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Uses of fly ash from New Mexico coals

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FIGURE 1—Coronado Generating Station, near St. Johns, Arizona, operated by Salt River Project. Coronado burns Menefee Formation coal from the McKinley mine, northwest of Gallup, New Mexico. Photo by Salt River Project Communications Services, ©SRP.

Abstract

New Mexico produced 26.7 million short tons (st) of coal in 1997. Two-thirds of this tonnage is delivered to three electrical generating stations in New Mexico. All but a small portion of the remaining production is shipped by rail to generating stations in Arizona (Fig. 1). New Mexico coals are high in ash content, from 13% to 27%, creating a significant amount of coal-combustion byproducts, most of which is fly ash. The use of fly ash from New Mexico is significant (1.59 million st), about 44% of the total fly-ash production (3.59 million st) in 1997. New Mexico coals produce Class F fly ash with a high silica and low calcium content. These characteristics make New Mexico fly ash a beneficial admixture for portland cement concrete, particularly in the Southwest where alkali-silica reactivity is a problem because of the type of aggregate available.

Pozzolanic materials

ASTM C618 defines pozzolans as siliceous or siliceous and aluminous materials that in themselves possess little or no cementitious value but will, in a finely divided form and in the presence of moisture, chemically react with calcium hydroxide in cement at ordinary temperatures to form compounds possessing cementitious properties.

Historic use

Both the Greeks and Romans were aware that certain volcanic deposits when finely ground and mixed with lime yielded a mortar that was superior in strength and resistant to the action of either fresh or salt water. The Greeks used pozzolanic volcanic tuff from the Island of Thera (Santorin). Later, this material was successfully used in concrete for lining the Suez Canal (Lohtia and Joshi, 1995). The Romans used volcanic tuff found in the Bay of Naples, but the preferred material was a zeolitic tuff from the foothills of Mount Vesuvius, quarried at Pozzvoli. Romans used pozzolanic material or substitutes throughout their empire. The Romans used pozzolans found in southeastern France along the Rhine River. In England, where a suitable pozzolan was not available, tile and brick or pottery was ground as a replacement. The Romans probably discovered a volcanic tuff in northern Europe called Rhenish Trass that is still used today as a pozzolan in portland cement.

Natural vs. artificial pozzolans

Natural pozzolans can be divided into two categories: (1) volcanic ash, called tuff when indurated, in which the amorphous constituent is a glass produced by rapid cooling of magma and (2) those derived from rocks or earth in which the silica is mainly opal, such as diatomite/diatomaceous earth. Calcination, depending on clay content, and/or grinding may be necessary for use as a pozzolan (Flechsig, 1990).

Volcanic pozzolans are composed of glassy, coherent tephra in tuffs formed by the deposition and compaction of volcanic dust and ash. Volcanic deposits may also be fragmentary and unconsolidated, such as the Italian pozzolans. Volcanic pozzolans are a mixture of silicates and often contain both glass and crystals. Through explosive disintegration of magma, gases are released that form vesicles, and the break down of vesicles produces glass shards that have greater surface area. The increased surface area enhances instability and susceptibility to weathering. The normal weathering end products of volcanic

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ash are clays and zeolites. Zeolites, formed by hydrothermal weathering of volcanic glass, also react with lime when finely ground.

Natural pozzolans used today are either made from tuffs that contain 50–100% rhyolitic glass or from diatomaceous earth, which is made up of siliceous skeletons of silica-secreting algae (diatoms). Diatomaceous earth is the most lime reactive of all the natural pozzolans. This reactivity is due in part to the large surface area of the complex individual diatoms. The main component of diatomaceous earth is amorphous, hydrated, opaline silica that contains 6–10% water. Diatomaceous earth generally contains clay minerals that need to be calcined to improve reactivity. Calcining at 1472–1652°F converts the crystalline structure of the clay minerals to an amorphous, disordered structure that has a higher degree of pozzolanic activity.

Artificial pozzolans include burnt clay and shale, burnt gaize, burnt moler, and pulverized fuel ash or fly ash. Although clay, shale, gaize, and moler are natural, their pozzolanic characteristics or activity are increased by calcination; therefore, they are considered artificial. Calcining is necessary to destroy existing crystal structure and to form an amorphous or disordered alumino-silicate structure. Both clay and shale are more common than other natural pozzolans and are often used. Gaize is a soft, porous, highly siliceous sedimentary rock that has been used particularly when the pozzolanic cement will be exposed to seawater. Moler is a Tertiary-age deposit of diatomaceous earth containing significant amounts of clay. These deposits are found on the island west of Limfjord, Denmark. Moler is also used in cement exposed to seawater.

Fly ash is a byproduct of burning finely ground coal either for industrial application or in the production of electricity. The largest producers of fly ash are electrical generating stations. Fly ash is taken out of the flue gas by electrostatic precipitators, baghouses, or mechanical collectors. The composition of fly ash is dependent on the coal that is burned and on the efficiency of the combustion process. The majority of fly-ash particles are spherical and glassy.

Coal-combustion products

Origin of ash in coal

Ash, the inorganic, noncombustible portion of coal, consists of minerals and rock particles. Minerals are introduced either during or after deposition of peat or during the coalification process.

Detrital minerals are transported into the swamp or bog by either water or air. Channels cutting through the swamp bring in water-born minerals. During flooding, large amounts of sediment may be transported into the swamp, resulting in partings in the peat and ultimately in the coal seam. Bioturbation at the base of the coal swamp may mix minerals into the peat. Windblown dust can be significant because of the slow accumulation of peat in the swamp environment. When swamps are downwind of volcanic activity, they may receive large amounts of volcanic ash periodically. Short-lived, widespread volcanic events may be preserved as a layer of volcanic ash called a tonstein, German for “claystone.” Minerals introduced by wind or water include most clays, quartz, feldspar, apatite, and heavy minerals such as zircon and rutile.

Authigenic minerals are also present in coals, forming during or after deposition or during the coalification process. Precipitated minerals may be finely disseminated particles or mineral aggregates in the coal. These minerals include siderite, pyrite, and chalcedony. During late stages of coalification, minerals precipitate along joints and in other voids in the coal. Minerals formed late include calcite, dolomite, pyrite, quartz, and various chlorides. During secondary coalification, at greater depths and temperatures, chlorite may form by alteration of primary clay minerals.

Most (95%) of the mineral matter present in coal is clay, pyrite, and calcite. Clay minerals make up 60–80% of the total mineral content of coal. The types of clay minerals are dependent on the chemical conditions at the site of deposition. Clays can be detrital or secondary precipitates from aqueous solutions. Fresh-water swamps tend to favor in situ alteration of smectite, illite, and mixed-layer clay minerals to kaolinite because of the low pH. Illite is dominant in coals with overlying marine sediments that have developed in a moderately alkaline environment. Clay minerals can be finely dispersed throughout the coal, or they can form layers, such as tonsteins, from volcanic ash. Tonsteins in coals usually contain kaolinite, smectite, and mixed-layer clay minerals.

Minerals or other noncombustibles can be introduced during mining. Small partings are often mined with the coal, and some of the roof and floor, above and below the coal seam, may also be mixed with the coal, no matter how careful the mining operation. This dilution will add to the total content of noncombustible material and ultimately to the ash byproduct.

Byproducts of the combustion process

Coal for electrical generation is finely crushed, typically in ball or roll mills, and air-fed into a 1,900–2,700°F combustion chamber where carbon immediately ignites. During coal combustion, the volatile matter vaporizes to off gas, and carbon burns to heat the boiler tubes. The inorganic material, coal ash, becomes molten and either remains in the combustion chamber as slag on the boiler tubes or is carried away by the flue-gas stream or falls through to the bottom of the boiler. The molten minerals, such as clay, quartz, and feldspar, solidify in the moving flue-gas stream as it leaves the combustion chamber. The rapid cooling and air movement give approximately 60% of the fly-ash particles a spherical shape. Some coarse particles settle to the bottom of the ash hopper, forming bottom ash, and some cling to the sides of the boiler tubes, forming boiler slag. The amount of bottom ash and boiler slag is a function of the ash-fusion temperature of the coal. Lower fusion temperatures increase the amount of bottom ash and boiler slag. Boiler slag is undesirable because it lowers the efficiency of the boiler tubes, so it is regularly removed by sootblowing.

The ratio of fly ash to bottom ash produced by coal combustion is dependent on the type of burner and the type of boiler. Pulverized-coal burners produce more fly ash than cyclone burners, and pulverized-coal burners are the most common for coal-fired electrical generation. Several types of

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FIGURE 2—Electrostatic precipitators in foreground. Coal stockpile in background and conveyor system on right side of photo. Coronado Generating Station, St. Johns, Arizona.

pulverized-coal burners are used, and the amount of fly ash, which varies with firing method, ranges from 65% to 85%. Wet-bottom boilers are designed to process more bottom ash than dry-bottom boilers. Fly ash is removed from the flue-gas stream by either electrostatic or mechanical precipitators. Mechanical precipitators are typically baghouses, cyclones, or venturi scrubbers.

Flue-gas desulfurization is necessary to remove SO_2 to meet Clean Air Act Amendment standards. Dry scrubbing, which occurs before fly-ash collection, contaminates the fly ash. The wet-scrubber process creates flue-gas desulfurization sludge, another coal-combustion byproduct. Most flue-gas desulfurization units use lime, limestone, quicklime, or soda ash as a reactant with SO_2. The resulting byproduct commonly is gypsum, but sometimes it is calcium sulfite.

Fly-ash collection

Fly-ash collection is necessary to remove particulates from the flue gas before it is released into the atmosphere. The different methods of fly-ash collection have different efficiencies. The electrostatic precipitators (Fig. 2) can be as much as 99+% efficient for overall fly-ash removal (Helmuth, 1987) and are the most commonly used anti-pollution device. The electrostatic precipitators collect the coarse fly ash (>44 µm) first. The finer material is collected later along the air-stream path. The fly-ash particles are collected by size in several hoppers (Fig. 3) along the length of the electrostatic precipitators. Baghouses use fabric filter-tubes or envelopes for capturing fly ash from the flue gas. Baghouses are very efficient for all size ranges (0–44 µm) with an overall efficiency of 99+% (Helmuth, 1987). Wet venturi scrubbers have about the same efficiency as baghouses. Generally mechanical precipitators are less efficient than electrostatic precipitators or baghouses, although high-efficiency cyclones can reach an overall efficiency of 85%. Mechanical precipitators are less efficient at removing particles in the 0–20 µm range.

Economic advantages of fly ash as a pozzolan

Because fly ash is a byproduct, it has some advantages over other artificial and natural pozzolans. The first benefit of fly ash is to the generating station, offsetting some of the coal cost by being a saleable product and reducing fly-ash disposal costs. It neither requires calcining, nor does it have to be mined, thus reducing the energy typically needed to have a saleable product. Use of fly ash in cement, like most pozzolans, lowers the cost of the concrete and saves energy by replacing cement that would have to be purchased. The savings can be significant, as cement manufacturing is an energy-intensive process. Less calcining of limestone in the cement process is a benefit to the environment, reducing the amount of CO_2 generated. The emission savings are almost a 1:1 trade off by weight (Bob Kepford, pers. comm. 1999). The use of fly ash also lowers the need to mine materials for cement and reduces the cost for processing. A lesser benefit is the reduction of area needed for disposal of fly ash at power plants.

Characteristics of fly ash

Physical characteristics

Physical characteristics of fly ash include size, morphology, fineness, and specific gravity. Fineness is usually determined by the percentage of the ash retained on a 45-µm (325-mesh) sieve; ASTM C618 requires that no more than 34% of fly ash be retained. Size distribution can be quite variable, depending on the type of precipitator, and size can vary with coal even when it is from the same source.

Fly-ash particles consist primarily of glass spheres (often hollow) and spongy masses (Fig. 4). A large fraction of the particles are less than 3 µm in diameter, but the average size is 7–12 µm. Low-calcium fly ash tends to contain smooth spherical particles because of the lower proportion of surface deposits consisting of lime and alkali-sulfate impurities (Lohtia and Joshi, 1995). Higher-calcium fly-ash particles display a more uneven surface, pitted by the lime and alkali sulfates. Some of the spheres may be hollow and empty (cenospheres, Fig. 5) or may be packed with smaller spheres (plerospheres, Fig 6), depending on the burning and cooling conditions. Cenospheres may contain nitrogen or CO_2 and tend to float on disposal ponds, presenting a pollution problem when the wind blows. Cenospheres are produced more often from high-fusion

FIGURE 3—Ash hopper at the bottom of an electrostatic precipitator and ash conveying line. Coronado Generating Station, St. Johns, Arizona.

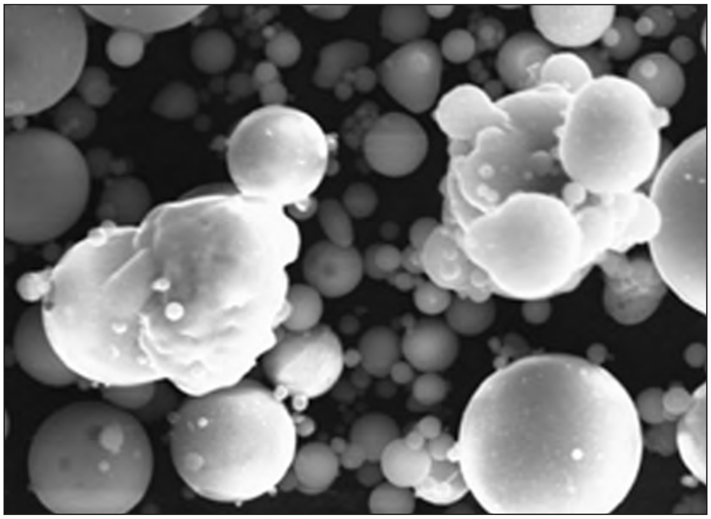

FIGURE 4—Secondary electron image of fly ash with glass spheres and masses. End product from Phoenix Cement, Cholla Generating Station. Field of view = 42 µm.

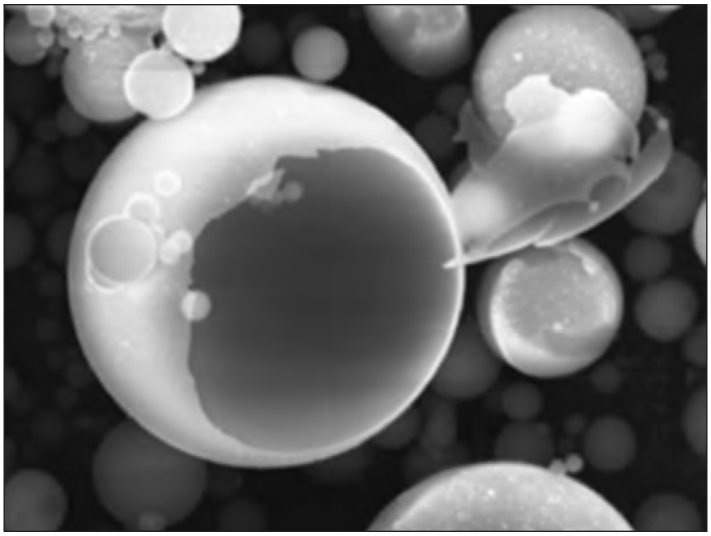

FIGURE 5—Cenosphere in fly-ash product from Phoenix Cement, Cholla Generating Station, as shown in secondary electron image. Field of view = 24 µm.

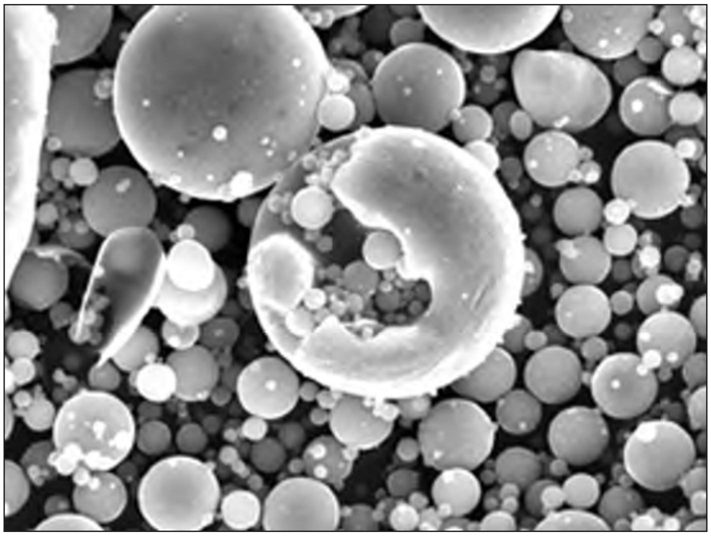

FIGURE 6—Plerosphere in ash from Coronado Generating Station, as shown in secondary electron image. Field of view = 54 µm.

coals (2600+°F) and coals with greater than 5% Fe_2O_3. The Fe_2O_3 provides the sole source of oxygen for expansion of molten silicate particles by reaction with dispersed carbons (Torrey, 1978, p. 354) to form CO_2. Fisher, Chang, and Brummer (1976) found the plerospheres more often in fly ash from western U.S. coals. A study by Carpenter, Clark, and Su (1980), specifically done to verify the presence of plerospheres, found, after crushing, intact spheres that did not contain smaller spheres. Only those spheres cracked or punctured before crushing contained smaller spheres. Their findings indicate that the smaller spheres were drawn into the larger spheres after they were cracked, which could have happened during collection in the precipitators.

Specific gravity of fly ash is related to chemical composition, color, and shape of the particles. Because of the variation in coal and its minerals, this number can be quite variable. The specific gravity can increase with the presence of opaque spherical magnetite or hematite particles if they are present in sufficient quantity. These materials, along with unburned carbon measured as loss on ignition (%LOI), affect the color of the fly ash. With larger quartz and mullite ($3Al_2{\cdot}2SiO_2$) content, the specific gravity will decrease. Grinding fly ash may release some volatiles trapped inside the spheres, increasing the specific gravity. Fly ash with a large fraction of low-density particles is more reactive than fly ash with higher-density particles having iron impurities. Pozzolanic reactivity is dependent on the amount of glass present with low specific gravity.

Chemical composition

Chemical constituents of fly ash are reported as oxides. These oxides are silica, SiO_2; alumina, Al_2O_3; calcium, CaO; iron, Fe_2O_3; magnesium, MgO; titanium or rutile, TiO_2; sulfur, SO_3; sodium, Na_2O; and potassium, K_2O. SiO_2 and Al_2O_3 make up 60–70% of the total ash, in some, but not all fly ashes. LOI is an indicator of unburned carbon, which is reported as a percent. The amount of unburned carbon is partly dependent on the degree of coal pulverization, rate of combustion, and air-fuel ratio as well as the type and source of the coal (Lohtia, and Joshi, 1995). Low NO_x burners tend to increase the unburned carbon and %LOI in the ash.

Trace elements in fly ash are dependent on the characteristics of the coal and the combustion process. According to Ray and Parker (1978) the distribution of major elements is about equal in the fly and bottom ash, but for some trace elements, a definite partition of elements occurs. Most authors cite a three-group classification of trace elements. Group 1 consists of elements equally concentrated in the bottom ash and fly ash. Elements in this group do not volatilize easily at coal-combustion temperatures and form bottom and fly-ash particles on which more volatile elements condense. Group 2 constitutes the elements that volatilize in the combustion chamber but condense downstream and are concentrated in the fly ash. Group 3 contains the volatile elements that remain in the gas phase during passage through the plant and are discharged to the environment with the flue gas. These groups can overlap, so Group 2 can be large and variable, depending on the coal being burned. Most studies include As, B, Be, Cd, Cu, Mo, Ni, Pb, Sb, Se, U, V, Zn, Ni, U as trace elements concentrated in the fly ash. Many of these elements have very low solubility in the ash matrix (Debra Pflughoeft-Hassett, pers. comm. 2000). Using fly ash in cementitious material can reduce the solubility of potentially toxic elements, by both chemical and physical mechanisms, and prevent them from leaching into the ground water (Bryggman and Nallick, 1993). In 1980 the EPA did an in-depth study of the utilization and disposal of fly ash on human health and the environment under the Resource Conservation and Recovery Act (RCRA). Their report to Congress recommended classification of pure stream fly ash, bottom ash, boiler slag and flue-gas desulfurization material as nonhazardous (Bevill Exemption). Individual states are left with the responsibility to develop solid-waste programs that address the concerns associated with specific coal byproducts (EPA, 1988). In early 2000 the EPA reconsidered this decision. On April 25, 2000, the EPA decided to not reclassify coal-combustion byproducts as a hazardous substance. However, they do plan to develop national standards to address the material either disposed in landfills or used in mine reclamation.

Classification of fly ash

According to ASTM C618 that classifies fly ash for use as a mineral admixture in portland cement concrete, there are two classes of fly ash, C and F (Table 1). Class C normally results from burning subbituminous coal and lignite and Class F from the burning of bituminous coals. Lignite can produce either a Class F or Class C fly ash. This definition is very broad and has exceptions. The significant difference between Classes C and F fly ash according to ASTM C618 is percent of $SiO_2 + Al_2O_3 + Fe_2O_3$. Fly ash not fitting within these two classes may be well suited for other applications such as soil and waste stabilization.

Class F fly ash with less than 10% CaO is considered low-calcium and is not self-hardening but commonly exhibits pozzolanic properties. Typically these ashes contain more than 3%LOI. Quartz, mullite, and hematite are major crystalline phases identified in North American Class F fly ash (Lohtia and Joshi, 1995, p. 675).

TABLE 1—Fly-ash chemical composition requirements according to ASTM C618. Complete ASTM C618 requirements are shown in Table 4.

Constituent	Class C	Class F
(SiO_2+Al_2O_3+Fe_2O_3) minimum %	50	70
CaO, maximum %	—	—
MgO, maximum %	—	—
SO_3, maximum %	5.0	5.0
Available alkali as Na_2O, maximum %	1.5	1.5
LOI, maximum %	6.0	6.0
Free moisture, maximum %	3.0	3.0

Class C fly ash containing more than 15% CaO is classified as high-calcium fly ash. Class C fly ash is derived typically from Wyoming and Montana subbituminous coals and some North Dakota and Gulf Coast lignites. In general, the higher CaO content indicates a higher degree of self-hardening. The Class C fly ashes have very low LOI of <1%. Crystalline phases of the Class C fly ash often include anhydrite, tricalcium aluminate, lime, quartz, periclase (MgO), mullite ($3Al_2 \cdot 2SiO_2$), merwinite ($Ca_3Mg\ [Si_2O_8]$), and ferrite (Lohtia and Joshi, 1995, p. 676).

Analyses of New Mexico fly ash

The amount of coal-combustion byproduct produced at each of the power plants varies, depending on the type of burners, precipitators, and the coal source (Table 2). New Mexico coals are ashy, varying from 13% to 27% ash content. Most New Mexico coals burned are subbituminous to high-volatile bituminous, so the fly ash normally would be Class C, but these coals produce low-calcium, low %LOI Class F fly ash, which is very desirable, particularly to counteract the alkali-silica reaction in concrete. In fact, New Mexico fly ash is considered high quality because of the very low %LOI and high SiO_2 content.

Table 3 shows typical fly-ash analyses from several of the New Mexico coal-fired generating plants with the ASTM C618 and New Mexico State Highway and Transportation Department specifications. The discussion that follows doesn't include Springerville analyses because this fly ash is contaminated by the dry scrubber system. This affects the SO_3 and CO_2 content of this fly ash and makes it unsuitable for use in concrete. For all of the analyses, the sum of SiO_2, Al_2O_3, and Fe_2O_3 is approximately 92% of the product. The %LOI varies but is less than 1% for all of the analyses, and for the majority it is <0.5%. The calcium content is <4% CaO, except for the analyses from the Escalante plant. The SO_3 content is very low in all the other samples, which is important because expansion and cracking in concrete is partly attributable to soluble sulfates and alkalis in the mineral admixture, in this case fly ash. The lower the SO_3, the less likely ettringite (calciumaluminosulfate) is to form (Malhotra and Mehta, 1996). The low Na_2O percent is favorable for using with reactive aggregate to avoid alkali-silica reaction and early disintegration of concrete.

Free moisture is a concern in fly ash because wet fly ash is difficult to handle. Moisture also causes the anhydrous constituents to become partly hydrated and lose their reactivity.

The percent retained on the 325 sieve (fineness) varies in New Mexico fly ash. The highest percent retained is from the San Juan Generating Station, which burns coals from the San Juan mine and particularly from the La Plata mine, both high-ash coals from the Fruitland Formation (Table 2). The percent retained on the 325 sieve represents the fly ash that is rejected for use in cement because it is considered too coarse to be reactive as a pozzolanic material.

Strength activity index (Table 3) indicates the pozzolanic activity of the fly ash by an accelerated test. All of the New Mexico analyses meet or exceed the ASTM minimum. Water requirement sets a maximum limit on the water required to obtain a standard consistency of portland cement-fly ash mixtures (Malhotra and Mehta, 1996). Water requirements are influenced by the grain size of the material and %LOI. The maximum for ASTM C618 is 105%; all of the New Mexico analyses are under this requirement, although the San Juan Generating Station fly ash is close to the maximum.

The ASTM sets a maximum limit on expansion in a test for soundness using a portland cement-fly ash mixture that is subjected to an autoclave. This test originally was developed for the evaluation of soundness of portland cements that show excessive expansion and cracking when MgO (periclase) or free CaO (lime) is present. Class F fly ash generally does not contain much of these two oxides, therefore this test serves no real purpose.

The last section in Table 3 deals with the effect of adding fly ash to portland cement concrete to counteract alkali-silica reactivity. ASTM C441 methodology determines the effectiveness of mineral admixtures in preventing excessive expansion caused by reaction between aggregates and alkalies (sodium and potassium) in portland cement mixtures. The reduction of mortar expansion is measured by the difference in expansion between high-alkali cement and high-alkali cement with fly ash. A control bar is made of the high-alkali cement and set in a controlled environment for 14 days. The expansion of the bar is then measured. Another bar with the high-alkali cement (300 g) plus fly ash with an absolute volume equal to the absolute volume of 100 g portland cement is made and placed in a controlled environment and measured for expansion at the end of 14 days. The percent difference of expansion is reported. These analyses (Table 3) show that the reduction of mortar-bar expansion is 65% or greater with New Mexico fly ash, a significant decrease. The second set of data in this section also follows ASTM C441, but low-alkali (LA) cement from the Tijeras cement plant, west of Albuquerque, New Mexico, was used as the control. The results with the Tijeras control are reported as 100% minus the %reduction in mortar-bar expansion with the fly ash. The expansion of the mortar bar with just Tijeras cement is about half of the percent expansion of the high-alkali cement mortar bar (Dale Diulus, Phoenix Cement, pers. comm. 1999).

The ASTM C618 standards are considered too lenient for the current market. These standards allow for a large amount of variability within in a type while still meeting ASTM standards. This has led to poor and variable results in concrete and has made many ready-mix concrete plants leery of using fly ash as an admixture. The key to creating confidence in fly ash as an admixture in concrete is to maintain a consistent product through testing and tighter classification between F and C fly ash.

Quantitative electron microprobe analyses on samples from the Cholla and Coronado generating stations indicate distinctive constituents within the fly ash. The majority of the spheres in the fly ash are essentially glass, possibly mullite. These spheres have ≥ 65% SiO_2, ≥ 20% Al_2O_3, 2–5% FeO, and minor amounts of Na_2O, K_2O, TiO_2, CaO, and MgO. Some of the spheres may be pyroxenes with approximately 30% SiO_2, ≥ 20% Al_2O_3, and > 20% FeO. These particles tend to be very bright in backscattered electron images because of the high iron content. The globular material (see Fig. 4) is essentially all SiO_2 (97–98%). Perhaps these are quartz fragments that never completely melted during the coal-combustion process.

Uses of coal-combustion byproducts

The American Coal Ash Association compiles statistics on the use of coal-combustion products in the United States (Table 4). Among the coal-combustion byproducts, fly ash has the most applications. In 1997, 60.26 million st of fly ash was produced in the U.S., and 19.32 million st was used. Cement, concrete, and grout are the biggest markets for fly ash (9.42 million st). Waste stabilization and structural fill are next in tonnage of fly ash used (3.12 million st and 2.88 million st). A large percentage (30%, 5.1 million st) of bottom ash is also used, and a large amount of the total bottom-ash usage is in structural fill (1.38

TABLE 2—New Mexico 1997 coal receipts and quality burned at Arizona and New Mexico electrical generating stations with statistics.

						Average coal quality[1]											
State	Company	Plant	Coal source	Sale	Receipts (1,000 st)[1]	Btu/ lb	Sulfur (% by wt)	Ash (% by wt)	Unit Id[2]	Unit type[2]	Summer capacity (megawatts)[2]	Year of commercial operation[2]	Precipitator type	% Efficiency	Receipts x % ash	% Fly ash of total ash[3]	Tons of fly ash based on ash content (1,000 st)[3]
Arizona																	
	Arizona Electric Power Coop.	Apache	McKinley	Contract	775.00	9,930	0.44	13.3							103.08		
									2	ST	175	1979	Electrostatic	97%			
									3	ST	175	1979	Electrostatic	97%			
										Total	350			97%		80%	*79.99*
	Arizona Public Service	Cholla	McKinley, Lee Ranch (10%)	Contract	1,928.00	9,926	0.44	13.44							259.12		,
				Spot	1,259.00	9,549	0.42	13.70							172.48		
									1	ST	110	1962	Mechanical	60%			
									2	ST	280	1978	Mechanical	60%			
									3	ST	280	1980	Electrostatic	97%			
		Unit owned by Pacificorp.							4	ST	420	1981	Electrostatic	97%			
										Total	1,090			84%		80%	*288.65*
	Salt River Project	Coronado	McKinley	Contract	1,400.00	9,949	0.44	13.56							189.84		
				Spot	695.00	9,718	0.44	14.74							102.44		
									CO1	ST	411	1979	Electrostatic	97%			
									CO2	ST	411	1980	Electrostatic	97%			
										Total	822			97%		80%	*226.81*
	Tucson Electric Power	Springerville	Lee Ranch	Contract	3,212.00	9,315	0.71	17.36							557.60		
									1	ST	400	1985	Dry scrubber prior to baghouse	97%			
									2	ST	400	1990	Same as 1	97%			
										Total	800			97%		80%	*432.70*
Arizona total					**9,269.00**												**1,028.15**
New Mexico																	
	Arizona Public Service	Four Corners	Navajo	Contract	7,848.00	8,836	0.78	21.83							1,713.22		
									1	ST	170	1963	Wet venturi	99%			
									2	ST	170	1963	Wet venturi	99%			
									3	ST	220	1964	Wet venturi	99%			
		Multiple ownership							4	ST	745	1969	Baghouse	99%			
		Multiple ownership							5	ST	745	1970	Baghouse	99%			
										Total	2,050			99%		80%	*1,356.87*
	Plains Electric Generation & Transmission Coop. Inc.	Escalante	Lee Ranch	Contract	1,071.00	9,177	0.71	17.91							191.82		
									1	ST	235	1984	Baghouse	99%			
										Total	235					80%	*151.92*
	Public Service of New Mexico	San Juan	San Juan & La Plata	Contract	6,856.00	9,319	0.87	24.46							1,676.98		
		PNM & TEP							1	ST	316	1976	Electrostatic	97%			
		PNM & TEP							2	ST	312	1973	Electrostatic	97%			
		Multiple ownership							3	ST	488	1979	Electrostatic	97%			
		Multiple ownership							4	ST	498	1982	Electrostatic	97%			
										Total	1,614			97%		65%	*1,057.33*
New Mexico total					**15,775.00**												**2,566.12**
AZ and NM total					***25,044.00***												***3,594.27***

[1] Cost and Quality of Fuels for Electric Utility Plants 1997 Tables, Energy Information Administration, May 1998, Table 30, unpublished tables. Web Site http:/www.eia.doe.gov/cneaf/electricity/cq/cq_sum.html.

[2] Inventory of Power Plants in the United States as of January 1, 1998, Energy Information Administration, December 1998, DOE/EIA-0095(98) Tables 20 and C1. ST= Steam-turbine boilers.

[3] Wet-bottom boilers—65%, Dry-bottom boilers—80%.

TABLE 3—Typical New Mexico fly-ash analyses

		APS–Cholla–McKinley+Lee Ranch	SRP–Coronado–McKinley	TEG–Springerville–Lee Ranch	APS–Four Corners–Navajo	PEG–Escalante–Lee Ranch	PNM–San Juan–San Juan+La Plata	ASTM C618 specs. Class F/C	NM State Highway and Transportation Department specs. Class F/C
Chemical analyses									
Ashed oxides, %	SiO_2	65.00	61.11	51.41	63.01	62.80	63.91		
	Al_2O_3	21.85	24.57	19.81	24.86	24.60	24.41		
	Fe_2O_3	4.66	6.11	3.41	4.93	4.15	3.60		
	Total	91.51	91.79	74.63	92.80	91.55	91.92	***70/50 min***	
	CaO	3.02	3.71	12.19	2.01	4.99	3.03		***10/-[1] max***
	MgO	1.13	1.27	0.81	1.05	1.06	0.92		***5 max***
	SO_3	0.10	0.31	5.12	0.02	0.21	0.13	***5 max***	
	Moisture	0.07	0.04	0.73	0.16	0.11	0.15	***3 max***	***1 max***
	LOI	0.21	0.38	3.28	0.37	0.41	0.73	***6 max***	***3 max***
	Variation, % points from average	na	na	na	na	0.07			
Total alkalies, %	Na_2O	1.43	na	1.06	1.61	0.39	0.93	***6 max***	
	K_2O	1.35	na	0.98	0.97	1.07	0.81		
	Equivalent Na_2O_3					1.09			
	Ashed oxide analyses total	98.82	na	98.80	98.99	99.79	98.62		
Available alkalies, %	Na_2O	0.84	0.79	0.99	0.61	0.19	0.44	***1.5 max***	***1.5 max***
	K_2O	na	na	na	na	0.15			
Physical analyses									
	Fineness, #325 sieve residue	14.20	20.50	na	13.70	27.40	31.40	***34 max***	
	Variation, % points from average	na	na	na	na	1.40	na		
	Density, g/cm³	2.15	2.15	na	2.07	2.14	1.98		
	Variation from average	na	na	na	na	0.47	na		
Strength activity index with portland cement	At 7 days, % control	81.00	82.00	na	87.00	78.40	81.00	***75 min***	
	At 28 days, % control	93.00	90.00	na	91.00	na	85.00	***75 min***	
	Water requirement, % of control	94.00	97.00	na	94.00	98.80	101.00	***105 max***	
	Soundness, autoclave expansion or contraction, %	-0.02	-0.02	na	-0.03	-0.01	-0.03	***0.8 max***	
Reactivity with cement alkalies, %[2]	Reduction of mortar expansion, %	65.00	71.00	na	65.00	na	na		
	Mortar expansion, % of LA Tijeras control	24.00	32.00	na	25.00	na	na	***100 max***	

[1] Fly ash meeting requirements of ASTM C618 and containing more than 10% CaO may not be used in concrete exposed to sulfate environments or with potentially reactive or known reactive aggregate.
[2] Determined in accordance with requirements of ASTM C441.

TABLE 4—Total coal-combustion product output and end use 1997 (in thousand st). Data from American Coal Ash Association, 1997.

	Fly ash	Bottom ash	Boiler slag	FGD	Total
Production	**60,265**	**16,905**	**2,742**	**25,163**	**105,075**
End use:					
Agriculture	35	8	0	56	99
Blasting grit/roofing granules	0	160	2,289	0	2,449
Cement/concrete/grout	9,422	605	11	202	10,240
Flowable fill	386	15	0	0	401
Mineral filler	286	131	109	0	526
Mining applications	1,414	163	0	105	1,682
Road base/subbase	1,418	1,287	1	18	2,724
Snow and ice control	0	724	56	0	780
Structural fills	2,878	1,384	85	1	4,348
Wallboard	0	0	0	1,604	1,604
Waste stabilization	3,118	206	0	15	3,339
Other	363	415	29	184	991
Total use	**19,317**	**5,097**	**2,579**	**2,183**	**29,176**
Percentage used	**32**	**30**	**94**	**9**	**28**
Total discarded	**40,947**	**11,808**	**163**	**22,980**	**75,898**
Percentage discarded	**68**	**70**	**6**	**91**	**72**

million st) and road base/subbase (1.29 million st). Some bottom ash is used as aggregate in concrete. Almost all boiler slag (94%) is used in the manufacture of blasting grit because of its considerable abrasive properties. Flue-gas desulfurization (FGD) material usage is minor (8.7%) in comparison to other coal-combustion byproducts. Most of the material is used in the manufacture of wallboard (1.60 million st). A lot of FGD material does not meet the purity specifications for wallboard without further processing. A small amount (200,000 st) of FGD material is used in the making of portland cement. FGD gypsum is a substitute for natural gypsum in these products. Most coal-combustion products are disposed of in ponds or landfills. Some power plants that are adjacent to the coal mine supplying the coal will return the fly ash to the mine for disposal in the pits or for use in reclamation. All disposal methods are regulated.

Use of fly ash

Cement, concrete

Fly ash added to cement improves many properties of concrete. The pozzolanic nature of fly ash adds a cementitious component to concrete, thus allowing replacement of cement and reducing the cost. Because of its spherical shape, fly ash acts like ball bearings and increases the workability of concrete to the point that the amount of fines in the aggregate can be decreased. It is a filler in that it reduces the total surface area to be coated with cementitious material. This characteristic can be advantageous when the aggregate is deficient in sand-size material (Lohtia and Joshi, 1995, p. 696). The addition of fine particles (1–20 µm) reduces the volume of voids in concrete mixes and lowers water use.

Setting time is a function of the type and amount of fly ash used. Low-calcium fly ash with high %LOI retards the setting time. High-calcium fly ash with low %LOI usually yields a much quicker setting time.

Heat of hydration is an exothermic reaction during hydration of portland cement. Adding fly ash to concrete reduces the exothermic temperature rise. As a rule of thumb, the percent reduction in heat liberation at 7–28 days is approximately one-half the percentage of fly-ash substitution for cement. Low-calcium (Class F) fly ash slows the rate of temperature rise more than high-calcium ash (Class C). Reduction of heat of hydration is particularly important in massive structures where the temperature increase becomes significant and can lead to cracking because of thermal stresses induced in hardened portions of the concrete mass.

Pozzolanic reactions occur after cement hydration begins when $Ca(OH)_2$ becomes available. By replacing a portion of the cement with fly ash, the rate of hydration is retarded and the pozzolanic reactions are manifested late in the aging process of the concrete. The fine-grained fly ash fills large voids. Formation of cementitious compounds by pozzolanic reaction causes pore refinement and reduces microcracking in the transition zone between the concrete and aggregate. This significantly improves the strength and durability of the concrete (Lohtia and Joshi, 1995). Because of retarded hydration, fly-ash concrete has low early strength. Strength increases over time and eventually meets and then exceeds the strength of concrete without fly ash.

Air-entrainment admixtures (AEA) are often used in concrete to enhance the frost resistance by increasing the void content of the cement. The addition of fly ash actually increases the demand for AEA. Class C fly ash (high-calcium) generally requires less AEA than Class F. The key point is the type of easily decomposed organic matter in the %LOI, which appears to increase the need for AEA. This increase can affect the amount of water used in the mixture as well.

Alkali-silica reactions (ASR) in cement are caused by the presence of reactive material in the aggregate, such as opal, chalcedony, siliceous shale, schist, and granitic gneiss. ASR occurs when silicate minerals react with alkali metal ions (Na_2O and K_2O) in portland cement paste to form gel. With moisture, the gel can swell and cause expansion and cracking of the concrete around the individual aggregate, resulting in pop outs. Fly ash is recognized as an effective way to control the ASR. The size of the fly-ash particles (0–45µm) and the pozzolanic action improve the packing of cementitious materials and reduce the permeability of the concrete. This reduces the ion migration and available moisture in the cement, increasing the resistance to ASR. Fly ash is also preferentially attacked by alkaline solutions (sacrificial silica), which protects the aggregate from ASR. The New Mexico State Highway and Transportation Department requires a 20% minimum of Class F fly ash when using aggregate that is reactive or that has the potential to be reactive (New Mexico State Highway and Transportation Dept., 1999).

Concrete in certain applications must resist chemical attack by seawater, sulfate-bearing ground water, or leaching by acidic waters. Fly ash often improves the resistance of the concrete to these chemical attacks by progressively consuming highly vulnerable $Ca(OH)_2$ through pozzolanic reaction. Again, pozzolanic activity reduces permeability, making it harder for the harmful chemicals to penetrate the concrete. Both Class C and F fly ash can be effective cement replacements for controlling sulfate attack. For more information on cement and concrete, see Austin and Barker (1998).

Other uses

Road construction. Fly ash, particularly high-calcium Class C fly ash, combined with lime can improve soils for roadway construction. This mixture can be substituted for more expensive material and can be used alone without the addition of other cementitious material. Fly ash can also be mixed with recycled pavement and used to create a new base course, particularly on secondary roads. This reduces the need for additional aggregate. Fly ash is used in roller-compacted concrete (RCC), which is a very stiff concrete that is laid with asphalt paving equipment. This type of concrete requires large amounts of fine aggregate, which can be substituted with fly ash. Fly ash increases the strength of RCC through its pozzolanic properties, lowers the cost, and does not require finishing. The low heat of hydration when fly ash is substituted for a portion of the cement is important for RCC because it is commonly used in large structures such as dams.

Structural fill. Fly ash has been used in embankments, highway shoulders, and as load-bearing structural fill. It is inexpensive and available in bulk, and it is easily

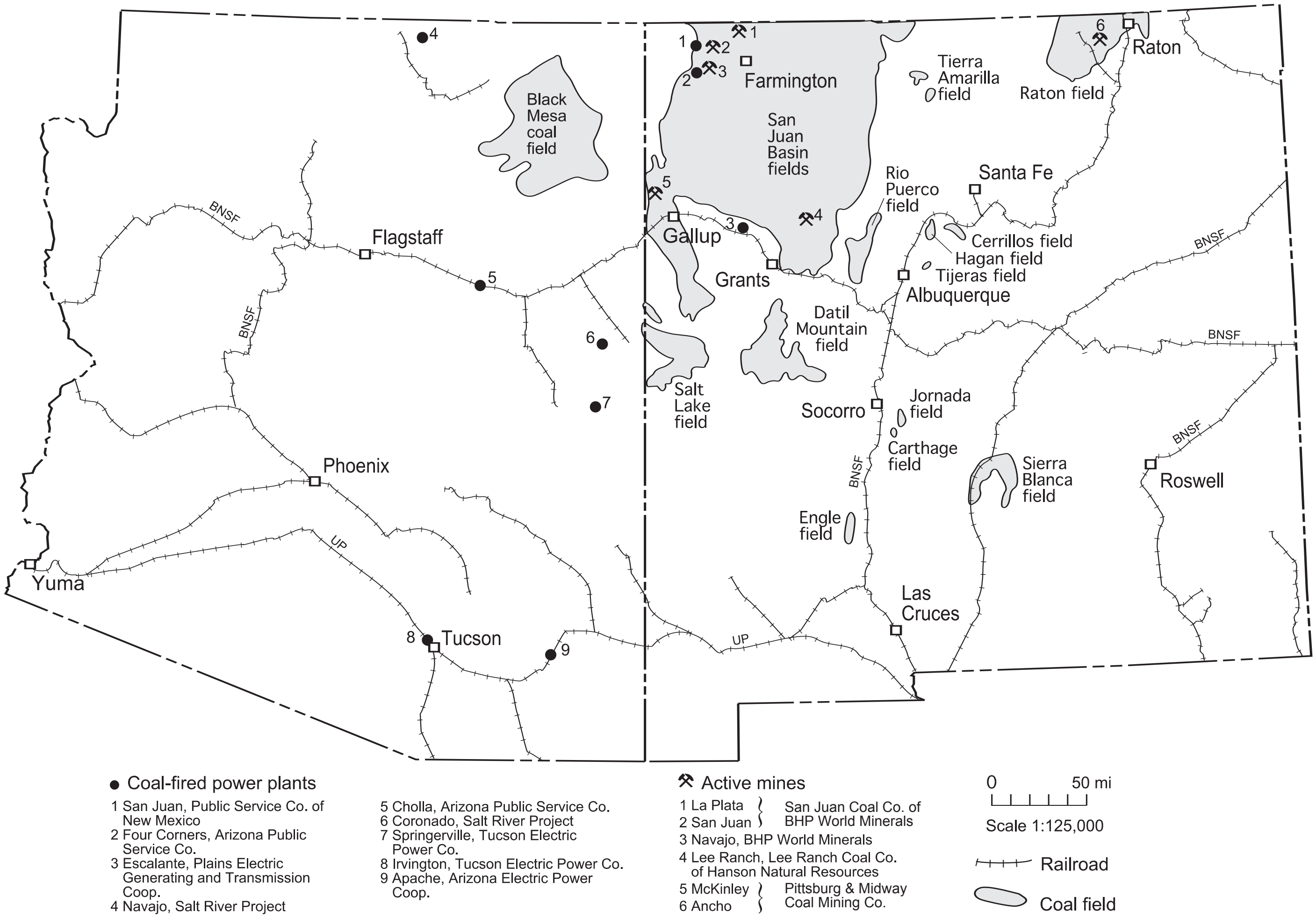

FIGURE 7—New Mexico coal mines and New Mexico and Arizona coal-fired power plants.

handled. The fly ash is compacted with normal construction equipment and shows little settling compared with conventional materials. This material has low-unit weight and is ideal for placement on low-bearing-strength underlying soils. Fly ash has relatively high shear strength for its unit weight, which makes it ideal for placement under building foundations (American Coal Ash Association, 1995). Two concerns must be addressed when using fly ash for these applications, dust control and preventing leaching by ground water.

Waste stabilization. Fly ash can be used to stabilize hazardous materials by solidifying them into an inert mass. Class C fly ash is more useful for this application and could help to offset the use of more costly lime.

Production of fly ash from New Mexico coals

New Mexico produced 26.77 million st of coal in 1997 from five surface operations (New Mexico Energy, Minerals, and Natural Resources Dept., 1998). Five of New Mexico's coal mines are in the San Juan Basin in the northwest part of the state (Fig. 7). The Raton Basin, in northeast New Mexico, has one operating coal mine. Most of New Mexico's coal is used to produce electricity. Four Corners, San Juan, and Escalante generating stations in New Mexico consumed 15.78 million st (Table 2) of coal from mines within the San Juan Basin (Fig. 7). Apache, Cholla, Coronado, and Springerville generating stations consumed 9.27 million st of San Juan Basin coal (Fig. 7). Approximately 1.5 million st is mined annually in the Raton Basin, and 523,000 st is shipped by rail to a Wisconsin utility. The remaining coal production is sold to small industrial plants.

New Mexico's coals are Late Cretaceous to Paleocene in age and are generally low-sulfur, subbituminous to high-volatile bituminous in rank. The San Juan Basin in northwest New Mexico has three Late Cretaceous coal-bearing sequences: the Crevasse Canyon, Menefee, and Fruitland Formations. Three of the five mines (Navajo, San Juan, La Plata; Fig. 7) in the San Juan Basin are mining Fruitland Formation coals. The McKinley mine, north of Gallup, is producing coal from the Menefee–Crevasse Canyon Formations. Menefee coals are mined at the Lee Ranch mine. The only mine in the Raton Basin, the Ancho Canyon, mines coals in the Raton Formation.

The La Plata and San Juan mines ship all their production to Public Service Company of New Mexico's San Juan Generating Station (Fig. 7). Navajo mine delivers all of its production to the Four Corners Generating Station operated by Arizona Public Service. McKinley mine is close to rail and sells coal to the Apache, Cholla, and Coronado generating stations in Arizona (Fig. 7). Lee Ranch ships coal by rail to Escalante near Prewitt, New Mexico, and to the Springerville Generating Station in western Arizona. Lee Ranch also supplies approximately 10% of the coal consumed at Cholla Generating Station, owned by Arizona Public Service (Kimber Belknap, APS, pers. comm. 1999).

Fly-ash production in New Mexico

Table 2 lists the source of coal, type of precipitators, and estimated tonnage of fly ash for the Arizona and New Mexico power plants burning New Mexico coals. All the plants are steam turbine boilers, and most have electrostatic precipitators; however, the older units (Table 2) tend to have wet

FIGURE 8—Phoenix Cement classifying and storage facility at Cholla Generating Station, Joseph City, Arizona.

venturi or baghouse precipitators.

The total estimated fly ash produced in 1997 from the seven generating stations burning primarily New Mexico coal is 3.59 million st (Table 2), approximately 14% by weight of the total New Mexico coal consumed at the seven facilities. This estimate was derived using the data in Table 2 and the following equation:

total receipts x ash percent x
%efficiency x %fly ash of the total ash

A *total receipt* is the amount of coal burned and *%efficiency* is the precipitator efficiency.

The total useable fly ash is the material not disposed of in ponds or landfills. Fly ash from the Springerville plant is contaminated by the dry scrubbers (0.432 million st), ash from Cholla units 1 and 2 (about 0.135 million st) is contaminated, and in 1997 San Juan was putting all its fly ash back into the mine pits. The ash from the wet venturi scrubbers on units 1 and 2 of the Cholla Generating Station is contaminated with the reaction products of calcium sulfite and calcium sulfate and is sent to the evaporation ponds (Mike Machusak, APS, pers. comm. 1999). Accounting for these factors and the percent coarse fly ash (>45 µm), the estimate of the total useable fly ash from New Mexico coals in 1997 is about 1.59 million st. Approximately 44% of New Mexico's fly ash is being put to use. This is a significant amount considering only 32% of the fly ash produced in the U.S. is utilized.

Marketing of New Mexico fly ash

Several power plants burning New Mexico coal sell their fly ash to marketers for resale or admixing. Cholla and Four Corners generating stations, both operated by Arizona Public Service, sell their fly ash to Phoenix Cement of Phoenix, Arizona. Phoenix Cement has fly-ash classifying and load-out facilities on site at both power plants. San Juan, operated by Public Service of New Mexico, is in the process of contracting with Phoenix Cement to market its fly ash. Escalante Generating Station, owned by Plains Electric, sells its fly ash to Minerals Solutions, a subsidiary of the Lafarge Corporation, based in Reston, Virginia, which has interests in cement, construction materials, and gypsum. Coronado Generating Station has just changed marketers from Boral to Mineral Resources Technology (MRT), of Atlanta, Georgia, and Coronado has rebuilt its load-out facilities for truck and rail transportation of fly ash (Mark Bailey, SRP, pers. comm. 1999). Apache Generating Station, near Benson, Arizona, sells its fly ash to Boral Material Technologies. The only large generating station using New Mexico coal that does not sell any of its fly ash is Tucson Electric Power's Springerville plant (Bill Lucas, TEP, pers. comm. 1999). The dry scrubbers are an older design in which $CaSO_4$ is removed by the baghouse; therefore the fly ash has high CaO + $CaSO_4$ (Table 3) and is not considered saleable at this time.

Marketers and uses

For this study, the author contacted all of the generating stations using New Mexico coal. Two generating stations were visited that had fly-ash facilities on site. The following is a detailed description of these facilities.

Phoenix Cement. Most (95%) fly ash is sold as an admixture to cement directly to ready-mix concrete operations. A small portion of fly ash is interground with cement to produce Type IP cement (portland pozzolan, Austin and Barker, 1998). Another minor use of Phoenix Cement's fly ash is for cinder blocks and for road and soil stabilization.

Phoenix Cement has on-site testing, classification, and loading facilities at both the Cholla (Fig. 8) and Four Corners generating stations. They sample and test fly ash coming from each unit (Fig. 9) every 2 hrs to ensure consistency of the %LOI, fineness, and color (brightness) of the product. Phoenix Cement also air classifies the fly ash it receives from the power plants to maintain consistency of grain size in its product. Markets for its fly ash from Cholla Generating Station include Arizona, New Mexico, Utah, Colorado, and California. This product is sent by truck and by rail (Ron Helms, Phoenix Cement, pers. comm. 1999). Approximately 200,000–250,000 st of fly ash from the Four Corners Generating Station is sold to Phoenix Cement. The remainder is used at the Navajo mine for reclamation and stabilization (Craig Walling, APS, pers. comm. 1999). Fly ash sold to Phoenix Cement is trucked from Farmington to Gallup, New Mexico, where it is shipped by rail to California, Colorado, and Arizona markets. Phoenix Cement maintains storage facilities in its market areas to absorb excess fly-ash production and to maintain a steady flow of material to its customers on short notice. Some of its storage facilities are in Albuquerque, New Mexico; Mesa and Phoenix, Arizona; and San Diego, California. Fly-ash production is dependent on energy demands, therefore, the change in seasons causes fluctuations in the amount of product.

Mineral Resources Technology. MRT has just begun marketing the fly ash from Coronado Generating Station. Coronado had Boral as a marketer from 1979 to 1998. At this time, sales are in transition, but Coronado hopes to sell 200,000 st/yr to MRT (Jim Pratt, SRP, pers. comm. 1999). Coronado is rebuilding its fly-ash loading facility (Fig. 10), shipments by truck have begun, and rail shipments will begin in the near future. MRT tests the fly ash from the generating units for fineness, % LOI, and color by visual comparison to standards. Markets for this fly ash include Phoenix, Arizona; Colorado; Texas; New Mexico; and California. Shipment is by pneumatic and bottom dump truck and by rail cars. Rail transportation is used for the Los Angeles and San Francisco markets. When the unloading facility is complete, 20 rail cars per week should be transporting fly ash. At present, some fly ash is being shipped by vendor truck (bottom dump) from this facility to Holloman Air Force Base in New Mexico. Rail sales usually are 10 times greater than truck. Transportation and use of total fly ash from the Coronado Generating Station is 75% by rail, 16–18% by truck, and 7–9% into disposal ponds (Carl Hamblin, SRP, pers. comm. 1999).

Summary and conclusions

Fly ash is an artificial pozzolan that is a byproduct of the coal-combustion process to produce electricity. The type of coal, particularly the total silica, alumina, and iron oxides, and the amount of calcium-bearing minerals in the inorganic fraction determine the class of fly ash (C or F). The amount of fly ash produced at a generating station depends on the ash content of the coal, the burner, and boiler type. The precipitation equipment determines the amount of fly ash recovered. Fly ash that is saleable as an admixture to concrete or for other uses such as soil stabilization has to be captured from the flue gas before going through the SO_2 scrubbers. Coarse fly ash (>44 µm) is not used for cement because it is not reactive, but it can be used for road-base stabilization, flowable fill, and mineral filler in asphalt.

As an admixture, fly ash provides many attractive characteristics to concrete,

FIGURE 9—Phoenix Cement sampling vials for each generating unit at Cholla Generating Station. Ash samples are collected every 2 hrs for analyses.

FIGURE 10—Mineral Resources Technology load-out facility at Coronado Generating Station, St. Johns, Arizona.

including strength, lowering heat of hydration, workability, and resistance to alkali-silica reactions (ASR). The fine grain size enables it to fill void space within the concrete, which means less fine-grained aggregate is needed. The size of the fly-ash particles (0–45 µm) also improves the packing of cementitious materials and reduces the permeability of the concrete through pozzolanic action. Use of fly ash lowers the cost of the concrete and saves energy by replacing the need to purchase as much cement. Cement manufacturing is an energy intensive process so the savings can be significant and realize a reduction in CO_2 production. The average cost of cement in the U.S. is $83/st (U.S. Geological Survey, 1999). The average cost of fly ash is approximately $22/ton. The use of fly ash also lowers the need to mine materials for cement.

Because fly ash is a byproduct, it has some advantages over other artificial and natural pozzolans. Generating stations benefit from the sale of their fly ash because it offsets some of the coal costs, which include disposal cost of coal-combustion byproducts. This is important particularly with New Mexico coals, which are high priced, averaging $22.64/ton (New Mexico Energy, Minerals, and Natural Resources Department, 1998). Selling fly ash can also reduce the size of landfill or pond areas at a power-plant facility.

The use of fly ash from New Mexico is significant, 1.59 million st, approximately 44% of the total production (3.59 million st). Several factors influence the high use of New Mexico fly ash. Class F fly ash is desirable in the Southwest because of the significant problem of alkali-silica reactions (ASR) related to the alkaline rocks available in the region as aggregate. The high percentage (>60%) of silica is particularly important in counteracting ASR; it acts as a sacrificial silica, reducing the attack on the aggregate and reducing expansion that leads to cracks and spalling. A low %LOI makes for a light-colored fly ash, particularly desirable in the California market. Marketers, knowledgeable about the fly-ash market, handle the quality control, load-out facilities for transport, technical support, sales, and product promotion for all New Mexico fly ash that is sold. As with most industrial minerals, transportation and proximity to markets are crucial to having a marketable product. Most of the marketers have rail transportation on site or nearby. Because many of the generating stations in New Mexico and Arizona are not close to large markets and because fly ash is a low-cost product, it is vital to have access to railroad transportation. Having storage facilities at different locations in the market area is also important, particularly with the seasonal fluctuation in the production of fly ash. Most of the marketers of New Mexico fly ash (Phoenix Cement) have this capability.

A future concern that may affect the New Mexico fly-ash market is the predominance of fly ash sold from Arizona generating stations using coal from the McKinley mine (Apache, Cholla, and Coronado generating stations). This mine, operated by Pittsburg & Midway, is the oldest in the state, operating since 1962. The age of the mine and the decreasing reserve base have the potential to influence New Mexico's fly-ash market.

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