FLY ASH GENERATION AND UTILIZATION - AN OVERVIEW*

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ABSTRACT
This chapter describes production and utilization of fly ash throughout the world. The utilization potential for fly ash generated from conventional as well as advanced coal combustion technologies are addressed. Constructive use options for fly ash are divided into three classes: low technology applications; medium technology applications; and, high technology applications. The low technology applications include the use of fly ash in fills and embankments, pavement and subbase courses, subgrade stabilizations, landfill cover, soil improvement, land reclamation, slurried flowable ash, and water pollution control. The medium technology applications include the utilization of fly ash in blended cements, lightweight aggregates, various types of concrete, precast/prestressed products, bricks, blocks, paving stones, artificial reefs, etc. The high technology applications involve the use of fly ash as a raw material for metal recovery, filler for metal matrix composites, polymer matrix composites, and several other filler applications.

INTRODUCTION

Coal is used as a major source of energy throughout the world. In order to produce energy, pulverized coal is generally burned. During the combustion process, the volatile matter and carbon burn off, and the coal impurities such as clays, shale, quartz, feldspar, etc. mostly fuse and remain in suspension (Mehta, 1983). These fused particles are carried along with the flue gas. As the flue gas approaches the low temperature zones, the fused substances solidify to form predominately spherical particles which are called fly ash. The remaining matters which agglomerate and settle down at the bottom of the furnace are called bottom ash. Fly ash is captured by mechanical separators, electrostatic precipitators, or bag filters. It is a mixture of particles varying in shape, size, and composition. These particles can be classified as carbon from unburnt coal, thin-walled hollow spheres, and their fragments, magnetic iron containing spherical particles, and spherical particles (Berry and Malhotra, 1980; Berry and Malhotra, 1987; Berry et al. 1989; Mehta 1989). Size of spherical fly ash particles is found to lie in the range of 1 - 150 μm (Berry et al., 1989;

Mehta, 1989).

ASTM C-618 categorizes coal combustion fly ash into two classes: Class F and Class C. The Class F fly ashes are normally generated due to combustion of anthracite or bituminous coal. The Class C fly ashes are produced due to burning of lignite or subbutiminous coal. Most fly ashes are rich in SiO_2, Al_2O_3, and Fe_2O_3, and contain significant amounts of CaO, MgO, MnO, TiO_2, Na_2O, K_2O, SO_3, etc. ASTM Class C fly ashes (high-lime fly ashes) typically contain CaO in excess of 10% up to 40%, and Class F fly ashes (low-lime fly ashes) generally contain less than 10% CaO. Due to high CaO content, Class C fly ashes participate in both cementitious and pozzolanic reactions whereas Class F fly ashes predominately participate in pozzolanic reaction during the hydration process. Therefore, Class C fly ashes are classified as cementitious and pozzolanic admixtures/additives and Class F fly ashes as normal pozzolans for use in concrete. The requirements for some standards for fly ash use in concrete is shown in Table 1.

Traditionally, wet scrubbers, Flue Gas Desulfurization (FGD) systems, have been used to control power plant SO_2 emissions and they produce wet by-products. The residue from such systems consist of a mixture of calcium sulfite, sulphate, and fly ash in water. Solid content can vary between 5 to 15% before dewatering. More recent FGD systems convert the calcium sulfite to calcium sulfate (gypsum).

Table 1: Requirements for Bituminous Coal Fly Ash, as Stipulated by Selected Concrete Standards and Guidelines (Berry and Malhotra, 1987; Clarke, 1993)

Country		Australia	Austria	Canada	Denmark	France	Germany	India	Japan	Netherlands	Spain	UK	USA	USSR
Standard		AS 1129	ONORM B 3320	CAN/CSA A23.5	DS 411	PR P 18.501	DIN 1045	IS 3812	JIS A 6201	CUR Aanbe-veling 12	UNE 83-415	BS 3892	ASTM C618	GOST. 6269
loss on ignition	max wt%	8.0	5.0	12.0 (6.0)	5.0	7.0	5.0	12	5.0	5.0	6.0	7.0	12.0 (6.0)	10
moisture	max wt%	1.5	1.0		1.5				1.0	1.0	1.5	0.5	3.0 (3.0)	
SiO_2	min wt%					40		35	45					
SiO_2+Al_2O_3	min wt%				70									
SiO_2+Al_2O_3+Fe_2O_3	min wt%							70					70 (50)	
glass content	min wt%									70				
MgO	max wt%				5.0		5.0	5.0		4.0		4.0	5.0 (5.0)	
CaO (total)	max wt%						8.0^{R}			5.0				
CaO (free)	max wt%		2.0				1.5^{R}							
SO_3	max wt%	2.5	3.5		4.0	2.5	4.0	3.0		2.5	4.5	2.5	5.0	3.0
Cl	max wt%		0.1		0.1	0.1	0.1			0.1				
Na_2O**	max wt%				1.5	6.0	4.0	1.5					1.5 (1.5)	
particle density	min kg/m^3								1950					
Particle size:														
<µm20	min wt%						30							
<µm32	min wt%									60				
<µm40	min wt%						50							
<µm50	min wt%					40								
<µm80	min wt%					70								
<µm315	min wt%					98								
>µm45	max wt%	50		34	40						40	12.5	34 (45)	
>µm90	max wt%										15			
>µm150	max wt%	10												
Relative compressive strength														
28 days	min %		80				70		60	80	75	85^{R}	75	
90 days	min %						70		70		90			

^{R} indicates recommended or guide values

() bracketed values are for ash with high lime content (Type C)

Recent increased concern over SO_2 emissions from power plants has resulted in development of several advanced SO_2 control systems that produce dry by-products. Therefore, these new processes avoid the complexity and operating problems encountered in handling large volumes of liquid wastes produced in the case of FGD systems. In addition, no dewatering is needed prior to utilization or landfilling. However, these processes require costlier sorbent materials. The advanced systems include Atmospheric Fluidized Bed Combustion (AFBC), Lime Spray Drying, Sorbent Furnace Addition, Sodium Injection, and other clean coal technologies such as Integrated Coal Classification combined cycle process (IGCC), etc. The solid waste products generated by these processes have some physical and chemical properties significantly different than those for conventional coal ashes.

The AFBC process produces coal ash, sulfur reaction products, and calcined limestone reaction products. The sulfur reaction products are primarily composed of calcium sulfate and calcium oxide. The calcined limestone reaction primarily forms calcium sulfate. Chemical composition of the AFBC residues is given in Table 2. The chemical composition of the AFBC fly ash is similar to that of Class C fly ash except SO_3 and SiO_2 contents. AFBC SO_3 content is higher and SiO_2 content is lower relative to conventional Class C fly ash.

The spray dryer by-products consists of primarily spherical fly ash particles coated with calcium sulfite/sulphate, fine crystals of calcium sulfite/sulphate, and unreacted sorbent composed of mainly $Ca(OH)_2$ and a minor fraction of calcium carbonate. The spray dryer by-products are higher in concentrations of calcium, sulfur, and hydroxide, and lower in concentrations of silicon, aluminum, iron, etc. compared to a conventional Class C fly ash.

The Lime Furnace Injection (LFI) by-products are made up of primarily coal ash, calcium sulfite, calcium sulfate, and unreacted lime. By-products generated by LFI contain 40 to 70% fly ash, 15 to 30% free lime, and 10 to 35% calcium sulfate by weight. Chemical composition of LFI by-products is also given in Table 2.

The calcium injection process produces by-products similar to that of LFI and calcium spray dryer because of similarities in sorbents and injection methods used. The sodium injection process differs mainly from the calcium injection in regards to type of sorbent used. This process uses a sodium-based sorbent such as sodium bicarbonate, soda ash, trona, or nahcalite (ICF Northwest, 1988). By-products generated by this process include fly ash particles coated and intermixed with sodium sulfite/sulfate, and unreacted sorbent. The chemical composition of the sodium injection by-products is shown in Table 2. The IGCC process produces by-products similar to the above SO_2 control processes.

From the above description, it is evident that most SO_2 control processes generate a by-product similar to conventional fly ash. But due to sorbent addition, fly ash is modified to a great extent. The modified fly ash contain fly ash particles coated with sorbent and sorbent reaction products, and smaller non-fly ash particles composed of reacted and unreacted sorbents. Most coal combustion by-products generated from both conventional and advanced combustion processes are non-toxic.

Table 2: Clean Coal By-Products Chemical Composition (in %) (a) [ICF Northwest, 1988]

Sample No.	$A1_2O_3$	CaO	Fe_2O_3	MgO	K_2O	SiO_2	Na_2O	SO_3
AFBC:								
TVO3 (bed)	2.72	45.07	4.77	0.62	0.31	3.17	0.27	6.50(b)
TVO4 (char)	7.29	30.79	13.20	0.48	0.78	7.97	0.05	20.00
TVO5 (ash)	15.04	22.64	18.88	0.51	1.93	15.26	0.34	17.25
SFO6 (comp.)	6.12	39.13	17.11	0.54	0.72	6.04	0.29	12.00
Spray Dryer: (c)								
ARO7	25.20	21.73	3.26	0.84	1.69	21.17	3.29	17.50
STO7	12. 60	31.22	10.92	2.93	1.45	15.60	1.76	12.00
LRO7	21.20	26.88	6.11	2.33	0.74	17.72	2.08	12.25
HSO5	24.90	20.02	6.51	2.62	0.75	21.30	1.81	10.25
APO7	24.90	17.67	3.11	0.65	1.35	25.72	2.05	18.25
NVO4	15.00	21.32	4.83	1.53	0.60	20.42	6.58	14.00
RSO5	19.00	28.50	15.34	2.85	0.42	15.96	2.12	13.75
AVO6	18.00	19.03	9.23	4.62	1.46	24.52	9.17	11.50
Furnace Injection: (c)								
SRO7 (lime)	16.40	28.83	14.20	2.50	2.84	17.72	1.77	12.50
SRO9 (limestone)	17.20	29.15	16.48	0.82	2.96	19.33	1.64	11.25
OLO3 (limestone)	17.80	36.13	13.17	0.63	1.11	15.75	0.48	6.25
OLO4 (limestone)	17.10	40.00	11.91	0.70	1.08	16.18	0.51	5.50
OLO8 (limestone)	29.80	16.80	16.86	0.67	2.12	27.86	1.02	3.50
Calcium Injection:								
AHO6	9.07	40.57	2.17	0.56	0.82	10.27	0.59	NA
AA1O-01	31.37	15.39	8.86	1.13	3.37	29.95	1.24	NA
AA1O-02	31.37	13.99	8.86	1.13	3.37	27.81	1.27	NA
Sodium Injection:								
NXO4	28.90	4.54	2.50	1.16	0.77	25.18	24.78	12.00
NBO4	30.50	4.40	6.60	0.70	1.45	33.94	12.89	7.75

(a) All elements expressed as their oxides, but may occur in other forms.
(b) SO_3 content of the uncrushed sample; the crushed sample had a SO_3 content of 23.9%.
(c) These by-products were obtained from different sources.

PRODUCTION AND UTILIZATION RATE

During the last few decades, there has been a dramatic increase in coal ash production in the world due to increased amounts of energy being generated by coal-fired power plants. A number of researchers (Clarke, 1993; Manz et al., 1989; Manz, 1993) have compiled extensive data on production and utilization of coal ash in the world. Several eastern European countries, the states of the former USSR, and other countries which are marching toward rapid industrialization, such as China, and India, are showing increasing demand for coal. However, due to extensive restructuring in many countries (some European and the states of the former USSR), demand for coal is either practically constant or decreasing (Clarke, 1993). The countries producing large amounts of fly ash (10 million tons or more) are the former USSR (90 million tons), China (55 million tons), USA (48.5 million tons), India (36 million tons), South Africa (28 million tons), Poland (26.3 million tons), Germany including East and West (20.5 million tons), Turkey (15.3 million tons), Czechoslovakia (13.8 million tons), and United Kingdom (13.3 million tons), see Table 3. The countries producing fly ash in the range of 5 -10 million tons are Spain (7.4 million tons), Romania (7.0 million tons), Greece (5.7 million tons), and Bulgaria (5.3 million tons). Of the countries producing above 10 million tons of fly ash, the largest percentage of coal ash utilized was in the united Germany (47.4%) and the lowest is in the South Africa (0.8%) in 1989. The largest amount of coal ash utilization was in the united Germany (17.9 million tons) followed by China (16.2 million tons), USA (16.0 million tons), the former USSR (11.5 million tons), Yugoslavia (9.9 million tons), United Kingdom (5.5 million tons), and Poland (4.5 million tons). The major portion of the coal ash

Table 3: Coal Ash Production and Utilization in Thousand Tons in Various Countries in the World, 1987 and 1989 (Manz, 1993)

Country	Fly Ash	Bottom Ash & Boiler Slag	Cement Raw Material	Blended Cement	Cement Replacement	Grout	Nonaerated Blocks	Aerated Blocks
Australia	5539	1024			710			
Austria	341	43		78				
Belgium	872	150	65	174	309		96	
Bulgaria	5300	1060			20		50	
Canada	3463*	1096	132		445	3		5
Chile	200	18						
China	55,000	7500		369	1907			
Colombia	450	300		104			12	
Czechoslovakia	13,783	4334	8		23		9	312
Denmark	840	86	215	63	118			11
Finland	434	49	10	55	192			
France	2288	421	236	209	438			128
Germany (East)	12,479	6578		550	155			
Germany (West)	7980	4330		150	1250	200	530	
Greece	5730	516		757				
Hong Kong	1012	112		58	105			
Hungary	3880	937		145		3		239
India	36,000	4000		(a)				
Israel	370	40	40	210				
Italy	1249	131	775		250		20	27
Japan	3341	459	919	161	170			
Korea (South)	1929	214		100				
Mexico	1360	240		21	3			
Netherlands	765**	90		250	65		30	
Norway	0	0		95 (imported from Denmark)				
Poland	26,300	3200	78		260			920
Romania	7000	20,000		10	10			120
South Africa	28,000	32,000	250	72	89	20		
Spain	7391	1304		1100	300			
Sweden	225	25			10			
Taiwan	1089	272			393			
Thailand	1000	90						
Turkey	15,250	1865						
UK	13,300	2200		50	820	250	850	890
USA	48,458	16,776		821	5239	220		
Former USSR	90,000	35,000		1293	4240	10		78
Yugoslavia	12,147	1190	50	470		15	30	27
Total	414,765	147,650	2778	7365	17,521	721	1627	2757

Table 3: Coal Ash Production and Utilization in Thousand Tons in Various Countries in the World, 1987 and 1989 (Manz, 1993) (continued)

Country	Lightweight Aggregate	Bricks or Ceramics	Asphalt Filler	Structural, Land, or Embankment Fill	Pavement Base Course or Subgrade	Filler for Mines, Quarries, or Pits	Other	Total	% Used
Australia			10		30		20	770	11.4
Austria				18				96	25
Belgium		3	55	100	21		3	826	80.8
Bulgaria	30			10			5	65	1
Canada			1	610	55	40	20	1288	27.2
Chile								0	
China	62	4059		1200	2500	4600	1500	16197	25.9
Colombia	1			8	1		15	141	18.8
Czechoslovakia	91	29		934		39		1445	8
Denmark			17	319	40			783	84.6
Finland				75	55	25		412	85.3
France				105			433	1549	57.2
Germany (East)				4258	1045	700	448	7156	37.6
Germany (West)	320		50		1530	6420	260	10710	87
Greece								757	13.2
Hong Kong		74		271		616		1124	100
Hungary			1	168	12	29		597	12.3
India		(a)			(a)			800	2
Israel								250	61
Italy	3	28		126	2	35		1266	91.7
Japan	61	61	2	84	30	131	139	1758	46.2
Korea (South)								100	4.6
Mexico		18					3	45	2.8
Netherlands	120		125	120	50			760	82.6
Norway								95	100
Poland		345	12		270	1570	1000	4445	15.1
Romania		5		600				745	2.8
South Africa		21				40		492	0.8
Spain					100			1500	17.3
Sweden								10	4
Taiwan		49					4	446	32.8
Thailand								0	0
Turkey								0	0
UK	522			850		40	1195	5467	35.3
USA			204	2529	1300	20	5641	15974	24.4
Former USSR	2	842	980	4007		48		11500	9.2
Yugoslavia		65			200	5	123	985	7.4
Total	1212	5599	1457	16393	7241	14358	10809	90564	16.1

* + 180 imported from USA

** + 65 imported from West Germany and Belgium

(a) unknown quantity

used was in the form of fly ash; and, fly ash is composed of approximately 70 - 80% of the total coal ash produced.

Although 560 million tons of coal ash was produced in the world in 1989, only 90 million tons of this (about 16% of the total) was utilized (Manz, 1993). The utilization varied greatly from countries to countries, but in general countries producing lower amounts of coal ash reported higher percentage use of their total annual production. Concrete and concrete ingredients shared the largest use of fly ash markets. About 27.9 million tons were used world-wide in concrete production as a raw material in production of cement, in blended cement, and cement replacement. In 1989, the U.S.A. reported the largest amounts of annual use of coal ash in concrete in the world.

The U.S.A. showed rapid increase in fly ash use from 1.4 million tons in 1966 to 10 million tons in 1979 (Table 4). The utilization rate during 1979 - 1983 in the U.S.A. was less than 10 million tons. Beyond the 1983, except in 1986, the use of fly ash varied approximately between 10 - 12 million tons, the highest utilization occurred in 1990.

There has been about 300% increase in the amount of coal ash use as a cement replacement in the world compared to the amount used in 1977 (Manz, 1993). However, percent utilization of the total ash production is still very low. In most countries, lower utilization rate of coal ash is attributed to a number of regulatory and institutional constraints. The institutional constraints may include those requirements, standards, specifications, policies, procedures, and attitudes,

Table 4: Comparative Ash Collection and Utilization in the U.S.-1966 to 1990*

Year	Ash Collected in Millions of Tons				Ash Utilized in Millions of Tons			
	Fly Ash	**Bottom Ash**	**Boiler Slag**	**Total Ash**	**Fly Ash**	**Bottom Ash**	**Boiler Slag**	**Total Ash**
1966[a]	17.1	8.1	--	25.2	1.4	1.7	--	3.1
1967	18.4	9.1	--	27.5	1.4	2.3	--	3.7
1968	19.8	7.3	2.6	29.6	1.9	1.8	1.5	5.2
1969	21.1	7.6	2.9	31.7	1.9	2.0	1.0	4.9
1970	26.5	9.9	2.8	39.2	2.2	1.8	1.1	5.1
1971	27.8	10.1	5.0	42.8	3.3	1.6	3.7	8.6
1972	31.8	10.7	3.8	46.3	3.6	2.6	1.3	7.5
1973	34.6	10.7	4.0	49.3	3.9	2.3	1.8	8.0
1974[b]	40.4	14.3	4.8	59.5	3.4	2.9	2.4	8.7
1975	42.3	13.1	4.6	60.0	4.5	3.5	1.8	9.8
1976	42.8	14.3	4.8	61.9	5.7	4.5	2.2	12.4
1977	48.5	14.1	5.2	67.8	6.3	4.6	3.1	14.0
1978	48.3	14.7	5.11	68.1	8.4	5.0	3.0	16.4
1979	57.5	12.5	5.2	75.2	10.0	3.3	2.4	15.7
1980	48.31	14.45	3.64	66.40	6.42	4.26	1.75	12.43
1981	50.26	12.87	5.18	68.31	9.41	4.07	2.93	16.41
1982	47.91	13.13	4.37	65.41	7.95	3.63	1.97	13.55
1983	52.35	14.0	3.94	70.29	7.52	2.76	2.53	12.81
1984	51.32	13.62	4.21	69.15	10.43	2.96	2.65	16.04
1985	48.31	13.15	3.65	65.11	11.39	4.10	2.38	17.87
1986	49.26	13.41	4.13	66.80	8.78	3.59	2.15	14.52
1987	50.11	14.72	4.12	68.95	11.05	4.77	2.44	18.26
1988	50.91	14.27	5.03	70.20	11.36	5.43	2.83	19.83
1989	53.38	14.21	4.27	71.86	10.15	4.85	2.52	17.52
1990	48.93	13.71	5.23	67.87	12.42	5.36	3.25	21.03

[a] First year that data was taken.
[b] In 1974 a more comprehensive data collection program was developed, thus resulting in a substantial increase over previous year.

NOTE: 1 ton = 907 kg

* Compiled by CBU from American Coal Ash Association publications.

that adversely affect utilization of by-products (Kyper et al., 1993). The most dominant barrier in the utilization of fly ash appears to be the general lack of knowledge about fly ash, its properties and potential applications. This constraint can be overcome through education to the public, legislators, regulators, designer, contractor, etc. Such education should convince the potential users and the other associated parties that coal ash is a beneficial raw material not an inferior waste product. This may lead to development of regulations by environmental regulatory agencies and standard specifications by the contracting agencies associated with the fly ash utilization in construction materials (Kyper et al., 1993).

POTENTIAL USES OF COAL COMBUSTION BY-PRODUCT MATERIALS

The conventional coal combustion by-products utilization options are categorized into three classes of applications: Low Technology Applications; Medium Technology Applications; and, High Technology Applications. The following sections describe each of these categories of applications.

Low Technology Applications

The low technology applications for conventional coal combustion by-products are enumerated below.

Fills and Embankments. As a borrow material, fly ash is utilized in the construction of both structural and non-structural fills. Structural fills containing fly ash are used for the support of buildings and other structures, while non-structural fills made with fly ash are used for development of parks, parking lots, playgrounds, etc. The inclusion of fly ash in construction fills and embankments not only provides economical alternatives to natural soils and rocks due to its availability in urban areas but also it improves their properties such as shear strength, pozzolanic properties, ease of handling, moisture insensitivity, etc. (Collins, 1992, Baker, M., Jr., Inc., 1984; GAI Consultants, Inc., 1986; GAI Consultants, Inc., 1992).

Backfills. Fly ash is used as a backfill material for bridge abutments, buildings, retaining walls, trenches, excavations, etc. This is primarily because of favorable properties of this material, such as light weight, high shear strength, self-hardening properties, etc.

Pavement Base and Subbase Courses. For construction of base and subbase courses for pavements, fly ash is used in either with a combination with lime or portland cement, and aggregate; a combination with cement and lime; or a combination with the on-site soils, with or without the addition of lime (GAI Consultants, Inc., 1992). In general, the behavior of the fly ash and the stabilizer mixture is similar to that of a fine-grained soil cement mixture, but pozzolanic reaction of the fly ash results in an increase in strength and impermeability with time. This enhances the durability of the base or subbase course.

Subgrade Stabilization. A subgrade is a surface which acts as a foundation for pavements, floor slabs, embankments, or other structures. Fly ash alone or in combination with lime, is used to stabilize the subgrade in order to reduce plasticity, enhance strength, and improve workability of weak soils (GAI Consultants, Inc., 1992). The subgrade stabilization is needed in the construction of roadways, parking areas, railroad beds, building foundations, airport runways, etc.

Landfill Cover. Fly ash is an excellent cover material for landfills due to its several favorable properties such as compactability, shrinkage, and cementing behavior. It can be used in place of silts or clays for daily, intermediate, and final covers. The use of fly ash cover becomes economically attractive where other soils are scarce.

Soil Improvement. Addition of fly ash to soil results in improvements of infiltration characteristics, moisture-holding capabilities, and plant nutrients (trace elements) (Jacobs et al., 1991).

Land Reclamation. Fly ash can be used to neutralize the acidity of soil by increasing its pH value (Jacobs et al., 1991; Warren et al., 1991; Waagepetersen and Kofod, 1991). The reclamation of soil to be used for agriculture, turf-grass, parkland, etc., has been accomplished by adding fly ash to it.

Flowable Ash Slurry. The flowable ash slurry is a low strength material whose strength can vary between 50 to 1200 psi (0.34 - 8.22 MPa). This type of material contains large amounts of fly ash (20 to 90% of the total mix), low amounts of cement, and requires high water-to-cementitious material ratio to produce a high degree of fluidity. The resulting material is suitable for foundations, bridge abutments, buildings, retaining walls, utility trenches, as backfills, etc.; for abandoned tunnels, sewers, and other underground facilities as fills; and as embankments, grouts, etc. (Baker/TSA, Inc., 1990; Brendel et al., 1988; Naik et al., 1990 b).

Water Pollution Control. Fly ash can be utilized in water pollution control. This includes neutralization of acidic wastewaters, phosphorus removal from wastewater, physical conditioner for sludge dewatering, sorbent for various organics, sealing of contaminated sediments, etc. (Baker, M., Jr., Inc., 1984).

Medium Technology Applications

A great deal of research has been done to find use of fly ash in cement, concrete, and other cementitious composites.

Blended Cement. In order to save a significant amount of energy and cost in cement manufacturing, fly ash is utilized as a component of blended cements. Fly ash is used as either a raw material in the production of the cement clinker, interground with the clinker or blended with the finished cement (Clarke, 1993; Manz, 1993; Baker, M., Jr., Inc., 1984; Baker/TSA, Inc., 1987; Baker/TSA, Inc., 1990). Fly ash can be substituted for up to 8% of the clinker in manufacture of cement (Clarke, 1993). Gypsum obtained from FGD process may be added to the clinker as a set retarding agent.

Lightweight Aggregates. Fly ash has been utilized in manufacture of aggregates. Both sintered (fired) and unfired (cold bonded) processing methods are used to manufacture lightweight fly ash aggregates for use in lightweight concrete structures (Baker, M., Jr., Inc., 1984; Courts, 1991; Hay and Dunstan, 1991).

Low-Strength, Structural Grade, and High-Strength Concretes. In general, inclusion of fly ash in concrete provides economical, ecological and technical benefits (Berry and Malhotra, 1987; Langley, 1991; Malhotra and Painter, 1988; Naik and Ramme, 1990; Naik et al., 1991; Naik and Singh, 1991; Naik et al., 1992 a). The technical benefits include the improvement in properties of fresh and hardened concrete. In general, adding of fly ash as a partial replacement of cement in concrete mixtures improves workability, pumpability, cohesiveness, and causes reduction in water requirements, bleeding and segregation of fresh concrete. It also enhances strength and durability of hardened concrete due to both pore and grain refinements resulting from pozzolanic reaction of fly ash. Strength and durability properties of concrete up to an optimum level of cement replacement by fly ash is either equivalent or superior to no-fly ash concrete. More recent studies have shown that high-volume fly ash concrete having more than 50% cement replacement with either Class C or Class F fly ash can be proportioned to meet strength requirements for structural applications (Naik et al., 1992 a).

Paving Concrete. This concrete is proportioned to obtain lower slump compared to structural grade as well as high strength concretes. Recent studies have revealed that concrete containing large amounts of fly ash (for cement replacement in excess of 50% by weight) can be proportioned to meet strength and durability requirements for highway paving work (Naik et al., 1992 a; Naik et al., 1993).

Lightweight Fly Ash Concrete. This type of concrete can be manufactured by using lightweight aggregates made with or without fly ash in which fly ash is used as a partial replacement of cement, which also enhances the pumpability of such concretes (Baker, M. Jr., Inc., 1984; Courts, 1991).

Precast/Prestressed Products. The use of fly ash in high strength precast/prestressed concrete has been limited due to manufacturers concern about slow strength gain of fly ash concrete systems at very early age. Recent studies have substantiated that superplasticized fly ash concrete with low water-to-cement ratio can be proportioned to meet the very early age strength as well as other requirements for precast/prestressed concrete products. Researchers (Naik et al., 1990 a; Prusinki et al., 1993) have reported that concrete incorporating Class C fly ash to replace cements up to 30% attains high early strength appropriate for precast/prestressed concrete products. Additionally, workability and finishability is improved and water demand is decreased when fly ash is added to the mix. Improved workability of concrete mixture with fly ash results in products with sharp, distinctive corners and edges (ACI 226 Committee, 1987).

Concrete Pipe. Concrete pipe made with fly ash is superior to no-fly ash concrete pipe (ACI 226 Committee, 1987; Davis, 1954). Fly ash pipes are more watertight and more resistant to weak acids and sulfates attack relative to plain portland cement concrete pipes.

Roller Compacted Concrete. Roller compacted concrete (RCC) is placed and compacted by using asphalt paving equipment for construction of pavement or earthwork equipment for construction of dams (GAI Consultants, Inc., 1992). This concrete has been used in some pavements and several major concrete dams in the U.S.A. RCC is very low in water-to-cementitious ratio (zero slump) and contains higher proportions of fine particles to reduce segregation. The lower water-to-cement ratio results in higher strength compared to the conventional mix. Fly ash can be used in large amounts as a fine filler material as well as a pozzolan in the RCC mix (Berry and Malhotra, 1987; Golden, 1991, a).

Autoclaved Cellular Concrete (ACC). Autoclaved cellular concrete (ACC) or aerated concrete is a lightweight material. It is manufactured using powder silica sand, portland cement, limestone, aluminum powder, and water as raw materials. In the case of fly ash ACC, fly ash replaces 30 to 100% of the sand. In order to manufacture ACC, the ingredients are mixed into a slurry and poured into greased molds up to two-thirds of their depth. The reactions that occur between the aluminum powder, calcium hydroxide, and water generate hydrogen gas which aerates the mixture producing millions of non-connected microscopic cells (Pytlik and Saxena, 1991).

The fly ash autoclaved cellular concrete can consume about 20 - 35 lbs of fly ash per cu. ft. of the finished products (Golden, 1991 a). Several manufactures, namely Celcon, Durox, Thermalite, YTONS, etc., are using fly ash in production of autoclaved concrete blocks. The U.K. and the

USSR are the major users of fly ash in ACC. Thermolite in the U.K. uses 600,000 metric tons of fly ash annually to produce 1.5 million cubic meters of ACC blocks. In 1989, SILBET in the USSR utilized 367,200 metric tons of coal ash and shale-oil fly ash in production of ACC blocks. The ACC is manufactured in a number of shapes to allow flexibility in construction of structural units such as blocks, wall and roof panels with or without reinforcement, lintels, beams, tongue and groove jointed panels, etc. Compared to plain portland cement ACC, the fly ash ACC offers several advantages such as lower weight, higher insulation capability (R-value of 10 to 12 for six inch thick material), a fire rating of at least two hours, more easily worked with carpenter's tools, etc. (Golden, 1991 a; Pytlik and Saxena, 1991).

Bricks, Blocks, and Paving Stones. Fly ash can be utilized in manufacture of the fired, unfired, and steam cured bricks (Wei, 1992; Rai, 1991; Naik et al., 1992 b; Shen and Wu, 1991; Frigione et al., 1993). It can also be used in clay bricks as a large-volume replacement of clay (Naik et al., 1992 b). In the U.S.A., the Coal Research Bureau of West Virginia University has developed a method for molding and firing brick from a mixture of 72% fly ash, 25% bottom ash, and 3% sodium silicate (Naik et al., 1992 b). A more recent study at the Center for By-Products Utilization (CBU), UW-Milwaukee, Wisconsin, U.S.A. has shown that a mixture of large quantities of fly ash, low amounts of cement, and sand, can be proportioned to produce good quality bricks. Blocks and paving stones can also be manufactured by adding appropriate amount of coarse aggregate to the mixture (Wei, 1992).

Other Binders. Fly ash can be used to manufacture mortar for brick walls, grouts, etc.

Manufacture of High-Strength Ceramic Products. Fly ash can be used in high-flexural strength ceramics. These include railroad ties, electric line insulators, fence posts, etc. Currently these products are being made with concrete or clay-based materials.

Filler in Asphalt Mixture. Fly ash can be used as a mineral filler in the asphaltic concrete mixtures. The use of fly ash as an asphalt additive is economically attractive, and its performance in the asphaltic mixture compares favorably with other fillers (Baker M. Jr., Inc., 1984).

Artificial Reefs. A number of projects (Baker M. Jr., Inc., 1981; Michaud, 1986; New York State Energy Research and Development Authority, 1984; Research Foundation of State University of New York, 1984; Baker et al., 1991; Livingston et al., 1991) have been carried out to make artificial reefs with blocks composed of fly ash, bottom ash, FGD sludge, lime, and cement. These studies have substantiated that these by-product materials perform equivalent or better than conventional artificial reef materials. Most investigations have indicated that reefs made with coal-combustion by-products are environmentally sound and economically feasible.

Waste Stabilization/Solidification. Coal ash is utilized effectively in stabilization/solidification technologies for both industrial and municipal wastes (Eklund, 1991; Fazzini et al., 1991; Smith, 1991; Collins and Fazzini, 1991; Smith, 1991; Tyson, 1991; Burnham, 1993; Smith, 1993; Albino et al., 1993). These wastes can be inorganic, organic, or combined/complex. The wastes can be further classified as hazardous or non-hazardous wastes. Addition of fly ash to wastes can improve their handling characteristics due to increased fluidity. Fly ash is used as a binding agent alone or in conjunction with other binders such as lime, portland cement, etc. for stabilization of the wastes. The reactions of fly ash in the mix, both cementitious and pozzolanic, results in formation of C-S-H matrix in which wastes are entrapped or microencapsulated (Tyson, 1991). The mixture of waste containing fly ash with or without other binders is proportioned to meet environmental criteria especially leaching characteristics, and strength and durability requirements.

High Technology Applications

Material Recovery. Several metals have been extracted from fly ash. In general, two methods are used to recover metals from fly ash: the direct acid leaching (DAL) and pressure digestion- acid leach (PDA) for extraction of metals. The major metals extracted from fly ash are alumina and iron, and the other trace elements include chromium, cobalt, manganese, etc. The resource components of fly ash for which favorable cost-effective process exists are carbon, magnetite, cenospheres, and metals such as alumina, iron oxide, etc. (Golden, 1991 a, b).

Fillers for Polymer Matrix Composites (PMC). Cenospheres derived from fly ash are an ideal filler material for manufacture of polymer matrix composites (Hemmings and Berry, 1986; Kline and Associates, 1990; Quanttroni et al., 1993; Kruger and Toit, 1991). The polymeric matrix can be composed of either thermoplastic or thermosetting plastics. Due to spherical shape of these particles, they offer several advantages over the fillers having irregular shapes (Golden 1991 a). These include: ease of wetting and dispersion, uniform stress distribution during molding, reduced shrinkage during cooling, reduced warpage of injection molding components, reduced wear of fabrication equipment, etc. The use of such fillers not only reduces the demand for costly plastic matrix materials but also improves several properties of the matrix. The polymer matrix materials that have been used in such PMC include epoxy resins, polypropylene, nylon, PVC, polyethylene, etc. The improvement in properties of the composites due to inclusion of the cenosphere are compressive strength, elastic modulus, reduction in thermal expansion, and thermal conductivity. However, mostly tensile strength and fracture properties deteriorate due to inclusion of large amounts of the filler. Therefore, optimum level of the filler concentration should be determined for a particular application.

Metal Matrix Composites (MMC). Fly ash has been used as a component of the metal matrix of a suitable composite prepared by foundry processes (Keshavaram, 1986; Rohatgi et al., 1991; Rohatgi et al., 1993). Researchers have shown that second phase particles can improve physical, mechanical, and tribological properties of the matrix material. In general, inclusion of fly ash particles in aluminum alloy matrix has shown a decrease in its density, and increases in its elastic modulus, abrasion resistance, and hardness (Rohatgi et al., 1993). Besides, the replacement of aluminum with fly ash would provide large savings in cost of the materials. It is reported that such a low-cost composite can be made suitable for a number of automotives and electromechanical applications such as pistons, cylinder liners, bearings, and current collectors. However, a very limited information is available about fatigue and fracture behavior of such composites. Additional research is needed to evaluate these properties of the composites made with fly ash before they can be recommended for commercial applications.

Other Filler Applications. There are several applications where currently aluminum hydrate, calcium carbonate, kaolin, mica, talc, and ground silica are used. For such applications fly ash cenosphere can be utilized (Golden, 1991 a). Other potential filler applications include asphalt roofing shingles, wallboards, joint compounds, carpet backing, vinyl flooring, industrial coatings, etc.

The fly ash cenospheres have also been found (Baker M. Jr., Inc., 1984) appropriate for numerous applications such as: (1) tape for fireproofing and insulating high voltage cables; (2) closed pore insulating material being used as heat shields in aerospace industries; (3) liquid epoxy molding systems for electronic castings; (4) foundry sand to reduce weight and improve flow of sand used in molding; (5) molded ornament panels used in furniture; (6) fabrics for protecting personnel from molten metals; (7) replacement for glass beads in synthetic foam used to achieve buoyancy in oceanographic applications; and, (8) medium for growing turf grass.

Mineral Wool. Mineral wool is primarily a glassy, fibrous insulating material. It is generally manufactured from mixtures of metal processing slags and limestone or silica (Hnat and Talley, 1991). Studies (Baker M., Jr., Inc., 1984; Hnat and Talley, 1991) have shown that mineral wool can be manufactured using either bottom ash or fly ash. These ashes can be processed to produce fine insulating fibers, similar to that of commercial mineral wool.

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