Sources 204 and 205. However, Sources 206 and 208 particles are somewhat cleaner than Source 205. Therefore, cement-based construction materials made from Sources 206 and 208 may also lead to higher quality cement-based materials due to lower water demand compared with Source 205. However, Sources 206 and 208 do not have as many spherical particles as Sources 204 and 205; therefore, Sources 206 and 208 may require somewhat higher water for a given fluidity (i.e., workability or slump) for cement-based materials than Sources 204 and 205. Overall, Source 204 probably would perform better in cement-based construction materials compared to Sources 205, 206, and 208. It is interesting to note that the samples that appear to have the least amount of materials adhering to the spherical fly ash particles, Sources 206 and 208, also happen to be the most reactive and possibly better sources for use in cement-based materials.

Source 207 has fewer spherical particles than Sources 206 and 208 and it contains some irregular shaped particles (possibly due to deposit of the remainder of unreacted lime or limestone sorbent used). There are also clearly visible hydrated particles in Source 207, with some phases of crystalline products observable as well as possibly the presence of ettringite.

Source 209 has few spherical particles and many irregular shaped particles (possibly due to deposit of the remainder of unreacted lime or limestone sorbent used) and agglomerated fine particles along with spherical particles.

Source 210 has even fewer spherical particles than Source 209, but not as many irregular shaped particles as Source 209.

Source 221 is almost similar to Source 210 but not as clean as Source 210; deposits of fine particles weree observed.



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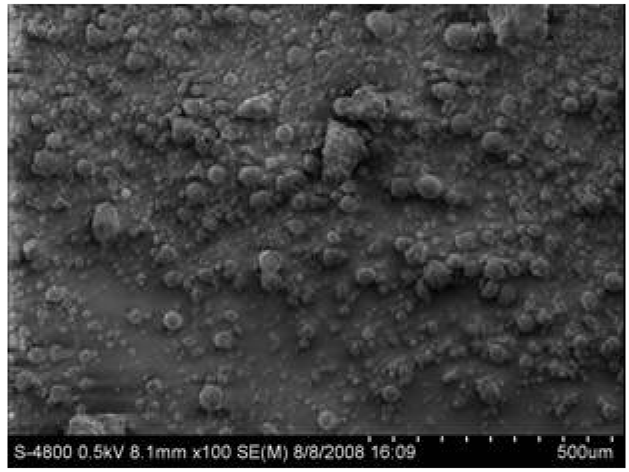

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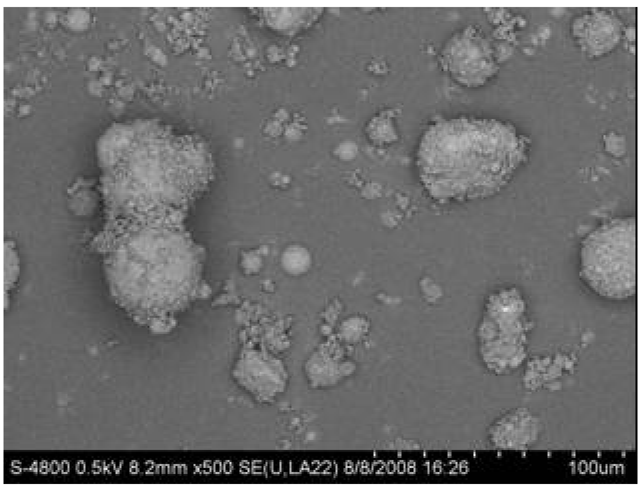

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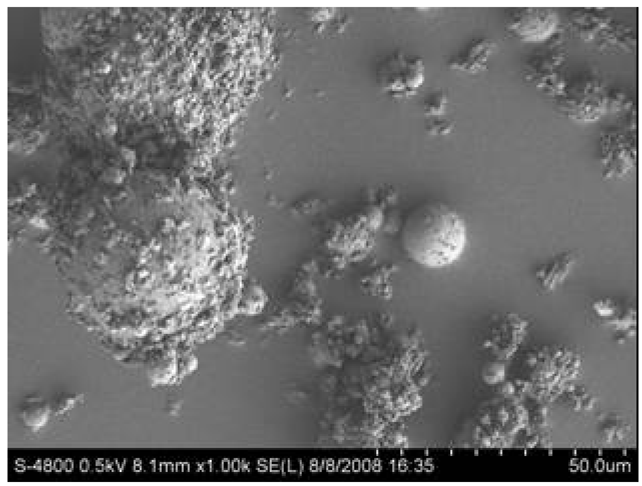

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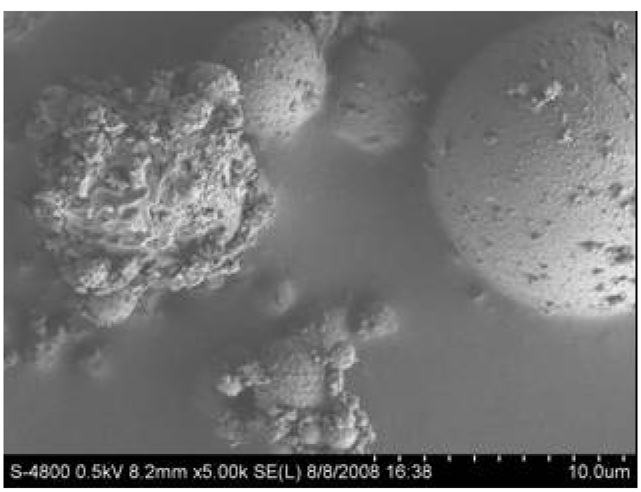
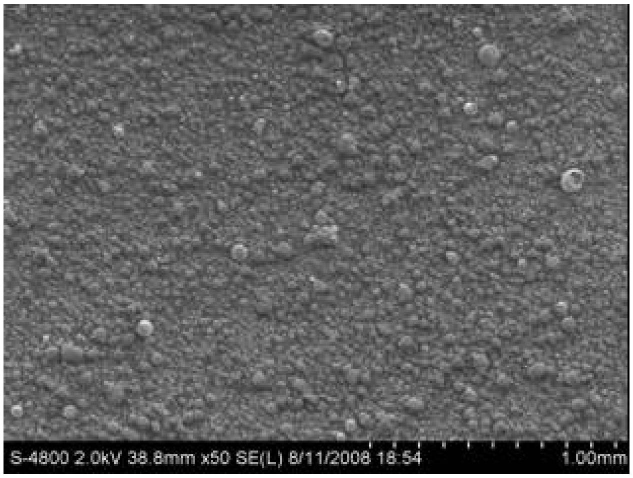


e) 5000x

Figure 3-1
SDA Sample 204: Electron micrographs at five levels of magnification



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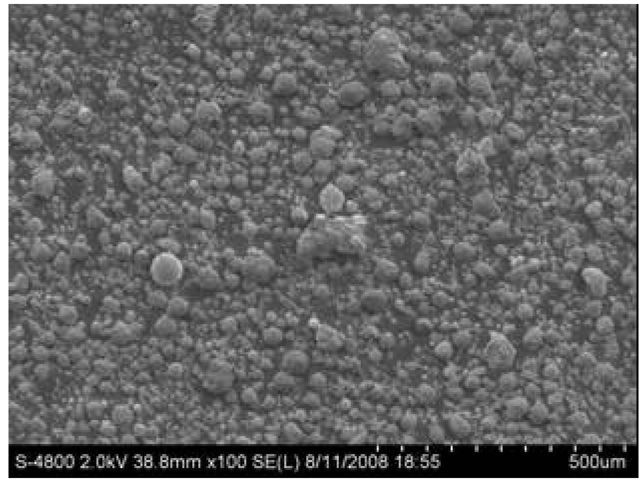

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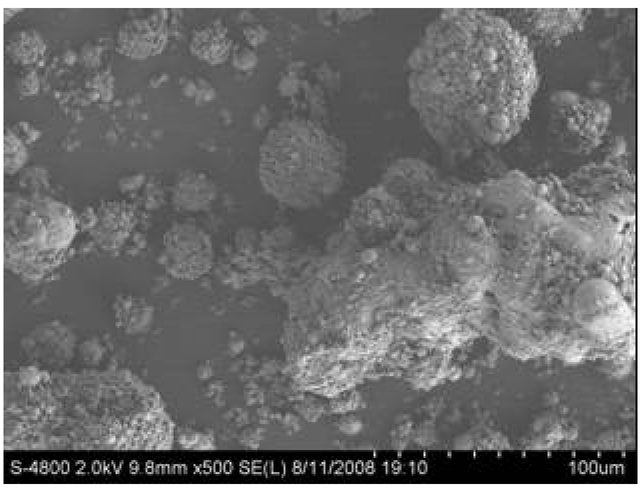

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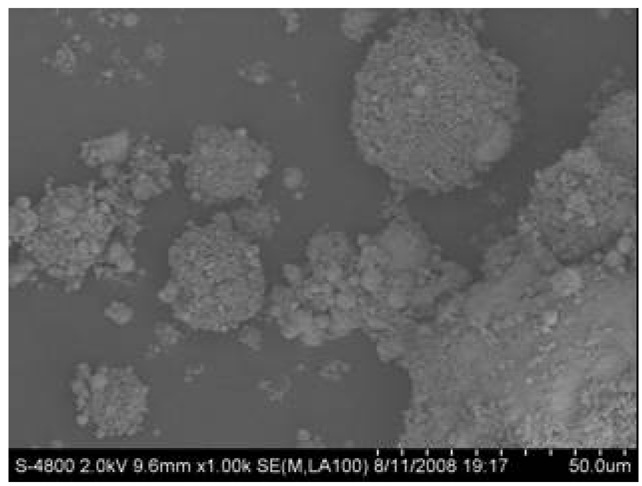

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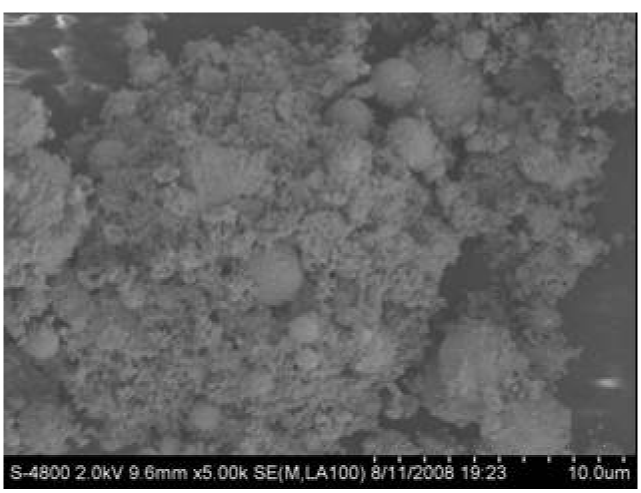

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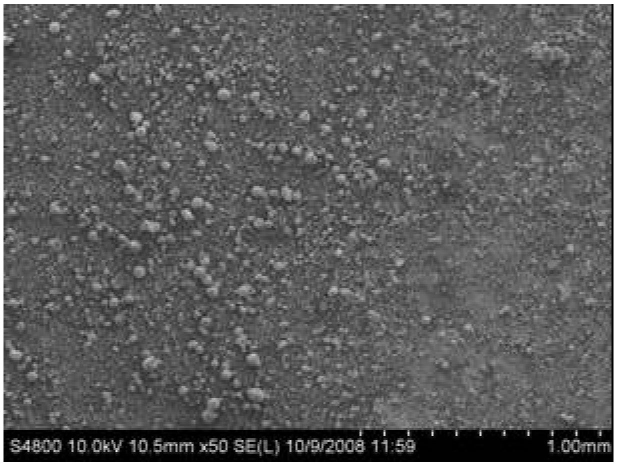
Figure 3-2
SDA Sample 205: Electron micrographs at five levels of magnification



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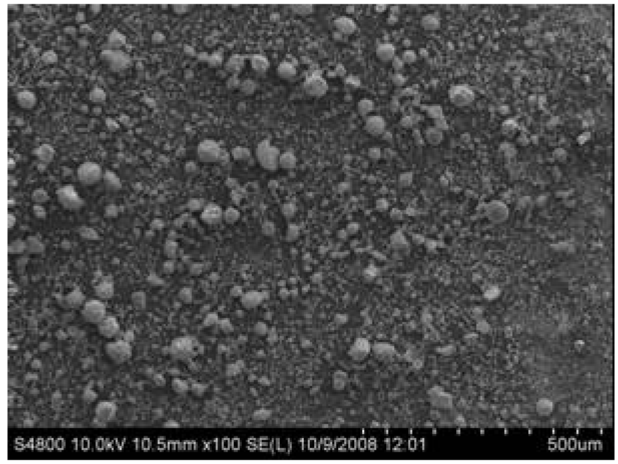

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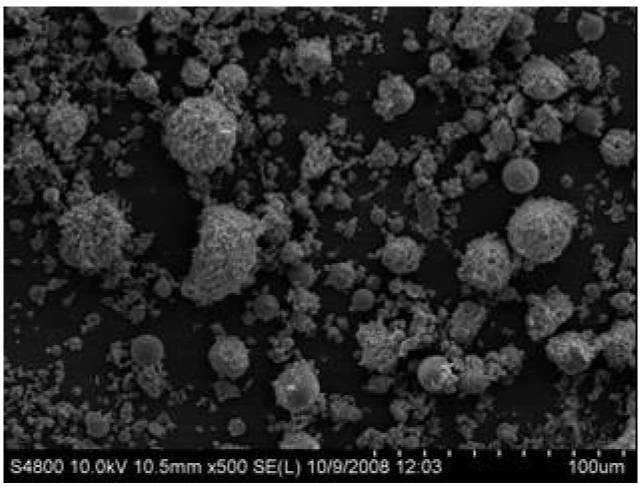

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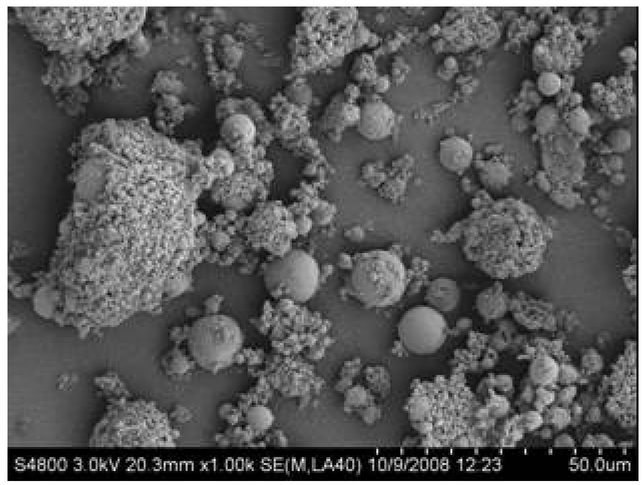

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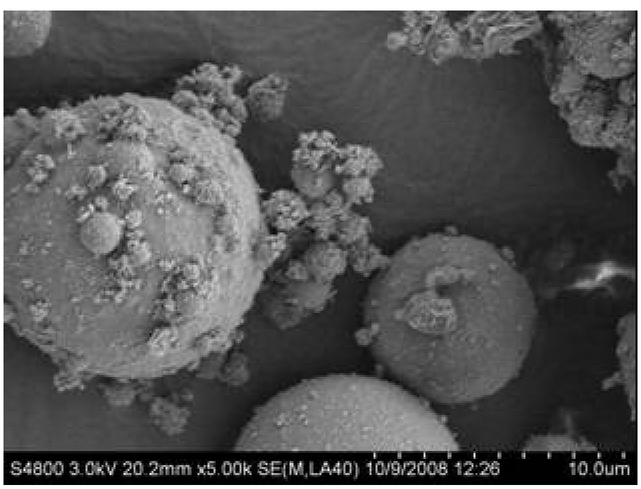
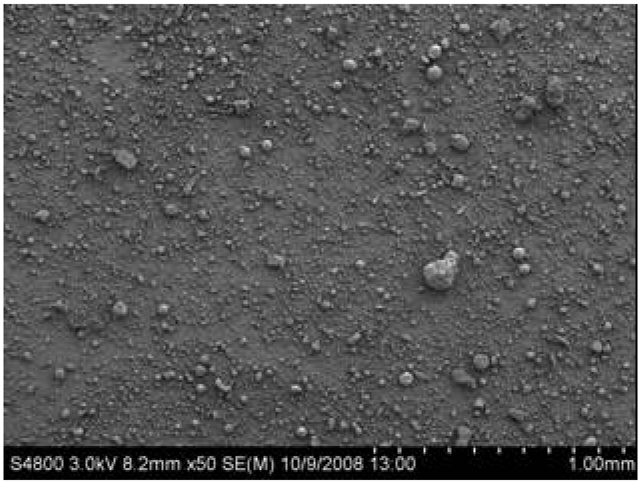


e) 5000x

Figure 3-3
SDA Sample 206: Electron micrographs at five levels of magnification



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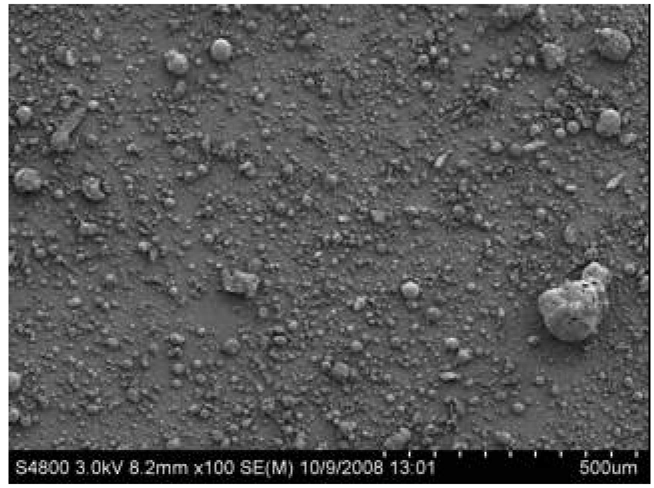

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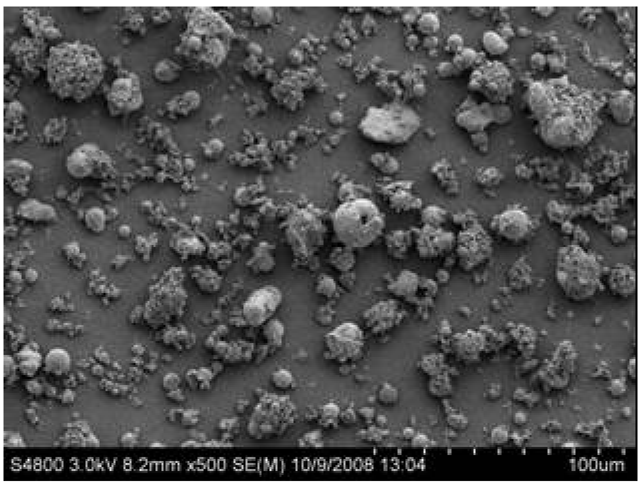

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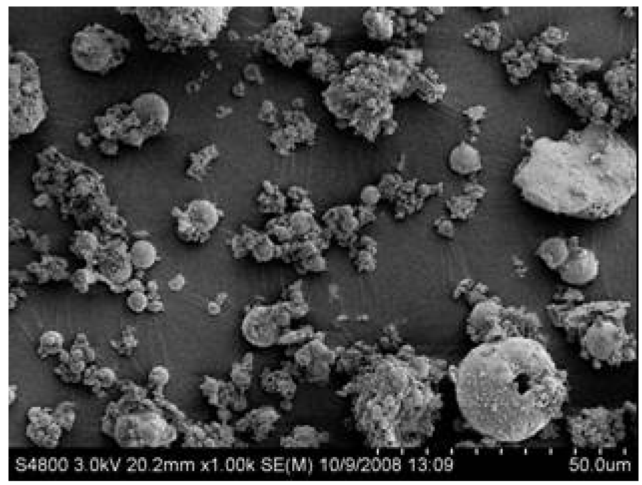

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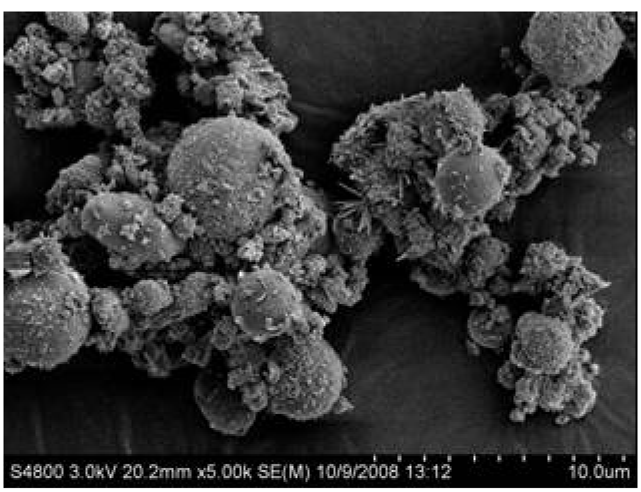
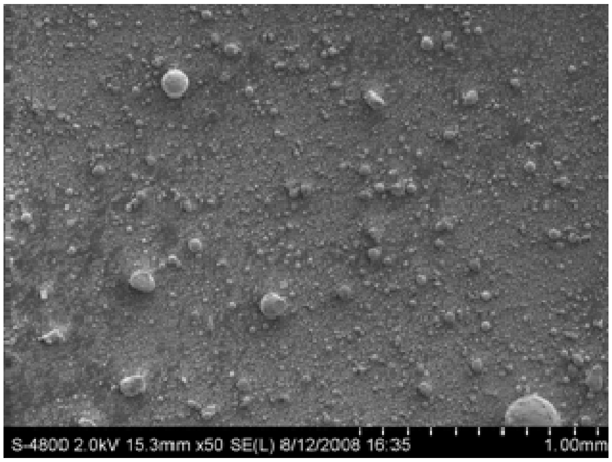


e) 5000x

Figure 3-4
SDA Sample 207: Electron micrographs at five levels of magnification



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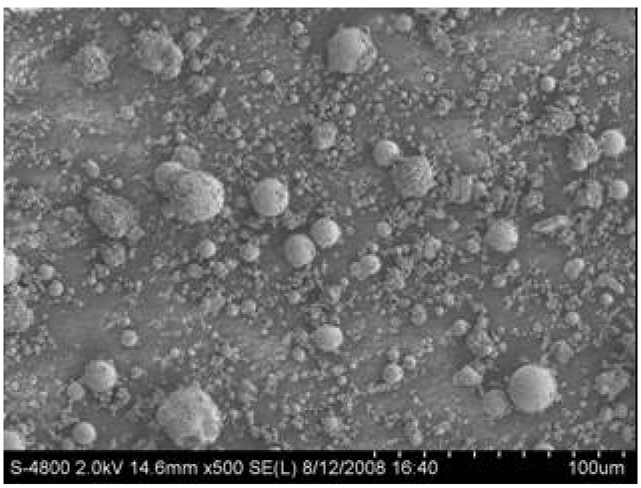
b) 100x



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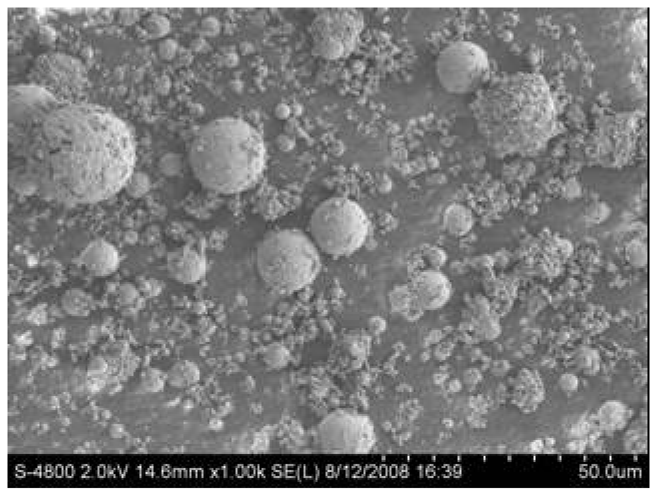

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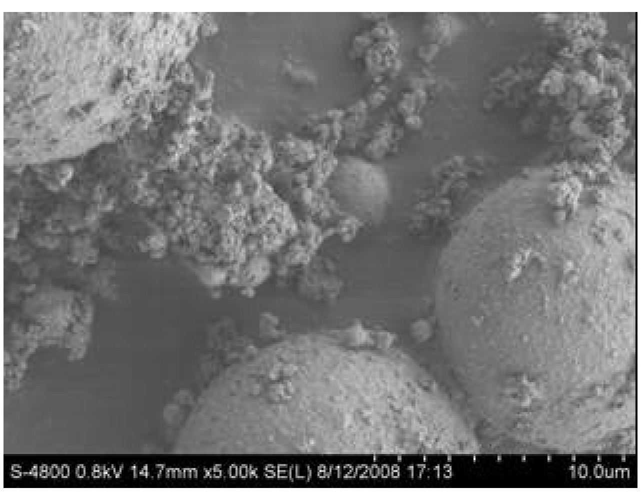
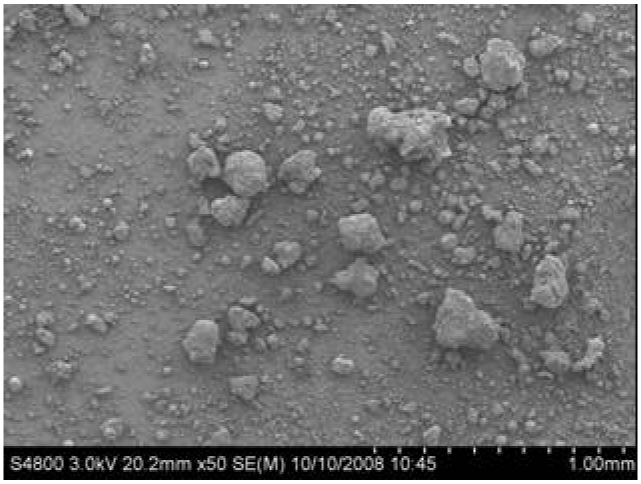


e) 5000x

Figure 3-5
SDA Sample 208: Electron micrographs at five levels of magnification



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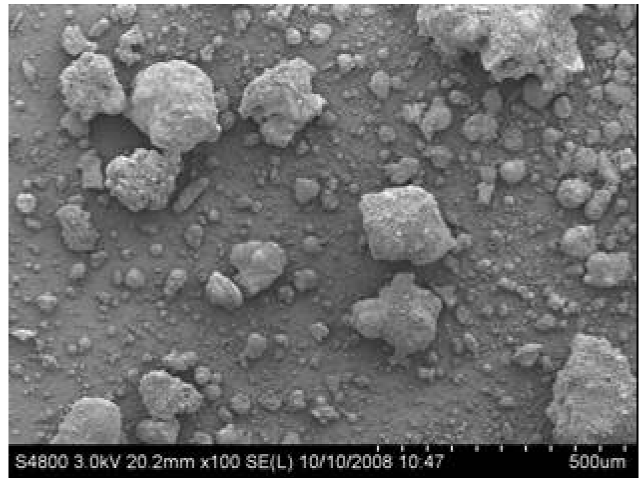

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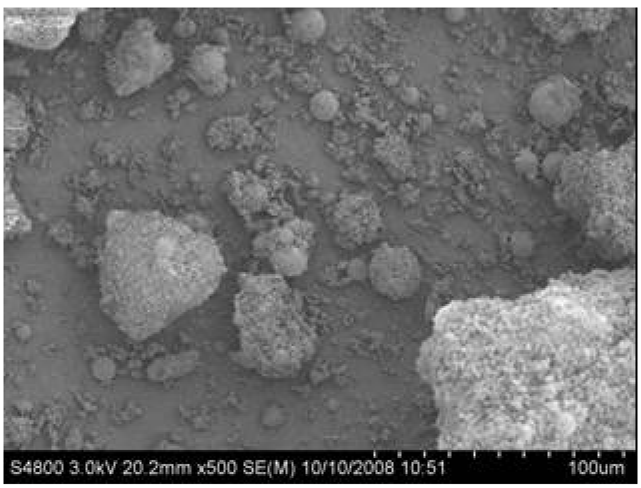

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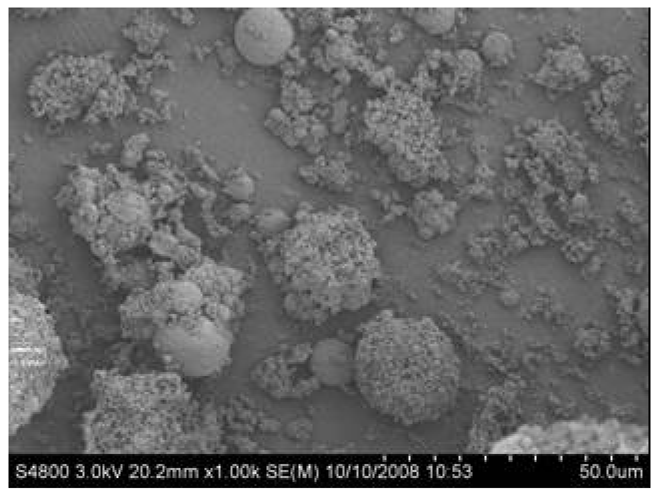

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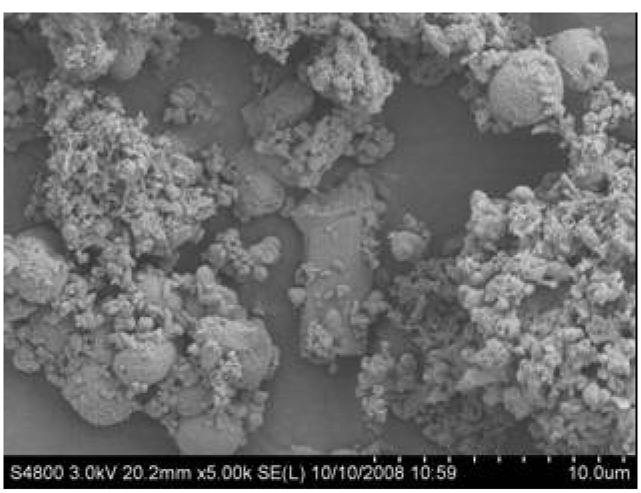
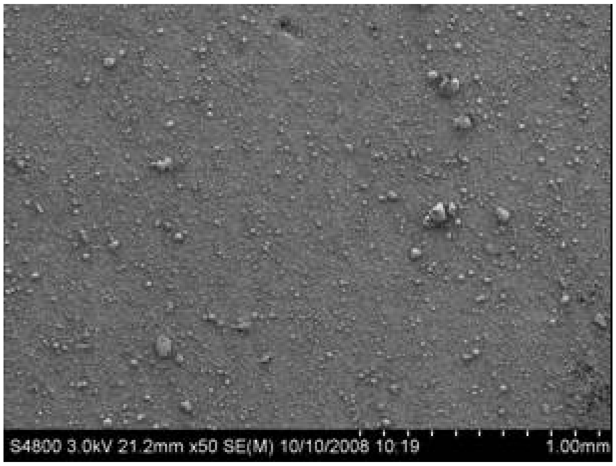


e) 5000x

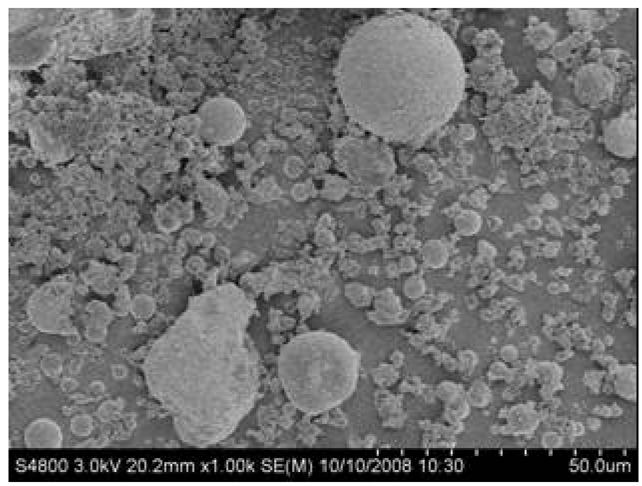
Figure 3-6
SDA Sample 209: Electron micrographs at five levels of magnification



a) 50x

b) 100x

c) 500x



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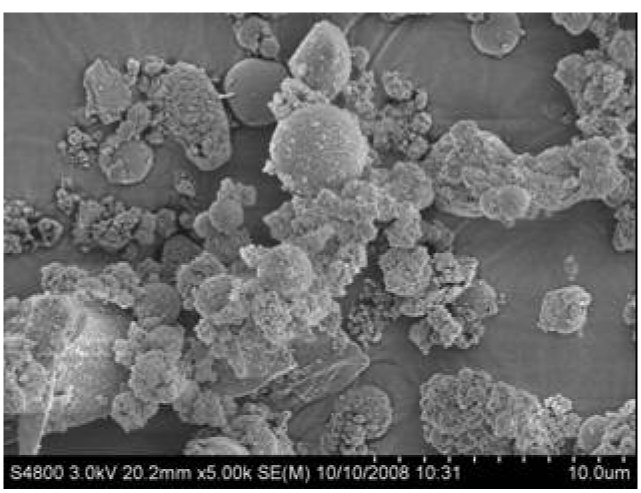
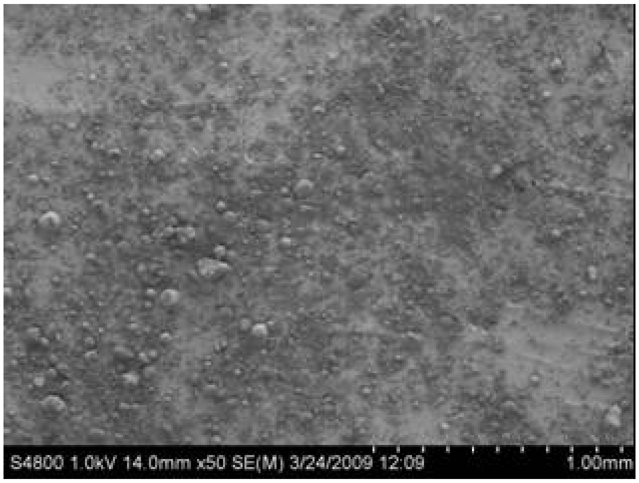


e) 5000x

Figure 3-7
SDA Sample 210: Electron micrographs at five levels of magnification



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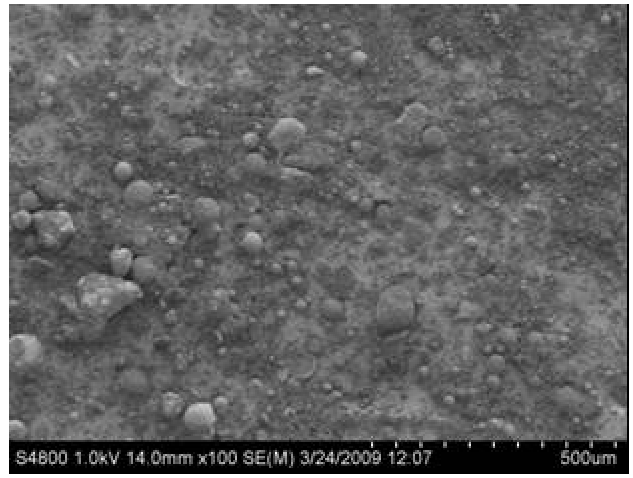

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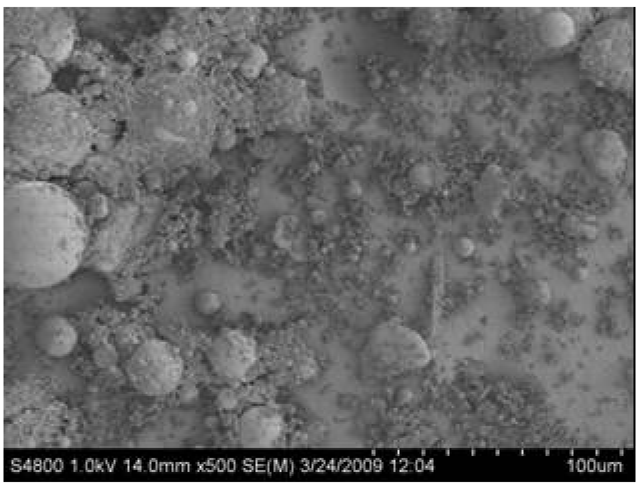

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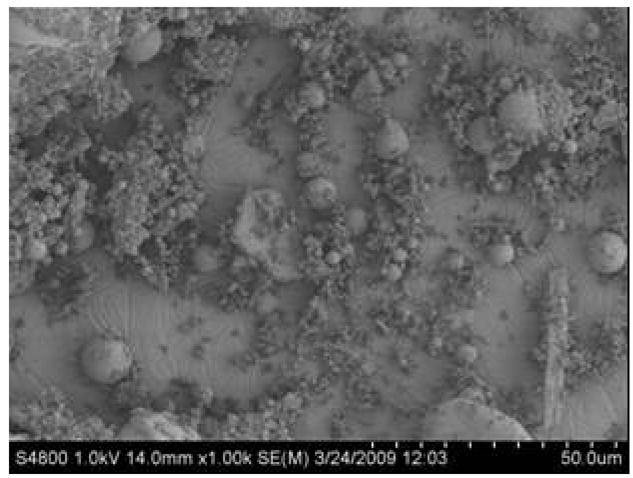

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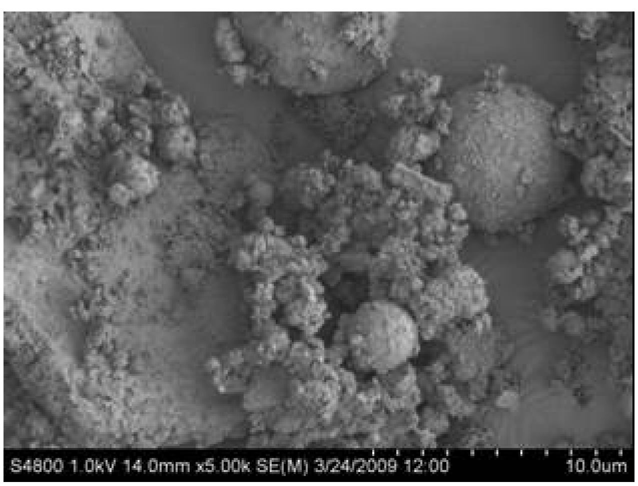

e) 5000x

Figure 3-8
SDA Sample 221: Electron micrographs at five levels of magnification

4
SUMMARY

There are many types of cement-based construction materials that can be manufactured using the SDA products discussed in this report. In the order of highest-value to lowest-value, the five types of cement-based construction materials are: Type 1 – structural-grade concrete, up to about 8,000 psi concrete, including bricks, blocks, and paving stones; Type 2 – medium-strength concrete, about 4,000 psi concrete, including bricks and blocks; Type 3 – low-strength concrete, less than 3,000 psi; Type 4 – flowable slurry mixture, which with appropriately late age could be crushed into making aggregates for base course and sub-base course for pavements for highways, roadways, and airfields, parking lots, and storage yards; and Type 5 – low-strength flowable slurry for filling voids and excavations.

Category 1: Sources 208 and 205 – potential for all five types (Types 1 through 5) of cement-based materials.

Category 2: Sources 207, 210, and 221 – potential for four types (Types 2 through 5) of cement-based materials.

Category 3: Sources 206, 204, and 209 – potential for three types (Types 3 through 5) of cement-based materials.

The eight SDA products tested show promise for applications in blended cement, mortar, and concrete applications. This initial selection (Categories 1, 2, and 3) was based on the physical, chemical, mineralogical, and microscopic properties obtained to date.

The most important next phase for evaluation of these SDA products is testing for setting and hardening, as well as expansion/shrinkage. After these data are collected, mortar and concrete mixtures need to be made to evaluate their performance for mechanical and durability properties as well as expansion/shrinkage characteristics.

5
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