

## Kinetics of Beneficiated Fly Ash by Carbon Burnout

Joseph M. Okoh, Joseph N. D. Dodoo, and Adria Díaz

Department of Natural Sciences,  
University of Maryland Eastern Shore, Princess Anne, MD 21853

### INTRODUCTION

Coal combustion, the predominant source of energy in the United States and many other countries, results in the production of huge amounts of a waste material known as fly ash. During combustion some minerals present in coal such as clay may be altered thermally, while others, such as silica, remain unaltered. The thermally treated coal impurities, along with small amounts of unburned coal, make up the fly ash. Fly ash is collected in the dust-collection systems that remove particles from the exhaust gases of power plants and consists mostly of small spheres of glass of complex composition involving silica, ferric oxide, and alumina. The composition of fly ash varies depending on the parent coal and furnace operating conditions. In general, the major constituents of fly ash are  $\alpha$ -quartz ( $\text{SiO}_2$ ), mullite ( $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ), hematite ( $\text{Fe}_2\text{O}_3$ ), magnetite ( $\text{Fe}_3\text{O}_4$ ), lime ( $\text{CaO}$ ), and gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) (1). Fly ash is described as being either Class C, normally produced from lignite or subbituminous coal, or Class F, produced from burning anthracite or bituminous coal, in the American Society for Testing and Materials Standard Specification C618 (2). The basic chemical requirements set forth for the two classes are listed in Table 1.

The structural configuration of fly ash consists of thin-walled spheres made of silicon dioxide or complex compounds of silicon dioxide, which can be hollow (cenospheres) or filled with smaller solid spheres (plerospheres). The majority of fly ash particles collected from an electrostatic precipitator are between 20 and 80  $\mu\text{m}$  in diameter, with specific gravity ranging from 1.59 to 3.10  $\text{g}/\text{cm}^3$  (3). The electric utility industry produces nearly 48 million tons of fly ash annually in the United States. Currently 25% of the fly ash produced is utilized while the rest is disposed of in landfills. This practice raises concern as leaching of heavy metals contained in fly ash may contaminate groundwater and water supplies. In addition to this environmental effect, the costs of disposal and the generally finite spaces available for storage of the huge amounts of fly ash produced each year have prompted interest in utilization of fly ash (4,5). Many uses of fly ash have been developed over the years including its use as a pigment in paints and coatings, as filler for plastics and as an agent for removal of contamination from waste waters (6). The use of fly ash as a substitute in concrete products seems to be one of the most attractive solutions and is by far the largest market for fly ash today.

### Use of fly ash in concrete

Typical specifications state that fly ash may be used to replace up to 15% of Portland cement (7). Portland cement is an hydraulic cement that contains various proportions of four primary compounds:  $\text{Ca}_3\text{SiO}_5$ ,  $\text{Ca}_2\text{SiO}_4$ ,  $\text{Ca}_3\text{Al}_2\text{O}_6$ , and  $\text{Ca}_4\text{Al}_2\text{Fe}_2\text{O}_{10}$ . Upon setting of concrete, the calcium silicates undergo hydration and hydrolysis to form a gelatinous hydrated silicate on the surface of sand and rock particles, a process known as solidification (See reaction a). Over long periods of time, removal of water from the hydrates by dry cement particles lead to hardening of concrete.



It is the well-known pozzolanic behavior of fly ash that makes it particularly attractive for the preparation of mortar and concrete. In the presence of moisture, the siliceous and/or siliceous-alumina components in fly ash react with calcium hydroxide, a by-product of the initial reaction between cement and water, at ordinary temperatures to form additional cementitious compounds (7-9). The several types of calcium silicate and calcium aluminate that are formed provide additional bonding and strength. The use of fly ash as a substitute in the preparation of concrete or mortar leads to technical advantages in the final product that are beneficial to the concrete industry. Fly ash having low loss on ignition and high fineness is known to improve the properties of both fresh and hardened concrete. In terms of concrete durability, fly ash interaction reduces permeability, increases sulfate resistance and freezing and thawing resistance among other properties (9).

In spite of the advantages of the use of fly ash in concrete, currently only 25% of the fly ash generated is subsequently utilized. The key issue for utilization of this material is the availability of high-quality fly ash (7,9). The American Society for Testing and Materials has established specifications for use of fly ash as a pozzolan in concrete related to these four characteristics. In terms of chemical composition the sum of silica, alumina and iron oxide must be at least 70% to ensure that sufficient reactive compounds are present to react with lime. A 3.0% limit is placed on moisture content to minimize caking and packing of the fly ash in shipping and storage. The requirement for pozzolanic activity requires that the strength developed by the test mixture in which 35% of the volume of cement is replaced with the same volume of fly

ash shall be a minimum of 75% of the strength of the control specimen after storage for 1 day or 7 days. Fineness is one primary characteristic of fly ash that relates to its pozzolanic activity, and the maximum value for fly ash retained when wet sieved on 45  $\mu\text{m}$  is set at 34 % (10,11).

A product of the combustion of anthracite and bituminous coals, fly ash often contains residual carbon particles. A high carbon content is reported to have a detrimental influence on certain concrete properties. In addition to their effect on the color of concrete, carbon particles tend to dramatically reduce the efficiency of air-entraining admixtures commonly used to impart desirable properties, including increased durability, to concrete (12). The air-entraining admixtures are organic materials which when added to the gauging water of a concrete mix entrain a controlled quantity of air in uniformly dispersed microscopic bubbles. Air-entraining agents are characteristically long chain molecules with a polar group at one end, and which therefore become concentrated at the air-liquid interface with the polar groups in the liquid and their non-polar parts out of it. This results in the inner surfaces of bubbles being composed of hydrophobic material formed by the non-polar parts of the molecules which act as a barrier to the entry of water during mixing or placing and on any other occasion when the paste is saturated (13). This stable foam of closely spaced, spherical pores has a remarkable effect on the ability of concrete to withstand freeze-thaw cycling. Air entrainment also increases the workability of otherwise similar concrete. The majority of commercial products are based on a relatively small number of raw materials including abietic and pimeric acid salts, fatty acid salts, alkyl-aryl sulphonates, alkyl sulphates and phenol ethoxylates (14). The carbon present in fly ash adsorbs a portion of the air-entraining agent, which makes it unavailable for creating the needed conditions for stable air bubbles. The amount of adsorption varies with the amount of carbon present and, probably, with the form of such carbon (11). Since a proper air bubble network is not achieved freezing and thawing resistance is decreased in concrete made with high carbon fly ash. Maximum allowable levels of residual carbon have been set by specifying authorities. These levels are usually designated as Loss on Ignition, which provides a rough estimate of the true value, as the test procedure is designed to oxidize any combustibles by using high temperatures and long residence times. The American Society for Testing and Materials has established a maximum value of 6% residual carbon in fly ash used in concrete, but levels no higher than 3% are generally demanded by the industry when the ash is sold to replace cement in concrete (4,11).

## OBJECTIVE

The main objective of this project was to determine the kinetics of fly ash beneficiation by carbon burnout. The kinetics of the reactions of carbon present in fly ash with oxygen as the reactant gas was investigated at various reaction temperatures, partial pressures of reactant gas and total surface area.

The reaction rate (R) for oxidation of carbon in this project can be evaluated in terms of the rate of mass loss:

$$R = -\frac{dm}{dt} = k_{air} \Sigma(O) P^n$$

where  $k_{air}$  is the reaction rate coefficient,  $P$  is the pressure of the reacting gas,  $n$  is the reaction order and  $\Sigma(O)$  the surface area. This equation is based on the rate law proposed by Hinshelwood (15) for the reaction between a porous solid and gas :

The temperature dependence of carbon gasification will be evaluated from the Arrhenius equation:

$$k = A e^{-E_a/RT}$$

where  $k$  is the rate constant,  $R$  is the universal gas constant and  $T$  is the absolute reaction

## EXPERIMENTAL PROCEDURE

### Fly ash samples

The fly ash samples used in this study (Table 2) were obtained from the Delmarva Power Indian River plant. Samples were collected from the landfill, oven-dried at 100 °C to remove moisture and fractioned according to particle size

. The sieve sizes used had openings of 44, 74, 149 and 250  $\mu\text{m}$  (U.S. mesh sieve sizes #325, #200, #100 and #60, respectively). The fraction of fly ash particles greater than 250  $\mu\text{m}$  was discarded. The three size-fractionated fly ash samples obtained were then heated at 200  $^{\circ}\text{C}$  under nitrogen for 3 hours using a Lindberg furnace to drive off water absorbed in interstitial spaces of the bulk sample or water physically adsorbed on the surface of individual particles. Three hours were considered ample time for complete removal of moisture since a 50 mg-sample of fly ash heated at 200  $^{\circ}\text{C}$  under nitrogen in a thermogravimetric analyzer lost all adsorbed water, indicated by no weight loss, after approximately one hour. For convenience and easy handling of data, the three size-fractionated fly ash samples were labeled as follows: fly ash particles with diameters between 149  $\mu\text{m}$  and 249  $\mu\text{m}$  were labeled as s#100; fly ash particles with diameters between 74  $\mu\text{m}$  and 148  $\mu\text{m}$ , as s#200; fly ash particles with diameters between 44  $\mu\text{m}$  and 73  $\mu\text{m}$ , as s#325. The samples were kept in airtight containers until used in the experiments.

### Surface Area Measurements

Before measurement, approximately 0.2 grams of each fly ash sample were degassed at 150  $^{\circ}\text{C}$  for twenty-four hours. The sample tube was then transferred to the analysis port for surface area and porosity determinations (See Appendix A for analysis conditions). The ASAP instruments calculate volume as a function of a change in pressure. From this volume the information necessary to determine the surface area characteristics of a sample is generated. The following reports were obtained from the  $\text{N}_2$  adsorption-desorption isotherms of fly ash samples:

*BET Surface Area report:* listing the relative pressures, volumes adsorbed and BET transformations at the points selected for use in surface area data reduction. From these points a plot is generated which defines the BET characteristics (Appendix A).

*Micropore Area and Micropore Volume (t-plot) report:* listing the statistical thickness calculated at each relative pressure selected for micropore data reduction. A plot of the volume adsorbed at the pressure of interest provides micropore volume, area, and external surface (16,17).

*BJH Pore Volume and Area Distribution report:* based on the method developed by Barrett, Johner, and Halenda to determine the mesopore volume/area distribution which accounts for both the change in adsorbate layer thickness and the liquid condensed in pore cores (18,19).

### Carbon oxidation reactions

Reaction rates for the oxidation of carbon present in the fly ash samples were determined in the temperature range of 550-750  $^{\circ}\text{C}$  for the three fly ash samples. At each selected temperature the reaction rate was determined at three different partial pressures of the reacting gas (0.213 atm, 0.168 atm, and 0.126 atm).

Taring was carried out with and without gas flow. The gas flow was set at 60 standard cubic centimeters. For each run, approximately 50 mg fly ash samples were placed in the quartz cup within the TG chamber. Previous analysis had indicated 50 mg to be an adequate sample size given that the average carbon content of the fly ash was about 9% (See Table 4). The amount of carbon in the fly ash was confirmed by analysis with a Scanning Electron Microscope with an Energy Dispersive X-ray Analyzer. The sample was held in a nitrogen gas flow for 5-10 minutes to allow its weight to stabilize. The chamber was then heated at a rate of 25  $^{\circ}\text{C min}^{-1}$  until the desired temperature was reached. At this point, the gas flow was manually switched from nitrogen to air. The sample was held at this final condition until there was no weight loss, from 1-4 hours. The presence of a nitrogen atmosphere during the temperature ramp in the TGA prevented oxidation of carbonaceous materials until the sample reached the selected temperature, when air is admitted to the chamber.

For runs at different partial pressures of oxygen, vacuum was applied to the chamber during the isotherm period of the run. Data was collected for each run as a continuous record of the sample mass, temperature and time with a PC interfaced to the TG. The TG files were exported to MicroSoft Excel for analysis.

## RESULTS AND DISCUSSION

### Surface Area Measurements

Surface area and porosity results for fly ash samples are listed in Tables 3- 5. For the fly ash samples studied, surface area increases as particle size increases. At high size ranges, irregular porous fly ash particles of carbonaceous origin are expected to be predominant contributing to the high surface area found for large particles (20). The higher surface areas for fly ash s#100 can be then attributed to the presence of highly porous carbonaceous particles. Figure 5 shows a plot of surface area vs. carbon content and particle size and illustrates this dependence of surface area on carbon content. A typical adsorption-desorption isotherm of fly ash samples s#100 is shown in Figure 1. All three isotherms revealing the presence of porosity in the fly ash samples analyzed.

Experimental isotherms can be analyzed by the t-plot method devised by deBoer and co-workers (21), in which

the volume of adsorbed gas is plotted vs. film thickness, calculated from the Harkins and Jura equation (14), for a reference solid. The slope of the line yields the effective surface area. Deviation from this line is indicative of porosity: points above the line indicate additional volume held by capillary condensation and points below the line indicate blockage of pore throats, occluding the interior surface area. The  $t$  curves of the three fly ash samples used in this study show deviations from linearity which suggest that the fly ash samples are porous. Pore size distribution curves were obtained for fly ash samples s#100, s#200 and s#325, respectively. BJH adsorption pore size distribution reports indicated that no pores were open at both ends. Average pore diameters were similar for the three fly ash samples: Average pore diameters obtained from adsorption data were approximately 115 Å.

### Carbon oxidation reactions

Oxidation reactions were carried out on three different size-fractioned fly ash samples at temperatures of 550 °C, 650 °C and 750 °C. At each given temperature, runs were performed at reactant gas pressures of 0.213, 0.168 and 0.126 atm. Respectively. Figure 2 shows a typical weight vs. time trace for oxidation of fly ash s#100 at 750 °C. This figure depicts weight changes after oxygen was introduced in the TG.

Reaction rates were determined for each oxidation reaction using the initial rate law and the proportionality law. For the initial rate law method, the slope of the linear portion of the sigmoid curve of wt vs. time was used to calculate reaction rates. For the proportionality law method, the sigmoid curve of weight vs. time was converted to a straight line by plotting  $\ln t$  vs.  $\ln(\ln W - \ln W_i)$ , or  $qt$  vs.  $q(qW - qW_i)$ , where  $W$  is the weight at any given time and  $W_i$  is the asymptote. The slope of the line obtained, which comprised the whole reaction event, was used to calculate reaction rates. The rate of weight loss was normalized to initial weight and the surface area of the specific size-fractioned fly ash. The dependence of reaction rate on reaction temperature was evaluated with the Arrhenius equation. For each of the three fly ash samples, the activation energy at various pressures of reactant gas was evaluated from Arrhenius plots. Activation energies for the size-fractioned fly ash samples used in this study ranged from 43 kJ/mol to 131 kJ/mol. Tables 11, 12 and 13 list the values of Arrhenius parameters obtained at various pressures of reactant gas for fly ash samples s#100, s#200, and s#325, respectively. Other studies have found activation energies for coal fly ash to be about 59 kJ/mol for the temperature range 275 °C-350 °C. In the same study higher activation energies were found for MSW fly ash (104 kJ/mol-142 kJ/mole) (22). Activation energies were found to be inversely proportional to pressure for the three fly ash samples. Indeed, these values decrease with decreasing pressures indicating some effect of mass transport on activation energy. For porous materials, the concentration of reactant gas decreases to almost zero inside the pores at low partial pressures of reactant gas limiting the reaction and lessening the effect of increasing temperatures on reaction rate. In our samples, pores ranged from 44 Å to 116 Å in diameter. BHJ adsorption/desorption pore distribution reports revealed that no pores were open at both ends, only one end of the pores was open to the external surface. This implies that the oxygen concentration decreases inside the pores at low oxygen pressures thus confirming that carbon burn off occurred in the zone II kinetic regime.

No consistent trend was observed for the change in activation energy with particle size so that it is not possible to determine how the rate effects of temperature varied with particle size. At a reactant gas pressure of 0.213 atm, the value of the energy of activation decrease with increasing particle size, but this does not apply to reactant gas pressures of 0.168 atm and 0.126 atm. These inconsistencies in activation energies demand a close look at the rate data obtained for the oxidation of carbon in fly ash. Throughout this study, it has been assumed that the weight loss of fly ash is due exclusively to the oxidation of carbon present in fly ash. Calculations of weight loss for fly ash sample s#100 at 550 °C, 650 °C and 750 °C resulted in values of 9.5 mg, 11.4 mg, and 12.2 mg, respectively. The greater values of weight loss at high temperatures (650 °C and 750 °C) suggest that weight loss in fly ash at these temperatures is not caused only by carbon oxidation. In a study of the accuracy of the loss-on-ignition test, Brown and Dykstra (23) performed thermogravimetric analysis on fly ash samples produced by four distinctive kinds of coal boilers. Samples were heated under nitrogen to a temperature of 725 °C. For all the fly ash samples analyzed, large weight losses were observed between 600-710 °C originating from the calcination of limestone or dolomite in the fly ash. All of the samples showed weight losses from processes other than just water desorption and carbon oxidation. In fact, portlandite  $[\text{Ca}(\text{OH})_2]$ , occurring at 400 °C, and carbonate calcination were the largest contributors to weight loss. Limestone, which is mostly calcite ( $\text{CaCO}_3$ ) or dolomite  $[\text{CaMg}(\text{CO}_3)_2]$  is usually added as fine particulate material to fluidized bed combustors. It's generally calcinated at the high temperatures of the boilers to lime,  $\text{CaO}$ , but fine particulate matter can be entrained in the gas flow through the boilers and, therefore, lime and limestone can appear in fly ash. Lime is extremely hygroscopic and will readily form portlandite  $[\text{Ca}(\text{OH})_2]$  in the presence of water. High levels of naturally occurring carbonates in coal can also contribute to the presence of limestone and dolomite in fly ash. From the ongoing discussion, it becomes obvious that at temperatures above 600 °C weight losses from these minerals will yield overestimates of unburned carbon content in fly ash. Therefore, it is reasonable to suspect that carbonate calcination may have contributed to weight losses during reactions carried out at 650 °C and 750 °C, and consequently, confounded the calculations of reaction rates for oxidation of carbon in fly ash. Given that the calculated reaction rates

correspond to total weight loss and not only to carbon oxidation, it is not possible to evaluate the rate dependence on temperature based on the data collected.

### **Rate dependence on pressure**

The information presented in the tables 6-8 also provide information on the dependence of the reaction rate on oxygen pressure. The rate dependence of oxidation of fly ash s#100 on partial pressure of oxygen revealed a trend of increasing rate with decreasing concentration of reactant for both rate estimates. The higher rates at lower partial pressures of oxygen may be accounted for by the presence of volatiles in the fly ash. At low concentrations of oxygen (high vacuum), volatile compounds such as adsorbed organic species entrained in the porous system of the fly ash evolved rapidly, contributing to weight loss in fly ash. The increasing rate with decreasing pressure may also be due to the ease of transport of products away from reaction sites within pores with lowering pressure. This trend of increasing rate with decreasing concentration of reactant is also observed in fly ash s#200 and fly ash s#325 for the initial rate estimates only.

The effect of reactant gas concentration on reaction rates of fly ash was evaluated using the equation:

$$R=k[O_2]^a$$

where  $[O_2]$  is the concentration of oxygen. The slope of the plot of the  $\ln R$  vs.  $\ln O_2$  represents the rate dependence on oxygen concentration, (Tables 9-12).

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Table 1. Chemical Requirements of Fly Ash

Chemical component	Fly Ash Class	
	C	F
SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub> -min %	50.0	70.0
SO <sub>3</sub> -max %	5.0	5.0
Moisture content-max%	3.0	3.0
Loss on ignition- max %	6.0	6.0

Source: Reference 2.

Table 2. Chemical composition of Delmarva Power fly ash

Variable analyzed	Percentage of total weight
Silica (SiO <sub>2</sub> )	40.34
Aluminum (Al <sub>2</sub> O <sub>3</sub> )	27.59
Iron (Fe <sub>2</sub> O <sub>3</sub> )	9.75
Calcium (CaO)	2.49
Magnesium (MgO)	0.42
Sodium (Na <sub>2</sub> O)	0.62
Potassium (K <sub>2</sub> O)	2.36
Titanium (TiO <sub>2</sub> )	2.60
Sulfur (SO <sub>3</sub> )	0.40
Loss on Ignition	8.93
Loss on Drying	27.99
pH	8.0

Source: Reference 37.

Table 3. Results of surface area analysis of fly ash particles s#100

<b>Area</b>	
BET Surface Area	5.5348 m <sup>2</sup> /g
BJH Adsorption Cumulative Surface Area of Pores <sup>1</sup>	2.6233 m <sup>2</sup> /g
BJH Desorption Cumulative Surface Area of Pores <sup>1</sup>	3.0693 m <sup>2</sup> /g
<b>Volume</b>	
BJH Adsorption Cumulative Pore Volume <sup>1</sup>	0.007592 cm <sup>3</sup> /g
BJH Desorption Cumulative Pore Volume <sup>1</sup>	0.007853 cm <sup>3</sup> /g
<b>Pore Size</b>	
Average Pore Diameter (4V/A by BET)	44.6874 Å
BJH Adsorption Average Pore Diameter (4V/A)	115.7567 Å
BJH Desorption Average Pore Diameter (4V/A)	102.3468 Å

<sup>1</sup> Pores between 17 and 3000 Å Diameter

Table 4. Results of surface area analysis of fly ash particles s#200

<b>Area</b>	
BET Surface Area	3.9922 m <sup>2</sup> /g
BJH Adsorption Cumulative Surface Area of Pores <sup>1</sup>	2.2145 m <sup>2</sup> /g
BJH Desorption Cumulative Surface Area of Pores <sup>1</sup>	3.1105 m <sup>2</sup> /g
<b>Volume</b>	
BJH Adsorption Cumulative Pore Volume <sup>1</sup>	0.006431 cm <sup>3</sup> /g
BJH Desorption Cumulative Pore Volume <sup>1</sup>	0.006934 cm <sup>3</sup> /g
<b>Pore Size</b>	
Average Pore Diameter (4V/A by BET)	44.7863 Å
BJH Adsorption Average Pore Diameter (4V/A)	116.1695 Å
BJH Desorption Average Pore Diameter (4V/A)	89.1701 Å

<sup>1</sup> Pores between 17 and 3000 Å Diameter

Table 5. Results of surface area analysis of fly ash particles s#325

<b>Area</b>	
BET Surface Area	3.0028 m <sup>2</sup> /g
BJH Adsorption Cumulative Surface Area of Pores <sup>1</sup>	1.8355 m <sup>2</sup> /g
BJH Desorption Cumulative Surface Area of Pores <sup>1</sup>	2.2171 m <sup>2</sup> /g
<b>Volume</b>	
BJH Adsorption Cumulative Pore Volume <sup>1</sup>	0.005284 cm <sup>3</sup> /g
BJH Desorption Cumulative Pore Volume <sup>1</sup>	0.005536 cm <sup>3</sup> /g
<b>Pore Size</b>	
Average Pore Diameter (4V/A by BET)	49.8128 Å
BJH Adsorption Average Pore Diameter (4V/A)	115.1592 Å
BJH Desorption Average Pore Diameter (4V/A)	99.8740 Å

<sup>1</sup> Pores between 17.000 and 3000.000 Å Diameter

Table 6. Rate dependence on temperature at three different partial pressures of reactant gas (oxygen) for fly ash particles s#100.

Pressure of reactant gas (atm)	Temperature (°C)	R(initial rate law) (mg/g.m <sup>2</sup> sec)	R(Proportionality law) (mg/g.m <sup>2</sup> sec)
0.213	550	0.0188	2.267
	650	0.0736	12.165
	750	0.1520	28.630
0.168	550	0.0302	3.182
	650	0.1036	19.787
	750	0.1830	121.462
0.126	550	0.0345	3.533
	650	0.1710	23.9084
	750	0.2320	123.012

Table 7. Rate dependence on temperature at three different partial pressures of reactant gas (oxygen) for fly ash particles s#200.

Pressure of reactant gas (atm)	Temperature (°C)	R(initial rate law) (mg/g.m <sup>2</sup> sec)	R(Proportionality law) (mg/g.m <sup>2</sup> sec)
0.213	550	0.0069	7.306
	650	0.0219	165.032
	750	0.1586	618.738
0.168	550	0.0100	3.953
	650	0.0213	59.323
	750	0.1629	320.759
0.126	550	0.0147	37.093
	650	0.1100	19.099
	750	0.1724	143.103

Table 8. Rate dependence on temperature at different partial pressures of reactant gas (oxygen) for fly ash particles s#325.

Pressure of reactant gas (atm)	Temperature (°C)	R(initial rate law) (mg/g.m <sup>2</sup> sec)	R(Proportionality law) (mg/g.m <sup>2</sup> sec)
0.213	550	0.0035	12.098
	650	0.0290	72.420
	750	0.1462	584.638
0.168	550	0.0265	7.757
	650	0.1296	79.421
	750	0.2252	504.078
0.126	550	0.0675	60.793
	650	0.2110	343.650

750	0.2455	828.588
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Table 9. Arrhenius parameters for oxidation reaction of fly ash particles s#100 at various partial pressures of reactant gas.

Po <sub>2</sub> (atm)	Initial rate data		Proportionality data	
	Ea (kJ/mol)	A	Ea (kJ/mol)	A
0.213	73.85	13.55	135.06	22.12
0.168	68.28	7.61	146.43	23.45
0.126	63.81	4.21	92.37	17.69

Table 10. Arrhenius parameters for oxidation reaction of fly ash particles s#200 at various partial pressures of reactant gas.

Po <sub>2</sub> (atm)	Initial rate data		Proportionality data	
	Ea (kJ/mol)	A	Ea (kJ/mol)	A
0.213	108.40	10.69	157.43	25.18
0.168	95.78	9.16	154.91	24.09
0.126	88.07	8.84	**	

\*\*no regression

Table 11. Arrhenius parameters for oxidation reaction of fly ash particles s#325 at various partial pressures of reactant gas.

Po <sub>2</sub> (atm)	Initial rate data		Proportionality data	
	Ea (kJ/mol)	A	Ea (kJ/mol)	A
0.213	131.44	13.55	135.06	22.12
0.168	76.12	7.61	146.43	23.45
0.126	43.92	4.21	92.37	17.69

Table 12. Results from regression analysis of ln R vs. ln O<sub>2</sub> for oxidation of fly ash s#100, s#200, and s#325 at 550 °C. The slope, a, represents the oxygen concentration dependence.

Fly Ash Samples	a	R <sup>2</sup>
s#100	-1.132	0.87
s#200	-1.437	0.99
s#325	-5.553	0.93

Figure 2. Fly ash s#100 oxidation at 750 C and 1.00 atm.

