Advanced Multi-Product Coal Utilization By-Product Processing Plant

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DISCLAIMER

ABSTRACT

The objective of the project is to build a multi-product ash beneficiation plant at Kentucky Utilities 2,200-MW Ghent Generating Station, located in Carroll County, Kentucky. This part of the study includes an investigation of the secondary classification characteristics of the ash feedstock excavated from the lower ash pond at Ghent Station.

The market study for the products of the processing plant (Subtask 1.6), conducted by Cemex, is reported herein. The study incorporated simplifying assumptions and focused only on pozzolan and ultra fine fly ash (UFFA). It found that the market for pozzolan in the Ghent area was oversupplied, with resultant poor pricing structure. Reachable export markets for the Ghent pozzolan market were mostly locally served with the exception of Florida. It was concluded that a beneficiated material for that market may be at a long term disadvantage. The market for the UFFA was more complex as this material would compete with other beneficiated ash and potential metakaolin and silica fume as well. The study concluded that this market represented about 100,000 tons of sales per year and, although lucrative, represented a widely dispersed niche market.

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LIST OF ABBREVIATIONS

UFFA: Ultra Fine Fly Ash
CUBs: Coal Utilization By-products
CCPs: Coal Combustion Products
MMC: Metal Matrix Composite
SAI: Strength Activity Index
GGBFS: Ground Granulated Blast Furnace Slag
LG&E: Louisville Gas & Energy
TVA: Tennessee Valley Authority
FWHA: Federal Highway Administration
LOI: Loss on Ignition
SF: Silica Fume
MK: Metakaolin
SCM: Supplementary Cementing Materials
tpy: Tons Per Year

EXECUTIVE SUMMARY

The project area is located in Carroll County, Kentucky, approximately one mile northeast of Ghent, Kentucky. The lower ash pond is situated immediately adjacent to U.S. Highway 42 on the southwest corner of the Ghent power plant site. Disposal of ash into the 120-acre pond began when the Ghent power plant became operational in 1973 and continued over a period of 20 years until the upper ash pond became operational in 1993.

A mobile demonstration plant with a feed rate of 2.5 tph was constructed and operated at the Ghent site. The plant was used to evaluate four different flowsheet configurations for beneficiation of the stored ash at Ghent Station as well as to generate several tons each of various processed ash products. The processed ash products were used for performance evaluations in mortar and concrete, as well as process addition in the manufacture of cement clinker. The field work was completed in the second quarter of this calendar year.

This quarterly report focused on the market assessment of products from the project. It was conducted by Cemex/MRT and is enclosed herein.

The market assessment focused on pozzolan and ultra fine fly ash (UFFA) exclusively. It was assumed that the other products of the study, Polymer Filler Fly Ash Metal Matrix Composite (MMC) Fly Ash, Fine Carbon, Coarse Carbon, Cenospheres, Magnetite and Lightweight aggregate bottom ash, either had too low a price, were not present in sufficient abundance, or represented significant unknown factors to be considered. Pozzolan and UFFA were considered to be mutually exclusive products.

The technology developers at the University of Kentucky would like to point out that the simplifying assumptions made for the market study by Cemex/MRT were reasonable and necessary to produce a definitive report. These assumptions however do not cover all cases. For example, pozzolan production and UFFA production are not in fact mutually exclusive nor are other products, such as cenospheres, actually valueless.

The assessment of the local market for pozzolan suggested that it is already oversupplied and undervalued and additional supplies will only further deteriorate market pricing. The local pozzolan Fly Ash market (fly ash used as a partial replacement for Portland Cement) has 500,000 tpy more supply than the current demand and Unit 2 at Trimble County will add about 125,000 additional tons to that surplus supply in 2008. The local price is $10 to $14 per ton. The main competition for Ghent would be the LG&E Trimble County Station.

Consideration of exporting the pozzolan to more distant markets was more promising but still problematic. Most markets outside of Florida are adequately supplied, as of now, by local producers. Significant quantities of pozzolan are shipped into the

Florida market. It was concluded however that the markets that supply Florida are oversupplied and a beneficiated pozzolan would have a competitive disadvantage in the longer term.

The markets for UFFA were somewhat different. There is some UFFA on the market and the State of Texas DOT has some relevant specifications. It was considered to be a niche product with limited demand. Competing materials include silica fume and metakaolin. The total demand in the United States for ultra fine pozzolans is in the range of 100,000 tpy, and that is currently equal to the supply. The current price for ultra fine pozzolans including UFFA is in the range of $200 to $300 per ton. There is no reason to expect demand to depart from its historical relationship to Portland cement demand.

INTRODUCTION

This project will complete the final design and construction of an ash beneficiation plant that will produce a variety of high quality products including pozzolan, mineral filler, fill sand, and carbon. All of the products from the plant are expected to have value and be marketable. The ash beneficiation process uses a combination of hydraulic classification, spiral concentration and separation, and froth flotation. The advanced coal ash beneficiation processing plant will be built at Kentucky Utility's 2,200 MW Ghent Power Plant in Carrollton, Kentucky. The technology was developed at the University of Kentucky Center for Applied Energy Research (CAER) and is being commercialized by CEMEX Inc. with support from LG&E Energy, Inc., the UK CAER, and the U.S.DoE.

This quarterly report focuses on the results of Subtask 1.6, market survey, which was largely conducted during the previous quarter. This work was entirely that of Cemex and is reported herein. The technology developers at the University of Kentucky would like to point out that the simplifying assumptions made for the market study by Cemex/MRT were reasonable and necessary to produce a definitive report. These assumptions however do not cover all cases. For example, pozzolan production and UFFA production are not in fact mutually exclusive nor are other products, such as cenospheres, actually valueless.

Subtask 1.6 Market Survey

OBJECTIVE

The stated objective of this subtask is to identify the demand and the prices for the various coal utilization by-products (CUBs) that could be produced by the proposed processing plant. For the remainder of this document the term Coal Combustion Products (CCPs) will be used instead of CUBs since CCP is the term used by the coal ash industry for these materials.

CCPs

The CCPs that could be produced by the proposed processing plant include:

- Pozzolan Fly Ash
- Ultra Fine Fly Ash (UFFA)
- Polymer Filler Fly Ash
- Metal Matrix Composite (MMC) Fly Ash
- Fine Carbon
- Coarse Carbon
- Cenospheres
- Magnetite
- Lightweight Aggregate Bottom Ash

Based upon data supplied by the University of Kentucky in the completion of other subtasks, the last 5 CCPs in the list have very low potential revenues due to low

production rates, low values in the current market, or both. With low potential revenues these 5 CCPs would have limited impact on the economic feasibility of a processing plant. Therefore, a detailed market assessment for these 5 CCPs was not conducted.

The American Coal Ash Association (ACAA) does not list the use of fly ash for polymer filler and metal matrix composites in its annual Production and Use Survey. These products need to be better defined and the market would need to be developed. Therefore, a detailed market assessment for polymer filler and metal matrix composites was not conducted.

The first two CCPs in the list, Pozzolan fly ash and UFFA, are the primary products for the proposed processing plant. However, if UFFA is produced the remaining Pozzolan fly ash would not have sufficient performance to be marketable since most of the pozzolanic activity comes from the UFFA that has been removed. Therefore, these two CCPs are mutually exclusive and only one could be produced at Ghent. This market assessment focuses on these two products.

POZZOLAN FLY ASH

Product Description

Pozzolan fly ash is principally used as an admixture in concrete as a partial substitute for Portland cement to improve in strength, durability and cost of the concrete. Pozzolan fly ash is usually considered a commodity with Class C fly ashes having a slightly higher value than Class F. The price is usually established to maintain a price advantage in the local market due to trucking costs from other sources. Reliability of supply and quality consistency are other factors that affect demand and price.

The fly ash from the proposed plant would be classified as a Class F fly ash meeting ASTM C 618 requirements. In addition, this product would have an LOI less than 2 % so it could be competitive in both the local and distant markets. The fineness and strength activity index (SAI) for this pozzolan fly ash is expected to be similar to other Class F fly ashes.

Local Market

This study considers a local market an area that is financially attractive when shipping by truck. This includes the cost of shipping and the competitive supply and demand situation in the market area. Since the Ghent site is in the Ohio River Valley which contains numerous other sources, the local market for each source is relatively close to the source. Sources and markets within 100 miles of the Ghent Station have been considered in this market study. Competing fly ash sources within this radius are shown in Table 1.

TABLE 1
COMPETING SOURCES
100 MILE RADIUS FROM GHENT

PLANT	CITY	STATE	TONS/YR	CLASS	PRICE[1]
CLIFTY CREEK	MADISON	IN	177,000	C	$21.00
MILL CREEK	LOUISVILLE	KY	200,000	F	$14.00
TRIMBLE COUNTY	BEDFORD	KY	120,000	F	$14.00
MIAMI FORT	NORTH BEND	OH	70,000	F	$10.00
ZIMMER	MOSCOW	OH	335,000	F	$10.00
LAFARGE TERMINAL	INDIANAPOLIS	IN	0	C	$28.20
TOTAL			**902,000**		

[1] $/ton fob source

Table 1 indicated the total supply of fly ash in the local market is about 900,000 tpy. The population in the local market area is about 7,500,000 and the per capita cement consumption is about 0.38 tons per capita per year based on USGS cement consumption data and US Census population data. This study assumes fly ash is used in 70 % of all Portland cement applications with a 20 % substitution ratio. The fly ash demand is therefore estimated to be about 400,000 tons/yr in the local market. Consequently there is a surplus of 500,000 tons/yr of fly ash in the local market.

Fly ash replaces cement in concrete on about a 1:1 basis in concrete, and the price of cement is about $100 per ton. Therefore, if the demand for fly ash was equal to or higher than the supply, the price should be in that range. In states where demand exceeds supply the price of fly ash is in the range of $70/ton. The low price of fly ash in the local market as shown in Table 1 indicates the fly ash supply far exceeds the demand in the local market.

Trimble County and Clifty Creek are within 50 miles of the Ghent station and Mill Creek Miami Fort and Zimmer are within 100 miles. All of these sources are competitive in at least one, and in some cases two, of the local major markets which include Cincinnati, Louisville, Lexington, Indianapolis, and Dayton.

LG&E's Trimble County Station would be the primary competitive source with pozzolan fly ash from Ghent. The Trimble County Station typically sells about 20,000 tpy in the local market at about $14 per ton. In the near term, this 20,000 tpy is the maximum local market demand and price for pozzolan fly ash from Ghent. Demand is expected to grow very slowly over the 10 year economic life for the proposed plant investment and prices are not expected to increase significantly. The reasons for this are:

- Miami Fort and Zimmer have a freight advantage to the Cincinnati, Northern Kentucky, and Dayton markets,

- Indianapolis is nearly 100 % a Class C market due to existing fly ash supply and is over 100 road miles away from Ghent
- Much of Louisville is a Class C market and LG&E's Mill Creek Station supplies the Class F for this market.

Construction of the Ghent pozzolan fly ash plant would add significantly to the local market supply and the forecast price is less than estimated operating costs. Finally, the fly ash production at Trimble County is scheduled to double by 2008 when Unit 2 comes on line further adding to the oversupply. Therefore, the demand and price for Pozzolan Fly Ash produced at Ghent would both be very low in the local market.

Export Markets

In the contract documents export markets were defined as "distant" markets that could be reached by river barge or rail. Examples of distant markets given were Florida and the major cities along the Ohio and Mississippi Rivers. All of these markets except Miami, Florida have local fly ash sources and some have terminals for receiving and distribution of fly ash from distant sources. All fly ash terminals in these markets are rail served; none are river barge served. Though river transport is less costly per mile this mode requires significantly higher investment in larger silos and sophisticated unloading machinery compared to rail terminals. If barge transportation were economically attractive it would be utilized for supplying the existing demand.

None of the fly ash supplied to the distant markets is beneficiated. All of this fly ash comes from oversupplied markets in Texas and the Ohio River Valley. In these markets utilities offer these fly ashes at very low price or with a freight subsidy to encourage beneficial use rather than landfilling. The cost of beneficiating the Ghent fly ash is a significant disadvantage in comparison to these competing sources. Many of the distant sources selling non beneficiated fly ash in the studied distant markets have additional volume available to meet the demand growth forecast over the economic life of this plant project.

Following is a detailed assessment of the Florida and Ohio and Mississippi River market areas.

Florida

- Florida can be reached by rail. The major markets are Tallahassee, Jacksonville, Orlando, Tampa Bay, and Miami.
- Fly ash is currently being railed into Florida from the Ohio River Valley and Texas.
- Fly ash from LG&E's Mill Creek station is currently being railed into Florida and that station has much more high quality fly ash available to meet demand growth.

Following is a review of the fly ash market in each of the Florida markets.

Tallahassee

- This market is currently supplied by a beneficiated fly ash from Jacksonville, some Georgia fly ash with high trucking costs, and a distant fly ash from another Ohio River Valley source.

Jacksonville

- This market is primarily supplied by a beneficiated fly ash from Jacksonville.

Orlando

- This market is currently supplied by fly ash from the local municipal power station, and from a power plant in Crystal River. Ground granulated blast furnace slag (GGBFS) is also produced in this market and competes with fly ash.

Tampa Bay

- This market is currently supplied by power plants in Crystal River and Tampa. Tampa Electric Company has announced plans to beneficiate all Big Bend Station fly ash adding over 200,000 tpy supply to this market.
- The southern portion of this market area is currently supplied by a terminal in Punta Gorda which distributes fly ash from Texas.

Miami

- This market currently uses imported GGBFS and Texas fly ash from the Punta Gorda terminal.
- A major ready mix company is supplied with fly ash directly from Texas.

Ohio and Mississippi River Valleys

- Cincinnati and Louisville are part of the local market for Ghent product.
- The major markets on the Ohio and Mississippi River systems are Pittsburgh, Huntington-Ashland, Evansville, St Louis, Chicago, Quad Cities, Minneapolis, Memphis, Baton Rouge, and New Orleans.
- There are numerous coal-fired power stations along the Ohio, Illinois, and upper Mississippi Rivers creating an over supply of fly ash in most of these markets.

In summary, the demand in nearly all of these markets is being met with local fly ash sources or with distant sources that have fly ash prices near $0 per ton fob the source. Therefore, the export markets have insufficient demand and value compared with the higher cost to produce pozzolan fly ash at Ghent.

A detailed review of each market follows.

Pittsburgh

- This Class F market is currently supplied by power plants within the local market by sources in western Pennsylvania and eastern Ohio.

Huntington-Ashland

- This Class F market is currently supplied by power plants within the local market by sources in western West Virginia and eastern Ohio.

Evansville

- This Class F market is currently supplied by power plants within the local market by sources at Petersburg, Indiana and Owensboro, Kentucky.

St Louis

- This Class C market is currently supplied by power plants within the local market including Labadie and Festus, Missouri and two plants in western Illinois.

Chicago

- This Class C market is currently supplied by numerous power plants along the Illinois River in the local market plus additional power plants and a rail terminal in southern Wisconsin.
- For a few years a river barge terminal in Calumet City supplied Class C fly ash to southern Chicago, but this operation has stopped. It is unlikely that this terminal would be economically attractive.

Quad Cities

- This Class C market is currently supplied by power plants along the Mississippi within the local market.

Minneapolis

- This Class C market is currently supplied by power plants within the local market.

Memphis

- This Class C market is currently supplied by a power plant within the local market, plus others in Missouri and Illinois.
- The TVA Cumberland station, a very large, high quality, Class F source, is within 150 miles

Baton Rouge and New Orleans

- This Class F market is currently supplied with beneficiated fly ash from a power plant in Hattiesburg, Mississippi. Future demand growth is projected to be accommodated by existing sources with excess supply capacity.

ULTRA FINE FLY ASH (UFFA)

Product Description

UFFA is principally used as an admixture in concrete as a partial substitute for Portland cement to achieve very high strengths and excellent durability of the concrete. Due to high price, UFFA is specified for applications requiring high-strength (>7,000 psi), sulfate or corrosion resistance, and resistance to alkali silica reactivity. These high durability applications include high-rise buildings, highway bridges, and marine structures. A Federal Highway Administration (FWHA) study (Appendix 1) comparing 8 and 12 % substitution of UFFA with baseline straight Portland cement concrete shows UFFA decreases chloride permeability and diffusion coefficient, and increases direct current resistivity of concrete.

UFFA is produced at one power station in Texas, and is marketed as Boral Micro 3. It is considered a niche product with low usage rates and high price relative to conventional fly ashes and Portland cement (2 - 4 times).

UFFA has no ASTM specifications at this time, but Texas DOT has established the following specification:

1. Must conform to the TX DOT specifications for Class F fly ash.
2. Strength Activity Index (SAI) must be 85% of control at 7 days and 95% of control at 28 days.
3. 90% of the particles must be less than 8.5 microns, and 50% of the particles must be less than 3.25 microns.
4. Less than 6% may be retained on a 45 micron sieve when wet sieved.
5. Maximum moisture is 1%.
6. Maximum Loss on Ignition (LOI) is 2.0%.

Market

Because UFFA is a niche product with low demand and high price the market is national with a focus on the largest cities with tall concrete buildings, and coastal areas. Since little is known about the production and sales from the one known source for UFFA the demand and pricing of competitive ultra fine pozzolan products was used to define the market for UFFA.

Competitive Products

The competitive products for UFFA from the Ghent station are Boral Micron 3, silica fume, and metakaolin. Table 2 compares the performance of Portland Cement concrete containing none of these admixtures with concrete containing various ultra fine pozzolans.

TABLE 2
PERFORMANCE OF ULTRA FINE POZZOLANS COMPARED TO CEMENT ONLY

Property	UFFA	Silica Fume	Metakaolin
Water Requirement	Better	Worse	Neutral
Air Content	Worse	Neutral	Neutral
Workability	Better	Worse	Better
Segregation and Bleeding	Better	Better	Better
Heat of Hydration	Lower	Neutral	Neutral
Setting Time	Slower	Neutral	Neutral
Finishability	Better	Worse	Better
Pumping	Better	Worse	Better
Low Temp Curing	Worse	Neutral	Neutral
High Temp Curing	Better	Worse	Better
Early Strength	Worse	Better	Better
Late Strength	Better	Better	Better
Permeability and Absorption	Better	Better	Better
ASR	Better	Better	Better
Sulfate Attack	Better	Better	Better
Corrosion of embedded steel	Better	Better	Better
Carbonation	Worse	Worse	Worse
Deicer Scaling	Worse	Worse	Worse
Chemical Resistance	Better	Better	Better
Plastic Cracking	Neutral	Worse	Neutral
Drying Shrinkage and Creep	Neutral	Neutral	Neutral
Expansion (Soundness)	Neutral	Neutral	Neutral
Freeze-thaw resistance	Neutral	Neutral	Neutral
Concrete Color	Darker	Dark	White

Boral Micron 3

Boral Mineral Technologies, a fly ash marketing company, separates this UFFA from Class F fly ash. Because it is fly ash, Boral 3 is generally an amorphous (glassy) alumina silica and silicate. Iron and calcium are the other major (>3% each) constituents. The particle shape is spherical with a mean diameter of 3 microns. Typical Class F fly ash has a mean diameter of 20-30 microns. Boral Micron 3 is gray colored due to the carbon and iron content. The product is packaged in 25 pound bags, one-ton super-sacs, and is also sold in bulk.

There is no public data on the demand for this product, but CEMEX is a large supplier of ready mix concrete in Texas and has only used less than 1,000 tons of Boral Micron 3 in the first 3 quarters of 2006.

The price for this product FOB the Rockdale, TX Plant is,

- Bag/sack - $340.00 / ton
- Bulk - $320.00 / ton.

Silica Fume

Silica fume (SF) is a byproduct from the production of ferrosilicon metals. It is amorphous (glassy) silica. Minor constituents (<10% total) are iron, calcium, magnesium, potassium, sodium, alumina, and carbon. Like fly ash, silica fume particles are spherical but with a mean diameter less than 0.2 microns. Silica fume has no ASTM specifications at this time.

Silica fume is typically used in concrete to reduce permeability, reduce ASR, and increase sulfate resistance. Concrete mixes with over 5% silica fume exhibit increased water demand and poorer workability compared to concrete with UFFA.

There are five domestic SF producers listed in the Silica Fume Association. The source locations are:

- Elkem Materials, Inc - Alloy, WV
- Norchem, Inc. - Beverly, OH and Selma, AL
- AIMCOR - Bridgeport, AL
- Simcala, Inc. - Mt. Meigs, AL
- SKW Metals and Alloys, Inc. - Calvert City, KY

The product is typically sold packaged in 25 pound bags and in bulk.

There is no public data on the demand for this product so information was obtained from individuals who are familiar with the market.

- Elkem production is estimated at 30,000 tons per year
- Total US production is estimated at 100,000 tons per year
- Global consumption is estimated at 1,000,000 tons per year.
- Not all silica fume is used as an admixture in concrete.
- The largest ready mix concrete supplier in the United States consumes approximately 40 tons of silica fume per month totaling about 480 tons per year.

Based upon this information the estimated national demand for silica fume used as an admixture for concrete is approximately 50,000 to 100,000 tpy.

One of the larger suppliers, (Elkem) lists the following, FOB their warehouse as of August 8, 2006:

- Bulk $ 0.1025 / lb ($205.00 / Ton)
- 25 lb bag through 2000 lb bags (Densified) $0.1425 / lb ($285.00 / ton)
- 50 lb through 1650 lb bags (Undensified) $0.1425 / lb (285.00 / Ton)

These prices are exactly the same as quoted in 2004 which implies ample supply and no increase in the perceived value of silica fume in the marketplace.

Metakaolin

Metakaolin (MK) is a reactive alumino silicate pozzolan formed by calcining purified kaolinite at a specified temperature range. MK 3 is generally an amorphous (glassy) alumina silicate. Because the production of this product is controlled to make the products it contains limited amounts of crystalline material that is not reactive in concrete. The kaolinite ore is processed to remove impurities so only minor constituents remain including iron, calcium, and titanium. Because the material is milled like cement the particle shape of this product is angular. The literature for MetaMax indicates that this MK has a typical mean diameter of 1.2 microns, compared to 0.3 microns for silica fume, 3 microns for UFFA, and 20 to 30 microns for typical Class F fly ash. MetaMax and other MK are very white in color.

MK must meet ASTM C618 standards as a natural pozzolan. Appendix 5 lists an NRMCA Comparison of MK (PowerPozz) and silica fume which indicates similar performance for compressive strengths. The product is typically sold packaged in 55-pound bags and 1-ton pound super-sacs, and is also sold in bulk. Larger producers of MK are BASF-Engelhard (MetaMax products), Burgess and others located in central Georgia between Macon and Augusta.

ISG purchased a company in South Carolina in 1999 and began producing MK. It was given the name CEMax, met the requirements of ASTM C-618 Type N, and reportedly replaced microsilica as a high-performance pozzolan. ISG shut down the operation after a few years.

There is no public data on the demand for this product, but the closure of the ISG facility indicates a relatively low demand. The price of their MK was$6.25-$8.75 per 50 lb bag ($250-$350 / ton)

Summary

The location of the Ghent facility compared to the competitive sources does not suggest either a major freight advantage or a disadvantage compared to competitive materials for the UFFA at Ghent.

Based upon the competitive products the total market demand for UFFA would be about 100,000 tpy and the selling price at the production location would be within the range of $200 to $300 per ton.

MARKET SUMMARY

GHENT LOCAL MARKET

- The local pozzolan Fly Ash market (fly ash used as a partial replacement for Portland Cement) has 500,000 tpy more supply than the current demand and Unit 2 at Trimble County will add about 125,000 additional tons to that surplus supply in 2008. The local price is $10 to $14 per ton. The main competition for Ghent would be the LG&E Trimble County Station.

DISTANT MARKETS

- The export or distant pozzolan market also has a supply that exceeds demand in most of the locations. There are no existing barge terminals for fly ash in the markets identified. Most of the distant supplies into these markets are provided to the marketer at about no cost.

ULTRAFINE POZZOLAN MARKET

- The total demand in the United States for ultra fine pozzolans is in the range of 100,000 tpy, and that is currently equal to the supply. The current price for ultra fine pozzolans including UFFA is in the range of $200 to $300 per ton. There is no reason to expect demand to depart from its historical relationship to Portland cement demand.

Appendix 1
FHWA Ultra Fine Fly Ash Comparison of Materials

As compared to typical fly ash, with a mean particle diameter ranging from 20-30 micrometers, ultra fine fly ash can be produced with a mean particle diameter of 1-5 microns. The reduced particle size means that the pozzolanic reaction, which is normally a slow process, is accelerated. Further, the finer particles may more completely react than the coarser particles of fly ash. So, the durability and strength benefits that one observes with a typical fly ash at a late age (more than one year) can be attained at a much earlier age (less than 90 days) and with a smaller dosage of an ultra fine fly ash. Table 10-1 shows typical mix designs containing ultra fine fly ash.

Typically, ultra fine fly ash is used at a replacement rate of 5 to 15 percent of the cement weight. At these dosage levels, it has been demonstrated that ultra fine fly ashes contribute more to concrete strength gain and permeability reduction than common AASHTO M 295 (ASTM C 618) fly ash, and will perform comparable to highly reactive pozzolans such as silica fume. Concrete durability properties such as resistance to alkali-silica reaction, sulfate attack, and corrosion are also enhanced by ultra fine fly ash.

Table 10-1: Typical mixes using ultra fine fly ash.

	Portland Cement Concrete	8% Ultra Fine Fly Ash	12% Ultra Fine Fly Ash
Cement, kg/m^3 (lb/yd^3)	375 (632)	345 (582)	330 (556)
Ultra Fine Fly Ash, kg/m^3 (lb/yd^3)	-	30 (50)	45 (76)
Total Cementitious Material, kg/m^3 (lb/yd^3)	375 (632)	375 (632)	375 (632)
Water, kg/m^3 (lb/yd^3)	150 (253)	150 (253)	150 (253)
Water/Cementitious Material	0.40	0.40	0.40
High Range Water Reducer, ml/100 kg (oz/100 lb)	625 (9.6)	438 (6.7)	364 (5.6)
Slump, mm (in)	145 (5.75)	135 (5.25)	160 (6.25)
Rapid Chloride Permeability Test, coulombs			
28-day	2027	857	707
90-day	1567	418	314
2-year	1103	338	242
Direct Current Resistivity, 10^{12} m^2/s			
28-day	14.5	31.0	40.6
90-day	24.5	79.9	93.9
2-year	25.8	81.1	107
Chloride Diffusion Coefficient, 10^{12} m^2/s			
40-day	133	53.3	48.6
90-day	103	37.7	27.9
2-year	94.2	13.3	9.38

Appendix 2
TX DOT Requirements for UFFA

Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete" and the following table:

Supplementary Specification Requirements

Item	Limit
Calcium oxide (CaO) variation in percentage points of CaO from the average of the last 10 samples (or less, provided 10 have not been tested) must not exceed ±	4.0
Moisture content, maximum, %	2.0
Loss on ignition, maximum, %	3.0
Increase of drying shrinkage of mortar bars at 28 days, maximum, %	0.03

- Ultra-Fine

Ultra-fine fly ash must conform to the requirements listed above for Class F fly ash with the following exceptions and additions:

Additional Ultra-Fine Specification Requirements

Item	Limit
Pozzolanic activity index	-
◆ 7-day, minimum, % of control ◆ 28-day, minimum, % of control	85 95
Particle size distribution, as measured by laser particle size analyzer	-
◆ particles less than 3.25 microns, minimum, % ◆ particles less than 8.50 microns, minimum, %	50.0 90.0
Fineness, amount retained when wet-sieved on 45-μm sieve, maximum, %	6.0
Moisture content, maximum, %	1.0
Loss on ignition, maximum, %	2.0

Appendix 3
TX DOT Mix Design Options

For structural concrete and any other class of concrete designed using more than 520 lb. of cementitious material per cubic yard, use one of the mix design options shown below.

For concrete classes not identified as structural concrete and designed using less than 520 lb. of cementitious material per cubic yard, except that Class C fly ash may be used instead of Class F fly ash for Options 1, 3, and 4 unless
sulfate-resistant concrete is required.

a. Option 1. Replace 20 to 35% of the cement with Class F fly ash.
b. Option 2. Replace 35 to 50% of the cement with GGBFS.
c. Option 3. Replace 35 to 50% of the cement with a combination of Class F fly ash, GGBFS, or silica fume. However, no more than 35% may be fly ash, and no more than 10% may be silica fume.
d. Option 4. Use Type IP or Type IS cement. (Up to 10% of a Type IP or Type IS cement may be replaced with Class F fly ash, GGBFS, or silica fume.)
e. Option 5. Replace 35 to 50% of the cement with a combination of Class C fly ash and at least 6% of silica fume, UFFA, or metakaolin. However, no more than 35% may be Class C fly ash, and no more than 10% may be silica fume.
f. Option 6. Use a lithium nitrate admixture at a minimum dosage of 0.55 gal. of 30% lithium nitrate solution per pound of alkalis present in the hydraulic cement.
g. Option 7. When using hydraulic cement only, ensure that the total alkali contribution from the cement in the concrete does not exceed 4.00 lb. per cubic yard. of concrete when calculated as follows:

> lb. alkali per cu. yd. lb. = ((cement per cu. yd.) × (% Na_2O equivalent in cement))/100

In the above calculation, use the maximum cement alkali content reported on the cement mill certificate.
h. Option 8. For any deviations from Options 1-7, perform the following:

- Test both coarse and fine aggregate separately in accordance with ASTM C 1260, using 440 g of the proposed cementitious material in the same proportions of hydraulic cement to supplementary cementing material to be used in the mix.
- Before use of the mix, provide the certified test report signed and sealed by a licensed professional engineer demonstrating that the ASTM C 1260 test result for each aggregate does not exceed 0.10% expansion.

Appendix 4
National Ready Mixed Concrete Association comparison of Silica Fume, Ground Blast Furnace Slag and Portland Cement

For concrete, reference ASTM C 94 which allows the use of SCMs such as fly ash, slag, and silica fume in the mix. Encourage the use of fly ash and ground granulated blast furnace slag in your specifications for most applications. Use silica fume when super high strength or exceptional durability is required. Most concrete for construction uses some fly ash replacement of Portland cement. ASTM C 618 provides standards for fly ash. Fly ash is used in concrete to replace 5 to 65 percent of the Portland cement. For blast furnace slag, specify ASTM C 989. Slag is used to replace 20 to 70 percent of cement in the mix. For silica fume, specify ASTM C 1240. It can be used effectively as a replacement for cement in quantities of 5 to 12 percent.

The ready mixed concrete industry consumes about 75% of the cement shipped in the U.S. Besides Portland and blended cement it uses a large quantity of industrial byproduct material that would otherwise be considered waste products. These include fly ash from the coal burning power plants, slag from the manufacture of iron and silica fume from the silicon/ferro-silicon metal industry.

NRMCA estimates the volume of ready mixed concrete produced in the US using some validated assumptions and the data on cement shipments reported by the US Geological Survey of the U.S. Department of Interior. The approximately annual ready mixed concrete production of 430 million cubic yards represents a $30 billion industry.

Appendix 5
NRMCA Comparison of
Metakaolin (PowerPozz) and Silica Fume

In this study, 9 mortar mixes were produced: Two of the mixes were Class F Flyash/HRM combinations and will be reported separately. For the remaining 7 mixes, the following cementitious materials were used:

Mix 1:	Type 1 Ordinary Portland Cement (Control)
Mix 2:	OPC / 5% PowerPozz™ HRM
Mix 3:	OPC / 10% PowerPozz™ HRM
Mix 4:	OPC / 15% PowerPozz™ HRM
Mix 5:	OPC / 5% Silica Fume
Mix 6:	OPC / 10% Silica Fume
Mix 7:	OPC / 15% Silica Fume

The percentages of supplementary cementing materials were replacements by weight of Portland cement, not additions.

The mortars were produced with a water: binder ratio of 0.40.

The compressive strength results reported are the averages of two cubes

Phase 1 Results

Results from Phase 1 are reported in Table A-1.

Project: Comparative Strength Testing of PowerPozz™ High Reactivity Metakaolin
Subject: Strength Activity Index with Portland Cement (ASTM C-311)

TABLE A-1. Phase 1

TEST DATA							
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
Materials	Control	5% PP HRM	10% PP HRM	15% PP HRM	5% Silica Fume	10% Silica Fume	15% Silica Fume
Type 1 Cement (g)	667	633	600	567	633	600	567
PowerPozz™ (g)	–	34	67	100	–	–	–
Silica Fume (g)	–	–	–	–	34	67	100
Standard Sand	1428	1428	1428	1428	1428	1428	1428
Superplasticizer, Daxad 199g)	0.42	0.80	1.67	2.52	1.25	3.29	5.55
Water (g)	267	267	267	267	267	267	267
W/C Ratio	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Flow, at 15 drops of flow table (%)	115	115	115	120	110	125	115

TEST RESULTS							
Compressive Strength (Mpa) Strength Activity Index @ 24 hrs.	23.4 1.0	25.3 1.05	27.6 1.15	28.0 1.17	24.1 1.03	28.8 1.20	29.8 1.24
Compressive Strength (Mpa) Strength Activity Index @ 3 Days	41.0 1.0	42.7 1.04	47.7 1.16	49.0 1.2	44.2 1.08	44.0 1.07	45.0 1.1
Compressive Strength (Mpa) Strength Activity Index @ 7 Days	48.7 1.00	54.0 1.11	60.2 1.24	62.9 1.29	53.7 1.10	60.9 1.25	62.9 1.29
Compressive Strength (Mpa) Strength Activity Index @ 28 Days	57.7 1.00	63.4 1.10	70.4 1.22	73.7 1.28	66.7 1.16	76.1 1.32	78.9 1.37
Compressive Strength (Mpa) Strength Activity Index @ 56 Days	55.7 1.00	64.2 1.15	68.8 1.24	76.1 1.37	67.3 1.21	74.2 1.33	77.7 1.39
*56 day results are based on 1 cube only							