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Utilization of CFB Fly Ash for Construction Applications

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R. E. Conn and **K. Sellakumar**
Foster Wheeler Development Corporation
Livingston, NJ

A. E. Bland
Western Research Institute
Laramie, WY

ABSTRACT

Disposal in landfills has been the most common means of handling ash in circulating fluidized bed (CFB) boiler power plants. Recently, larger CFB boilers with generating capacities up to 300 MW_e are currently being planned, resulting in increased volumes and disposal cost of ash by-product. Studies have shown that CFB ashes do not pose environmental concerns that should significantly limit their potential utilization. Many uses of CFB ash are being investigated by Foster Wheeler, which can provide more cost-effective ash management.

Construction applications have been identified as one of the major uses for CFB ashes. Typically, CFB ash cannot be used as a cement replacement in concrete due to its unacceptably high sulfur content. However, CFB ashes can be used for other construction applications that require less stringent specifications including soil stabilization, road base, structural fill, and synthetic aggregate. In this study, potential construction applications were identified for fly ashes from several CFB boilers firing diverse fuels such as petroleum coke, refuse derived fuel (RDF) and coal. The compressive strength of hydrated fly ashes was measured in order to screen their potential for use in various construction applications. Based on the results of this work, the effects of both ash chemistry and carbon content on utilization potential were ascertained. Actual beneficial uses of ashes evaluated in this study are also discussed.

INTRODUCTION

CFB combustion has developed into a mature technology for burning a wide range of fuels, while still achieving strict air emissions requirements. Typically, fuels are burned in a CFB boiler with the addition of limestone to capture SO_2 in a solid form. With larger CFB boilers being brought online, a greater emphasis has been placed on enhanced beneficial use of ash than in the past. Studies have shown that the environmental impact from CFB ashes is less than those from p.c. ashes and should not limit their utilization as marketable by-products (Conn and Sellakumar, 1997; Young, 1996).

Traditionally, p.c. fly ash has often been sold for use as an admixture in the production of Portland cement. The utilization options for CFB ashes are somewhat more diverse than p.c. ash, due to the effect of sorbent (calcium) on the overall ash chemistry. These options include agricultural applications, construction applications and waste treatment.

Beneficial use for construction purposes is one of the most common markets for CFB ash. These uses include soil stabilization, road base, structural fills, and synthetic aggregate. To qualify for these uses, the ash must have special properties and pass certain ASTM tests. Compressive strength is one of the most important physical properties a material must possess when being considered for different construction applications. The unconfined compressive strength is measured by ASTM test methods which involves curing of the ash at 100% relative humidity for specified periods of time. Depending upon the specific application, different degrees of compressive strength are required. In this study, the unconfined compressive strength was measured for hydrated CFB fly ashes from boilers firing a wide range of fuels. These results provided a indication of potential construction uses for fly ashes with very different compositions.

The specific objectives of this work were:

- To assess the technical feasibility of CFB ash use in construction applications; and,
- To evaluate the effects of ash composition on compressive strength and potential construction uses.

CHARACTERIZATION OF FLY ASHES

Nine fly ashes evaluated in this study were obtained from CFB boilers firing diverse fuels such as bituminous gob (0.5% S), low volatile bituminous coal (0.3% S), high sulfur (4.7%) bituminous coal, petroleum coke (5.0% S), and RDF (0.3% S). Table 1 lists the chemical composition for selected fly ashes as determined by x-ray fluorescence. The loss on ignition (LOI) was composed of moisture, organic carbon, and carbonate. Moistures were typically less than 1.0% and the carbonate carbon was less than 0.2%. The free lime (CaO) content was calculated based on the ratio of SO_3 and CaO from the ash oxide analysis and the carbonate carbon content.

As shown in this table, the fly ashes had significantly different chemical compositions as would be expected considering the types of fuels being fired. The bituminous gob fly ash was composed primarily of coal ash since it was taken from a boiler that does not use limestone injection for sulfur capture. The bituminous coal fly ash samples contained both coal ash and sorbent, with relatively high amounts of free lime. Fly ash from petroleum coke was composed mainly of sorbent compounds due to the low ash content of the fuel. Finally, the RDF fly ash had a composition fairly similar to that of a bituminous coal. However, most of the calcium in the fly ash was inherent in the RDF and not derived from sorbent, since a sand bed is used for CFB solids inventory. Some calcium in the RDF fly ash did originate from the semi-dry scrubber used to remove SO_2 and HCl from the flue gas.

The LOI was relatively low for most of the fly ashes and less than 5%. One notable exception was the fly ash obtained from firing a low volatile Australian bituminous coal with somewhat low reactivity. Although the LOI was high (18.9%), the fuel combustion efficiency was greater than 97% in the CFB boiler. The apparently high LOI in this fly ash was partially a result of low fuel ash and sulfur contents (low sorbent injection rate). Therefore, the unburned carbon exited in the fly ash without much dilution from fuel ash or sorbent.

Table 1 Chemical Analysis of Fly Ashes

Oxide, wt%	Bituminous Gob	Low Volatile Bituminous	High Sulfur Bituminous	Petroleum Coke	RDF
SiO_2	54.1	41.7	24.8	3.0	20.8
Al_2O_3	33.8	33.6	15.4	nil	23.6
TiO_2	1.4	1.9	0.7	nil	2.9
Fe_2O_3	4.3	3.5	3.5	0.1	3.3
CaO	4.1	14.9	19.2	54.0	26.8
MgO	1.2	0.9	0.5	2.5	4.3
Na_2O	nil	0.2	nil	nil	2.2
K_2O	1.1	0.8	1.5	nil	1.2
SO_3	1.6	3.4	7.4	41.9	4.8
LOI	3.5	18.9	2.8	4.7	5.4
Free CaO	3.0	12.5	14.0	21.5	16.3

Table 2 Major Compounds Identified by XRD

Bituminous Gob	Low Volatile Bituminous	High Sulfur Bituminous	Petroleum Coke	RDF
SiO_2	$CaSO_4$	$CaSO_4$	$CaSO_4$	$CaSO_4$
Fe_2O_3	SiO_2	SiO_2	SiO_2	$CaSO_3$
$K_2Al_6Si_6O_{22}$	Fe_2O_3	Fe_2O_3	$Ca_3V_2O_8$	$CaCl_2$
	$Al_2Si_2O_7$	$Al_2Si_2O_7$	$Ni_3V_2O_8$	Al_2O_3
				SiO_2

Phase analyses of the ashes by x-ray diffraction (XRD) are shown in Table 2. The coal fly ashes were composed primarily of anhydrite ($CaSO_4$), hematite (Fe_2O_3), silica (SiO_2), and dehydroxylated clays. Anhydrite was not found in the bituminous gob fly ash, since it did not contain sorbent. The petroleum coke ash was composed principally of sorbent derived compounds and minor amount of silica (3.0%). As shown in Table 2, calcium vanadate was observed in the petroleum coke fly ash indicating some interaction of the sorbent with vanadium present in the petroleum coke (Anthony et al, 1995a; Bryers, 1995; Conn, 1995). The RDF fly ash contained calcium chloride ($CaCl_2$) and calcium sulfite ($CaSO_3$) which were probably formed in the semi-dry scrubber used to treat the flue gas.

The general physical properties of the ashes were also determined, including poured and compacted bulk densities, specific gravity, particle size distribution, and moisture. These physical properties of the as-received ashes are presented in Table 3.

Table 3 Physical Properties of Fly Ashes

% passing, microns	Bituminous Gob	Low Volatile Bituminous	High Sulfur Bituminous	Petroleum Coke	RDF
600	100.00	99.96	100.00	99.98	98.60
300	99.93	99.92	99.99	99.96	98.28
150	98.48	99.79	98.75	99.43	97.70
74	79.08	96.70	86.26	92.57	90.33
44	79.08	83.98	64.18	70.45	70.99
Bulk density, pour/compact kg/m^3 (lb/ft^3)	700/996 (43.7/62.2)	541/841 (33.8/52.5)	916/1167 (57.2/72.9)	786/1182 (49.1/73.8)	589/841 (36.8/52.5)
Spec. gravity	2.43	2.21	2.66	2.96	1.80
Moisture, %	0.68	0.99	0.47	0.24	1.63

The fly ashes were all relatively fine with greater than 80% passing a 200-mesh screen (74μm). As a result, these ashes can readily be made into cement-type pastes without further milling. The poured bulk density of the fly ashes ranged from about 34 to 57 lb/ft^3 (385 to 913 kg/m^3); the compacted bulk density of the fly ashes were slightly higher and ranged from 53 to 74 lb/ft^3 (849 to 1186 kg/m^3). The specific gravity ranged from 1.8 to 3.0 for the fly ashes. The RDF fly ash had a relatively low specific gravity compared to the other ashes, probably since it contained a different type of inorganics. This ash was derived from fine inorganics in RDF, not limestone sorbent or coal minerals. Moisture was generally less than 1.0%, except for the RDF fly ash, which contained 1.6% moisture.

EXPERIMENTAL PROCEDURES

Unconfined compressive strength of the fly ashes was measured similar to ASTM C-109. A paste was prepared by mixing about 35% by weight water and 65% fly ash to form 0.75 in. (1.91 cm) pellets in a plastic mold. The bulk density of the ash in these pellets was about 60 lb/ft^3 (960 kg/m^3). For soil stabilization tests, fly ash (15% by weight) was mixed with clays to form a pellet. These samples were cured under saturated conditions at 23^{o}C for 3, 7 and 28 days. The compressive strength of the hydrated samples was then measured using a compressive testing machine. These test results are shown in Table 4 for the five fly ashes.

Table 4 Fly Ash Unconfined Compressive Strength, psi*

Curing time	Bituminous Gob	Low Volatile Bituminous	High Sulfur Bituminous	Petroleum Coke	RDF
3 days	9	10	550	45	100
7 days	40	90	760	95	190
28 days	41	350	1490	520	145

* For simplicity, compressive strength units in Tables 4, 6, 7, and 9 are listed in English units; metric units are included in the text.

This procedure was intended to simulate the actual construction uses in which cement pastes would be made from fly ashes. Considerably less water is used in the ASTM C-109 procedure compared to the hydration technique used in this study. In addition, the ash bulk density was less than that typically used for ASTM C-109. As a result, the compressive strengths may differ somewhat from those obtained by the ASTM test. However, the relative trends between different fly ash samples would be expected to be similar for both procedures.

In most cases no other materials were mixed with the fly ashes except water. Strength development resulted solely from the self-cementing properties of the ashes. No concrete-type mixtures incorporating sand or aggregate were evaluated in this study. The fine size distribution of the fly ashes makes them ideal candidates for producing pastes simply with the addition of water. Bottom ashes may also be suitable for some construction applications, but could require milling to a desired, much finer size distribution.

CONSTRUCTION USES FOR CFB ASHES

Laboratory tests were performed to address the use of different fly ashes in a number of construction applications including (1) cement replacement and manufacturing, (2) structural fills, (3) road base, (4) synthetic aggregate, and (5) soil stabilization.

CONCRETE AND CEMENT PRODUCTION

CFB fly ash may be used in concrete and cement production as (1) as a replacement of cement in Portland cement concrete; (2) a pozzolanic material in the production of pozzolanic cements; and (3) a set retardant interground with cement as a gypsum replacement. The use of CFB fly ash as a pozzolan for replacement of Portland cement in concrete is restricted by ASTM C-618 specifications as shown in Table 5. Several of the key specifications are FAS content ($Fe_2O_3 + Al_2O_3 + SiO_2$), SO_3 content, and LOI. Only the bituminous gob fly ash would qualify as a Class F pozzolan. The RDF fly ash nearly qualifies as a Class C pozzolan, but its high chlorine content (4.5%) would probably limit its actual usage in cements.

Table 5 Fly Ash Properties Versus ASTM Pozzolan Specifications for Cement Replacement

	Bituminous Gob	Low Vol Bituminous	High S Bituminous	Petroleum Coke	RDF	ASTM C-618
SiO_2+Al_2O_3 + Fe_2O_3, %	92.2	78.8	43.7	3.1	47.7	Class F >70 Class C >50
SO_3, %	1.6	3.4	7.4	51.7	4.8	5 max
LOI, %	3.5	18.9	2.8	2.2	5.4	6 max
Fineness,% >44 µm	20.9	16.0	35.2	29.5	29.0	34 max
Moisture,%	0.68	0.99	0.47	0.24	1.63	3 max

The potential also exists for using CFB ash for regulating the set time of Portland cement, instead of conventionally used gypsum (calcium sulfate dihydrate). Tests were conducted with petroleum coke fly ash that contained high concentrations of CaO and SO_3 (calcium sulfate). Quantitative XRD analysis showed that this fly ash contained 66% $CaSO_4$ and 30% CaO. To compare performance of cements with the fly ash and with commercial grade gypsum, three samples were prepared with a Type I cement clinker including:

- 94.5% clinker, 4.6% gypsum;
- 94.5% clinker, 2.3% gypsum, 2.8% fly ash; and
- 94.5% clinker, 5.6% gypsum.

The cements were ground in a batch ball mill and tested for compressive strength and time of set according to ASTM standards C-109 and C-191, respectively.

The results in Table 6 confirmed the strength characteristics of the three cements exceeded the standard specifications of ASTM C-150. The cements using the petroleum coke fly ash slightly outperformed the control cement with conventional gypsum in 28-day strength tests. Setting time was shorter for the experimental cements, but remained comfortably within standard limits. Test results would be expected to vary for cement clinkers of different compositions.

Table 6 Physical Testing of Cements Using Petroleum Coke Fly Ash as Set Retardant

	ASTM C 150	4.6% gypsum	2.3% gypsum 2.8% fly ash	5.6% fly ash
Compressive strength, psi				
1 day		3040	2970	3200
3 days	1800	3800	4030	4360
7 days	2800	4760	4760	4700
28 days		5670	5950	5820
Setting time, min				
no less than	45			
no more than	375			
actual		135	110	76

STRUCTURAL FILLS

Natural soil borrow, granular fill, boiler slag, and other embankment or structural fill materials are typically tested to determine their shear strength (Brendal et al, 1997). Cementitious materials such as fly ash, however, are more appropriately evaluated by the unconfined compressive strength test. Table 7 lists the general strength requirements for structural fill materials.

Table 7 General Strength Requirements for Different Construction Uses (Brendal et al., 1997)

Compressive Strength, psi	Structural Fill		Road base	Road base	Stabilized Soil
	Flowable	Compacted			
7 days			>400	>500	
28 days	50 - 150	>1000	>600		>400

The two major types of structural fill materials are (1) flowable (or excavatable) and (2) compacted or embankment. Flowable fill is a cementitous material that can be used as a substitute for compacted soil. Several uses include excavatable backfills, trench/pipe bedding, and mine void filling. Flowable fill is usually mixed in a ready-mix concrete truck, with mixing continuing during transport to prevent segregation. Although flowable fill may be designed for use under high loads, this material is typically designed for a compressive strength of 50 to 150 psi (345 to 1035 kP) at 28 days. (Note that this strength may continue to increase with time.) Strengths lower than 50 psi

(345 kP) are insufficient for use as a structural fill. Strengths higher than 150 psi (1035 kP) at 28 days could result in fill materials which would not allow excavation.

Compacted fills and embankments require materials with high strength for supporting heavy loads and should be considered permanent. These materials should not be considered for use around pipes, utility lines, or other locations that may need to be accessed. As shown in Table 7, strength at 28 days in excess of 1000 psi (6.9 MP) is required for this type of structural fill.

Compressive strength results (Table 4) show that only the RDF fly ash would qualify as a flowable fill since its 28-day strength was 145 psi (100 kP). It should also be noted that this ash showed considerable rapid expansion upon hydration, resulting in a very porous material. In fact, the hydrated ash pellets grew in volume by 50% in only ten minutes. The reason for this expansion is uncertain, but may be due to reaction of fine aluminum metal and $Ca(OH)_2$ in the ash with water resulting in evolution of hydrogen gas. This reaction is similar to that used for autoclave cellular concrete (ACC).

The high-sulfur bituminous coal fly ash would qualify as a permanent compacted fill and had a relatively high 28-day strength of near 1500 psi (10.3 MP). This high strength is not surprising since the ash nearly qualifies as a Class C pozzolan or self-cementing material. As a result, it is currently being marketed as a component in permanent fill materials. Relatively high strength ash such as this can be made to exhibit lower strengths for excavatable fill, simply by the addition of sand.

Free lime, particularly in combination with FAS components, is one of the key ash components that influence the strength of hydrated ashes. The compressive strength did correlate with the free lime content of most of the bituminous coal fly ashes as shown in Figure 1. This figure also contains data from other fly ashes not listed in Table 1. Free lime, once hydrated to calcium hydroxide, would be expected to undergo pozzolanic reactions with ferric oxide, aluminum oxide and silicon oxide (FAS) components in the ash to form complex hydrates:

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow CaO{\cdot}SiO_2{\cdot}2H_2O \qquad (1)$$

$$Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow CaO{\cdot}Al_2O_3{\cdot}2H_2O \qquad (2)$$

$$SiO_2 + Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow CaO{\cdot}SiO_2{\cdot}Al_2O_3{\cdot}2H_2O \qquad (3)$$

$$Fe_2O_3 + Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3{\cdot}2H_2O \qquad (4)$$

In addition, the development of strength can result from formation of ettringite $[Ca_6Al_2(SO_4)_3(OH)_{12}{\cdot}26H_2O]$. Ettringite forms from soluble calcium hydroxide, alumina, and gypsum (Anthony, et al., 1995b; Bland and Brown, 1997). With RDF ash, ettringite formation could occur relatively quickly compared to coal ashes. Compared to coal ashes, the hydrated RDF ash probably contained more soluble aluminum in the form of aluminum hydroxide $[Al(OH)_2)]$, a key reactant in ettringite formation, instead of aluminosilicate minerals. Consequently, expansion must not be a critical property if the RDF ash is to be used as a flowable fill.

The low-volatile bituminous fly ash did not develop very high strength despite its moderate free lime content of 12.5%. The cause of low strength development is unclear. The high carbon content of the ash (LOI = 18.9%) may have been responsible for limiting its strength development. On the other hand, the lower $CaSO_4$ content of this ash may have limited the formation of etrringite or gypsum. There is conflicting evidence as to the effect of high carbon content on the strength development of CFBC ashes.

Figure 1 also shows compressive strength data for a low volatile bituminous coal fly ash, which also had a relatively high LOI of 12%. This fly ash was obtained from a boiler firing a 4.5% S low-volatile coal with significant inert carbon content. Although this fly ash had 12% LOI, it developed a 28-day strength of 1620 psi (11.2 MP), possibly due to its high free lime content of 22.5%. Consequently, it appears that high LOI may not limit the strength of hydrated ash, provided it contains sufficient free lime and FAS to form pozzolanic reactions or soluble alumina and calcium sulfate to from ettringite or gypsum.

The RDF ash was also very high in free lime content (16.3%) and almost qualifies as a Class C pozzolan. This ash developed low strength even though it would be expected to have considerable self-cementing properties. This low strength was a result of the formation of a porous hydrated ash as mentioned earlier.

The petroleum coke fly ash listed in Table 1 had high free-lime content, yet moderate compressive strength [520 psi (3.6 MP) after 28 days]. The petroleum coke ash developed this moderate strength due to hydration reactions of lime and calcium sulfate, not pozzolanic reactions:

$$CaO + H_2O \rightarrow Ca(OH)_2 \text{ calcium hydroxide} \qquad (5)$$

$$CaSO_4 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O \text{ gypsum (slow)} \qquad (6)$$

Insignificant pozzolanic reactions would be expected with this ash since it contains only minor amounts of FAS components (3% SiO_2). Another petroleum coke fly ash (see Figure 1) developed considerably higher strength (820 psi/5.7 MP) but contained only 8.6% free lime. This strength would nearly qualify the ash as a suitable compacted fill, since it almost meets that required by the ASTM C-109 test. As a result, calcium sulfate content may be a better indication of strength development than free lime for hydrated petroleum coke ashes, since it may be the principal bonding mechanism.

As shown in Table 4, the bituminous gob fly ash did not develop any significant strength since it contained little free lime (no self-cementing properties). The effect of lime addition on ash compressive strength was investigated. As shown in Figure 2, addition of only 10% lime (by weight) roughly doubled the 28-day strength (93 psi/641 kP) of the fly ash making it suitable for excavatable (flowable) fill use. Addition of 25% lime increased the 28-day compressive strength to 750 psi (5.2 MP). Slightly higher amounts of lime addition should make the mixture suitable for use as a compacted fill.

The effect of different additives on the strength of hydrated petroleum coke fly ash was also investigated. As shown in Figure 3, addition of Portland cement and coal fly ash/Portland cement raised the compressive strength after 28 days to greater than 1500 psi (10.3 MP). This additional strength was partially a result of pozzolanic reactions of free lime with FAS components in the cement or fly ash. These mixtures would have sufficient strength to qualify as potential compacted fills. Addition of blast furnace slag to the petroleum coke ash did not result in as high as strength, possibly due to its lower FAS content.

Compressive strength is only one of the physical properties that fill materials must meet. Other geotechnical tests must also be met such as expansion, swell and permeability. The expansion test is defined by specific ASTM standards C-157. Expansion of the fill material is undesirable and often occurs in hydrated coal ashes due to formation of ettringite. However, with coal ashes, the expansion generally occurs over a longer period of time (up to six months) compared to that mentioned earlier for the RDF ash.

The permeability of an ash is a measure of the rate at which a fluid passes through a material and, along with leachate data, may be used to estimate possible impacts on groundwater quality. For comparison purposes, a permeability coefficient of 1×10^{-7} cm/sec or lower is often required for clay liners in landfills. A 1×10^{-6} cm/sec coefficient corresponds to a percolation rate of approximately 0.3 meters per year. Permeability data for CFB fly ashes has been shown to range from about 10^{-5} to 10^{-9} cm/sec (Radian Corp., 1992).

ROAD BASE

CFB fly ashes have the potential as substitutes for lime or fly ash in road base construction or as a sole material. To provide strength, durability, and dimensional stability, the following criteria should be applied to CFB ash as road base:

- The 7-day unconfined compressive strength when cured under moist conditions at 70^{o}F to 73^{o}F (21^{o}C to 23^{o}C), must be 400 to 450 psi (2.8 to 3.1 MP).

- The strength of the mix must increase with time (GAI Consultants, 1992). The 28-day unconfined compressive strength should be at least 550 to 600 psi (3.8 to 4.1 MP).

- Expansion requirements are not well established. However, it is suggested that linear expansion be restricted to between 0.1 to 0.5% (Minnick, 1982).

As shown in Table 4, only the high-sulfur bituminous coal fly ash would meet the 7-day strength requirements for road base. The bituminous gob ash with 25% lime addition would also have suitable strength to be used as road base material. Probably lower strengths were obtained by the hydration of the ashes than would be obtained with less moisture according to the ASTM D698 optimum moisture and compaction.

The petroleum coke fly ash had nearly sufficient 28-day strength, but not enough 7-day strength to qualify as a road base material. Addition of Portland cement was shown to increase the 7-day strength of the fly ash, such that it would qualify as a road base material (Figure 3). However, the potential might exist for long-term expansion due to the formation of ettringite.

Experience with the petroleum coke CFB ash has shown that it can be used as a road base without expansion problems (Tharpe and Abdulally, 1997). Road base material is made batchwise from a hydrated mixture of about 70% fly ash and 30% bed ash. The hydrated material is compacted with heavy equipment and allowed to cure for several weeks. After curing, the ash is then reclaimed and sized for different uses. The pressure from the compaction probably helps yield a product with sufficient strength for road base. Expansion with this material is not a problem since the ettringite formation does not occur, probably due to lack of Al_2O_3 in the ash.

Mixtures using small percentages of CFB coal fly ash in aggregate-based mixes have been tested which developed adequate strength without excessive expansion. Although mixtures of moderate proportions of CFB ashes may allow beneficial use of greater quantities of material, test road bases with moderate percentages of CFB ash experienced excessive expansion (Minnick, 1982). The long-term formation of ettringite has been attributed to these expansion problems. The high-sulfur bituminous coal and RDF ashes (Table 1) would be expected to have the greatest potential for expansion. The high-sulfur bituminous ash has a significant SO_3 content (7.4%), while the RDF ash contains considerable aluminum metal.

AGGREGATE

The aggregate market encompasses conventional aggregate products, such as masonry units and ready-mix concrete. Also, with crushing, aggregates can be produced for use in asphalt paving, road base construction, and roller compacted concrete. Lightweight aggregate can also be used in many structural building products. As such, synthetic aggregate for construction application appears to be a major market for CFB ashes, as well as a method for storage of ash in the construction off-season. Preliminary testing of pelletized CFB ash indicated that the material meets the different engineering requirements for its use as an aggregate (Bland, et al., 1993; Bland, 1994).

There are three methods that can be used to form synthetic aggregate from CFB ash: mechanical agglomeration, briquetting, or forming large blocks. With mechanical agglomeration, the aggregates are formed by adding water to the ash to form spheroids pellets in a mixer. This agitation process of agglomeration causes the individual particles to ball together as a consequence of mechanical and capillary forces and is free of external compacting forces. In the briquetting method, a machine uses molding pressures to compact the mixture within a mold. Synthetic aggregates can also be made by large blocks or beams with ash and water. The blocks/beams are cured to a desired strength and then crushed and graded.

Fresh pellets, briquettes or blocks/beams do not have enough strength for most aggregate uses. The strength requirement of synthetic aggregate must be achieved by curing. The bonding between individual particles is attained by cementing and pozzolanic reactions, which are accelerated at curing temperatures between 100^oF to 200^oF (38^oC to 93^oC).

As shown in Table 4, only the high-sulfur bituminous fly ash had sufficient strength (>500 psi or 3.4 MP at 7 days) when hydrated to qualify as an aggregate material. The other fly ashes might require additives such as lime, fly ash, or Portland cement to achieve sufficient strength. Although the RDF fly ash did not develop suitable aggregate strength when hydrated, it has shown promise as a material for synthetic aggregate production from a proprietary chemical process.

As mentioned earlier, compaction of the ash during hydration may also be a means of increasing the strength of the final aggregate product. Another option would be to cure the hydrated ash at a higher temperature to achieve the required strength. Compressive strength is only one of the tests which materials must pass to be suitable as aggregate. Los Angeles abrasion resistance (ASTM C-131) and soundness (ASTM C-88) test requirements must also be met.

Western Research Institute (WRI) has developed a proprietary process for CFBC ashes that makes them amenable for aggregate production (Bland, 1998). The SYNTAG^{TM} process is designed to reduce the expansion properties of the hydrated CFBC ashes (Figure 4). The SYNTAG process reduces the expansion for a medium sulfur coal derived CFBC ash to less than 0.1%. The untreated CFBC ash exhibited expansion in excess of 0.8%. The SYNTAG process has been shown to produce an aggregate that meets the ASTM and American Association of State Highway Officials (AASHO) specifications including LA abrasion resistance and the soundness (Table 8).

Table 8 Summary of Properties of SYNTAG^{TM} Products Made with CFBC Ashes

Aggregate Properties	SYNTAG Product		ASTM Specification
	A	B	
Crush strength, lbs (kg)			
24 hours	232/105	262/119	No specification
7 days	255/116	342/155	
90 days	nd	380/172	
LA Abrasion Resistance			
Grade	B	B	
Loss, %	28.5	17.2	
Soundness (ASTM C-88)			15% maximum loss
Loss, %	8.2	0.28	

SOIL STABILIZATION

The use of CFB ash for stabilization of soils is a potentially large ash use market. Soil stabilization can be defined as a means of permanently altering soil to increase its strength and bearing capacity, and decrease its water sensitivity and volume change potential (National Lime Association, 1991). This ash use application is similar to the cement stabilization commonly applied to the construction industry. Soil stabilization can eliminate the need for expensive borrow materials, expedite construction by improving wet or unstable soil, or allow reduced pavement thicknesses by improving subgrade conditions.

Soil stabilization is based on the treatment of clay soils with a material to provide strength and stability. Cement-fly ash and lime-fly ash mixtures are commonly employed at levels of 10 to 20% of the soil. CFB ashes that exhibit self-cementing characteristics have been proposed as viable stabilizing agents.

When the stabilizer is mixed with moist, plastic soils, a hydration reaction occurs in which calcium ions are released. As a result, cation exchange and flocculation-agglomeration occurs which reduces the moisture content and improves the plasticity characteristics of the amended soil (Brendel, et al., 1997).

The long-term strength of stabilized soils may increase due to pozzolanic reactions. In cement-stabilized soil, the hydration of the different cement constituents occurs at different rates, providing cementitious hydration products responsible for the early and long-term strength gains. In lime stabilized soil, the pozzolanic reaction depends upon the cooperative reaction between the lime and soil. Many soils contain silica, alumina, and iron, which will react with lime and develop long-term strength. Usually cement stabilization is used for coarse-grained soils such as sands, silt or clay-type sands and gravels; lime stabilization is used for fine-grained soils such as silts or clays.

The effect of CFB fly ash addition on the strengthening of clays was evaluated as shown in Table 9. In these tests, 15% fly ash was added to fine kaolinite and illite clays (<200 mesh). These mixtures were then hydrated and cured for a period of 28 days. To be a suitable stabilizing agent, a 28-day strength of 400 psi (2.8MP) is recommended for the ash-soil mixture. Samples of raw clay were also cured for comparison.

Table 9 Effect of 15% Fly Ash Addition on 28 Day Strength of Clays, psi

	Kaolinite	Illite
No fly ash	50	70
Bituminous gob	55	70
Low vol bituminous	70	110
High S bituminous	400	520
Petroleum coke	250	400
RDF	60	80

As shown in Table 9, the high-sulfur bituminous and petroleum coke fly ashes resulted in significant strengthening of the clays, probably due to their relatively high free lime contents. This petroleum coke ash is currently being used in the Gulf Coast region for stabilizing weak soils (Tharpe and Abdulally, 1997). The RDF fly ash did not increase the strength of the clays significantly, even though it had a relatively high free-lime content. This fly ash resulted in considerable expansion when added to the clays, thus limiting strength. The low-volatile bituminous fly ash did not produce significant strengthening of the clays.

For a material to be considered as a cementing agent for soil stabilization, the material must also show other properties in addition to strength development. These characteristics include freeze/thaw durability, and wet/dry durability in compliance with ASTM D-560 and D-559.

CONCLUSIONS

CFB ashes can be used for a variety of construction applications including cement replacement, structural fill, road base, aggregate and soil stabilization. This study screened the potential construction uses of a variety of CFB fly ashes by measuring the compressive strength of hydrated ash after curing. The different potential uses for the fly ashes evaluated in this study are summarized in Table 10. The summary listed in Table 10 assumes that the fly ash is the sole material used in each application. Based on the results of this study the following conclusions can be made:

- Ashes low in free lime (bituminous gob) typically have little construction uses besides cement replacement or in some cases excavatable fill. However, the addition of free lime may make them suitable for use as permanent fill, road base or soil stabilization.

- High carbon content (LOI >15%) may limit potential construction uses (other than cement replacement) of fly ash, depending upon its free lime content. High carbon content may limit the development of strength when the ash is hydrated. However, additional work needs to be done with high LOI ashes in order to verify the effect of carbon on hydrated ash strength.

- Petroleum coke ash has several potential uses including gypsum substitute in cement, soil stabilization, road base and probably compacted fill. Actual usage of petroleum coke ash in these applications has confirmed the laboratory screening of this type of ash. Strength development with hydrated petroleum coke ash is due to hydration of calcium compounds, not pozzolanic reactions. The strength required for compacted fills (>1000 psi/6.9 MP) was nearly obtainable by simple hydration and might be achieved by adhering to ASTM C-109 test standards.

- Self-cementing ashes high in FAS components and free lime (particularly high-sulfur bituminous ashes) have the potential for most construction applications. However, long-term expansion of the material is possible and needs to be tested before use in certain applications. This long-term expansion will depend primarily on the ash sulfate and soluble alumina contents.

- RDF ash is high in FAS and free lime, yet appears suitable for only excavatable fill uses. A high degree of expansion occurs with this material when hydrated, thus reducing strength development.

Table 10 Summary of Potential Construction Uses for Fly Ashes Evaluated in This Study

Fly Ash	Cement		Structural Fill		Soil Stabilization	Road Base	Aggregate
	Pozzolan	Gypsum Substitute	Compacted	Excavatable			
Bituminous Gob	**x**						
LV (0.3% S) Bituminous				**?**			
High S Bituminous			**x**		**x**	**x**	**x**
Petroleum Coke		**x**	**x**		**x**	**x**	
RDF				**x**			

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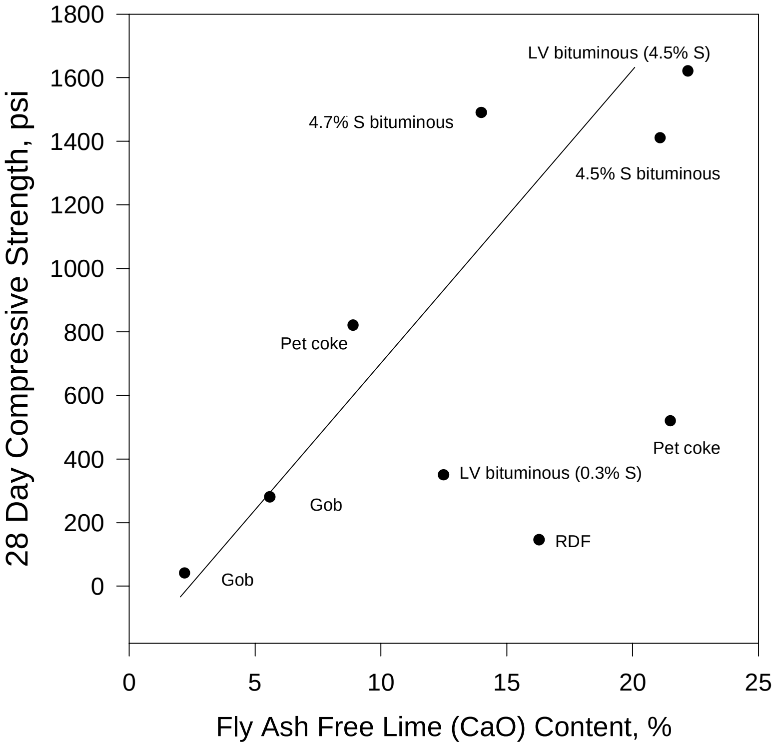

Figure 1 Effect of Free Lime Content on Hydrated Ash Strength

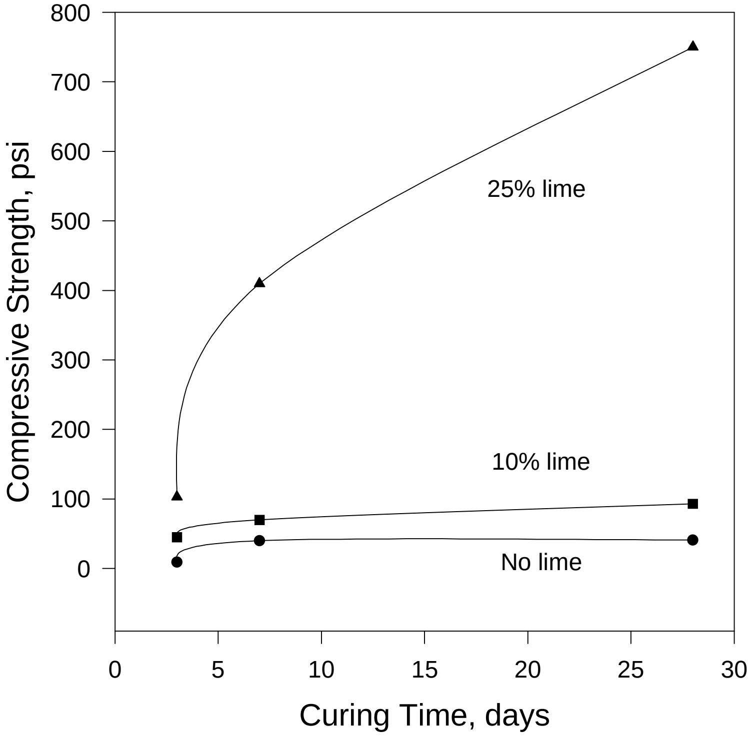

Figure 2 Effect of Lime Addition on Compressive Strength of Bituminous Gob Ash

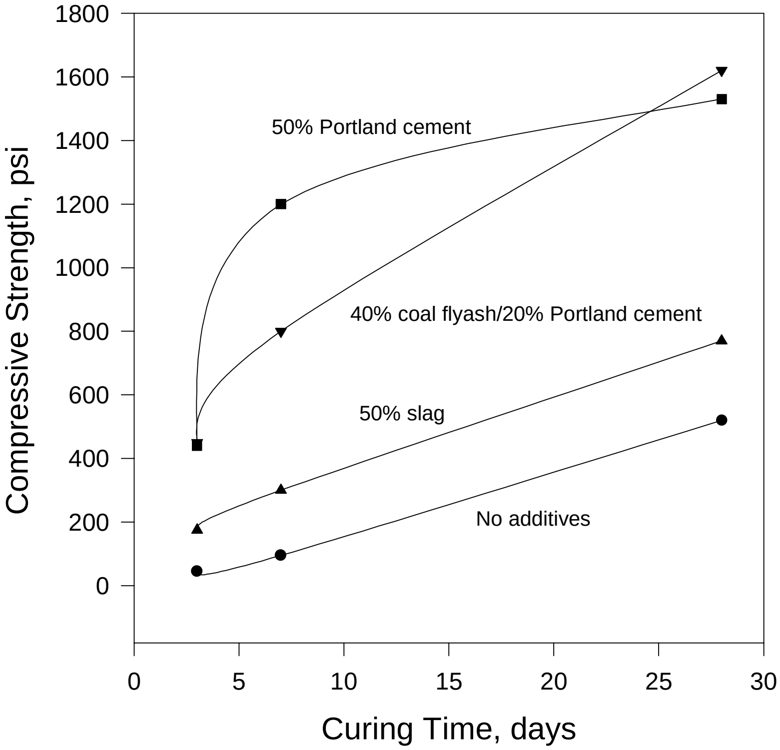

Figure 3 Effect of Additives on Petroleum Coke Ash Compressive Strength

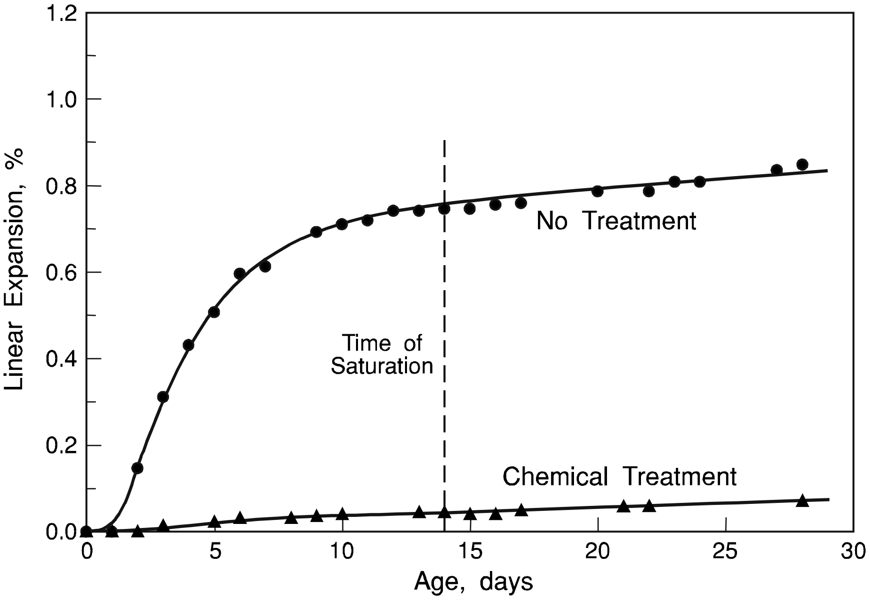

Figure 4 Effect of SYNTAG^{TM} Treatment on the Linear Expansion of CFBC Ash