Coal Combustion Products Utilization Handbook

Ramme – Tharaniyil

Second Edition

A We Energies Publication

we energies

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2nd Edition

A We Energies Publication

This book is dedicated to all the individuals who have worked in support of the development of beneficial utilization of We Energies' coal combustion products.

Special thanks go to our teacher, Professor Tarun Naik, Director of the Center for By-Products Utilization at the University of Wisconsin-Milwaukee.

And Dr. Haifang Wen of Bloom Consultants, LLC for his technical review and updates in the second edition.

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Contents

Contents

Contents

Contents

Preface

This second edition of the coal combustion products utilization handbook is developed with the intent of providing practical, technical and regulatory compliance information to the users of We Energies' coal combustion products. We hope that this book will serve as a ready reference tool for engineers, architects, construction managers and contractors in using We Energies coal combustion products (CCPs) in various construction applications. This handbook contains chapters dedicated to major product categories and their applications.

The information in this handbook will help develop an understanding of the generation, properties, construction applications and performance of CCPs. It also contains sample specifications that can be used as references in developing project specifications that utilize CCPs. A list of references is provided at the end of this handbook for the reader who is looking for a deeper understanding of the material.

The authors invite your questions and comments via e-mail or mail for consideration in future editions, and can be contacted at:

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Chapter 1

Background and History of We Energies Coal Combustion Products (CCPs)

Figure 1-1: Fly ash "flying away" from We Energies' Lakeside Power Plant prior to the advent of collection in electrostatic precipitators and bag houses.

In the early days of the power generation industry, coal combustion products (CCPs) were considered to be a waste material. The properties of these materials were not studied or evaluated seriously and nearly all of the coal combustion products were landfilled. In the course of time, the cementitious and pozzolanic properties of fly ash were recognized and studied by several individuals and institutions. The products were tested to understand their physical properties, chemical properties and suitability as a construction material. During the last few decades these "waste" materials have seen a transformation to the status of “by-products” and more recently “products” that are sought for construction and other applications.

During the past several decades, generation of electricity through various coal combustion processes has grown to accommodate increased population and associated industrial and commercial development in the United States and other parts of the world. These coal combustion processes leave behind residues that are referred to as CCPs.

The initial CCPs were called cinders and were formed from burning lump coal on grates in stoker furnaces. These cinders were sometimes used as road gravel and sometimes as a lightweight aggregate in manufacturing masonry “cinder” blocks.

Figure 1-2: Bottom ash "cinders" from We Energies' Wells Street Power Plant destined for road surfacing and other applications.

In the 1920's, more effective methods of firing power plant boilers were invented. These new processes involved burning pulverized coal instead of lump coal. While the process was a more efficient method of firing, the process generated an increased stream of fine combustion products and lower quantities of cinders. This fine combustion product is called fly ash, and the cinders that are relatively finer are called bottom ash. As environmental awareness and landfilling costs have grown, CCP generators and government regulators have encouraged the beneficial use of industrial by-products, including coal ash.

According to the American Coal Ash Association (ACAA), combustion of coal in the United States alone generated approximately 128.7 million tons of coal combustion products in 2002, including approximately 76.5 million tons of fly ash, 19.8 million tons of bottom ash, 29.2 million tons of flue gas desulfurization (FGD) materials, and 1.9 million tons of boiler slag (1). Of the fly ash produced, approximately 12.6 million tons were used in cement, concrete, and grout applications; and another 14.1 million tons were used in various other applications.

In some parts of the world, CCP utilization rates are much higher than that of the United States. For example, in the Netherlands CCP utilization is about 104% (Netherlands imports ash, as their supply is less than demand). CCP utilization in Denmark is approximately 90% and in Belgium over 73%. CCP utilization in other parts of Europe varies widely from around 10% to 60%.

The United States is the world's second largest producer of fly ash (second only to China). However, CCP utilization in the United States is relatively low. This presents opportunities to make use of this valuable mineral resource (2). By 2002, approximately 45.5 million tons (35.4%) of coal combustion products were used in the United States. This percentage is expected to increase, as a result of the new uses for CCPs, increased awareness of proven technologies, and global focus on sustainable development.

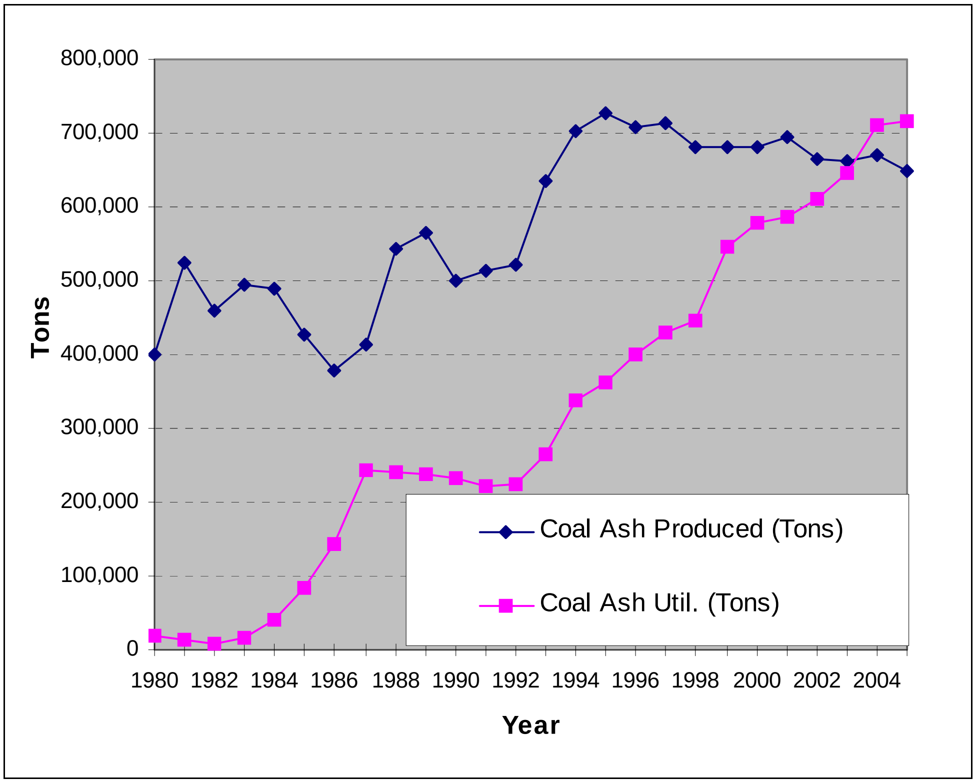


Figure 1-3: We Energies Coal Ash Production and Utilization

*Data collected up to 2003 and forecast through 2005

Coal fired power generation has gone through several process modifications to improve efficiency, control the quality of air emissions, and to improve the quality of combustion products. The variety of coal that is burned influences the chemistry of combustion products significantly. The introduction of low sulfur coal has improved the quality of air emissions and also generally improved the quality of fly ash.

The provisions of the Clean Air Act Amendments have also affected nitrogen oxide (NO_X) emissions and their controls for the electric utility industry. In November 2002, the Wisconsin DNR promulgated Rule NR 428 to control NO_X emissions for several source categories, including coal-fired utility boilers, to provide for a regional NO_X control strategy to address the 1-hour ozone nonattainment area within southeastern Wisconsin. Rule NR 428 requires a 0.32 lb./MMBtu NO_X emission limit for existing coal-fired utility boilers in the 2003 ozone season (May 1-September 30) and increases stringency over time to an emission limitation of 0.27 lb./MMBtu for existing coal-fired utility boilers in the 2008 ozone season and thereafter. On December 4, 2002, the Michigan DEQ promulgated final revisions to Rule 801 which requires a 0.25 lb./MMBtu NO_X emission limitation for the Presque Isle Power Plant starting in the 2004 ozone season. Furthermore, on April 29, 2003, We Energies entered into a consent decree with U.S. EPA to reduce NO_X emissions to a system-wide 12-month rolling average (annual) emission rate of 0.270 lb./MMBtu beginning on January 1, 2005 and down to a system-wide 12-month rolling average (annual) emission rate of 0.170 lb./MMBtu on January 1, 2013 and thereafter. U.S. EPA is in the process of promulgating regulations to address nonattainment of the 8-hour ozone and the fine particulate matter (PM2.5) ambient air quality standards. NO_X emissions control plays a vital role in addressing both of those control strategy development efforts and could result in a system-wide emission limitation below 0.10 lb./MMBtu for coal-fired utility boilers.

The process for reducing NO_X emissions through combustion control technologies has generally increased the amount of unburned carbon content and the relative coarseness of fly ash at many locations. In particular, post-combustion control technologies for NO_X emissions such as selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) both utilize ammonia injection into the boiler exhaust gas stream to reduce NO_X emissions. As a result, the potential for ammonia contamination of the fly ash due to excessive ammonia slip from SCR/SNCR operation is an additional concern. An SCR installed at We Energies Pleasant Prairie Power Plant (P4) began operation in 2003. Ammonia contamination has become an intermittent problem and daily fly ash testing is in place to ensure that ammonia levels are acceptable. We Energies has also developed a fly ash beneficiation process to remove and reuse ammonia if needed in the future.

Regulations to reduce sulfur dioxide emissions results in the introduction of wet scrubber flue gas desulfurization (FGD) systems which can produce gypsum as a by-product. In 1990, overall annual sulfur dioxide (SO_2) emissions from electric utility companies had fallen 46%. In 1990, the Clean Air Act Amendments were enacted, requiring electric utility companies nationwide to reduce their collective SO_2 emissions by the year 2000 to 10 million tons per year below 1980 emission levels (or 40%). Utility SO_2 emissions will be capped at 8.9 million tons per year in the year 2000 and thereafter. Many western coals and some eastern coals are naturally low in sulfur and can be used to meet the SO_2 compliance requirements. Blending coals of different sulfur contents to achieve a mix that is in compliance with applicable regulation is also common. Nearly 70% of utilities use compliance fuel to achieve the SO_2 emission level currently mandated. Wet FGD systems are currently installed on about 25% of the coal-fired utility generating capacity in the United States (3). Currently, there are no FGD systems operating on We Energies Power Plants, but they are planned for installation on the proposed supercritical Elm Road Generating Station units, Pleasant Prairie Power Plant, and Oak Creek Power Plant Units 7-8.

Figure 1-4: This 170-acre coal ash landfill is located in Oak Creek, Wisconsin, where over 3,700,000 cubic yards of coal ash are stored.

It is important to distinguish fly ash, bottom ash, and other CCPs from incinerator ash. CCPs result from the burning of coal under controlled conditions. CCPs are non-hazardous. Incinerator ash is the ash obtained as a result of burning municipal wastes, medical waste, paper, wood, etc. and is sometimes classified as hazardous waste. The mineralogical composition of fly ash and incinerator ash consequently is very different. The composition of fly ash from a single source is very consistent and uniform, unlike the composition of incinerator ash, which varies tremendously because of the wide variety of waste materials burned.

The disposal cost of coal combustion by-products has escalated significantly during the last couple of decades due to significant changes in landfill design regulations. Utilization of CCPs helps preserve existing licensed landfill capacity and thus reduces the demand for additional landfill sites. Due to continued research and marketing efforts, We Energies was able to utilize 98% of coal combustion products in 2003 compared to only 5% in 1980. Increased commercial use of CCPs translates to additional revenues and reduced disposal costs for We Energies, which in turn translates to lower electric bills for electric customers.

The use of CCPs in construction reduces the need for quarried raw materials, manufactured aggregates and Portland cement. Replacement of these virgin and manufactured materials with CCPs helps to reduce emissions associated with their manufacturing and processing. When fly ash and bottom ash are used beneficially as engineered backfill material, this material is replacing sand or gravel that would have been quarried and transported from various locations. The use of CCPs helps preserve sand and gravel pits and quarries as well as provides construction cost savings associated with their operation. It is also important to keep in mind that every time Portland cement is replaced or displaced with fly ash, CO_2 and other emissions to the atmosphere from cement production are reduced by decreasing the need for limestone calcination as well as the fossil fuel that is consumed for production.

The Wisconsin Department of Natural Resources (WDNR) has been monitoring the progressive beneficial utilization of industrial by-products, including CCPs. In 1998, WDNR introduced a new chapter to the Wisconsin Administrative Code - Chapter NR 538 "Beneficial Use of Industrial Byproducts", to encourage the use of industrial by-products. According to the WDNR, the purpose of Chapter NR 538 is "to allow and encourage to the maximum extent possible, consistent with the protection of public health and the environment and good engineering practices, the beneficial use of industrial by-products in a nuisance-free manner. The department encourages the beneficial use of industrial by-products in order to preserve resources, conserve energy, and reduce or eliminate the need to dispose of industrial by-products in landfills."

Figure 1-5: Landfilling of fly ash can seem overwhelming.

We Energies has made significant progress in finding uses for its coal ash, and it is interesting to look back at this quote from *Path of a Pioneer – A Centennial History of the Wisconsin Electric Power Company* by John Gurda, 1996, page 210:

> Solving one problem in the air created another on the ground: what to do with millions of tons of fly ash. Recycling had provided an early solution to some of the company's waste

> problems. In the late 1920's, cinders from the Commerce and East Wells plants had been mixed in a building material called Cincrete, which was used in the Allen-Bradley plant, the Tripoli Shrine, and other Milwaukee landmarks. Cinders were in short supply after the system converted to pulverized coal, but fly ash found some acceptance as a concrete additive after World War II. Hard, heat-resistant, and convincingly cheap, it was used in everything from oil well casings to airport runways. Demand, however, never threatened to outstrip supply; most of WEPCO's "used smoke" ended up in landfills.

Concrete continues to be the leading utilization application today; however many new and promising technologies have also been introduced and proven which are discussed in the balance of this handbook.

Chapter 2

CCPs and Electric Power Generation

Coal is one of the most commonly used energy sources for the generation of electricity. In the process of generating power from coal, large quantities of CCPs are produced. CCPs are the solid residues that remain after the combustion of coal within a furnace.

In the early years of power generation by a coal-fired generating plant, coal was fired in a furnace with stoker grates. Today most coal-fueled power plants are fired with pulverized coal.

Electric Power Generation

In the most simplified form, a coal-fired power plant process can be described as follows. Coal is first passed through a pulverizer where it is milled to the consistency of flour. The powdered coal is mixed with a steady supply of air and is blown to the furnace where it burns like a gas flame. Pulverized coal firing is more efficient than stoker firing. With stoker firing, there is always a bed of coal on the grate, which contains a considerable amount of heat that is lost when it is removed. With pulverized coal, the coal burns instantly, and in this way the heat is released quickly and the efficiency of the process is higher. If the coal supply is cut off, combustion ceases immediately (4).

The heat generated by burning pulverized coal in the furnace in the presence of air is used to generate steam in a boiler. In its simplest form, the boiler consists of steel tubes arranged in a furnace. The hot gases pass through the banks of tubes, heating the tubes. The boiler is supplied with a steady flow of water, which is turned to steam in the tubes. The steam is collected in the upper drum of the boiler and is directed to pipes leading to a turbine (4).

The turbine can be compared to a windmill. The steam generated in the boiler is directed to the fan blades in the turbine and causes the rotor assembly to turn. The blades are arranged in groups or stages and the steam is forced to flow through the different stages. In doing so, the steam loses some of its energy at each stage, and the turbine utilizes the steam energy efficiently to spin the rotor shaft.

The turbine rotor shaft is coupled to an electric generator. When the steam from the boiler pushes against the blades fitted to the turbine rotor, it spins together with the generator rotor. The generator rotor is simply a large electromagnet. The electromagnet rotates inside a coil of wire. The magnetic field issuing from the rotating electromagnet travels across the turns of wire in the stationary coil and generates electric current in the wire.

Depending on the number of turns in the coil, the magnitude of the current in the coil increases or decreases. The electric voltage and current generated in the generator can be increased or decreased using a transformer for transmission to consumers. Figure 2-1 is a basic flow diagram of a typical coal-fired power plant. The above description of the turbine/generator is very simple, but in a real power plant, the system is more complex with multiple stages and additional equipment to increase efficiency.

In addition to the above pulverized coal technology, an alternate power generation technology is Integrated Gasification Combined Cycle (IGCC). The IGCC process is designed to break down coal into its basic constituents and obtain a synthetic gas (syngas) that is burned in combustion turbines. The gas conditioning process enables the separation of any contaminants from the syngas prior to its use as fuel. Excess heat is also utilized to produce steam for steam turbine use. The IGCC system consists of coal gasifiers, air separation units, gas conditioning systems, steam turbine generators, and sulfur recovery systems, etc. Figure 2-2 shows a basic diagram of an IGCC plant process. One of the most significant advantages of IGCC is that the technology can achieve greater emissions reductions.

CCP Generation

The description in the past few paragraphs summarizes the primary operations taking place in a coal-fired power plant for the generation of electricity. In the coal combustion process, CCPs are also generated in direct proportion to the variety and quantity of coal consumed. The pulverized coal is burned in the furnace to generate heat, and the hot gases then pass around the bank of tubes in the boiler and are eventually cleaned and discharged through the plant chimney. In large power plants that consume large quantities of coal, substantial quantities of coal ash are produced. This ash that is collected in electrostatic precipitators or baghouses is called fly ash.

In electrostatic precipitators the flue gas is passed between electrically charged plates where the fly ash particles are then attracted to the plates. Baghouses can also be used to collect ash with bags that filter the fly ash out of the flue gas stream. The fly ash particles are then periodically knocked off the plates or bags and fall into the hoppers located at the bottom of the electrostatic precipitators or baghouses. The fly ash is then pneumatically transported to storage silos. The storage silos are equipped with dry unloaders for loading dry bulk semi tankers or rail cars and wet unloaders for conditioned ash or disposal applications.

Bottom ash is formed when ash particles soften or melt and adhere to the furnace walls and boiler tubes. These larger particles agglomerate and fall to hoppers located at the base of the furnace where they are collected and often ground to a predominantly sand size gradation. Some bottom ash is transported to storage dry, but most is transported wet from the furnace bottom to dewatering bins where water is removed prior to unloading and transport to construction sites or storage stockpiles. Figure 2-3 shows the typical ash generation process in a coal-fired power plant.

The ash collected from pulverized-coal-fired furnaces is fly ash and bottom ash. For such furnaces, fly ash constitutes a major component (80 to 90%) and the bottom ash component is in the range of 10 to 20%. Boiler slag is formed when a wet-bottom furnace is used. The ash is kept in a molten state and tapped off as a liquid. The ash hopper furnace contains quenching water. When the molten slag contacts quenching water, it fractures, crystallizes, and forms pellets, resulting in the coarse, black, angular, and glassy boiler slag. The boiler slag constitutes the major component of cyclone boiler by-products (70 to 85%). The remaining combustion products exit along with the flue gases. Currently, We Energies power plants do not produce boiler slag.

Flue gas desulfurization (FGD) material is the solid material resulting from the removal of sulfur dioxide gas from the utility boiler stack gases in the FGD process. The material is produced in the flue gas scrubbers by reacting slurried limestone or lime with the gaseous sulfur dioxide to produce calcium sulfite. Calcium sulfite can be further oxidized to synthetic gypsum (calcium sulfate) which has the same chemical composition as natural gypsum. The dewatering system removes water from the calcium sulfate or synthetic gypsum slurry leaving the FGD absorber modules using centrifuges or belt filter presses. A belt conveyor system transports the dewatered materials from the dewatering building to an adjacent storage shed.

The above CCPs are produced in pulverized coal fired plants. In IGCC facilities, the sulfur-containing gases from the acid gas removal system are converted to elemental sulfur or sulfuric acid. Sulfur dioxide combines with oxygen and water to form sulfuric acid; the reaction of hydrogen sulphide and sulfur dioxide forms water and elemental sulfur. Either elemental sulfur or sulfuric acid would be suitable for sale to other industries for various process uses. If elemental sulfur is produced, a storage tank would be provided to hold molten sulfur until it could be transferred to railcars for shipment off-site. Sulfur can be used in bituminous mixtures, sulfur-concrete, and in the manufacture of fertilizer, paper, etc. If sulfuric acid is produced, above ground storage tanks are constructed to temporarily hold the acid until it is transported off site by specially designed rail cars or trucks for commercial use, such as wastewater treatment or the production of phosphate fertilizer.

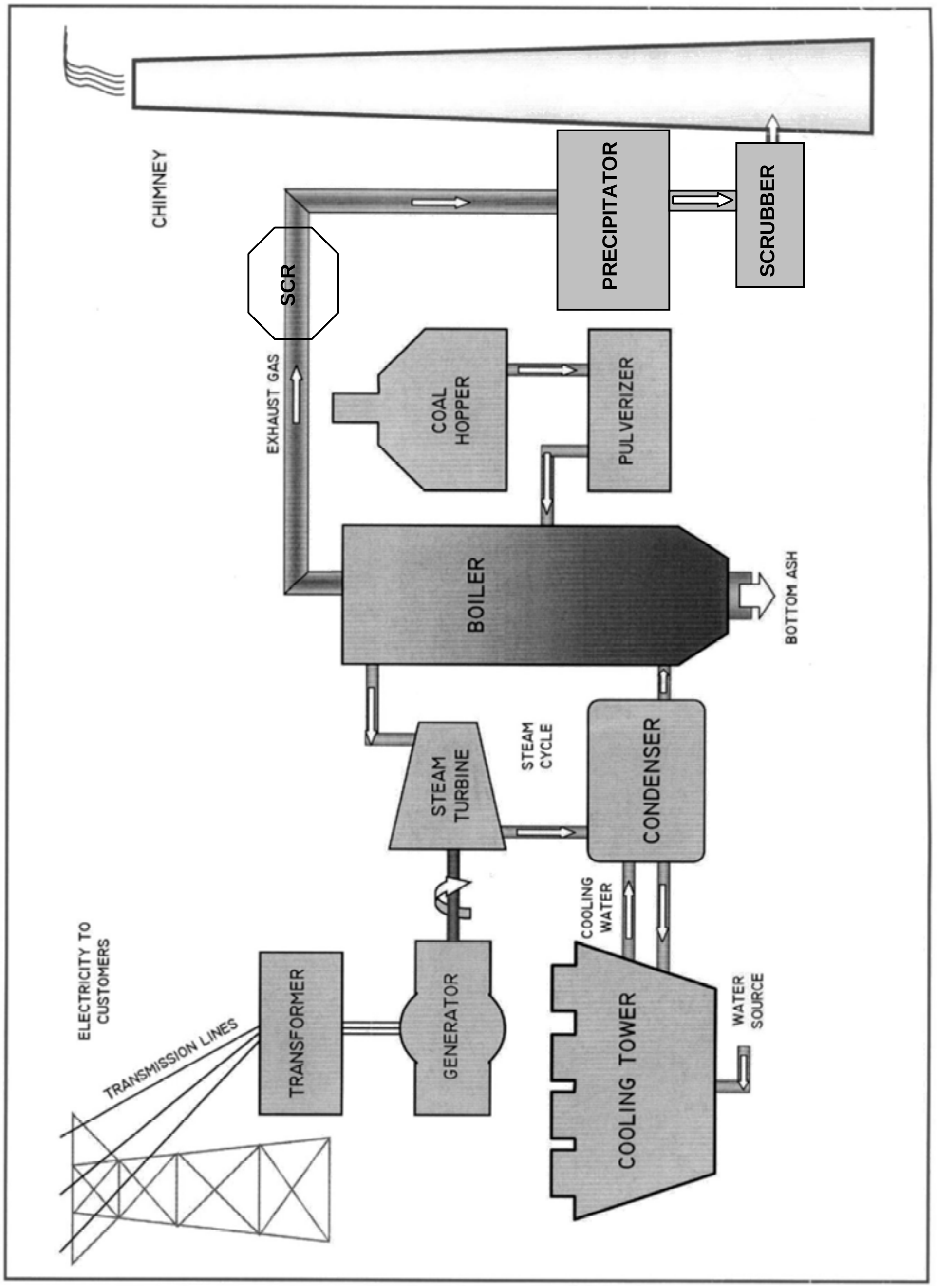


Figure 2-1: Basic Diagram of Coal Fired Power Generation

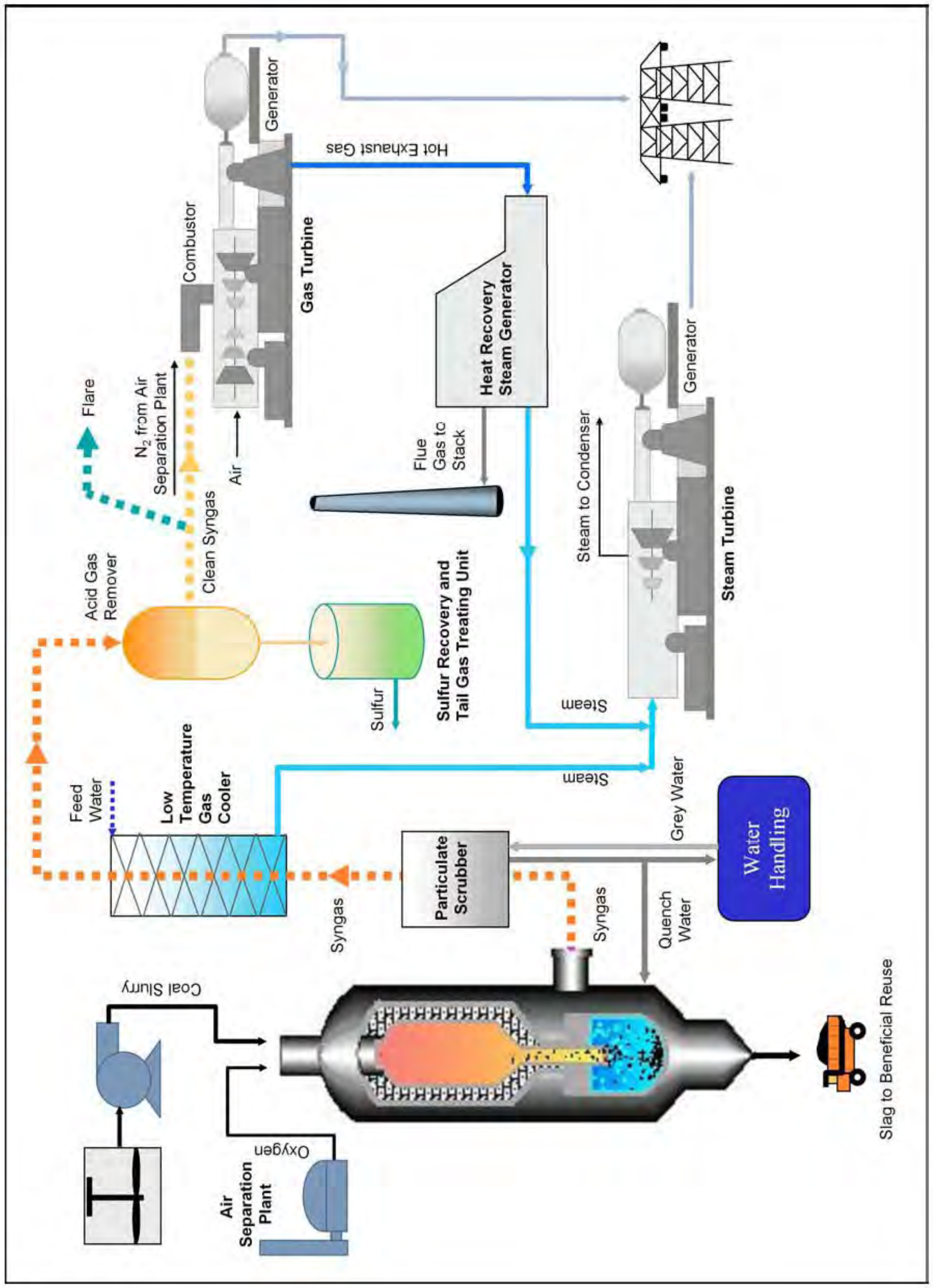


Figure 2-2: Basic Diagram of an IGCC Plant Process (5)

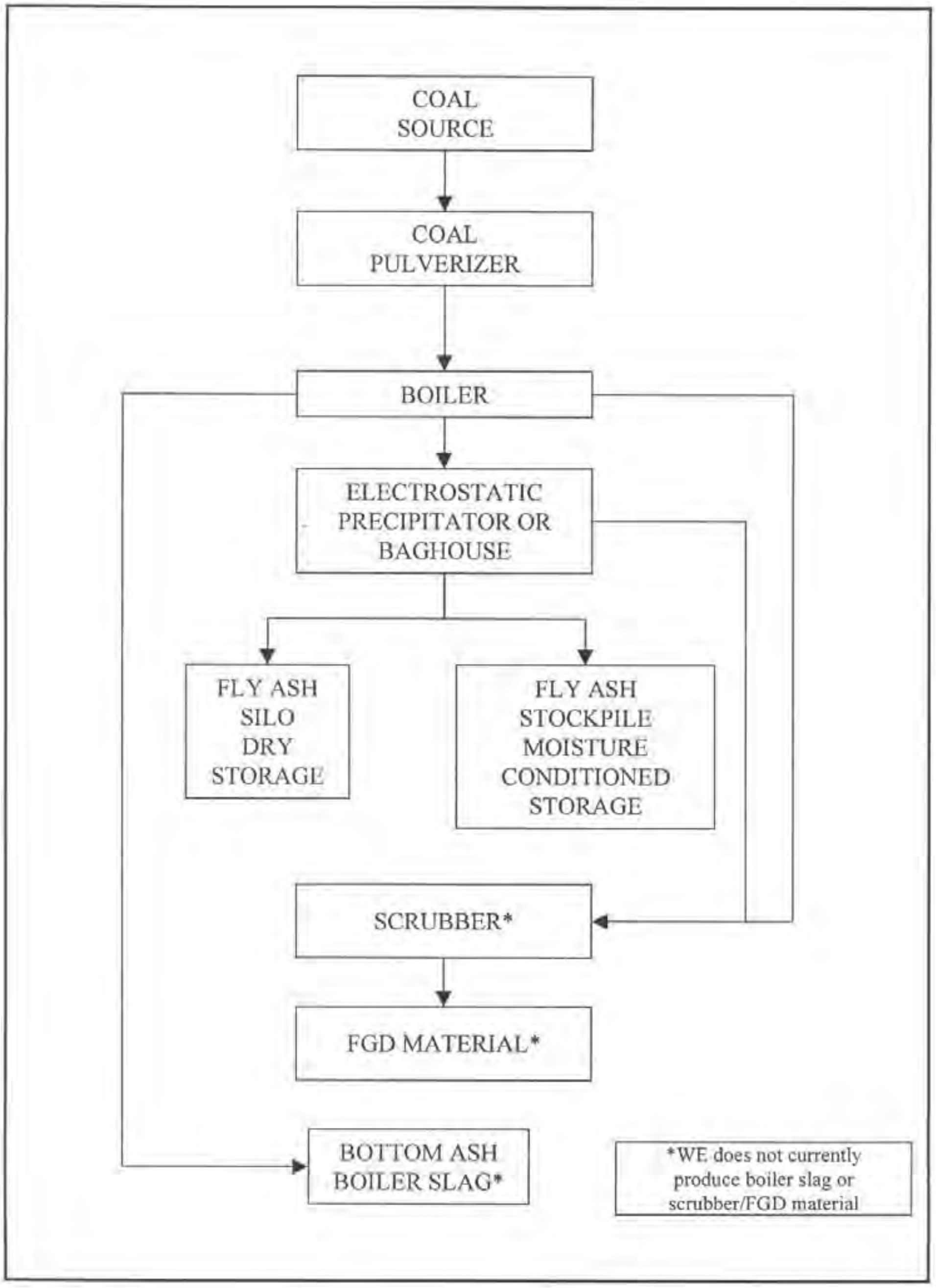


Figure 2-3: Typical Ash Generation Process in a Coal Fired Power Plant

Properties of Fly Ash

Fly ash is a fine powder that is collected from the combustion gases of coal-fired power plants with electrostatic precipitators and/or bag houses. Fly ash particles are very fine, mostly spherical and vary in diameter. Under a microscope they look like tiny solidified bubbles of various sizes. The average particle size is about 10 μm but can vary from <1 μm to over 150 μm (6).

The properties of fly ash vary with the type of coal used, grinding equipment, the furnace and the combustion process itself. ASTM (American Society for Testing and Materials) C618-03 "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete", classifies fly ash into two categories – Class F and Class C fly ash. Combustion of bituminous or anthracite coal normally produces Class F (low calcium) fly ash and combustion of lignite or sub-bituminous coal normally produces Class C (high calcium) fly ash. Table 2-1 shows the normal range of chemical composition for fly ash produced from different coal types.

Table 2-1: Normal Range of Chemical Composition for Fly Ash Produced from Different Coal Types (%)

Compounds	Bituminous Coal	Sub-bituminous Coal	Lignite
SiO_2	20 - 60	40 - 60	15 - 45
Al_2O_3	5 - 35	20 - 30	10 - 25
Fe_2O_3	10 - 40	4 - 10	4 - 15
CaO	1 - 12	5 - 30	15 - 40
MgO	0 - 5	1 - 6	3 - 10
SO_3	0 - 4	0 - 2	0 - 10
Na_2O	0 - 4	0 - 2	0 - 6
K_2O	0 - 3	0 - 4	0 - 4
LOI	0 - 15	0 - 3	0 - 5

Although ASTM does not differentiate fly ash by CaO content, Class C fly ash generally contains more than 15% CaO, and Class F fly ash normally contains less than 5% CaO. In addition to Class F and Class C fly ash, ASTM C618 defines a third class of mineral admixture - Class N. Class N mineral admixtures are raw or natural pozzolans such as diato-maceous earths, opaline cherts and shales, volcanic ashes or pumicites, calcined or uncalcined, and various other materials that require calcination to induce pozzolanic or cementitious properties, such as some shales and clays (7).

Table 2-2 gives the typical composition of Class F fly ash, Class C fly ash and Portland cement .

Table 2-2: Typical Chemical Composition of Fly Ash

Compounds	Class F Fly Ash		Class C Fly Ash		Portland Cement	
	Typical*	ASTM C-618	Typical**	ASTM C-618	Typical***	ASTM C-150
SiO_2	36.9	---	41.36	---	20.25	---
Al_2O_3	18.1	---	21.83	---	4.25	---
Fe_2O_3	3.6	---	5.56	---	2.59	---
$SiO_2+Al_2O_3+Fe_2O_3$	58.6	70.0 (min%)	68.75	50.0 (min %)	---	---
CaO (Lime)	2.85	---	19.31	---	63.6	---
MgO	1.06	---	3.97	---	2.24	6.0 (max %)
SO_3	0.65	5.0 (max%)	1.42	5.0 (max %)	---	3.0 (max %)
Loss on Ignition	33.2	6.0	0.8	6.0	0.55	3.0 (max %)
Moisture Content	0.14	3.0 (max%)	0.01	3.0 (max %)	---	---
Insoluble residue	---	---	---	---	---	0.75 (max %)
Available Alkalies as Equivalent Na_2O	1.36		1.64		0.20	---

* Class F Fly Ash from PIPP Units 5-6 with high carbon content

** Class C Fly Ash from PPPP

*** Type 1 Portland Cement from Lafarge Corporation

Determining Fly Ash Quality

The loss on ignition (LOI) is a very important factor for determining the quality of fly ash for use in concrete. The LOI values primarily represent residual carbonaceous material that may negatively impact fly ash use in air-entrained concrete. A low and consistent LOI value is desirable in minimizing the quantity of chemical admixtures used and producing consistent durable concrete. Activated carbon powder is being tested in various power plant systems to remove mercury from the combustion gases. Ordinary activated carbons that are commingled with fly ash can present two issues when used as a cementitious material in concrete. First, activated carbon has a high affinity for air entraining admixtures, making predictable air content in concrete very difficult. This phenomenon may also be true for other chemical admixtures as well. Secondly, carbon particles can present aesthetic issues for architectural concrete in terms of a darker color or black surface speckles.

Another important factor affecting fly ash concrete quality is its fineness, which is a measure of the percent of material retained on the no. 325 sieve. The condition and the type of coal crusher can affect the particle size of the coal itself. A coarser coal may leave a higher percentage of unburned residues. Also, a coarser gradation means there is less particle surface area of contact, which leads to a less reactive ash.

Uniformity of fly ash is another factor that is important in most applications. The characteristics of the fly ash can change when a new coal source is introduced in the power plant. Each generating station's fly ash is different and it is important to determine its chemical and physical properties before it is used in commercial applications.

Based on the Unified Soil Classifications System, fly ash particles are primarily in the silt size range with the low end falling in the clay category and top end in the sand range. For geotechnical applications, fly ash is sometimes classified as a sandy silt or silty sand, having a group symbol of ML or SM (8).

The specific gravity of fly ash is generally lower than that of Portland cement, which typically has a specific gravity of 3.15. We Energies fly ash sources range from a specific gravity of 2.05 to 2.65. Table 2-3 shows some typical geotechnical engineering properties of fly ash. These properties are useful when fly ash is used in applications such as backfilling for retaining walls or constructing embankments.

Major Fly Ash Uses

Class C fly ash has been widely used for soil stabilization. It can be incorporated into the soil by disking or mixing (10). Fly ash can increase the subgrade support capacity for pavements and increase the shear strength of soils in embankment sections when proportioned, disked and compacted properly.

One of the ways that fly ash stabilizes soil is by acting as a drying agent. Soil with a high moisture content can be difficult to compact during spring and fall. Adding fly ash to the soil and mixing will quickly reduce the moisture content of the soil to levels suitable for compaction. Fly ash has been widely used to reduce the shrink-swell potential of clay soils. The cementitious products formed by the hydration of fly ash bond the clay particles. The swell potential is substantially reduced to levels comparable to lime treatment.

Table 2-3: Typical Geotechnical Properties of Fly Ash (8)

Testing Descriptions	Results
Internal Friction Angle	26° - 42°
Initial Stress-Stain Modules (triaxial test)*	30 MPa
Stress-Stain Modules (plate load tests)*	100 MPa
Modules of Subgrade Reactions (300 mm diameter plates [Ks])*	130 KPa/mm
California Bearing Ratio, Unsoaked (Low Lime Fly Ash)**	10.8-15.4
California Bearing Ratio, Soaked (Low Lime Fly Ash)**	6.8-13.5
Cohesion***	0
Permeability	10^{-4} cm/sec - 10^{-6} cm/sec
Maximum Dry Density (60-110 lb/cu ft)	960-1760 kg/m^3

* The values shown are from Reference (7). No data is readily available to establish a range.

** From Reference (9)

*** C = 0 recommended for Class F fly ash. Additional laboratory testing required to establish C for Class C Fly Ash.

When fly ash is used to stabilize subgrades for pavements, or to stabilize backfill to reduce lateral earth pressure or to stabilize embankments to improve slope stability, better control of moisture content and compaction is required. Pulvamixers are generally used to get thorough, rapid mixing of fly ash, soil and water.

All fly ash is pozzolanic and Class C fly ash is also cementitious. It reacts with calcium hydroxide produced by the hydration of cement in the presence of water to form additional cementitious compounds. This property of fly ash gives it wide acceptance in the concrete industry.

Class C fly ash has been successfully utilized in reconstructing and/or upgrading existing pavements. In this process, commonly known as cold-in-place recycling (CIR) or full depth reclamation (FDR), existing asphalt pavement is pulverized with its base, and the pulverized mixture is stabilized by the addition of fly ash and water. The cementitious and pozzolanic properties of fly ash enhance the stability of the section. Fly ash recycled pavement sections have structural capacities substantially higher than crushed stone aggregate base. A new asphaltic concrete wearing surface is then installed above the stabilized section.

Fly ash is an artificial pozzolan. The pozzolanic property of volcanic ash was known to the Romans almost 2000 years ago. Pozzolans are the vitamins that provide specific benefits to a particular mixture (11). The word “pozzolan” comes from the village of Pozzuoli, near Vesuvius, where volcanic ash was commonly used. The Romans used a mixture of lime and volcanic ash or burnt clay tiles in finely ground form as a cementing agent. The active silica and alumina in the ash combined with the lime was used to produce early pozzolanic cement. Some of the old Roman structures like the Coliseum and the Pont du Gard are good examples of structures built with early volcanic ash cements (12).

Extensive research has been conducted in utilizing fly ash in concrete, masonry products, precast concrete, controlled low strength materials (CLSM), asphalt and other applications. These applications are discussed in the following chapters.

Properties of Bottom Ash

Bottom ash particles are much coarser than fly ash. The grain size typically ranges from fine sand to gravel in size. Chemical composition of bottom ash is similar to that of fly ash but typically contains greater quantities of carbon. Bottom ash tends to be relatively more inert because the particles are larger and more fused than fly ash. Since these particles are highly fused, they tend to show less pozzolanic activity and are less suited as a binder constituent in cement or concrete products. However, bottom ash can be used as a concrete aggregate or for several other civil engineering applications where sand, gravel and crushed stone are used.

For coal type comparison of bottom ash, it is helpful to refer to the following tables. Table 2-4 shows typical chemical composition of bottom ash obtained by burning bituminous coal and sub-bituminous coal.

Table 2-4: Chemical Composition of Bottom Ash

Compound	Symbol	Bottom Ash from Bituminous Coal % (Mass)	Bottom Ash from Sub-bituminous Coal % (Mass)
Silicon Dioxide	SiO_2	61.0	46.75
Aluminum Oxide	Al_2O_3	25.4	18.76
Iron Oxide	Fe_2O_3	6.6	5.91
Calcium Oxide	CaO	1.5	17.80
Magnesium Oxide	MgO	1.0	3.96
Sodium Oxide	Na_2O	0.9	1.28
Potassium Oxide	K_2O	0.2	0.31

* Mass percentage values shown may vary 2 to 5% from plant to plant.

Table 2-5 shows the gradation of bottom ash from two We Energies power plants. The gradation of bottom ash can vary widely based on the coal pulverization and burning process in the power plant, the variety of coal burned, and the bottom ash handling equipment.Table 2-6 gives typical geotechnical properties of bottom ash produced from combustion of bituminous coal. These values are based on research conducted in Australia (8). Table 2-7 shows some geotechnical properties of bottom ash based on studies performed in the United States (9).

Table 2-5: Gradation of Bottom Ash

% Passing Sieve Size	MCPP	PPPP
3/4”	100.0	98.29
1/2”	96.2	94.3
#4	85.1	77.3
#8	74.4	59.0
#16	60.5	41.8
#30	47.2	27.7
#50	35.8	18.0
#100	26.9	10.4
#200	20.7	4.8

MCPP - Milwaukee County Power Plant
PPPP - Pleasant Prairie Power Plant

Table 2-6: Geotechnical Properties of Bottom Ash (8)

Test Description	Results	Test Method [a]
Liquid Limit (lower) (16 samples)	Mean Value: 45.5 Maximum: 52.0 Minimum: 40.0	T108
Plastic Limit (lower)	Non-Plastic (All 16 Samples)	T109
Linear Shrinkage	Nil	T113
Coefficient of Saturated Permeability	3.47×10^{-6} m/sec hydraulic gradient 2 unstabilized 3.47×10^{-7} m/sec hydraulic gradient 1.3 (+6% lime)[b] 6.94×10^{-8} m/sec hydraulic gradient 1.3 (+6% lime)[c]	Constant Head Permeameter
Coefficient of Saturated Permeability	3.47×10^{-6} m/sec hydraulic gradient 2 unstabilized 3.47×10^{-7} m/sec hydraulic gradient 1.3 (+6% lime)[b] 6.94×10^{-8} m/sec hydraulic gradient 1.3 (+6% lime)[c]	Constant Head Permeameter
Maximum Dry Density	1.06t/m^3 at 35% moisture content (unstabilized) 1.165 t/m^3 at 20% moisture content (with 6% lime)	T11 T140
Unconfined Compressive Strength	Unstabilized: 0 - 0.3 MPa With 6% lime: 3.30 MPa (mean 28 day strength)	T141
California Bearing Ratio	Mean: 70% Standard Deviation: 13.5%	T142
Modified Texas Triaxial	Standard Deviation: 13.5% Unstabilized: Class 2.9 @ 25.2% moisture content Class 3.0 @ 23.2% moisture content Class 3.3 @ 28.2% moisture content Tests with lime added gave Class 0 after 11.2 days	T171

[a] Test methods refer to RTA (Road and Traffic Authority, New South Wales, Australia) procedures.

[b] This sample was compacted at 25% moisture content and cured 24 hours prior to testing.

[c] This is the same sample after 72 hours continuous testing. Leaching of lime was evident.

Table 2-7: Geotechnical Properties of Bottom Ash (9)

Property	Bottom Ash
Specific Gravity	2.1-2.7
Dry Unit Weight (lb/cu.ft)	45-100
Plasticity	None
Maximum Dry Density (lb/cu.ft)	75-100
Optimum Moisture Content (%)	12-24
Los Angeles Abrasion (%)	30-50
Friction Angle (°)	38-42 32-45 (<0.37 in.)
Coefficient of Permeability (cm/sec)	$10^{-2} – 10^{-3}$
California Bearing Ratio (%)	40-70

Properties of Boiler Slag

Boiler slags are predominantly single-sized and within a range of 5.0 to 0.5 mm. Ordinarily, boiler slag particles have a smooth texture, but if gases are trapped in the slag as it is tapped from the furnace, the quenched slag will become somewhat vesicular or porous. Boiler slag from the burning of lignite or subbituminous coal tends to be more porous than that of the bituminous coals. The gradation of typical boiler slag is shown in Table 2-8. Compared to natural granular materials, the maximum dry density values of boiler slag are from 10 to 25% lower; while the optimum moisture content values are higher.

Table 2-8: Gradation of Boiler Slag (9)

% Passing Sieve Size	Boiler Slag
3/4”	-
3/8”	-
#4	90-100
#10	40-60
#20	-
#40	<10
#60	-
#140	-
#200	<5

Table 2-9 shows the chemical composition of boiler slag. The chemical composition of boiler slag is similar to that of bottom ash, as shown in Table 2-4, though the production process of boiler slag and bottom ash is relatively different.

Table 2-10 gives the typical geotechnical properties of the boiler slag. The friction angle of boiler slag is within the same range as those for sand and other conventional fine aggregates. Boiler slag exhibits high CBR value, comparable to those of high-quality base materials. Compared to bottom ash, boiler slag exhibits less abrasion loss and soundness loss resulting from its glassy surface texture and lower porosity (9).

Table 2-9: Chemical Composition of Selected Boiler Slag (9)

Compound	Symbol	Boiler Slag from Bituminous Coal % (Mass)	Boiler Slag from Lignite Coal % (Mass)
Silicon Dioxide	SiO_2	48.9	40.5
Aluminum Oxide	Al_2O_3	21.9	13.8
Iron Oxide	Fe_2O_3	14.3	14.2
Calcium Oxide	CaO	1.4	22.4
Magnesium Oxide	MgO	5.2	5.6
Sodium Oxide	Na_2O	0.7	1.7
Potassium Oxide	K_2O	0.1	1.1

Table 2-10: Geotechnical Properties of Boiler Slag (9)

Property	Boiler Slag
Specific Gravity	2.3-2.9
Dry Unit Weight (lb/cu.ft)	60-90
Plasticity	None
Maximum Dry Density (lb/cu.ft)	82-102
Optimum Moisture Content (%)	8-20
Los Angeles Abrasion (%)	24-48
Friction Angle (°)	38-42 36-46 (<0.37 in.)
Coefficient of Permeability (cm/sec)	$10^{-2} – 10^{-3}$
California Bearing Ratio (%)	40-70

Boiler slag has been frequently used in hot mix asphalt because of its hard durable particles and resistance to surface wear. It can also be used as asphalt wearing surface mixtures because of its affinity for asphalt and its dust-free surface, increasing the asphalt adhesion and anti-stripping characteristics. Since boiler slag has a uniform particle size, it is usually mixed with other size aggregates to achieve the target gradation used in hot mix asphalt. Boiler slag has also been used very successfully as a seal coat aggregate for bituminous surface treatments to enhance skid resistance.

Properties of Synthetic Gypsum

FGD product scrubber material is generated as calcium sulfite; some plant unit scrubbing systems are of the forced oxidation design and result in a synthetic gypsum (calcium sulfate) material. Calcium sulfite FGD scrubber material can be fixated with lime, fly ash or cement and used for road base, while the synthetic gypsum is frequently used for wallboard or as a cement additive. Table 2-11 shows the typical physical properties (particle size and specific gravity) of calcium sulfite and synthetic gypsum, indicating synthetic gypsum is coarser than calcium sulfite (9). The purity of synthetic gypsum ranges from 96%-99%, depending on the sorbent used for desulfurization and proportion of fly ash collected with the synthetic gypsum. Table 2-12 presents the typical chemical composition of synthetic gypsum (13) and Table 2-13 shows the typical geotechnical properties (14).

Table 2-11: Typical Physical Properties of FGD Material

Property	Calcium Sulfite	Synthetic Gypsum (Calcium Sulfate)
Particle Sizing (%)		
Sand Size	1.3	16.5
Silt Size	90.2	81.3
Clay Size	8.5	2.2
Specific Gravity	2.57	2.36

Compared to natural gypsum, the handling of synthetic gypsum is difficult because synthetic gypsum is abrasive, sticky, compressive, and considerably finer (<0.2 mm). The adhesiveness of synthetic gypsum decreases with the increase in particle size and the decrease of free water content. Temperature has little effect on the adhesiveness of synthetic gypsum in storage. High temperatures, however, cause a significant amount of degradation of synthetic gypsum particles (13). The bulk physical properties of synthetic gypsum are similar to fly ash and can be handled similarly. However, synthetic gypsum is primarily crystalline in its morphology while fly ash is primarily glassy or amorphous. The typical moisture content of synthetic gypsum is about 10%-15%. Synthetic gypsum can be transported by rail, road, water, or pipeline; however it is best transferred using mechanical conveyors.

Table 2-12: Typical Chemical Composition of Synthetic Gypsum (13)

Constituent	Weight Fraction (%)
Ca	24
SO_4	54
CO_3	3
SiO_2	2.7
Inert	1.3
H_2O	15
PH=7	

Table 2-13: Typical Geotechnical Properties of Dewatered Synthetic Gypsum (14)

Testing description	Results
Maximum Dry Density (lb/cu.ft)	81.5 @ 35% optimum moisture content
Permeability (cm/sec @ one month)	1.0×10^{-5}
Unconfined Compressive Strength (psi @ one month)	31-52
Plasticity	None
Compressibility, strain	0.9-2.4
Cohesion (psi)	0 @ consolidated drained condition 8 @ unconsolidated undrained condition
Internal Angle of Friction	39

The quality of gypsum produced is directly proportional to the sulfur content of the fuel being burned. Quality synthetic gypsum material produced from the proposed wet scrubbers could be used for the production of wallboard and other products. Fixated or stabilized gypsum has been successfully utilized for road base or structural fill construction by blending with quicklime and pozzolanic fly ash, cement, or self-cementitious fly ash. Synthetic gypsum in wet form can benefit the cement grinding process by inducing inherent moisture into the ball mill, thus providing additional cooling.

Current We Energies CCP Sources

Fly ash and bottom ash are the predominant CCPs produced at We Energies' six coal-fired power plants located in Wisconsin and upper Michigan. These power plants generate electricity for use by residential, industrial and commercial customers and also generate fly ash and bottom ash as an end product. We Energies together with regulators, universities, consultants and research institutions are committed to developing alternative environmentally friendly beneficial applications for fly ash and bottom ash.

During the past two decades, several construction products have been developed and marketed. The beneficial utilization of these materials in concrete and other construction products can preserve virgin resources, lower energy costs and yield high-performance construction materials. We Energies has conducted extensive testing of these products to evaluate their properties. The product test information is given in the following chapters to help customers better understand the materials and their applications.

Annual fly ash and bottom ash production at We Energies typically totals approximately 662,000 tons of which nearly 517,000 tons of fly ash and 101,000 tons of bottom ash were beneficially used in 2003. The breakdown by power plant is shown in Table 2-14. The primary uses of We Energies bottom ash include pavement and foundation subbase materials and landfill drainage layer construction. For We Energies fly ash, the primary uses include cementitious material for concrete and concrete products, feedstock for Portland cement manufacture, and liquid waste stabilization(15).

Table 2-14: Annual Coal Combustion Products Production*

Source	Total Ash (Tons)	FA (Tons)	BA (Tons)
MCPP	4,363	1,735	2,628
PPPP**	282,389	231,488	50,901
OCPP	134,898	111,534	23,364
VAPP	85,899	75,569	10,331
PWPP	33,013	29,701	3,311
PIPP U1-4	41,375	37,599	3,776
PIPP U5-6	41,928	37,302	4,626
PIPP U7-9**	38,521	30,003	8,518
Total	662,387	554,932	107,456

*Actual production figures for 2003

**Ash production from ash fuel is included

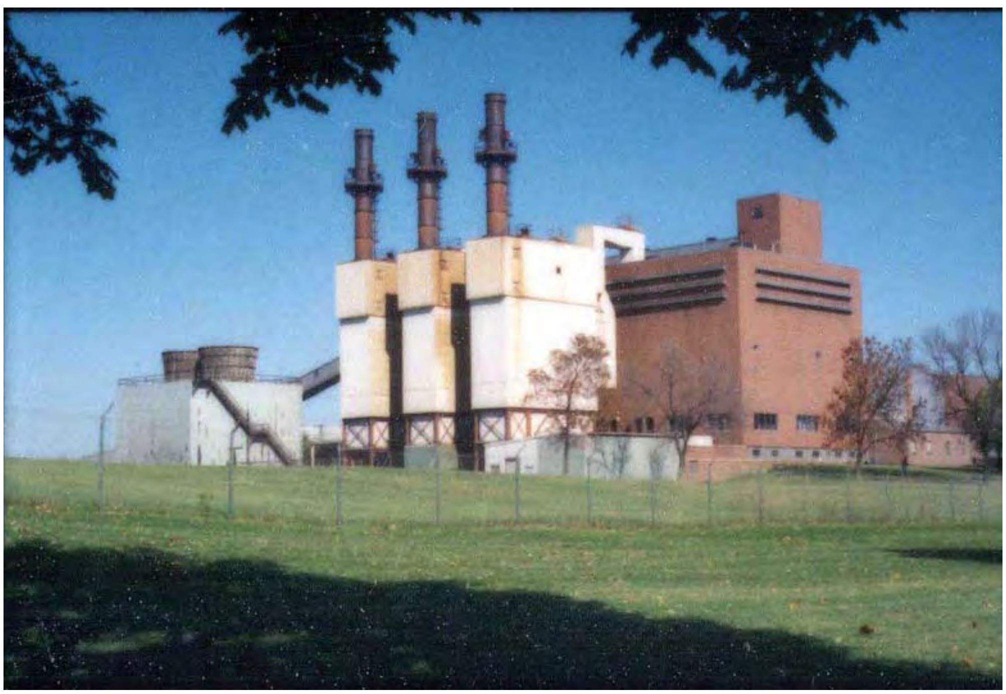
The following coal fired power plants are owned and operated by We Energies:

1. Milwaukee County Power Plant (MCPP)
2. Oak Creek Power Plant (OCPP)
3. Pleasant Prairie Power Plant (PPPP)
4. Port Washington Power Plant (PWPP) (Retirement planned for 2004)
5. Valley Power Plant (VAPP)
6. Presque Isle Power Plant (PIPP)

Of the above power plants, the first five are located in southeastern Wisconsin and the last, Presque Isle Power Plant, is located in upper Michigan.

Milwaukee County Power Plant (MCPP)

9250 Watertown Plank Road, Wauwatosa, Wisconsin 53226



This 10 MW, stoker-fired plant is located in Milwaukee County, adjacent to the Milwaukee County Medical Complex. Combustion products are primarily bottom ash with some fly ash that are commingled in a single dry storage silo. Annual coal ash production is approximately 4,400 tons. The MCPP burns low-sulfur bituminous coal.

Oak Creek Power Plant (OCPP)

4801 East Elm Road, Oak Creek, Wisconsin 53154

This 1154 MW pulverized coal-fired plant is located in the city of Oak Creek, Milwaukee County, near the Milwaukee-Racine county line. It supplies electrical energy to the company's power grid and produces approximately 112,000 tons of fly ash and 23,000 tons of bottom ash by burning a sub-bituminous coals. Fly ash and bottom ash are handled by separate conveyance/storage systems.

All bottom ash is removed as necessary by the company's designated bottom ash marketing agent, A.W. Oakes & Son, who manages a stock pile for this product on site. The stock pile allows for beneficial use activities that require larger quantities of materials.

Oak Creek Power Plant also has a 20,000 ton fly ash storage facility for winter production.

Pleasant Prairie Power Plant (PPPP)

8000 95th Street, Kenosha, Wisconsin 53142

This 1210 MW, pulverized coal-fired plant is located in the town of Pleasant Prairie in Kenosha County. Each year it produces approximately 231,000 tons of fly ash and 51,000 tons of bottom ash by burning a blend of low sulfur sub-bituminous coals. Each CCP is handled by separate conveyance/storage systems. Fly ash that is not immediately transported offsite by the Company’s designated fly ash marketing agent, Lafarge, can be stored on site in a company-owned 12,000 ton capacity storage building.

All bottom ash is removed as necessary by the company's designated bottom ash marketing agent, A.W. Oakes & Son, who manages a stockpile for this product on site. The stockpile allows for beneficial use activities that require larger quantities of material.

Port Washington Power Plant (PWPP)

146 South Wisconsin Street, Port Washington, Wisconsin 53074

This 225 MW, pulverized coal-fired plant is located in the city of Port Washington in Ozaukee County. It supplies electrical energy to the company's power grid.

It produced approximately 30,000 tons of fly ash and 3,300 tons of bottom ash by burning low sulfur bituminous coal. One of the plant's three units (units 1) is equipped with a sodium bicarbonate sorbent injection system to capture sulfur oxides.

These reaction products are captured by the plant's electrostatic precipitators and are normally commingled with the remaining units 2 and 3 fly ash. PWPP was retired in 2004 and these units are being replaced with two 500 MW natural gas fired combined cycle units.

Valley Power Plant (VAPP)

1035 West Canal Street, Milwaukee, Wisconsin 53233

This 280 MW, pulverized coal-fired plant is located in downtown Milwaukee. It supplies both electric energy to the company's power grid and low-pressure

steam to the downtown heating district. It produces approximately 76,000 tons of fly ash and 10,000 tons of bottom ash by burning low sulfur bituminous coal. The fly ash is captured in bag houses using fabric filters.

Presque Isle Power Plant (PIPP)

2701 Lake Shore Boulevard, Marquette, MI 49855

This 617 MW coal fired power plant is located on the shores of Lake Superior in Marquette, Michigan. Units 1 through 6 burn low-sulfur bituminous coal, units 7, 8 and 9 burn a low-sulfur sub-bituminous coal. Electrostatic precipitators and baghouses remove 104,000 tons of fly ash. 17,000 of tons

bottom ash is removed by a hydraulic removal system. Presque Isle Power Plant also has 10,000 tons of company owned vertical fly ash silo storage.

Proposed Elm Road Generating Station (Oak Creek Power Plant Expansion)

We Energies is proposing to build approximately 1,830 MW of advanced technology coal based generating capacity on a large parcel of land located along the shore of Lake Michigan near the existing Oak Creek Power Plant (OCPP). The new facility, the Elm Road Generating Station (ERGS), is planned to consist of two super-critical pulverized coal (SCPC) units. The proposed in-service dates for the two SCPC units are 2007 and 2009. A simulation of the view after construction of the ERGS is shown in the following picture (5).

We Energies is committed to developing and implementing full utilization of its coal combustion products. The company is working with several research groups, universities, regulators, consultants, and trade associations to develop environmentally friendly “green” products and applications for its coal combustion products. The We Energies gas and electric utility service area is shown in Figure 2-4.

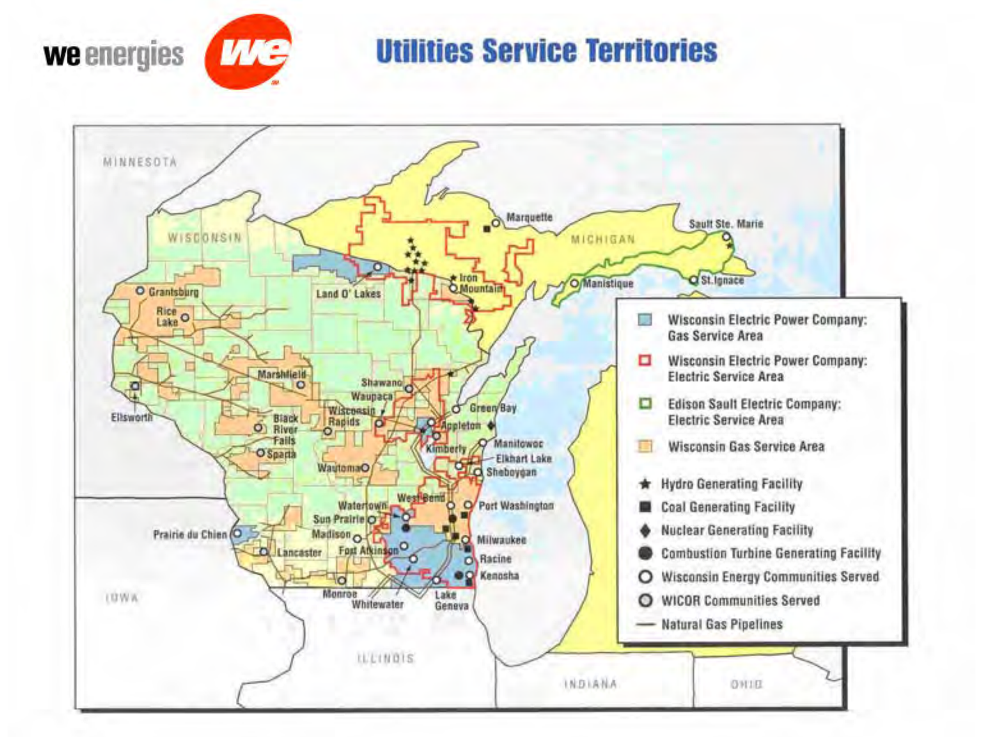


Figure 2-4: We Energies Service Territories

Chapter 3

Properties of We Energies Coal Combustion Products

Fly ash and bottom ash produced at the six coal-fired power plants that are owned and operated by We Energies have been subjected to extensive tests for physical and chemical properties. The type of coal, percentage of incombustible matter in the coal, the pulverization process, furnace types and the efficiency of the combustion process determine the chemical composition of the coal ash.

Another factor affecting the quality of coal ash is whether the power plant is base loaded or frequently being brought in and out of service. A base loaded plant operates at consistent temperatures and combustion rate. Plants that are frequently changing load or coming in and out of service tend to produce more variability in coal ash characteristics. The use of low NO_x burners at power plants has generally resulted in an increase in loss on ignition and carbon content in the fly ash. Likewise, many SO_x reduction processes result in higher sulfur compounds in the coal ash.

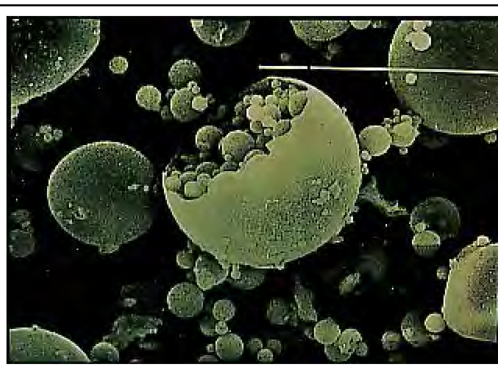


Figure 3-1: Fly ash particles are spherical and average about 10 microns in diameter

We Energies purchases coal from several mines. Several factors affect the selection of coal source, but the quality and cost of coal are two very important considerations. The consistency of fly ash does not change significantly if the coal used in the plant is from a single geological formation or from a consistent blend of coals. But when coal sources change, the chemical and physical properties of the fly ash may change significantly if the type or chemistry of coal is switched. At times, coal from different sources may be blended to improve air emissions, to reduce generation costs, to increase the efficiency of combustion and/or to improve the quality of fly ash generated.

Physical, Chemical and Mechanical Properties of Fly Ash

Table 3-1 gives the chemical composition of fly ash from various We Energies power plants. The results tabulated are based on tests performed at We Energies' own state-certified lab and various other outside certified testing facilities. We Energies fly ash marketers have on-site labs that test the fly ash generated from the power plant daily and more often if warranted. The quality and chemical composition of fly ash do not change very often because coal is usually purchased on long-term contracts. Fly ash from Pleasant Prairie Power Plant has actually been more consistent than many Portland cements.

Figures 3-2 and 3-3 show the loss on ignition and fineness consistency for Pleasant Prairie's fly ash. A customer may request samples for independent testing on a particular fly ash to independently determine its properties. As can be seen from Table 3-1, the chemical composition of fly ash differs from plant to plant and sometimes from unit to unit within a power plant.

Table 3-1: Chemical Composition of We Energies Fly Ash

Source	ASTM C618 Class F Class C	OCPP Units 5-6	OCPP Units 7-8	PIPP Units 1-4	PIPP Units 5-6	PIPP Units 7-9	PPPP	VAPP
SiO_2, %	- -	36.1	34.3	40.4	36.9	37.0	41.4	39.27
Al_2O_2, %	- -	19.5	19.4	18.5	18.1	18.6	21.8	15.93
Fe_2O_3, %	- -	6.0	5.7	4.2	3.6	5.5	5.6	4.57
$SiO_2+Al_2O_3+Fe_2O_3$, %	70.0 Min 50.0 Min	61.6	59.4	63.1	58.6	61.1	68.8	59.77
SO_3, %	5.0 Max 5.0 Max	1.6	1.4	0.6	0.7	2.4	1.4	1.11
CaO, %	- -	24.3	25.8	3.0	2.9	19.5	19.3	3.31
Moisture Content, %	3.0 Max 3.0 Max	0	0	0	0.1	0	0.0	0.00
LOI, %	6.0 Max * 6.0 Max	0.1	0.3	28.0	33.2	0.9	0.8	31.31
Available Alkali as Na_2O, %	AASHTO M 295-00 1.5 Max	1.3	1.4	0.7	0.7	1.8	1.3	- 0.6

*The use of Class F Pozzolan containing up to 12.0% loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.

Fly ash is classified as Class F or Class C by ASTM C618 based on its chemical and physical composition. We Energies contracts with marketers that distribute and test fly ash to ensure that customer supply, quality and consistency requirements are met.

The chemical composition of We Energies' fly ash generated by burning sub-bituminous coal is different from that generated by burning bituminous coal. For example, burning 100% Wyoming Powder River Basin (PRB) sub-bituminous coal produces fly ash with a calcium oxide content, typically in the range of 16 to 28%. However, burning 100% bituminous coal generates a fly ash with a CaO content in the range of 2 to 4%.

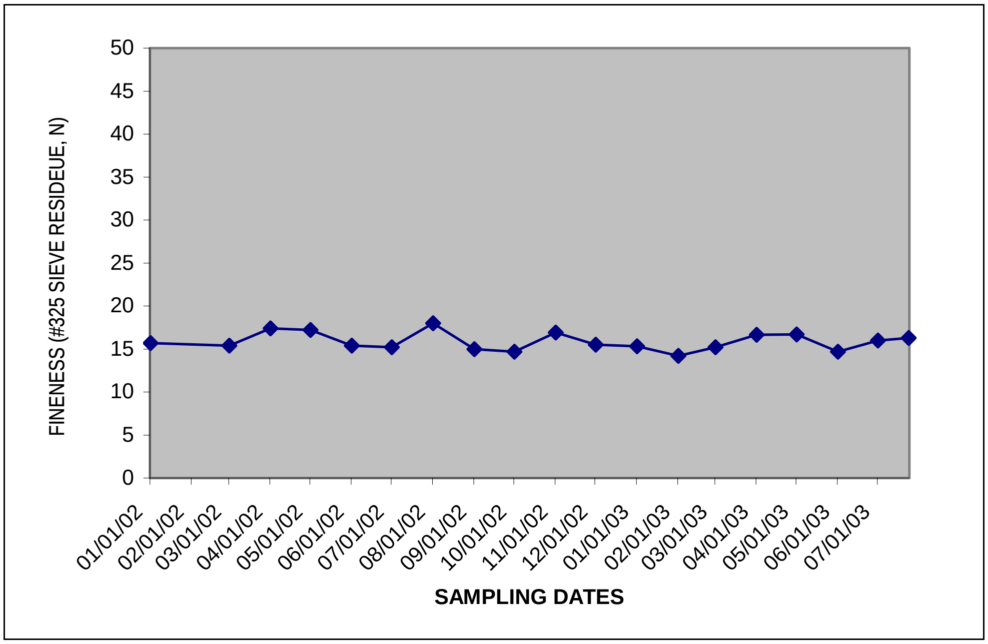


Figure 3-2: Fineness Consistency of PPPP Fly Ash

According to ASTM C618, when the sum of SiO_2, Al_2O_3 and Fe_2O_3 is greater than 70%, the fly ash can be classified as Class F and when the sum is greater than 50% it can be classified as Class C fly ash. The fly ash must also meet the ASTM C618 limits for SO_3, loss on ignition, fineness and other requirements.

Presque Isle Power Plant generates both Class C and Class F fly ash and has separate silos for each variety (see Table 3-1). By reviewing the chemical composition of fly ash from each plant, it is easy to determine if the fly ash is Class C or Class F and to select an ash that best meets end use requirements.

By graphing individual parameter test results, it is possible to identify any significant changes. This is helpful in order to determine if a specific fly ash is suitable for a particular application or whether a blend of one or more materials is needed.

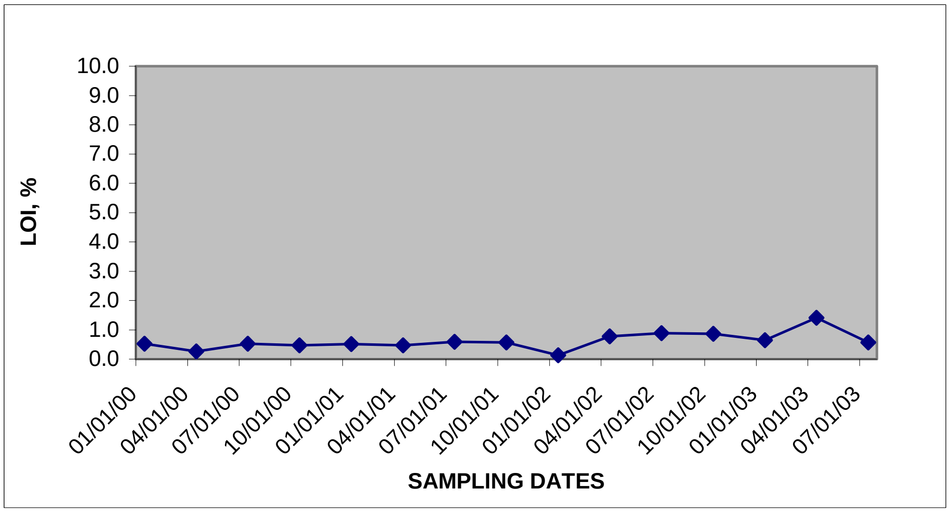


Figure 3-3: Loss on Ignition Consistency for PPPP Fly Ash

Table 3-2 shows the physical properties of fly ash at various We Energies power plants, along with the ASTM standard requirements.

Table 3-2: Fly Ash Physical Properties

SOURCE	ASTM C618 Class F	ASTM C618 Class C	OCPP Units 5-6	OCPP Units 7-8	PIPP Units 1-4	PIPP Units 5-6	PIPP Units 7-9	PPPP	VAPP
Fineness:									
Retained on #325 Sieve, (%)	34 Max	34 Max	7.2	14.0	33.7	31.2	15.7	14.4	64.9
Strength Activity Index with Portland Cement, (%) :									
% of Control @ 7 days	75 Min	75 Min	99.8	100.9	60.9	45.4	92.8	97.3	29.3
% of Control @ 28 days	75 Min	75 Min	104.6	104.6	63.8	52.0	95.6	98.4	34.0
Water Requirement:									
% of Control	105 Max	105 Max	92.6	93.4	109.5	116.5	92.6	92.6	121.9
Soundness:									
Autoclave Expansion (%)	0.8 Max	0.8 max	0.07	0.07	0.01	0.02	0.06	0.03	0.02
Specific Gravity	-	-	2.68	2.68	1.94	1.96	2.61	2.34	1.94

Physical, Chemical and Mechanical Properties of Bottom Ash

The coal combustion process also generates bottom ash, which is second in volume to the fly ash. Bottom ash is a dark gray black or brown granular, porous, predominantly sand size material. The characteristics of the bottom ash depend on the type of furnace used to burn the coal, the variety of coal, the transport system (wet or dry), and whether the bottom ash is ground prior to transport and storage. We Energies generates over 107,000 tons of bottom ash each year at its six coal-fired power plants.

It is important that the physical, chemical and mechanical properties of bottom ash be studied before it can be beneficially utilized. The primary chemical constituents of We Energies bottom ash are shown in Table 3-3. These chemical characteristics of bottom ash are generally not as critical as for fly ash, which is often used in concrete, where cementitious properties and pozzolanic properties are important.

Table 3-3: Chemical Composition of We Energies Bottom Ash

Constituent	PPPP	MCPP	OCPP Units 7	VAPP	PIPP Unit 1-6	PIPP Unit 7-9
SiO_2	47.50	54.15	46.29	57.32	56.84	48.64
Al_2O_3	19.27	30.22	18.55	23.14	24.17	19.00
Fe_2O_3	5.60	6.21	5.16	6.23	7.51	6.46
CaO	17.78	2.53	18.75	4.64	4.79	14.99
MgO	3.31	0.89	4.60	1.69	1.71	3.58
SO_3	0.33	0.37	0.52	0.85	0.65	0.82
Na_2O	0.90	0.39	1.02	1.22	1.06	2.54
K_2O	0.57	2.50	0.25	1.44	1.32	0.67

In the case of bottom ash, physical and mechanical properties are critical. We Energies has been studying the properties of bottom ash that are important in construction applications for comparison to virgin materials currently dominating the market.

An additional consideration for bottom ash is its staining potential if used as an aggregate in concrete masonry products. Staining can occur if certain iron compounds such as pyrite are present. Pyrites can also present corrosion potential for buried metals. For these applications, it is important to identify if pyrites exist in sufficient quantity to present a problem ($\geq$ 3.0 %).

Moisture-Density Relationship (ASTM D1557)

Bottom ash samples were tested to determine maximum dry density and optimum moisture content per the ASTM D1557 test method. The test results are shown in Table 3-4.

Table 3-4: Physical Properties of Bottom Ash

Bottom Ash Source	Max Dry Density, pcf	Optimum Moisture Content, %	Hydraulic Conductivity K(cm/sec)
OCPP	87.2	23.7	1.0×10^{-3}
MCPP	74.9	13.4	2.2×10^{-4}
PWPP	81.1	15.5	4.6×10^{-3}
PPPP	89.2	19.2	4.9×10^{-3}
Unit 1-6 PIPP	54.4	21.9	4.8×10^{-3}
Unit 7-9 PIPP	91.3	14.3	1.4×10^{-3}
VAPP	49.3	33.0	5.4×10^{-3}
SAND	110 – 115	7 – 17	10^{-2} to 10^{-3}

We Energies bottom ashes are generally angular particles with a rough surface texture. The dry density of bottom ash is lower than sand or other granular materials typically used in backfilling.

The grain size distribution is shown in Table 3-5. Figures 3-4 through 3-9 show the grain size distribution curves for the various We Energies bottom ashes.

Engineering Properties of We Energies Bottom Ash

Unlike fly ash, the primary application of bottom ash is as an alternative for aggregates in applications such as subbase and base courses under rigid and flexible pavements. It has also been used as a coarse aggregate for hot mix asphalt (HMA) and as an aggregate in masonry products. In these applications, the chemical properties are generally not a critical factor in utilizing bottom ash.

However, some engineering properties of the material are important and may need to be evaluated. These properties influence the performance of the material when exposed to freezing and thawing conditions and their associated stress cycles.

Table 3-5: Bottom Ash - Grain Size Distribution (ASTM D422)

Sieve Size	PPPP	MCPP	OCPP Units 5-6	OCPP Units 7&8	VAPP	PIPP Units 1-6	PIPP Units 7-9
3/4”	99.3	91.9	96.3	98.2	100	99.9	97.7
1/2”	98.7	76.1	91.8	91.8	100	99.7	93.7
3/8”	97.8	59.1	84.8	86.8	100	99.5	89.9
#4	90.6	28.2	77.3	73.2	99.9	96.8	76.6
#8	79.2	14.7	65.9	60.9	99.7	88.8	62.7
#16	60.9	6.3	56.9	48.8	99.2	75.8	49.4
#30	44.9	2.9	48.9	39.6	98.3	61.6	39.4
#40	37.1	2.0	43.5	34.7	96.1	53.5	34.8
#50	28.2	1.1	35.6	29.1	66.2	33.0	30.2
#100	15.7	0.3	23.0	19.9	48.0	16.8	23.0
#200	8.4	0.1	14.1	12.8	41.8	11.3	17.8

The major test procedures and standards established by AASHTO and followed by many Transportation and highway departments, including the Wisconsin Department of Transportation (WisDOT) and Michigan Department of Transportation (MODOT), are listed in Table 3-6.

Table 3-6: AASHTO Test Procedures

Test Procedure	AASHTO Designation
Soundness (Magnesium Sulfate/Sodium Sulfate)	AASHTO T-104
Los Angeles Abrasion	AASHTO T-96
Grain Size	AASHTO T-27
Modified Proctor	AASHTO T-180
Atterberg Limits	AASHTO T-89 and T-90
Resistance to Freeze/Thaw (50 Cycles)	AASHTO T-103

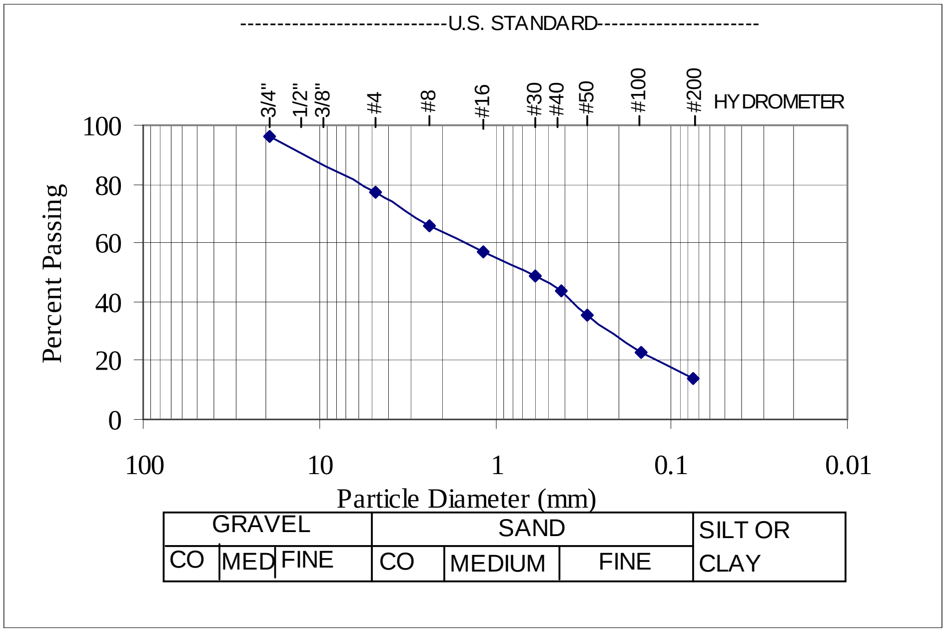


Figure 3-4: OCPP Bottom Ash Grain Size Distribution Curve

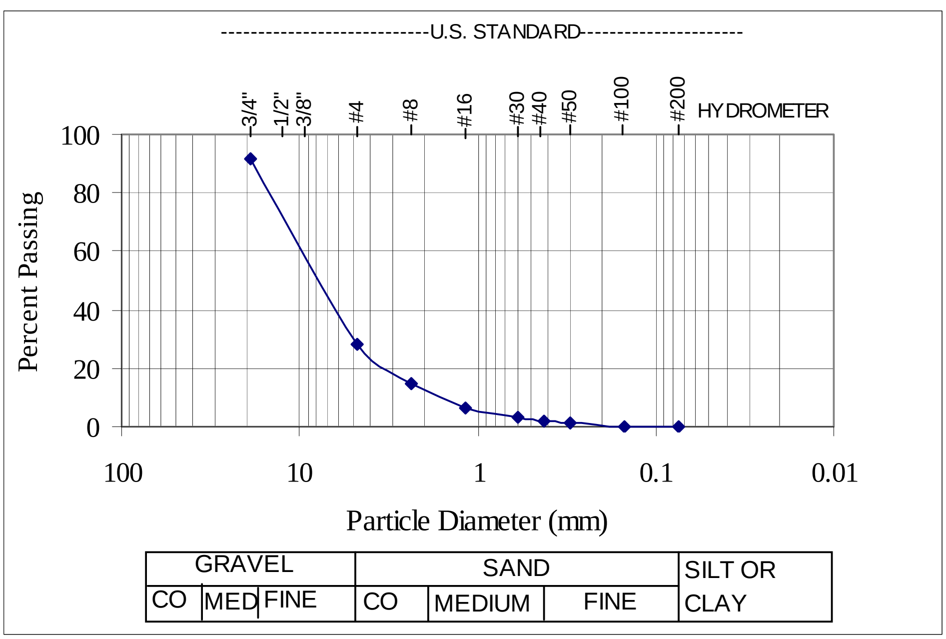


Figure 3-5: MCPP Bottom Ash Grain Size Distribution Curve

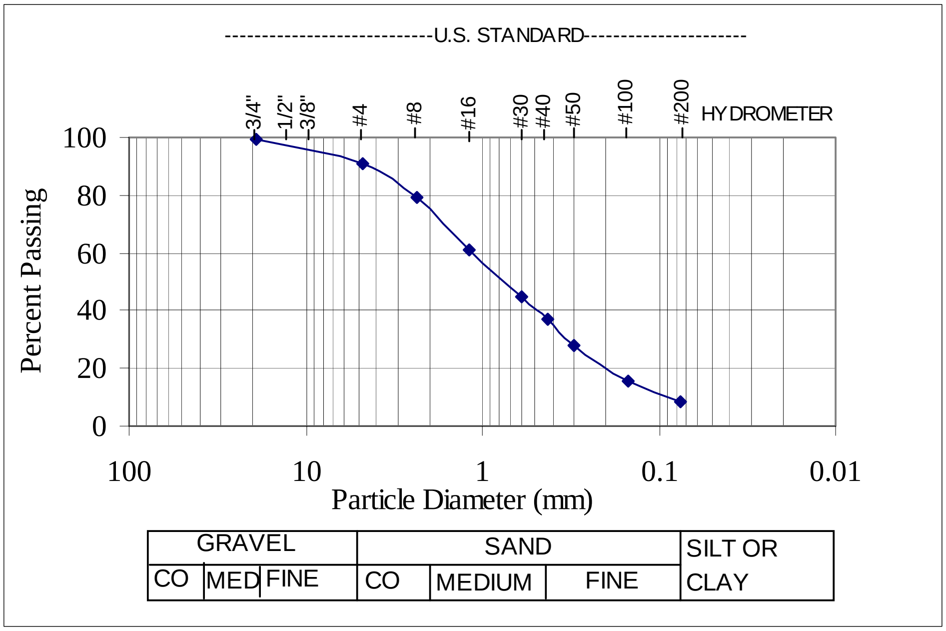


Figure 3-6: PPPP Bottom Ash Grain Size Distribution Curve

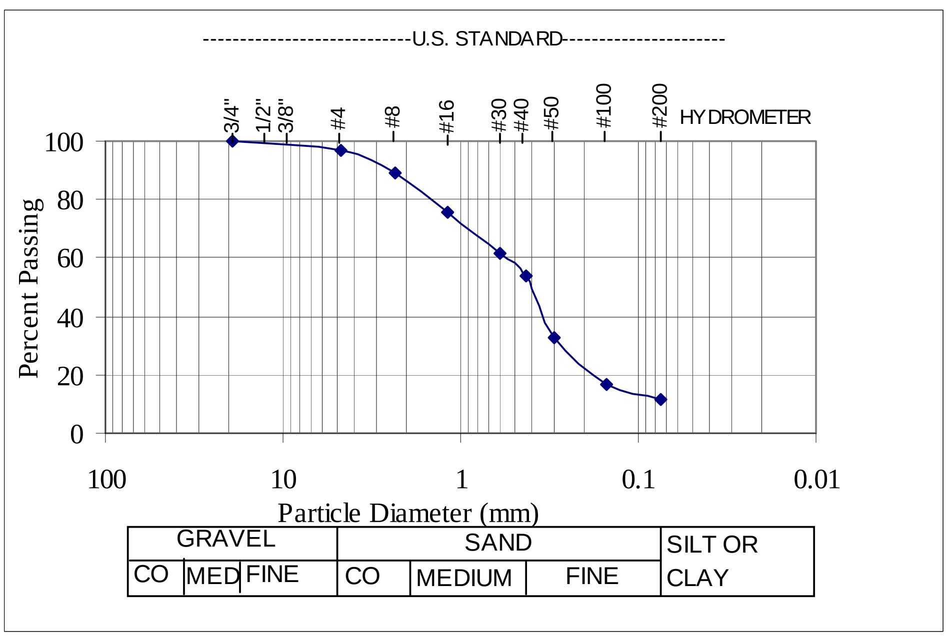


Figure 3-7: PIPP Units 1–6 Bottom Ash Grain Size Distribution Curve

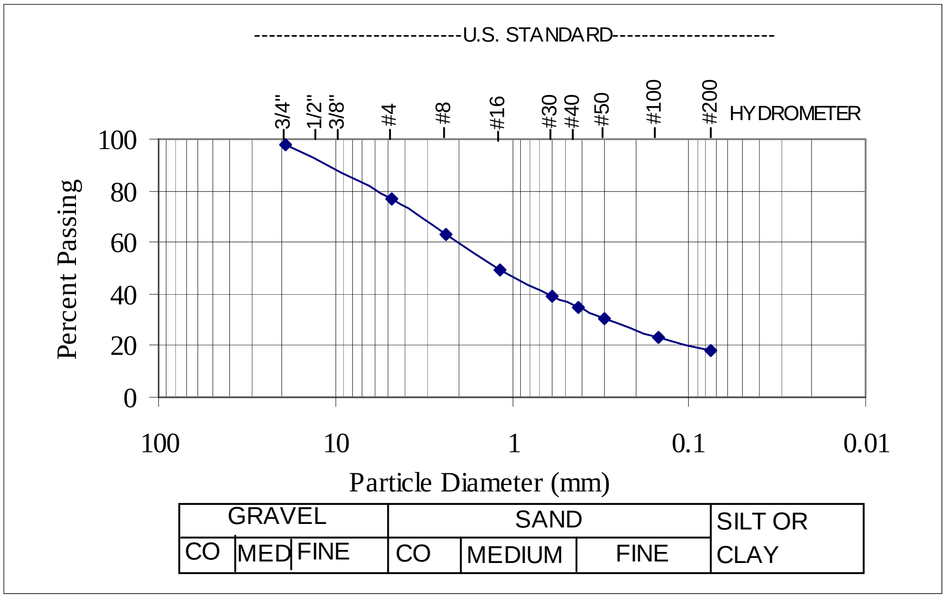


Figure 3-8: PIPP Units 7–9 Bottom Ash Grain Size Distribution Curve

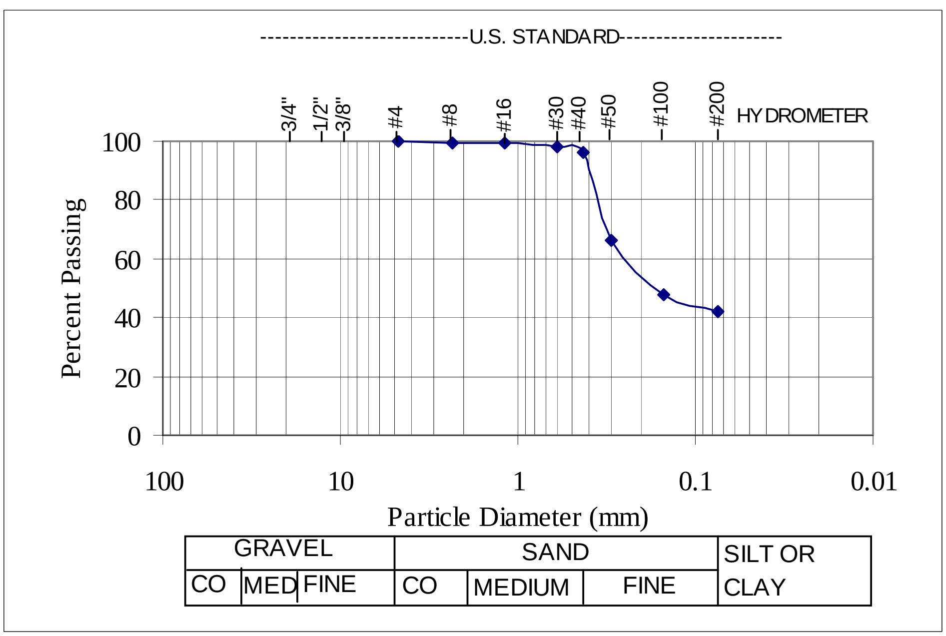


Figure 3-9: VAPP Bottom Ash Grain Size Distribution Curve

Results of Testing to AASHTO Standards

In early 1994 and 2004, testing was performed on We Energies bottom ash to evaluate its use as a base course material, as granular fill for subbase and as a coarse aggregate for hot mix asphalt (HMA), following the procedures in the AASHTO Standards. The test results were then compared with the requirements in the WisDOT's standard specifications (16) and the MDOT's standard specifications for construction (17). The test results are tabulated in Tables 3-7 and 3-8.

Atterberg Limit tests were performed on Pleasant Prairie and Presque Isle bottom ashes. The results show that all three materials tested are non-liquid and non-plastic. Section 301.2.3.5 of WisDOT Standard Specifications require that the base course aggregate not have a liquid limit of more than 25 and not have a plastic index of more than 6. WisDOT standard specifications do not identify a maximum liquid limit for hot mix asphalt coarse aggregate. Therefore, the bottom ash materials meet the WisDOT standard specification requirements for Atterberg Limits.

The Los Angeles Abrasion test results showed that the bottom ash samples tested were not as sound or durable as natural aggregate. However, the test results fall within the WisDOT limits of maximum 50% loss by abrasion for Mixtures E-0.3 and E-1.

WisDOT standard specifications require a minimum 58% fracture face for dense base course aggregate. The bottom ash meets the specifications, because of the angular texture in nature.

MDOT specifications limit a maximum loss of 50% for dense graded aggregates. Other grades of aggregates have a lower limit on abrasion loss. Hence, the samples tested meet only MDOT specifications for dense graded aggregates.

Pleasant Prairie bottom ash and Presque Isle bottom ash did not meet the gradation requirements of WisDOT section 305.2.2.1 of the Standard Specifications for base course aggregate, and section 401.2.5 for hot mixed asphalt coarse aggregate. The material requires blending with other aggregates and/or screening to meet requirements of WisDOT sections 305.2.2.1 and 401.2.5.

Pleasant Prairie bottom ash and Presque Isle units bottom ash met the gradation requirements for Grade 2 granular fill specified by WisDOT although both of these materials need to be blended, washed or screened to meet the WisDOT specification for Grade 1 granular fill. Presque Isle 5-6 bottom ash fails to meet the WisDOT requirements for granular fill.

Table 3-7: Summary Of We Energies Bottom Ash Test Data and Comparison to WisDOT Specifications (16)

Analysis	Pleasant Prairie Bottom Ash	Presque Isle Unit 1-6 Bottom Ash	Presque Isle Unit 7-9 Bottom Ash	Reference Specifications
Soundness				
Result				
Coarse Fraction	1.12	N/A	1.91	
Fine Fraction	2.45	3.91	3.18	
Compliance				
Coarse Fraction	Pass	N/A	Pass	WisDOT 301.2.3.5 & 460.2.7
Fine Fraction	Pass	Pass	Pass	WisDOT 301.2.3.5 & 460.2.7
Atterberg Limits				
Result	Non-Liquid/ Non-Plastic	Non-Liquid/ Non-Plastic	Non-Liquid/ Non-Plastic	
Compliance	Pass	Pass	Pass	WisDOT 301.2.3.5
Los Angeles Abrasion				
Result	46.8	N/A	47.7	
Compliance	Pass E-0.3 and E-1	N/A	Pass E-0.3 and E-1	WisDOT 301.2.3.5 & 460.2.7
Gradation				
Result	See this chapter	See this chapter	See this chapter	
Compliance				
As HMA Coarse Agg.	Fail (1)	Fail	Fail	WisDOT 460.2.2.3
As Base Coarse Agg.	Fail (1)	Fail (1)	Fail	WisDOT 305.2.2.1
As Granular Backfill	Pass Grade 2	Pass Grade 2	Fail (2)	WisDOT 209.2.2.
Freeze-Thaw Durability				
Result	N/A	N/A	N/A	
Compliance	N/A	N/A	N/A	AASHTO T-103 (50 Cycles)
Aggregate Angularity	(3)	(3)	(3)	CMM13.9

N/A- Not Available

(1) - Requires blending with other aggregate to meet specifications.

(2) - Requires blending, washing or screening to reduce the amount of fines to meet specifications.

(3) - Bottom ash is angular in nature.

Table 3-8: Summary of We Energies Bottom Ash Test Data and Comparison to Michigan DOT Specifications (17)

Analysis	Pleasant Prairie Bottom Ash	Presque Isle Unit 1-6 Bottom Ash	Presque Isle Unit 7-9 Bottom Ash	Reference Specifications
Soundness				
Result				
Coarse Fraction	1.12	N/A	1.91	
Fine Fraction	2.45	3.91	3.18	
Compliance				
Coarse Fraction	N/A (1)	N/A (1)	N/A(1)	AASHTO T-104
Fine Fraction	N/A (1)	N/A (1)	N/A (1)	AASHTO T-104
Atterberg Limits				
Result	Non-Liquid/ Non-Plastic	Non-Liquid/ Non-Plastic	Non-Liquid/ Non-Plastic	
Compliance	N/A (2)	N/A (2)	N/A (2)	AASHTO T-89 & T-90
Los Angeles Abrasion				
Result	46.8	N/A	47.7	
Compliance	(3)	N/A	(3)	MDOT 8.02.05
Gradation				
Result	See Attached	See Attached	See Attached	
Compliance				
As HMA Coarse Agg.	Fail (4)	Fail (4)	Fail (4)	MDOT 902
As Base Coarse Agg.	Fail (4)	Fail (4)	Fail (4)	MDOT 902
As Granular Backfill	Fail (4)	Fail (4)	Fail (4)	MDOT 902
Freeze-Thaw Durability				
Result				
Compliance				AASHTO T-103 (50 Cycles)

N/A = Not Available

(1) - MDOT does not have a specific requirement for soundness. Instead, MDOT relies on results of freeze-thaw durability.

(2) - MDOT does not have a specific requirement for Atterberg Limits.

(3) - Does not meet specifications for coarse aggregates or any of the open-graded aggregates. The materials meet the requirements for dense graded aggregates.

(4) - Material could be blended with another aggregate to help meet specifications.

Soundness test results for all three samples are well within the allowable limits per section 301.2.3.5 and section 460.2.7 of the WisDOT standard specifications. MDOT specifies a maximum percent material loss by washing through the No. 200 sieve in lieu of the soundness test. Both Pleasant Prairie bottom ash and Presque Isle bottom ash did not met the MDOT specification for a dense graded aggregate, a coarse graded aggregate nor an open graded aggregate.

In addition, Milwaukee County bottom ash met the gradation requirements of open graded aggregate and both Grade #1 and Grade #2 granular fill specified by WisDOT. Oak Creek bottom ash met the gradation requirements of Grade #2 granular fill specified by WisDOT.

Chapter 4

Concrete and Concrete Masonry Products Containing We Energies Fly Ash

Introduction

Coal combustion products have been used in the construction industry since the 1930's (6). Although the utilization of these products was limited to small-scale applications in the early days, the use of coal combustion products has gained increasing acceptance in the construction industry in the last few decades. The interest in coal combustion products significantly increased during the 1970's because of the rapid increase in energy costs and the corresponding increase in cement costs.

We Energies has been conducting extensive research to beneficially utilize fly ash and bottom ash generated at company-owned coal-fired power plants for construction applications. Many of these research efforts have been conducted in conjunction with universities, research centers and consultants, resulting in the development of cost effective and environmentally friendly products.

Today, We Energies fly ash and bottom ash are being widely used in the construction industry. Applications range from utilizing fly ash in the manufacture of concrete, concrete products, controlled low strength material (CLSM), liquid waste stabilization, roller-compacted no fines concrete, high-volume fly ash concrete, cold in place recycling of asphalt, lightweight aggregate, and in soil stabilization. Of all these applications, the use of fly ash as an important ingredient in the production of concrete is by far the largest application.

Background on Hydration Reaction, Cementitious, And Pozzolanic Activity

To understand the behavior of fly ash in contact with water or in a concrete mixture, it is important to understand the reaction that takes place in freshly mixed concrete and the process by which it gains strength. The setting and hardening process of concrete, which occurs after the four components consisting of coarse aggregate, fine aggregate, cement and water are mixed together, is largely due to the reaction between the components cement and water. The other two components, coarse aggregate and fine aggregate, are more or less inert as far as setting and hardening is concerned.

The major components of cement that react with water to produce hydration reaction products are tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF). The reactions can be summarized as shown below:

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH$$

tricalcium silicate + water → C - S - H + calcium hydroxide

$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH$$

dicalcium silicate + water → C - S - H + calcium hydroxide

$$C_3A + 3C\bar{S}H_2 + 26H \rightarrow C_3A(C\bar{S})_3H_{32}$$

tricalcium aluminate + gypsum + water → ettringite

$$C_3A + C\bar{S}H_2 + 10H \rightarrow C_3AC\bar{S}H_{12}$$

monosulphoaluminate hydrate

C_4AF forms hydration products similar to that of C_3A, where iron substitutes partially for alumina in the crystal structure of ettringite and monosulpho-aluminate hydrate.

In the absence of sulfate, C_3A may form the following reaction products (6):

$$C_3A + 6H \rightarrow C_3AH_6$$

$$C_3A + CH + 18H \rightarrow C_4AH_{19}$$

Fly ash is pozzolanic. A pozzolan is defined as "a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but which, in finely divided or powdered form, and in the presence of moisture, chemically reacts with calcium hydroxide at ordinary temperatures to form compounds that possess cementitious properties" (18).

The major reaction that takes place is between the reactive silica of the pozzolan and calcium hydroxide producing calcium silicate hydrate. The alumina in the pozzolan may also react with calcium hydroxide and other components in the mixture to form similar products.

High-calcium fly ash is both cementitious and pozzolanic and has self-hardening properties in the presence of moisture. The reaction products include ettringite, monosulphoaluminate and C-S-H. These products are also formed when cement reacts with water and causes hardening in the cement-water mixture.

The rate of formation of C-S-H in the fly ash-water mixture is normally slower than that in a cement-water mixture. Because of this, at ages greater than 90 days, fly ash-cement-water continues to gain strength; while the cement-water pastes do not show as significant a gain in strength. However, this hydration behavior of C_3A and C_2S in fly ash is the same as that in cement. Low calcium fly ash has very little or no cementing properties alone, but will hydrate when alkalis and $Ca(OH)_2$ are added.

Concrete Containing We Energies Fly Ash

For centuries, concrete has been widely used for a variety of applications ranging from sidewalk slabs to bridges and tall buildings. Concrete used in the early days had low strength and the applications were limited, partly due to the strength of the concrete and partly due to the lack of understanding of design principles.

With the evolution of more sophisticated materials and engineering designs, many problems associated with strength were solved and high-strength concrete designs were developed. Today, engineers can select a concrete mixture with a specified strength for a particular application. In most cases, strength of concrete is not a limiting factor on project design.

Durability of concrete has been a challenge since the early days of concrete production. With applications increasing, the demand to find concrete that "performs" is increasing. Most durability problems associated with concrete get worse in adverse weather conditions. For example, in cold weather regions, concrete that is subjected to freezing and thawing tends to disintegrate faster if it is porous. Porosity is generally considered the most significant factor affecting the long-term performance of concrete.

Portland cement concrete is a mixture of coarse aggregates, fine aggregates, cement and water. The properties of concrete prepared by mixing these four components depends very much on their physical and chemical properties and the proportions in which they are mixed. The properties of concrete thus prepared can be enhanced for specific applications by adding admixtures and/or additives.

The use of a particular admixture or additive has a definite purpose. For a particular application, it is important that the properties of the concrete be tailored to meet performance requirements.

Fly ash added in concrete as a supplementary cementing material achieves one or more of the following benefits:

- Reduces the cement content.
- Reduces heat of hydration.
- Improves workability of concrete.
- Attains higher levels of strength in concrete especially in the long term.
- Improves durability of concrete.
- Increases the “green” recycled material content of concrete.
- Attains a higher density.
- Lowers porosity and permeability.

The properties of fly ash, whether ASTM C618, Class C or Class F, and the percentages in which they are used greatly affect the properties of concrete. Mixture proportioning and trial batches are critical to obtaining concrete with the desired fresh and hardened properties. Fly ash may be introduced in concrete as a blended cement containing fly ash or introduced as a separate component at the mixing stage.

Most of the We Energies fly ash is being used in concrete as a separate component at the concrete batching and mixing stage. This allows the flexibility of tailoring mixture proportions to obtain the required concrete properties for the particular application. Ready-mixed concrete producers have greater control with respect to the class and amount of fly ash in the concrete mixture to meet the specified performance requirements.

Fly ash has several other properties, in addition to its cementitious and pozzolanic properties, that are beneficial to the concrete industry (19). Low-calcium fly ash (ASTM C618 Class F) has been used as a replacement for Portland cement in concrete used for the construction of mass gravity dams. The primary reason for this application has been the reduced heat of hydration of Class F fly ash concrete compared to Portland cement concrete. ASTM C618 Class C fly ash concrete may also have a slightly lower heat of hydration when compared to Portland cement concrete. However, low calcium Class F fly ash concrete generates still lower heat of hydration, a desirable property in massive concrete construction, such as dams and large foundations.

Studies have also revealed that certain pozzolans increase the life expectancy of concrete structures. Dunstan reported that as the calcium oxide content of ash increases above a lower limit of 5% or as the ferric oxide content decreases, sulfate resistance decreases (20).

Dunstan proposed the use of a resistance factor (R), calculated as follows:

$$R = (C-5)/F$$

Where C = percentage of CaO
Where F = percentage of Fe_2O_3

Dunstan summarized his work in terms of the selection of fly ash for sulfate-resistant concrete as follows (14):

R limits[a]	Sulfate Resistance[b]
< 0.75	Greatly improved
0.75 - 1.5	Moderately improved
1.5 - 3.0	No significant change
> 3.0	Reduced

[a] At 25% cement replacement
[b] Relative to ASTM Type II cement at a water/cementitious materials ratio of 0.45

The influence of pozzolans on the sulfate resistance of concrete is not completely understood today. However, based on the studies at the U.S. Army Corps of Engineers, Mather reported that a pozzolan of high fineness, high-silica content and high amorphousness is most effective against expansion due to sulfate attack.

Alkali-aggregate reactions (AAR) also cause expansion and damage in concretes produced with reactive aggregates and available alkalis from the paste. However, a variety of natural and artificial pozzolans and mineral admixtures, including fly ash, can be effective in reducing the damage caused by AAR. Researchers have reported that the effectiveness of fly ash in reducing expansion due to AAR is limited to reactions involving siliceous aggregate. The reactive silica in power plant fly ash combines with the cement alkalis more readily than the silica in aggregate. The resulting calcium-alkali-silica "gel" is nonexpansive, unlike the water-absorbing expansive gels produced by alkali-aggregate reactions. In addition, adding fly ash to concrete increases ASR resistance and improves the concrete's ultimate strength and durability while lowering costs.

The following factors are important in determining the effectiveness of using fly ash to control AAR.

- The concentration of soluble alkali in the system.
- The amount of reactive silica in the aggregate.
- The quantity of fly ash used.
- The type of fly ash.

According to Electric Power Research Institute (EPRI) studies (21), both Class C and Class F fly ash are effective at mitigating ASR in concrete when used as substitutes for Portland cement. The major difference between the two ash types is that a greater portion of cement must be replaced with Class C ash to provide the same effect as using Class F ash in a mix design with a smaller ash-to-cement ratio. According to EPRI studies, replacing Portland cement with Class C ash at volumetric rates of 30-50% is effective in controlling

ASR. The greater the proportion of Class C fly ash used in a mix, the greater the ASR control benefit.

The concentration of soluble (available) alkali and not the total alkali content is critical for the reaction. Studies have shown that if the acid soluble alkali-content is in excess of 5.73 lb./cu. yd., then it can cause cracking, provided that reactive aggregates are present. (This is approximately equivalent to 4.21 lb./cu. yd. as water-soluble alkali.) For high-calcium Class C fly ash, the amount of alkali in the ash affects the effectiveness of expansion reduction. Another study by EPRI (22) indicated that for high-calcium (22.5% CaO) moderate-alkali (2.30% Na_2Oeq) fly ash, the amount of fly ash required to control expansion due to ASR varies significantly from one aggregate to another. In the case of the extremely reactive aggregate, between 50%-60% of fly ash would be required to reduce expansion under the 0.10% level. For less reactive aggregate, a lower fly ash replacement level is required. For high-calcium (21.0% CaO) high-alkali (5.83 Na_2Oeq) fly ash, it still contributed in reducing ASR expansion; however, an expansion higher than 0.10% level occurred. Therefore, it is necessary to test the amount of alkali in the fly ash prior to incorporating it in the concrete to control ASR.

The following aggregates and their mineralogical constituents are known to react with alkalis:

- Silica materials - opal, chalcedony, tridymite and cristobalite
- Zeolites, especially heulandite
- Glassy to cryptocrystalline rhyolites, dacites, andesites and their tuffs
- Certain phyllites

Low-calcium (ASTM C618, Class F) fly ash is most effective in reducing expansion caused by alkali-silica reactions where the fly ash is used at a replacement level of approximately 20 to 30%. Once the replacement threshold has been reached, the reduction in expansive reaction for a given cement alkali level is dramatic. Additionally, the greater the proportion of cement replaced with Class F fly ash, the greater the ASR reduction. In some cases where silica fume, a very fine material that is high in reactive SiO_2, is used in concrete for high strength, adding Class F or Class C fly ash to create a "ternary blend" can significantly reduce ASR susceptibility without diminishing high concrete performance. The actual reaction mechanism on alkali-aggregate reaction and the effect of fly ash is not fully understood today and will require more research to find a satisfactory explanation.

Soundness of aggregates or the freedom from expansive cracking is one of the most important factors affecting the durability of concrete. At early ages, unloaded concrete cracks because of two reasons: thermal contraction and drying shrinkage. When concrete hardens under ambient temperature and humidity, it experiences both thermal and drying shrinkage strains.

The level of shrinkage strains depends on several factors, including temperature, humidity, mixture proportions, type of aggregates, etc. Shrinkage strain in hardened concrete induces elastic tensile stress. Cracks appear in concrete when the induced tensile stress exceeds the tensile strength of the concrete. Creep may reduce the induced tensile stress to a certain extent, but the resultant stress can be large enough for cracking concrete.

Using sufficient steel reinforcement has traditionally controlled cracking. However, using reinforcement does not solve this problem completely. By using reinforcement, fewer large cracks may be reduced to numerous invisible and immeasurable microcracks (23). Transverse cracks seen in bridge decks are typical examples. Cracking in concrete is the first step to deterioration, as it results in the migration of harmful ions into the interior of concrete and to the reinforcement.

Several preventive and mitigating measures can be used to minimize the degradation of concrete due to corrosion of reinforcing steel. The use of fly ash as a partial replacement of cement is a cost-effective solution (inclusion of fly ash in a mixture provides the same workability at a lower water content and lower cement content both of which reduces the concrete shrinkage). In several states across the country, the Department of Transportation (DOT) has made it mandatory to include fly ash as an ingredient. The heat of hydration is substantially reduced when fly ash is used in concrete as a partial replacement to cement.

Durability of concrete is very critical in most DOT applications, especially in regions subject to cold weather conditions. In such cases, the incorporation of fly ash in concrete is advantageous, even though the setting and hardening process may be slightly slower than ordinary Portland cement concrete.

Fly ash has been used in concrete for several decades. Research work on short-term and long-term behavior of concrete containing fly ash has been conducted by several research agencies. However, the properties of fly ash vary with the specific coal burned as well as the process of coal preparation, firing and collection.

Hence, We Energies has conducted research on the actual fly ash generated at its coal-fired plants. This research has been conducted with the aid of universities and research institutions in conjunction with concrete producers to develop mix designs that can be readily used for construction. Several parameters, both short-term and long-term, have been studied, and their performances evaluated to identify the suitability of the particular mixture design for a specific field application. One important point is the spherical shape of fly ash with its lubricating effect for pumping and the same workability with a lower water to cementitious materials ratio. Also, fly ash is finer than Portland cement and thus produces a denser concrete with lower permeability.

Compressive Strength of Concrete Containing We Energies ASTM C618, Class C Fly Ash (Phase I Study)

Concrete is used in several applications requiring different levels of strength. Most applications require concrete with a compressive strength in the range of 3,000 to 5,000 psi. Based on the type of application, engineers select a mixture design with a specified 28-day compressive strength. Other durability factors such as porosity or freeze-thaw resistance also influence the selection of a concrete mixture.

With the introduction of fly ash concrete, the long-term (56 day or 1 year) properties of concrete have shown dramatic improvement. Since long-term properties of concrete are vital, most construction professionals are interested in understanding the performance of fly ash and the resulting concrete made using fly ash.

The influence of We Energies fly ash on the quality of concrete has been studied for several years. Fly ash is used as a partial replacement for cement at various replacement levels. In order to understand the properties of We Energies fly ash and the short-term and long-term performance of concrete containing We Energies fly ash, a great amount of research work has been conducted.

The following data is from a research project conducted at the Center for By-Products Utilization at the University of Wisconsin-Milwaukee for We Energies (24). This work was done with the objective of developing mixture proportions for structural grade concrete containing large volumes of fly ash. ASTM C618, Class C fly ash from We Energies Pleasant Prairie Power Plant was used in this research project.

Preliminary mixture proportions were developed for producing concrete on a 1.25 to 1 fly ash to cement weight basis replacement ratio. The replacement levels varied from 0 to 60% in 10% increments. Water to cementitious materials ratios (w/c) of 0.45, 0.55 and 0.65 were used in this project to develop concrete with strength levels of 3,000 psi; 4,000 psi and 5,000 psi. It is interesting to observe that at fly ash utilization levels rising above 50%, Portland cement becomes the admixture or supplementary cementitious material.

Actual concrete production was performed at two local ready mixed concrete plants utilizing different cement and aggregate sources. Three quarter inch maximum size aggregates were used in the mixtures and the slump was maintained at 4”± 1”. Entrained air was maintained in the range of 5-6% ± 1%. The concrete mixtures were prepared at ready mixed concrete plants using accepted industry practices. Six-inch diameter by 12” long cylinder specimens were prepared for compressive strength tests. The compressive strength tests were performed at various ages in accordance with standard ASTM test methods. The chemical and physical properties of PPPP fly ash used in these tests are shown in Table 4-1.

Tables 4-2 to 4-4 show the mixtures designed for concrete in the various strength levels and various percentages of cement replacement with fly ash. The compressive strength results are shown in Tables 4-5 to 4-7.

Table 4-1: Chemical and Physical Test Data Pleasant Prairie Power Plant (PPPP) Fly Ash

Chemical Composition	Average (%)	ASTM C-618
Silicon Oxide (SiO_2)	40.89	---
Aluminum Oxide (Al_2O_3)	16.13	---
Iron Oxide (Fe_2O_3)	6.01	---
Total (SiO_2+Al_2O_3+Fe_2O_3)	63.03	50.0 min
Sulfur Trioxide (SO_3)	2.98	5.0 max
Calcium Oxide (CaO)	25.30	---
Magnesium Oxide (MgO)	4.56	5.0 max
Loss on ignition	.45	6.0 max
Available alkalies as Na_2O	1.19	1.5 max
Fineness % retained on #325 wet sieve	18.83	34.0 max
Pozzolanic activity index with cement 28 days with lime 7 days	 92.43 1805	 75.0 min 800 min
Water requirement % of the control	91	105 max
Soundness Autoclave expansion (%)	0.15	0.8 max
Specific gravity	2.58	---

Discussion of Test Results - 3,000 psi Concrete

Compressive strength test results for the six different 3000 psi concrete mixtures are shown in Table 4-2. The specified strength for these mixtures is 3,000 psi. These test results show that with an increase in cement replacement levels with fly ash, the early age compressive strength decreases.

The decrease is not significant for concrete with 20 and 30% replacement levels. At 7-day age, cement replacement with up to a 40% replacement level produces concrete with compressive strength comparable to that of the control mix. At 28-day age, all mixtures showed strength levels higher than the design compressive strength of 3,000 psi. However, concrete containing 40% replacement of cement with fly ash had the highest strength.

Table 4-2: PPPP Class C Fly Ash Concrete Mix and Test Data - 3000 psi (21 MPA) Specified Strength

Mix No.	P4 - 1	P4 - 2	P4 - 3	P4 - 4	P4 - 5	P4 - 6
Specified design strength, psi	3000	3000	3000	3000	3000	3000
Cement, lbs	425	341	300	255	210	171
Fly ash, lbs	0	100	150	208	260	310
Water, lbs	281	273	272	262	258	249
Sand, SSD, lbs	1610	1610	1610	1610	1610	1610
3/4" aggregates SSD, lbs	1810	1810	1810	1810	1810	1810
Slump, inch	4-l/4	4-l/4	4-l/4	3-l/2	3-3/4	4-3/4
Air content, %	1.2	1.0	1.0	1.2	1.1	0.8
Air temperature, °F	84	82	82	79	78	68
Concrete temperature, °F	82	82	82	82	82	80
Concrete density, pcf	153.4	154.1	154.6	154.8	154.5	154.7

Table 4-3: PPPP Fly Ash Concrete Mix and Test Data 4000 psi (28 MPA) Specified Strength

Mix No.	P4 - 7	P4 - 8	P4 - 9	P4 - 10	P4 - 11	P4 - 12
Specified design strength, psi	4000	4000	4000	4000	4000	4000
Cement, lbs	517	414	364	310	259	209
Fly ash, lbs	0	125	190	251	310	375
Water, lbs	297	284	273	274	272	242
Sand, SSD, lbs	1530	1530	1530	1530	1530	1530
3/4" aggregates SSD, lbs	1810	1810	1810	1810	1810	1810
Slump, inch	4-3/4	3-3/4	4	4-1/2	4	4
Air content, %	1.4	1.1	1.1	0.8	1.2	1.1
Air temperature, °F	90	92	93	88	78	68
Concrete temperature, °F	83	83	84	82	82	83
Concrete density, pcf	154.2	154.3	154.2	154.4	154.6	153.4

As the age of concrete increased, the compressive strength of all concrete mixtures containing fly ash increased at a level higher than that of the control mix. Concrete with 40% replacement of cement with fly ash continued to show the highest strength level, but all fly ash concrete mixtures showed strength levels higher than that of the control mix at the 56- and 91-day ages.

Discussion of Test Results - 4,000 psi Concrete

Mixes P4-7 through P4-12 were designed for a compressive strength of 4,000 psi. At an age of 3 days, 20% fly ash concrete showed the highest strength.

At the 7-day age, concrete with up to 50% cement replacement showed compressive strength levels comparable to that of the control mix P4-7. Mixes P4-8 and P4-9 with 20 and 30% replacements showed strengths higher than the control mixture at the 7-day age.

At the 28-day age, all mixtures showed strengths higher than the design strength of 4,000 psi. Also, all mixtures containing fly ash showed higher levels of strength compared to the control mix.

Mix P4-10 with 40% replacement of cement showed the maximum strength.

This trend continued at later ages with P4-11, the 50% replacement of cement with fly ash, showing the highest strength of 7387 psi at the 91-day age.

Table 4-4: PPPP Class C Fly Ash Concrete Mix and Test Data 5000 psi (34 MPA) Specified Strength

Mix No.	P4 - 13	P4 - 14	P4 - 15	P4 - 16	P4 - 17	P4 - 18
Specified design strength, psi	5000	5000	5000	5000	5000	5000
Cement, lbs	611	490	428	367	305	245
Fly ash, lbs	0	145	220	1295	382	411
Water, lbs	290	291	289	270	278	268
Sand, SSD, lbs	1450	1450	1450	1450	1450	1450
3/4" aggregates SSD, lbs	1810	1810	1810	1810	1810	1810
Slump, inch	4¾	4½	4½	4½	4½	4
Air content, %	1.1	1.1	1.0	1.0	1.5	1.3
Air temperature, °F	66	62	68	65	62	58
Concrete temperature, °F	70	63	72	69	70	70
Concrete density, pcf	155.7	155.3	155.3	155.2	155.3	155.0

Discussion of Test Results: 5,000 psi Concrete

Mixes P4-13 to P4-18 were designed with a 28-day compressive strength of 5,000 psi. At the 3-day age, concrete with 20% cement replacement showed compressive strength higher than that of the control mix P4-13.

However, concrete with up to 40% cement replacement showed compressive strength in the acceptable range. At the 7-day age, concrete with up to 40% cement replacement showed strength comparable to the control mix. At the

28-day age, all mixes showed strengths higher than the design strength of 5,000 psi.

Also, all fly ash concrete mixes showed strengths higher than the control mix, with the 40% cement replacement concrete showing the highest strength.

At the 56 and 91-day ages, the trend continued with the 50% cement replacement concrete showing the highest strength. Even the 60% replacement concrete showed 38% higher strength compared to the control mix at the 91-day age.

Conclusions: 3000 psi; 4000 psi and 5000 psi Concrete

In conclusion, these tests establish that good quality structurally strong concrete can be made with high cement replacements by fly ash. Even 50 and 60% replacements showed higher strengths than the control mixture at 56- and 91-day ages. But this level of cement replacement with fly ash generally will not be made for structural grade concrete for flexural members, such as beams where rapid form stripping is required.

However, these higher replacements may be used for mass concrete where early age strength levels are not needed. At the 40% cement replacement level, the strength levels at early ages are within acceptable limits and can be used for structural grade concrete.

Therefore, it can be concluded that fly ash from Pleasant Prairie Power Plant can be used in the manufacture of structural grade concrete with cement replacement levels of up to 40%, on a 1.25 to 1 fly ash to cement weight basis replacement ratio.

The following figures and tables show strength versus age and give the test data.

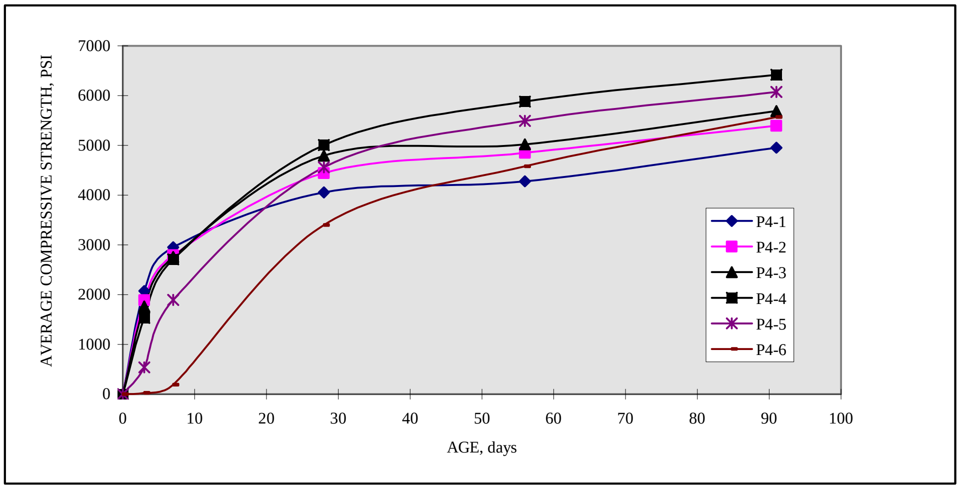


Figure 4–1: Compressive Strength vs. Age Comparison – Mix Nos. P4-1 through P4-6

Other important observations from this study are the following:

1. Replacement of cement with fly ash in concrete increases workability of the mixture.
2. The water demand decreases with the increase in fly ash content. For a given workability, the water to cementitious materials ratio decreases with increases in fly ash content.
3. Pleasant Prairie Power Plant fly ash can be used for the manufacture of structural grade concrete.

Table 4-5: PPPP Class C Fly Ash Concrete Strength Test Data - 3000 psi (21 MPA) Specified Strength

Mix No.	P4-1		P4-2		P4-3		P4-4		P4-5		P4-6	
Specified strength, psi	3000		3000		3000		3000		3000		3000	
Percent fly ash	0		20		30		40		50		60	
Compressive Strength, psi												
Test Age. days	Actual	Avg	Actual	Avg	Actual	Avg	Actual	Avg	Actual	Avg	Actual	Avg
1*	1715		1567		1378		1295		572		516	
1*	1695	1662	1541	1543	1386	1374	1297	1315	577	576	530	524
1*	1576		1521		1358		1353		578		527	
3	2020		1938		1758		1545		572		30	
3	2120	2072	1898	1886	1725	1764	1599	1534	526	537	24	26
3	2076		1822		1810		1459		514		25	
7	2995		2770		2820		2688		1936		202	
7	3065	2950	2784	2790	2775	2755	2712	2707	1810	1892	176	187
7	2789		2817		2670		2723		1931		182	
28	3986		4105		4605		5051		4545		3203	
28	4131	4055	4476	4440	4821	4789	5038	5004	4587	4556	3427	3396
28	4048		4738		4941		4923		4538		3558	
56	4363		4804		4947		5909		5445		4626	
56	4350	4276	5011	4850	4877	5019	5811	5881	5457	5492	4811	4576
56	4115		4735		5234		5923		5575		4290	
91	4960		5160		5850		6400		6080		5630	
91	4970	4953	5730	5393	5380	5687	6490	6417	6040	6073	5550	5567
91	4930		5290		5830		6360		6100		5520	

* After Accelerated Curing, Using Boiling Water Method

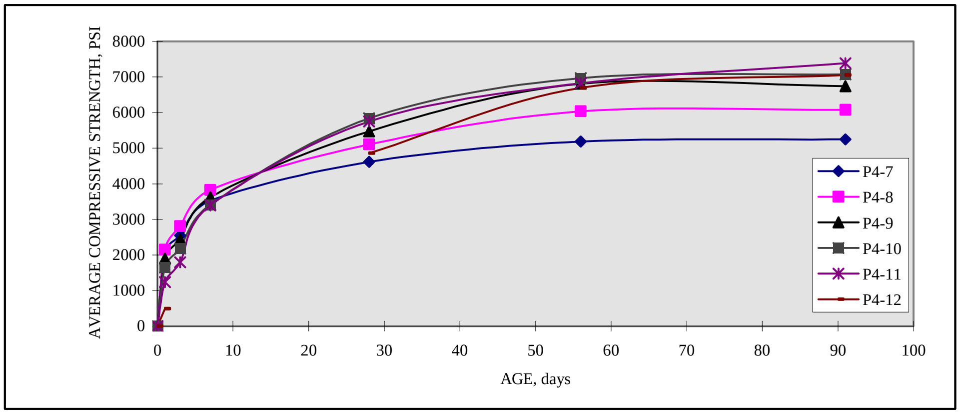


Figure 4–2: Compressive Strength vs. Age Comparison – Mix Nos. P4-7 through P4-12

Table 4-6: PPPP Class C Fly Ash Concrete Strength Test Data - 4000 psi (28 MPA) Specified Strength

Mix No.	P4-7		P4-8		P4-9		P4-10		P4-11		P4-12	
Specified strength, psi	4000		4000		4000		4000		4000		4000	
Percent fly ash	0		20		30		40		50		60	
Compressive Strength, psi												
Test Age. days	Actual	Avg	Actual	Avg	Actual	Avg	Actual	Avg	Actual	Avg	Actual	Avg
1*	2068	2055	2163	2148	1868	1893	1658	1647	1233	1240	514	490
1*	2041		2134		1887		1648		1220		472	
1*	2057		2148		1924		1636		1267		484	
3	2476	2548	2786	2808	2393	2436	2218	2181	1767	1793	40**	
3	2579		2789		2509		2194		1805		39**	
3	2590		2849		2407		2131		1807		43**	
7	3597	3521	3815	3828	3520	3625	3423	3411	3461	3395	70**	
7	3476		3899		3689		3524		3327		78**	
7	3490		3769		3667		3286		3398		88**	
28	4779	4612	5189	5102	5110	5471	5995	5840	5746	5749	4895	4858
28	4706		5140		5685		5628		5719		5030	
28	4350		4976		5618		5897		5782		4648	
56	5262	5183	5964	6034	6628	6811	7139	6967	6912	6825	6787	6694
56	5172		5926		6751		6621		6737		6659	
56	5114		6211		7054		7142		6827		6635	
91	5382	5249	5871	6075	6613	6742	6560	7075	7348	7387	7372	7057
91	5284		6172		6672		7310		7557		6731	
91	5080		6182		6942		7354		7257		7068	

* After Accelerated Curing, Using Boiling Water Method
** Cylinders were green when tested.

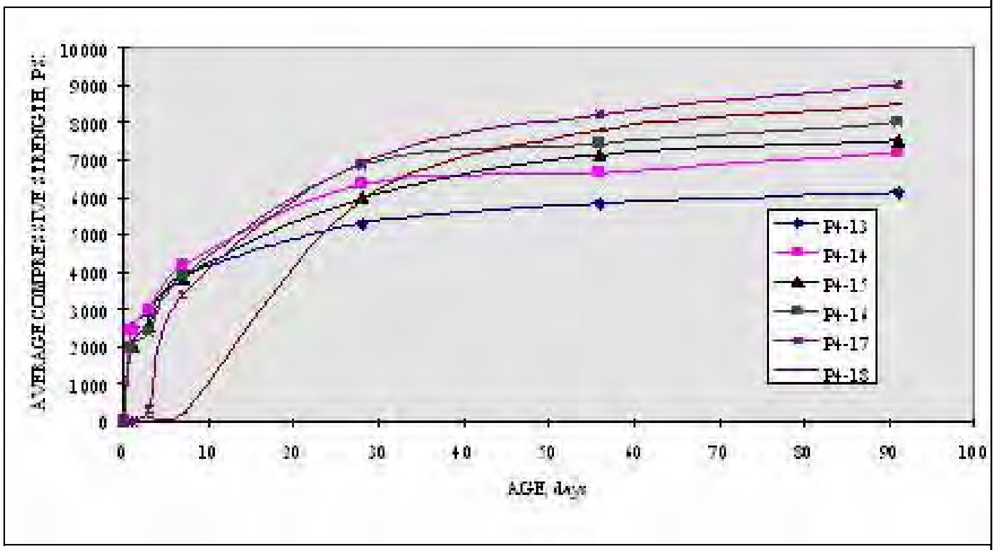


Figure 4-3: Compressive Strength vs. Age Comparison – Mix Nos. P4-13 through P4-18

Table 4-7: PPPP Class C Fly Ash Concrete Strength Test Data - 5000 psi (34 MPA) Specified Strength

Mix No.	P4-13		P4-14		P4-15		P4-16		P4-17		P4-18	
Specified strength, psi	5000		5000		5000		5000		5000		5000	
Percent fly ash	0		20		30		40		50		60	
Compressive Strength, psi												
Test Age. days	Act.	Avg	Act.	Avg	Act.	Avg	Act.	Avg	Act.	Avg	Act.	Avg
1*	2579		2438		2089		1938		1210		1315	
1*	2498	2519	2441	2448	2041	2044	1965	1942	1234	1230	1360	1336
1*	2481		2465		2003		1924		1246		1332	
3	2839		3115		2570		2390		287**		111**	
3	2930	2904	2936	2987	2570	2591	2379	2390	369**	324**	117	116**
3	2944		2909		2632		2401		285**		120**	
7	3811		4130		3762		3913		3430		203**	
7	4028	3902	4220	4168	3935	3854	3811	3892	3409	3392	206**	205**
7	3868		4154		3864		3952		3338		203**	
28	5002		6412		5839		6851		6919		5795	
28	5484	5300	6381	6353	6102	5993	6786	6864	7045	6935	6079	5931
28	5413		6266		6038		6954		6842		5919	
56	5803		6653		7240		7565		8174		7803	
56	5856	5848	6624	6667	7031	7148	7350	7452	8079	8237	7834	7795
56	5885		6723		7173		7442		8457		7749	
91	5900		7025		7179		8086		9012		8504	
91	6315	6134	7400	7209	7835	7519	8133	8004	9016	9012	8274	8493
91	6188		7201		7542		7792		9007		8701	

* After Accelerated Curing, Using Boiling Water Method
**Cylinders were green when tested.

Water Demand

Figures 4-4, 4-5 and 4-6 show the relationship between the amount of water and the percentage of fly ash replacement for the same workability corresponding to 3,000, 4,000 and 5,000 psi nominal compressive strength concrete mixtures shown in Tables 4-2 through 4-4. For a given workability (slump 4" ± 1"), it can be seen that as the percentage of fly ash increases in the mixture, the water demand decreases (25).

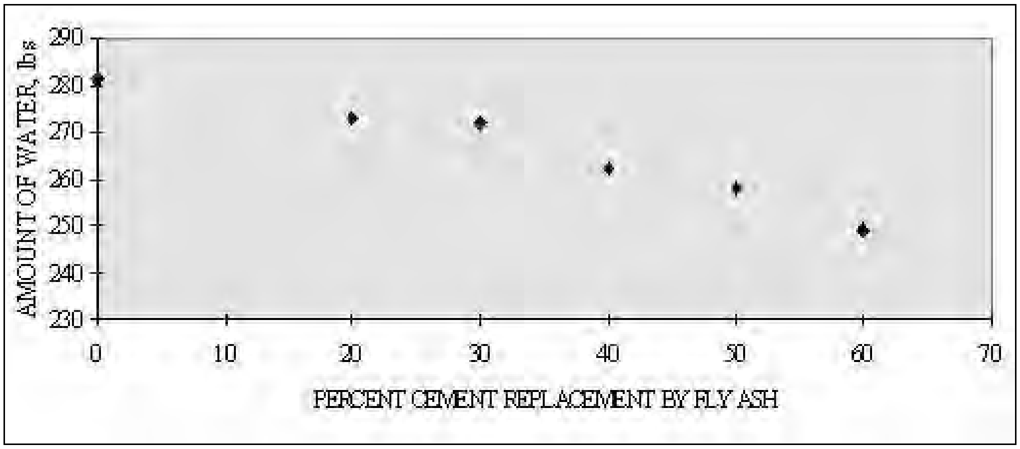


Figure 4-4: Relationship Between Water Demand and Cement Replacement by Fly Ash (3000 psi Concrete with the Same Workability)

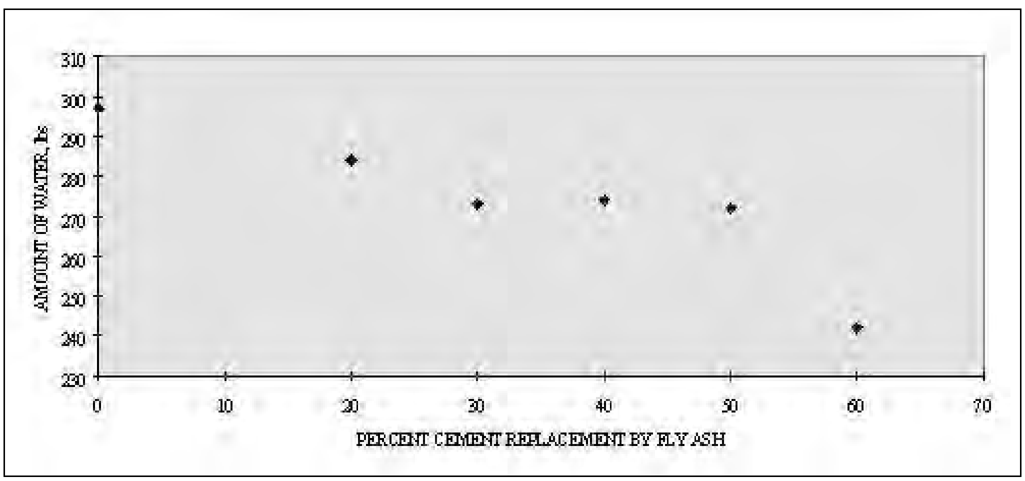


Figure 4-5: Relationship Between Water Demand and Cement Replacement by Fly Ash (4000 psi Concrete with the Same Workability)

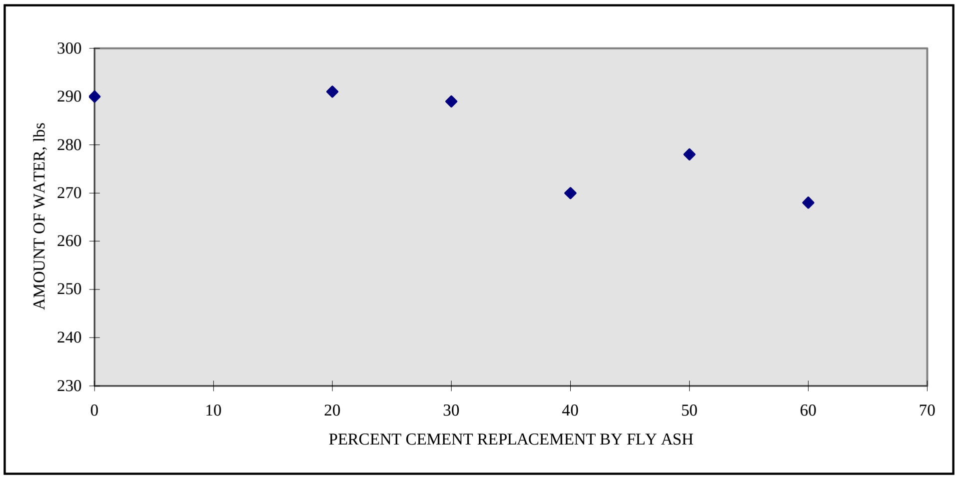


Figure 4–6: Relationship Between Water Demand and Cement Replacement by Fly Ash (5000 psi Concrete with the same Workability)

Figure 4-7 shows the relation between the water to cementitious material ratio and the percentage of cement replacement by fly ash for 3,000 psi; 4,000 psi and 5,000 psi concrete. The figure shows that as the percentage of cement replacement with fly ash increases the water to cementitious material ratio decreases. These results confirm that fly ash concrete requires less water when compared to a similar concrete mix without fly ash for a given slump. Less water equates to denser, less permeable concrete with higher durability.

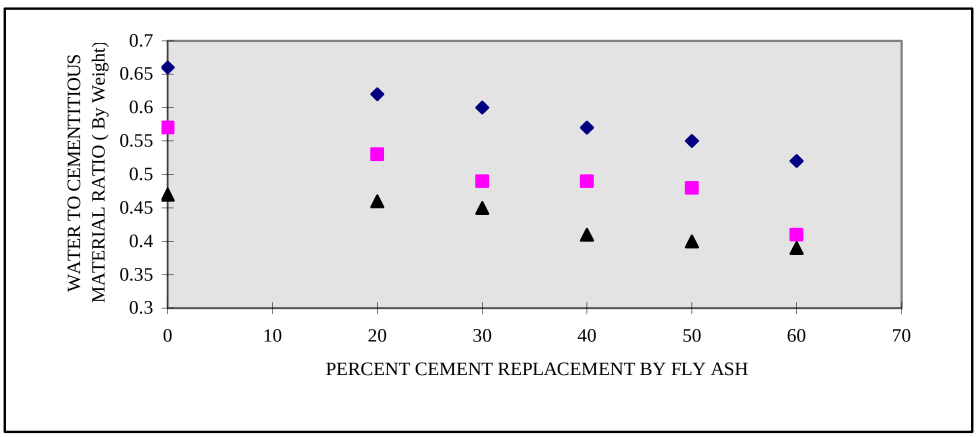


Figure 4–7: Relationship Between Water to Cementitious Ratio and Cement Replacement by Fly Ash (3000, 4000 and 5000 psi Concrete with the same Workability)

Workability

Slump is one measure of workability. Throughout the project, slump was measured and noted. Earlier researchers have reported that workability increases with the increase in fly ash content. This research confirms this same observation. Though the water to cementitious material ratio was reduced as the fly ash content increased, the same workability was obtained.

Time of Set, Modulus of Elasticity, Drying Shrinkage and Poisson's Ratio for We Energies ASTM C618 Class C Fly Ash Concrete (Phase II Study)

As an extension of the project to determine the compressive strength of ASTM C618, Class C fly ash concrete, it was decided to study the effects of Class C fly ash on time of set, modulus of elasticity, drying shrinkage and Poisson's ratio. Mixture proportions were developed for producing concrete on a 1.25 to 1 fly ash replacement for cement basis. The replacements were in the amounts of 35, 45 and 55%, on a weight basis. Basic w/c ratios of 0.45, 0.55 and 0.65 were proportioned for no fly ash concrete. Table 4-8 shows the mixture proportions with the actual w/c ratios for these fly ash concrete mixtures.

Time of Set

In order to determine the time of set, another set of mixtures were prepared. Table 4-8 shows the mixture proportions. P4-43, P4-24 and P4-25 are mixture designs with a 28-day compressive strength of 3,000 psi. Mixtures P4-44, P4-26 and P4-27 are designed for a 28-day compressive strength of 4,000 psi, and P4-45, P4-28 and P4-29 are designed for a 28-day compressive strength of 5,000 psi. Table 4-9 shows the initial and final setting time for fly ash concrete with cement replacement levels of up to 55%. For 3,000 psi concrete, the initial set time increased about an hour for every 10% increase in fly ash.

However, the actual initial setting time of 8 hours ± one hour is essentially the same for the 35, 45 and 55% cement replacement levels. The final set time is seen to increase about 90 minutes for every 10% increase in fly ash content, when compared to the 35% fly ash mix. But the actual final setting time of 8½ to 11½ hours would not have any serious effect on a typical construction project.

Table 4-8: PPPP ASTM C618 Class C Fly Ash Concrete Mix Data

NON-AIR-ENTRAINED CONCRETE

Mix No.	Total Cementitious Material, lbs/cy	Cement, lbs/cy	Fly Ash, lbs/cy	Water, lbs/cy	w/c *	Slump, in **	Air, % ***
P4-43	457	278	179	267	0.584	3.3	1.0
P4-24	471	236	235	267	0.567	3.3	1.4
P4-25	478	193	285	255	0.533	6.3	0.7
P4-44	557	337	220	273	0.490	6.2	0.8
P4-26	574	285	289	266	0.463	3.7	1.3
P4-27	580	235	345	264	0.455	5.8	0.8
P4-45	656	398	258	266	0.405	4.0	0.8
P4-28	700	350	350	275	0.393	3.8	1.0
P4-29	675	275	400	266	0.394	5.0	0.7

AIR-ENTRAINED CONCRETE

Mix No.	Total Cementitious Material, lbs/cy	Cement, lbs/cy	Fly Ash, lbs/cy	Water, lbs/cy	Daravair, ml/cy	w/c *	Slump, in **	Air, % ***
P4-46	537	316	221	254	193	0.473	3.2	6.0
P4-47	546	269	277	249	175	0.456	5.0	4.9
P4-38	555	222	333	240	194	0.432	3.6	5.6
P4-48	605	360	245	273	230	0.451	4.2	6.5
P4-39	616	305	311	265	216	0.430	4.7	5.6
P4-40	625	248	377	251	231	0.402	4.5	5.1
P4-49	751	464	287	295	248	0.393	4.5	6.1
P4-41	779	392	387	284	241	0.365	4.8	5.2
P4-42	797	320	477	264	255	0.331	3.8	4.6

* Based on total cementitious material

** Measured in accordance with ASTM Designation: C 143-78 Standard Test Method for Slump of Portland Cement Concrete

*** Measured in accordance with ASTM Designation: C 231-82 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

Table 4-9: Time of Setting*

Mix No.	Nominal 28-day Compressive Strength, psi	Nominal Percentage of Fly Ash	Time of Setting, HR:MIN	
			Initial	Final
NON-AIR-ENTRAINED CONCRETE				
P4-43	3,000	35	6:55	8:30
P4-24	3,000	45	7:45	9:55
P4-25	3,000	55	8:45	11:20
P4-44	4,000	35	7:35	9:25
P4-26	4,000	45	7:30	9:50
P4-27	4,000	55	7:55	10:25
P4-45	5,000	35	6:30	8:15
P4-28	5,000	45	7:15	9:25
P4-29	5,000	55	7:00	9:15
AIR-ENTRAINED CONCRETE				
P4-46	3,000	35	6:40	8:40
P4-47	3,000	45	8:15	10:25
P4-38	3,000	55	7:15	9:45
P4-48	4,000	35	7:30	9:45
P4-39	4,000	45	6:40	9:10
P4-40	4,000	55	6:55	9:30
P4-49	5,000	35	6:45	8:20
P4-41	5,000	45	7:30	9:40
P4-42	5,000	55	5:40	7:10

* Determined in accordance with ASTM Designation: C-403-85 Time of Setting of Concrete Mixtures by Penetration Resistance

The final setting time for 4000 psi and 5000 psi concrete showed much less increase with increase in fly ash content. The 5000 psi concrete with 55% fly ash content actually showed a decrease by 10 minutes for final setting time compared to 5000 psi concrete with 45% fly ash content.

The initial and final setting time for air-entrained concrete is also shown on Table 4-9. It can be seen from the results that the initial and final setting time for air-entrained fly ash concrete is not significantly different as the fly ash replacement is increased to levels of 55% for the 3,000; 4,000; and 5,000 psi concrete.

The final setting time for 5000 psi air-entrained concrete is actually less than that of 3000 psi and 4000 psi air-entrained concrete. The 3000 psi air-entrained concrete showed the maximum increase in setting time, when fly ash content is increased from 35 to 45%. But for the same strength concrete with 55% fly ash content, the setting time was lower than that of the mixture containing 45% fly ash. Hence, it is reasonable to believe that initial and final setting time is not significantly different for normal strength concrete with up to 55% replacement of cement with fly ash.

Modulus of Elasticity, Poisson's Ratio and Compressive Strength

Static modulus of elasticity, Poisson's ratio and compressive strength were determined for six different types of concrete. All six of the mixtures contained 45% replacement of cement with fly ash on a 1 to 1.25 ratio by weight. Mixtures P4-24, P4-26, and P4-28 were non-air-entrained concrete and mixes P4-47, P4-39, and P4-41 were air-entrained concrete mixtures. P4-24, P4-26, and P4-28 were designed for 3,000; 4,000; and 5,000 psi compressive strength, respectively. Also, P4-47, P4-39 and P4-41 were designed for 3,000; 4,000; and 5,000 psi compressive strengths respectively.

Table 4-10: ASTM C-469 Test Results at 28 Days * (Non-Air-Entrained Concrete)

Mix No.	Modulus of Elasticity psi x 10^6	Poisson's Ratio	Compressive Strength, psi
P4-24- A	**	**	6590
B	4.70	0.18	6380
C	4.75	0.18	6430
D	4.84	0.19	6730
Average	**4.76**	**0.18**	**6530**
P4-26-A	**	**	6290***
B	4.98	0.19	7530
C	5.11	0.19	7600
D	5.05	0.18	7680
Average	**5.05**	**0.19**	**7600**
P4-28- A	**	**	8850
B	4.97	0.18	8900
C	4.85	0.19	8880
D	4.86	0.19	9130
Average	**4.89**	**0.19**	**8940**

* Tested in accordance with ASTM Designation: C-469-83 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression.

** Determined to establish level of loading for modulus of elasticity determination.

*** Bad shear break-omitted from average.

Table 4-11: ASTM C-469 Test Results at 28 Days *
(Air-Entrained Concrete)

Mix No.	Modulus of Elasticity psi x 10^6	Poisson's Ratio	Compressive Strength, psi
P4-47- A	**	**	6210
B	4.19	0.17	6420
C	4.25	0.16	6520
D	4.23	0.16	6160
Average	**4.23**	**0.16**	**6160**
P4-39- A	**	**	6100
B	4.17	0.17	6240
C	4.15	0.16	6110
D	4.15	0.16	6110
Average	**4.17**	**0.17**	**6150**
P4-41- A	**	**	7180
B	4.37	0.21	7090
C	4.43	0.17	7370
D	4.37	0.18	7350
Average	**4.39**	**0.19**	**7250**

* Tested in accordance with ASTM Designation: C-469-83 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression.

** Determined to establish level of loading for modulus of elasticity determination.

As can be seen from Tables 4-10 and 4-11, the compressive strengths obtained were much higher than the design strength. In accordance with the ACI 318 Building Code, the static modulus of elasticity is equal to 57,000 $\sqrt{f'c}$. The values of modulus of elasticity shown in Table 4-10 for non-air-entrained and Table 4-11 for air-entrained fly ash concrete follow nearly the same well-established relationship between compressive strength and the static modulus of elasticity. A detailed discussion of the results can be obtained in reference 26.

The static Poisson's ratios obtained for these mixtures (both non-air-entrained and air-entrained) fall within the accepted limits for concrete of 0.15 to 0.20, with higher strength concrete showing a higher value.

Length Change (Drying Shrinkage in Air) and Expansion in Water

The test results for both air-entrained and non-air-entrained concrete with 45% replacement of cement with fly ash are shown on Table 4-12. The data from all of these mixtures fell between 0.014 and 0.046 for non-air-entrained mixtures and between 0.02 and 0.044 for the air-entrained mixtures.

The test results for expansion in water fell between 0.002 and 0.01 for non-air-entrained concrete and between 0.003 and 0.015 for air-entrained concrete.

Table 4-12: Length Change*

NON-AIR-ENTRAINED CONCRETE					
Mix No.	Expansion in Water, % 28 days	Shrinkage in Air (73°F, 50% RH), %			
		4 days	7 days	14 days	28 days
P4-24 A	0.009	0.015	0.026	0.031	0.039
B	0.009	0.015	0.023	0.031	0.036
C	0.010	0.014	0.024	0.029	0.037
Average	0.009	0.0l5	0.024	0.030	0.037
P4-26 A	0.003	0.023	0.033	0.038	0.046
B	0.007	0.0l8	0.030	0.035	0.041
C	0.002	0.021	0.030	0.032	0.039
Average	0.004	0.021	0.031	0.035	0.042
P4-28 A	0.006	**	0.030	0.036	0.043
B	0.009	**	0.027	0.035	0.040
C	0.009	**	0.028	0.034	0.042
Average	0.008		0.028	0.035	0.042
AIR-ENTRAINED CONCRETE					
Mix No.	Expansion in Water, % 28 days	Shrinkage in Air (73°F, 50% RH), %			
		4 days	7 days	14 days	28 days
P4-47 A	0.004	0.022	0.030	0.039	0.045
B	0.003	0.023	0.030	0.040	0.045
C	0.006	0.019	0.027	0.040	0.041
Average	0.004	0.021	0.029	0.038	0.044
P4-39 A	0.0200	0.005	0.014	0.023	0.027
B	0.020	0.003	0.013	0.021	0.028
C	0.017	0.007	0.014	0.023	0.026
Average	0.019	0.005	0.014	0.022	0.027
P4-41 A	0.016	0.006	0.014	0.022	0.028
B	0.019	0.009	0.018	0.026	0.032
C	0.015	0.002	0.012	0.018	0.024
Average	0.017	0.006	0.015	0.022	0.028

* Measured in accordance with ASTM Designation: C-157-80 Standard Test Method for Length Change of Hardened Cement Mortar and Concrete.

** Not measured.

Freezing and Thawing Durability

Freezing and thawing tests were performed on two 4,000 psi, 28-day compressive strength concrete mixtures with 45% fly ash replacement for cement. Mix P4-26 was non-air-entrained, and mix P4-39 was air-entrained. Tables 4-13 and 4-14 give the freeze-thaw test results for non-air-entrained concrete and air-entrained concrete, respectively. ASTM Test Designation C666-84, Procedure A, was followed. Non-air-entrained concrete failed after a low number of cycles of rapid freezing and thawing as expected. However, air-entrained concrete didn't indicate failure even after 300 cycles of freezing and thawing.

These test results demonstrate that properly air-entrained fly ash concrete with 45% of cement replacement with fly ash exhibits a high durability against freezing and thawing.

Table 4-13: Freeze-Thaw Tests* - Non-Air-Entrained Concrete

Mix No.	Percent Expansion at 25 Freeze-Thaw Cycles	Percent Expansion at 44 Freeze-Thaw Cycles
P4-26 A	0.189	0.293
B	0.180	0.258
C	0.130	0.189
Average	0.166	0.247
Mix No.	**Percent Weight Change at**	
	25 Freeze-Thaw Cycles	**44 Freeze-Thaw Cycles**
P4-26 A	+0.2	+0.4
B	+0.2	+0.3
C	+0.1	+0.2
Average	+0.2	+0.3
Mix No.	**Relative Dynamic Modulus of Elasticity at**	
	25 Freeze-Thaw Cycles, %	**44 Freeze-Thaw Cycles, %**
P4-26 A	61	45
B	71	58
C	78	45
Average	70	49
Mix No.	**Durability Factor**	
P4-26 A	5	
B	9	
C	10	
Average	8	

* Tested in accordance with ASTM Designation C-666-84 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A).

Table 4-14: Freeze-Thaw Tests* (Air-Entrained Concrete)

	Percent Expansion at Freeze-Thaw Cycle Indicated							
Mix No.	40	75	106	141	195	238	267	300
P4-39 A	0.004	0.011	0.022	0.030	0.041	0.057	0.062	0.078
B	0.004	0.012	0.021	0.024	0.028	0.041	0.047	0.053
C	0.008	0.0111	0.024	0.036	0.050	0.059	0.065	0.075
Average	0.005	0.011	0.022	0.030	0.040	0.052	0.058	0.068
	Percent Weight Loss at Freeze-Thaw Cycle Indicated							
Mix No.	40	75	106	141	195	238	267	300
P4-39 A	0.0	0.2	0.8	1.3	1.9	2.6	3.0	3.4
B	0.0	0.6	0.6	0.9	1.4	1.8	2.2	2.6
C	0.0	0.1	0.2	0.6	1.2	1.7	2.3	3.0
Average	0.0	0.3	0.5	0.9	1.5	2.0	2.5	3.0
	Relative Dynamic Modulus of Elasticity at Freeze-Thaw Cycle Indicated							
Mix No.	40	75	106	141	195	238	267	300
P4-39 A	99	98	98	97	95	90	86	83
B	99	99	99	98	98	98	95	92
C	99	99	99	98	98	98	97	96
Average	99	99	99	98	97	95	93	90
Mix No.	Durability Factor							
P4-39 A	83							
B	92							
C	96							
Average	90							

* Tested in accordance with ASTM Designation C-666-84 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A).

Phase II Test Result Conclusions

The following are the major results of this study:

1. For both air-entrained and non-air-entrained concrete, the initial and final setting time is not significantly different for normal strength concrete with up to 55% replacement of cement with fly ash.
2. For non-air-entrained and air-entrained fly ash concrete, with fly ash replacement of up to 45% and compressive strength in the range 3,000 to 5,000 psi, the static modulus of elasticity is in conformance with established relationships to compressive strength.
3. Poisson's ratio of these fly ash concretes is within the accepted limits for concrete.
4. Properly air-entrained high-volume fly ash concrete exhibits good resistance to freezing and thawing.

Abrasion Resistance of Concrete Containing We Energies ASTM C618, Class C Fly Ash

Abrasion is a common form of wear observed in pavements due to friction forces applied by moving vehicles. Abrasion wear can also occur due to rubbing, scraping, skidding or sliding of other objects on the pavement/concrete surface.

Resistance of concrete surfaces to abrasion is influenced by several factors including concrete strength, aggregate properties, surface finishing and type of toppings. Previous studies have reported that the abrasion resistance of a concrete surface is primarily dependent on the compressive strength of concrete.

ACI Committee 201 recommends a minimum compressive strength of 4,000 psi for concrete subjected to abrasion. Hard surface material, aggregate and paste having low porosity and high strength improves the abrasive resistance of concrete.

Abrasion Test Sample Preparation

ASTM C618, Class C fly ash from Pleasant Prairie Power Plant of We Energies was used in this study. Fine and coarse aggregate used in this project met ASTM C33 gradation requirements.

The Portland cement was Lafarge Type 1, meeting ASTM C150. Commercially available Catexol AE 260, air-entraining agent and a Daracem™ 100 superplastisizer were also used.

Mixture proportions are shown on Table 4-15. Of the 11 mixtures produced, three were control mixtures and the other eight mixtures contained ASTM C618, Class C fly ash. Mixture proportions containing fly ash replacement for cement on a 1.25 to 1 basis in the range of 15 to 75% by weight were established. The water to cementitious materials ratio was maintained at 0.35 ± 0.02 and air content was kept at 6 ± 1% for the primary mixtures. The mixtures that didn’t meet the above requirements were classified as secondary mixtures and these were not used for detailed analysis of test results.

Slab specimens for abrasion resistance were prepared according to ASTM C-31 procedures. Fresh concrete properties are reported in Table 4-15. Compressive strength test results are shown in Table 4-16.

Abrasion resistance tests were performed at 28 and 91 days after moist curing of the slab specimens. Abrasion tests were conducted on the specimens using ASTM C944 test methods. The ASTM C944 test produced a depth of abrasion of about one mm (0.04") after about 60 minutes of exposure to the abrasive force. This method was too slow. An accelerated method was developed as an alternative. Details of the method can be obtained from reference 27.

Table 4-15: Mixture Proportions Using Pleasant Prairie Power Plant - Class C Fly Ash, 6000 PSI (41.8 MPA) Specified Strength*

Mix. No.	C-1 (S)	C-2 (S)	C-3 (P)	P4-1 (S)	P4-2 (P)	P4-3 (P)	P4-4 (S)	P4-5 (S)	P4-6 (P)	P4-7 (P)	P4-8 (P)
Specified design strength (psi)	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000
Cement (lb/cu yd)	675	671	661	568	445	378	305	177	556	305	180
Fly Ash (lb/cu yd)	0	0	0	125	239	313	378	514	123	383	519
Water (lb/cu yd)	208	210	237	240	245	259	249	257	225	230	258
Water-to-cementitious ratio	0.31	0.32	0.36	0.35	0.36	0.37	0.36	0.37	0.33	0.33	0.37
Sand, SSD (lb/cu yd)	1212	1205	1207	1208	1158	1175	1153	1112	1190	1111	1084
1 in. aggregates, SSD (lb/cu yd)	2134	2113	2083	2092	2036	1998	1914	1861	2059	1933	1878
Slump (in)	1	1¾	4¾	2½	6¼	4¾	2¼	3	5¾	4½	4¾
Air content (%)	2.6	2.4	6.3	4.1	5.1	6.4	8.5	3.7	6.7	7	6.4
HRWR[1] (liq oz/cu yd)	71.0	70.0	74.6	75	73	71.0	68.0	67.6	73.5	68.8	67.0
AEA[2] (liq oz/cu yd)	7.2	9.0	7.0	7.8	9.0	13.3	21.0	23.4	10.8	22.9	35.7
Air Temperature (°F)	68	68	70	70	70	70	78	79	--	--	--
Concrete Temperature (°F)	69	68	73	73	73	78	78	79	70	78	77
Fresh Concrete Density (lb/ft^3)	156.0	156.0	148.6	152.7	149.4	147.3	140.3	145.8	149.8	145.9	147.6
Hardened Concrete density, SSD (lb/ft^3)	156.9	156.8	154.2	156.8	151.8	150.8	142.4	143.5	152.3	146.2	145.2

Notes:

[1] High Range Water Reducer (HRWR);

[2] Air-Entraining Agent

* Subdesignation P indicates primary mixes for this research project and S indicates secondary (duplicate) mixes. Main conclusions are shown with the data from the primary mixes only.

Abrasion Test Results and Discussion

The compressive strengths were measured at ages 1, 3, 7, 28 and 91 days, and are shown in Table 4-16. At early ages, fly ash concrete exhibited lower compressive strength compared to the control mix. At the 28-day age, 30% fly ash concrete showed peak compressive strength.

Beyond 30% cement replacement, the compressive strength decreased with an increase in fly ash content. The compressive strength of concrete also decreased with increasing air content. This is expected and has been reported by earlier researchers.

Abrasion tests were performed at ages of 28 and 91 days. Abrasion measurement using the modified method is a relative indicator of abrasion and is reported in Tables 4-17 and 4-18. Abrasion wear decreased with an increase in specimen age and resulting increased strength.

Concrete mixtures of up to 30% cement replacement by fly ash had abrasion resistance similar to that for fly ash concrete produced without fly ash. Beyond 30% cement replacement, abrasion resistance decreased. It can also be said that with the decrease in compressive strength, abrasion resistance decreased (abrasion wear increased).

The above work leads to the following key conclusions:

1. Concrete containing up to 30% cement replacement by fly ash exhibited similar or better compressive strength when compared to concrete produced without fly ash, at ages of three days and beyond
2. (See Figure 4-8).
3. Compressive strength is the key factor affecting abrasion resistance. Stronger concrete mixtures exhibited higher resistance to abrasion
4. (See Figure 4-9).
5. Effect of air content on abrasion resistance of concrete was insignificant within the tested range.

Table 4-16: Compressive Strength Test Data

Mix No.	C-1 (S)		C-2 (S)		C-3 (P)		P4-1 (S)		P4-2 (P)		P4-3 (P)		P4-4 (S)		P4-5 (S)		P4-6 (P)		P4-7 (P)		P4-8 (P)	
Specified Strength, psi	6000		6000		6000		6000		6000		6000		6000		6000		6000		6000		6000	
Percent fly ash	0		0		0		15		30		40		50		70		15		50		70	
Compressive Strength, PSI																						
Test Age, Days	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg
1	5380		5150		3870		4050		1875		1110		385		-		2480		-		-	
1	5130	5200	515	5240	3965	3955	3970	4015	1910	1780	1175	1125	300	400	-	*	2370	2425	-		-	*
1	5095		5450		4030		4030		1560		1090		335		-		2420		-		-	
3	6330		5955		4530		5090		3855		2610		1415		-		4300		1495		-	
3	6580	6440	5980	5955	4860	4925	4925	5100	4075	4045	2720	2640	1505	1490	60	55	4270	4240	1550	1655	-	*
3	6410		5935		4355		5290		4210		2590		1485		50		4155		1920		-	
7	6935		6540		5180		6245		5315		3560		2245		65		5070		2540		85*	
7	6950	6885	6750	6680	4905	5160	6270	6210	5340	5290	3450	3530	2240	2240	60	65	5250	5195	2410	2465	130**	100**
7	6770		6755		5100		6120		5210		3580		2150		70		5255		2545		90**	
28	7915		7760		6405		6885		7050		5290		3265		2305		6875		4630		3015	
28	7620	7715	7985	7870	6065	6280	7105	7220	6605	6875	5545	5200	3125	3170	2265	2365	6820	6750	4440	4615	2785	2535
28	7605		7875		6375		7665		6965		4760		3110		2530		6550		4775		1800	
91	9215		870		7000		8145		7920		5555		4295		3880		8655		5785		5360	
91	9140	9230	8940	8800	6965	6910	8290	8220	8225	8075	6020	6055	4305	4240	4415	4245	7525	7880	5550	5765	5040	4760
91	9340		8755		6770		8220		8074		6585		4125		4440		7455		5970		3885	

+ S = Secondary mixes, P = Primary mixes * These readings could not be recorded because the specimens were soft. ** Tested at 11 days.

Table 4-17: Abrasion Resistance Test Results at 28-Day Age

Mix No.*	C-1 (S)	C-2 (S)	C-3 (P)	P4-1 (S)	P4-2 (P)	P4-3 (P)	P4-4 (S)	P4-5 (P)	P4-6 (P)	P4-7 (P)	P4-8 (P)
Percent, Fly Ash	0	0	0	15	30	40	50	70	15	50	70
Time (m)	Depth of Wear, mm										
5	0.11	0.10	0.23	0.14	0.14	0.18	0.34	0.44	0.18	0.23	0.30
10	0.26	0.26	0.46	0.36	0.34	0.49	0.57	1.00	0.32	0.63	0.68
15	0.64	0.41	0.69	0.52	0.50	0.78	0.90	1.38	0.54	0.92	1.29
20	1.04	0.63	0.82	0.70	0.66	1.00	1.09	1.71	0.64	1.11	1.40
25	1.17	0.75	1.01	0.92	0.85	1.27	1.38	1.90	0.90	1.27	1.89
30	1.45	0.88	1.11	1.08	1.02	1.58	1.63	2.34	1.03	1.49	2.00
35	1.65	1.04	1.28	1.24	1.18	1.77	1.86	2.63	1.18	1.58	2.35
40	1.88	1.21	1.39	1.39	1.33	2.01	2.04	2.94	1.33	2.16	2.81
45	1.99	1.33	1.57	1.62	1.50	2.18	2.22	--	1.49	2.34	3.04
50	2.17	1.50	1.75	1.78	1.74	2.28	2.44	--	1.65	2.56	--
55	2.28	1.67	1.89	1.96	1.88	2.45	2.62	--	1.80	2.72	--
60	2.42	1.85	2.06	2.16	2.05	2.56	2.76	3.68	1.95	2.85	3.55

* P = Primary mixes, S = Secondary mixes

Table 4-18: Abrasion Resistance Test Results at 91-Day Age

Mix No. *	C-1 (S)	C-2 (S)	C-3 (P)	P4-1 (S)	P4-2 (P)	P4-3 (P)	P4-4 (S)	P4-5 (S)	P4-6 (P)	P4-7 (P)	P4-8 (P)
Percent, Fly Ash	0	0	0	15	30	40	50	70	15	50	70
Time (m)	Depth of Wear, mm										
10	0.23	0.23	0.29	0.26	0.17	0.29	0.46	0.48	0.27	0.57	0.61
15	0.43	0.45	0.49	0.41	0.35	0.54	0.74	0.74	0.53	0.88	0.96
20	0.55	0.62	0.75	0.62	0.53	0.78	0.96	0.90	0.64	1.10	1.25
25	0.72	0.75	0.96	0.79	0.76	1.01	1.18	1.15	0.82	1.50	1.51
30	0.74	0.90	1.10	0.94	0.90	1.18	1.37	1.39	0.99	1.65	1.68
35	1.13	1.03	1.24	1.11	1.04	1.29	1.55	1.64	1.10	1.77	1.89
40	1.27	1.12	1.39	1.27	1.18	1.50	1.74	1.85	1.26	2.01	2.03
45	1.37	1.27	1.46	1.44	1.31	1.71	1.92	2.04	1.39	2.16	2.16
50	1.50	1.41	1.58	1.53	1.48	1.85	2.04	2.24	1.50	2.27	2.32
55	1.64	1.50	1.68	1.65	1.64	1.97	2.21	2.38	1.59	2.33	2.47
60	1.80	1.63	1.77	1.75	1.70	2.08	2.34	2.54	1.71	2.41	2.59

* P = Primary mixes, S = Secondary mixes

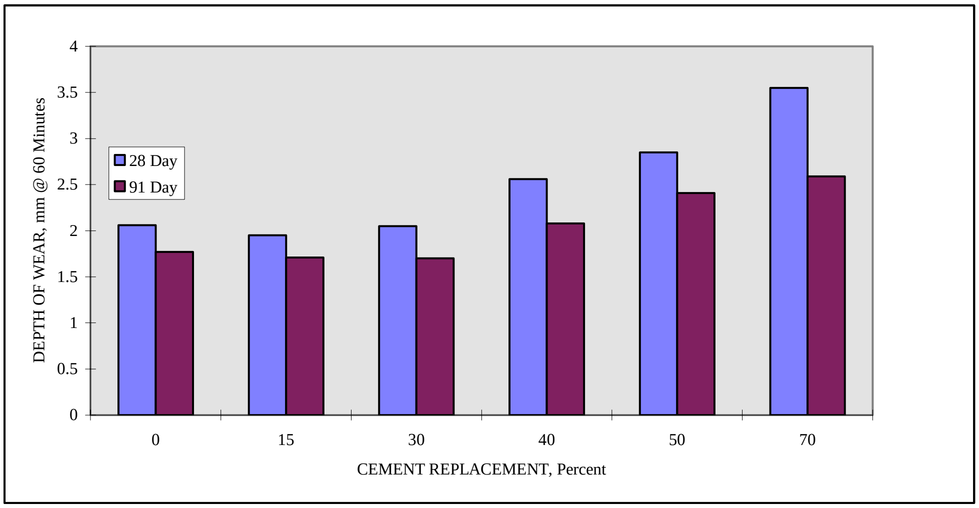


Figure 4–8: Abrasion Resistance vs. Cement Replacement with Class C Fly Ash

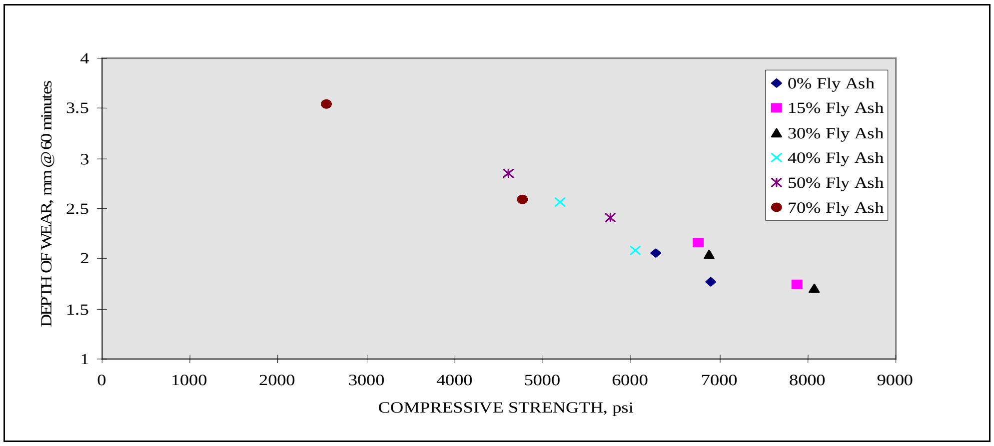


Figure 4–9: Abrasion Resistance vs. Compressive Strength of Concretes Containing Different Percentages of Fly Ash

Chloride Ion Permeability of High Strength We Energies Fly Ash Concrete Containing Low Cement Factor

Permeability of concrete is a very important factor affecting its durability. A decrease in permeability of concrete increases the resistance to the ingress of aggressive agents, which in turn, would lead to improved concrete durability.

The following discussion is based on a study conducted at the Center for By-Products Utilization at the University of Wisconsin in Milwaukee for We Energies. Several concrete mixes were designed with and without fly ash. The control mixture was designed for a 28-day compressive strength of 5800 psi without any fly ash. However, other mixtures were designed with various percentages of fly ash as a partial replacement of cement. ASTM C618, Class C fly ash from Pleasant Prairie Power Plant was used in these tests.

Table 4-19 shows the mixture proportions for the various mixtures, including fresh concrete properties. For this study, the water-to-cementitious materials ratio and air content for the primary mixtures were maintained at about 0.35 ± 0.02 and 6 ± 1%, respectively. The mixtures that did not meet these target parameters were called secondary mixes. The primary mixtures were used to make major conclusions, while the secondary mixes were used to study the effect of air content on concrete strength and permeability (28).

The concrete mixing procedure was performed according to ASTM C192 procedures, and specimens were also cast in accordance with ASTM C192 "Making and Curing Concrete Test Specimens in the Laboratory" procedures.

Compressive Strength Test Results

Compressive strength tests were measured per ASTM C39 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" procedures. Air and water permeability was measured in accordance with the Figg Method. Chloride ion permeability was measured according to ASTM C1202 "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Permeability".

Compressive strength results are shown in Table 4-20 and on Figures 4-10 and 4-11. Fly ash with up to 35% cement replacement and replaced on a 1.25 fly ash per 1.00 cement weight ratio, showed results similar to the reference concrete at a 3-day age. Beyond 30% cement replacement, the mixtures exhibited lower compressive strength when compared to the reference mixture. At the 28-day age the concrete showed strength levels comparable to the control mixture.

Table 4-19: Mixture Proportions Using ASTM Class C Fly Ash 5800 PSI Specified Strength

Parameter	Mixture No. *										
	C-1 (S)	C-2(S)	C-3(P)	P4-1(S)	P4-2(P)	P4-3(P)	P4-4(S)	P4-5(S)	P4-6(P)	P4-7(P)	P4-8(P)
Cement (lb/cu yd)	671	669	632	553	437	371	293	180	539	302	185
Fly ash (lb/cu yd)	0	0	0	121	234	307	364	523	120	381	533
Water (lb/cu yd)	207	211	228	234	224	253	238	258	217	229	261
[W(C + FA)]	0.31	0.31	0.36	0.35	0.33	0.37	0.36	0.37	0.33	0.34	0.36
Sand, SSD (lb/cu yd)	1205	1200	1150	1171	1141	1111	1052	1074	1168	1104	1023
25 mm aggregates, SSD (lb/cu/yd)	2122	2130	1992	2034	1975	1943	1852	1901	1989	1920	1930
Slump (inches)	1.0	1.8	4.7	2.6	6.3	4.7	2.2	3.0	5.7	4.5	4.7
Air content (%)	2.6	2.4	6.3	4.1	5.2	6.4	8.5	3.7	6.7	7	6.4
Superplasticizer (US fl oz/ cu yd)	69.9	69.9	75.1	69.9	72.5	69.9	67.3	67.3	72.5	69.9	67.3
Air entraining agent (US fl oz/ cu yd)	7.3	8.5	7.0	7.8	9.1	13.3	21.0	23.4	10.9	22.9	35.7
Air temperature (°F)	68	68	70	70	70	70	79	79	-	-	-
Concrete temperature (°F)	68	68	73	73	73	79	79	79	70	79	77
Fresh concrete density (lb/ cu yd)	4210	4210	4010	4120	4040	3980	3790	3940	4040	3940	3990
Hardened concrete density, SSD (lb/cu yd)	4240	4230	4160	4230	4100	4070	3840	3880	4110	3950	3920

* Subdesignation (P) indicates primary mixtures and (S) indicates secondary (duplicate) mixtures. Main conclusions are drawn based on the data obtained from primary mixtures. Secondary mixtures are used for analysis of effect of air content variations.

Table 4-20: Compressive Strength Test Results

Test Age (days)	Mixture No. *										
	C-1 (S)	C-2(S)	C-3(P)	P4-1(S)	P4-2(P)	P4-3(P)	P4-4(S)	P4-5(S)	P4-6(P)	P4-7(P)	P4-8(P)
	(a) Fly Ash (percent) –% of Total Cementitious Materials FA/(Cement + FA)										
	0	0	0	18	18	35	45	55	55	74	74
	(b) Compressive Strength (PSI) – Average of Three Test Observations										
1	5210	5240	3960	4020	2420	1780	1130	410	-	-	-
3	6440	5960	4580	5100	4230	4050	2640	1490	1650	60	-
7	6890	6690	5160	6200	5190	5290	3520	2230	2460	60	100
28	7710	7870	6280	7220	6740	6870	5200	3170	4610	2360	2540
91	9220	8800	6900	8220	7870	8080	6050	4230	5770	4250	4760
365	11480	11340	8480	10190	9090	10250	7240	4840	5650	5290	5920

* P and S refer to primary and secondary mixtures, respectively.

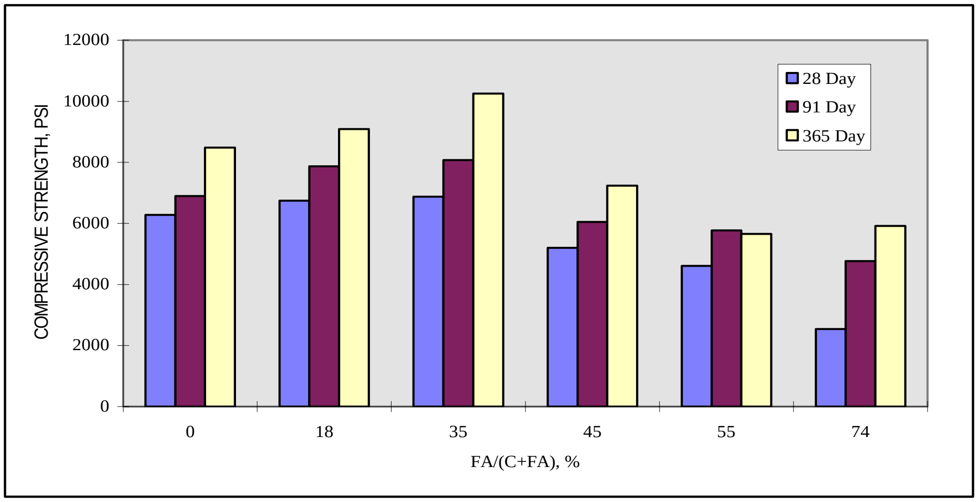


Figure 4–10: Compressive Strength of Concrete made with and without Fly Ash for Primary Mixtures

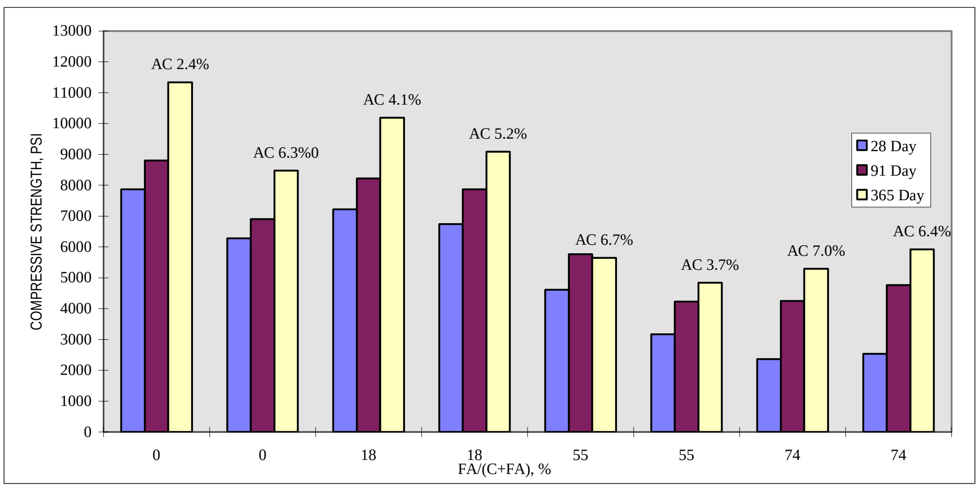


Figure 4–11: Compressive Strength of Concrete made with and without Fly Ash having Different Percentage of Air Content

Permeability Test Results

Concrete air and water permeabilities were measured at an age of 14, 28 and 91 days. Also, the chloride ion permeability was determined at 2 months, 3 months and 1 year. Air, water and chloride permeability values decreased with age, as expected, due to the improvement in concrete microstructure.

Air permeability test results are given in Table 4-21 and shown on Figures 4-12 and 4-13. At the 14-day age, concrete without fly ash and 18% fly ash concrete were rated “good” and mixtures with higher fly ash contents were rated “fair.” At the 28-day age, the reference mixture and mixtures with up to 45% fly ash were rated “good.” At the 91 day age, 55% fly ash mixtures showed the maximum resistance to air permeability. Figure 13 shows the effect of air content on the concrete’s resistance to air permeability. No specific relationship is seen between air permeability and air content for concretes with and without fly ash.

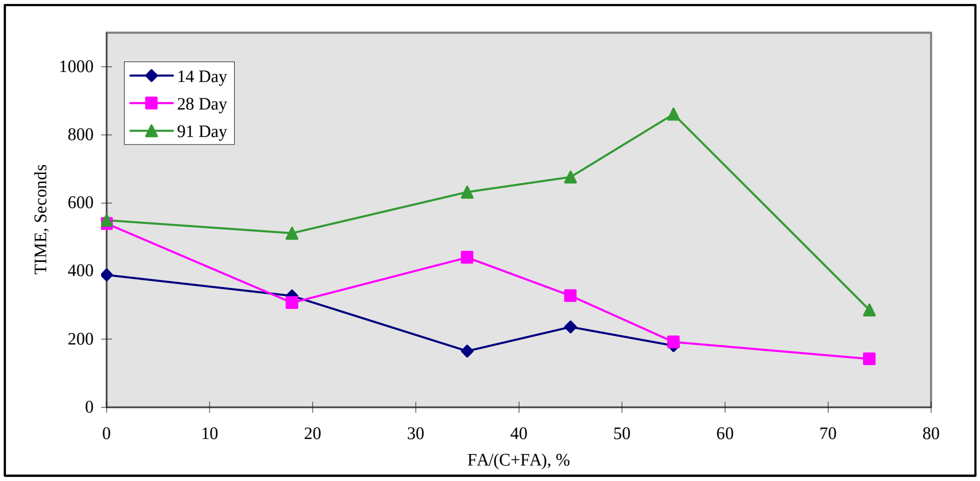


Figure 4–12: Air Permeability (Time) vs. Fly Ash Content for Primary Mixtures

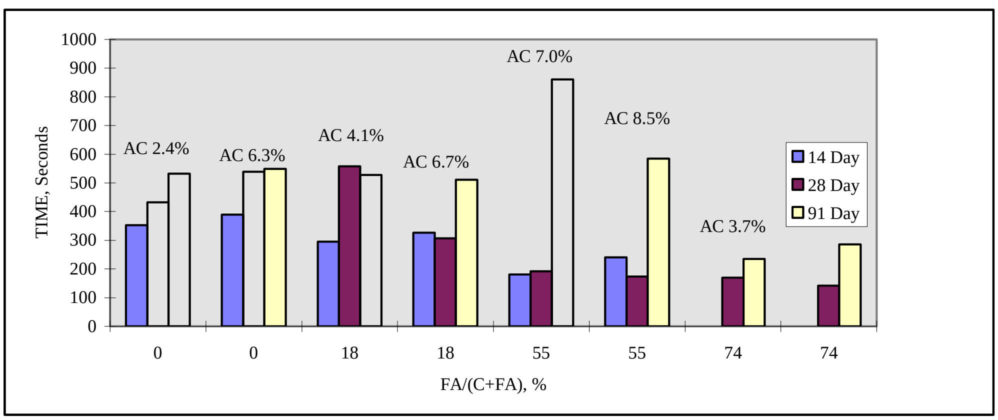


Figure 4–13: Air Permeability of Concrete with and without Fly Ash having Different Percentages of Air Content

Table 4-21: Air Permeability Test Results

Mixture No. *	Fly Ash ** (%)	Average Time*** (Seconds)		
		14-day	28-day	91-day
C-1 (S)	0	543	465	830
C-2(S)	0	352	433	532
C-3(P)	0	389	539	549
P4-1(S)	18	295	558	528
P4-6(P)	18	327	307	511
P4-2(P)	35	165	440	632
P4-3(P)	45	236	328	676
P4-4(S)	55	241	173	585
P4-7(P)	55	181	192	861
P4-5(S)	74	---	170	235
P4-8(P)	74	---	142	286

The following classification for the air permeability of concrete is used (Cather et al. 1984)

Time in Seconds for Pressure Change	Interpretation
<30	Poor
30 - 100	Moderate
100 - 300	Fair
300 - 1,000	Good
> 1,000	Excellent

* P = Primary; S= Secondary ** As a percentage of total cementitious materials, FA/(Cement + FA).
***Test data are average of five test observations.

Water permeability decreased as the age of concrete specimens increased, as shown on Figures 4-14 and 4-15 and on Table 4-22. At the 14-day age, concrete resistance to water permeability was improved for mixes with up to 35% fly ash when compared to the reference mixture without fly ash. The 18% to 45% fly ash mixtures were rated as “good.”

At 91 days, concrete mixtures with fly ash to total cementitious materials ratio of 35% to 55% were rated as "excellent." All other mixtures were only rated "good." In these mixtures, due to pozzolanic action, the grain structure showed substantial improvement. Water permeability showed no major variations when compared to variations in air content for all concrete with and without fly ash.

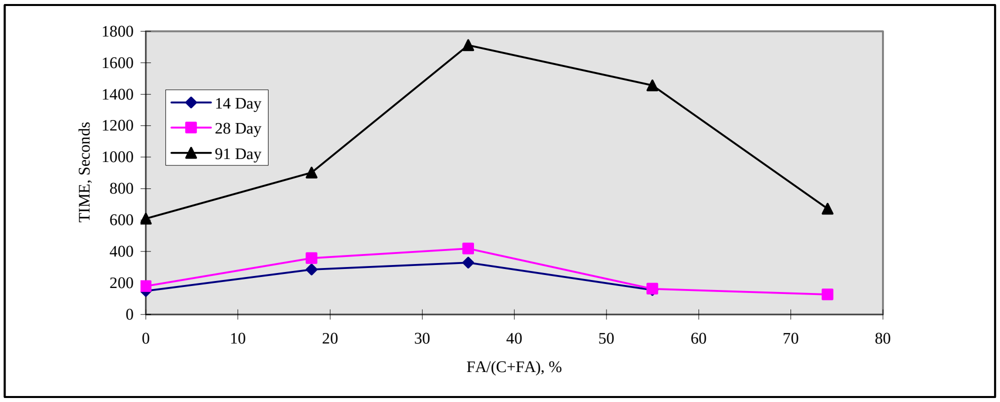


Figure 4–14: Water Permeability (Time) vs. Fly Ash Content for Primary Mixtures

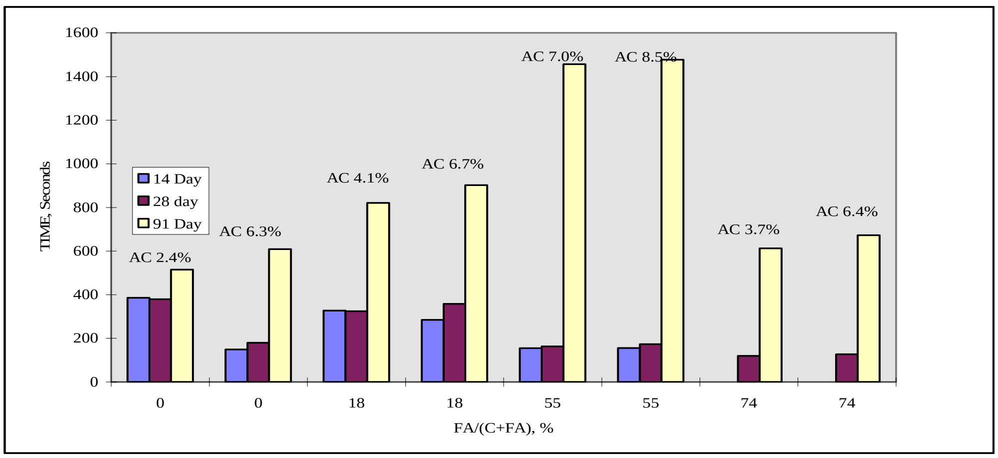


Figure 4–15: Water Permeability of Concrete with and without Fly Ash having Different Percentages of Air Content

Table 4-22: Water Permeability Test Results

Mixture No. *	Fly Ash** (%)	Average Time*** (Seconds)		
		14-day	28-day	91-day
C-1 (S)	0	294	392	614
C-2(S)	0	386	372	515
C-3(P)	0	149	180	609
P4-1(S)	18	327	324	821
P4-6(P)	18	285	358d	902
P4-2(P)	35	330	418	1,713
P4-3(P)	45	201	241	1,365
P4-4(S)	55	156	173	1,477
P4-7(P)	55	155	163[a]	1,457
P4-5(S)	74	--	120	613
P4-8(P)	74	--	127[a]	673

Time in Seconds for Absorption[b]	Protective Quality[b]
<40	Poor
40 - 100	Moderate
100 - 200	Fair
200 - 1000	Good
> 1,000	Excellent

* P = Primary; S= Secondary

** As a percentage of total cementitious materials, FA/(Cement + FA).

*** Test data are average of five test observations.

a Test was performed at 40 days.

b Classification based on Arup Research & Development

The chloride ion permeability of the concrete mixtures is shown in Table 4-23 and Figures 4-16 and 4-17. At the age of 2 months, the high-volume fly ash mixtures showed lower chloride ion permeability when compared to the reference mixture without fly ash, except for the 74% fly ash to total cementitious materials ratio concrete. The permeability in this case was in the range of 2,000 to 4,000 coulombs (rated “moderate”) per ASTM C1202 criteria. With additional time, the resistance to chloride ion permeability of these mixtures showed substantial improvement.

At the age of one year, all the fly ash concrete mixtures attained a “very low” (100 to 1,000 coulombs) level of chloride ion permeability in accordance with ASTM C1202 criteria where the reference mixtures exhibited a “low” (1,000 to 2,000 coulombs) level of chloride permeability.

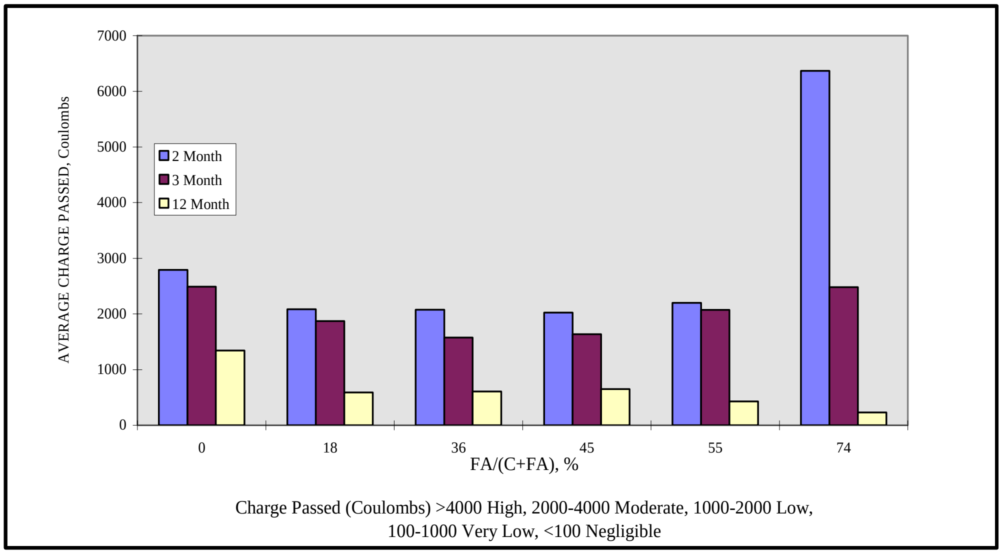


Figure 4–16: Chloride Permeability vs. Fly Ash Content for Primary Mixtures

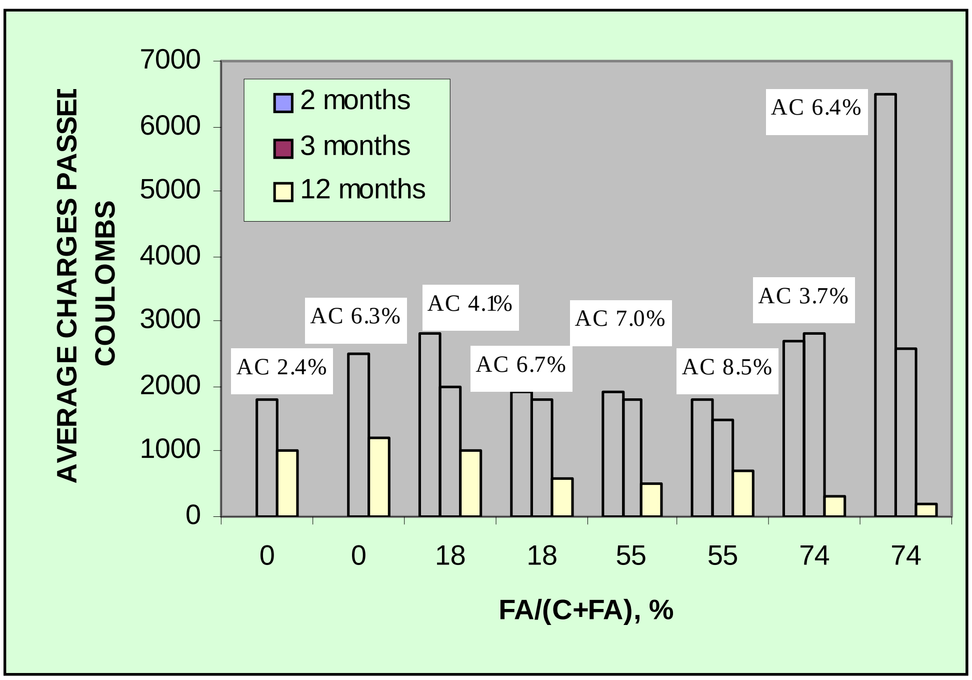


Figure 4–17: Water Permeability of Concrete with and without Fly Ash having Different Percentages of Air Content

Table 4-23: Chloride Permeability Test Results

Mixture No. *	Fly Ash** (%)	Average Charge Passed*** (Coulombs)		
		2-month	3-month	1-year
C-1 (S)	0	--	2,128	1,170
C-2(S)	0	--	1,729	1,085
C-3(P)	0	2,792	2,488	1,340
P4-1(S)	18	2,782	1,907	985
P4-6(P)	18	2,084	1,873	590
P4-2(P)	36	2,077	1,576	605
P4-3(P)	45	2,026	1,638	650
P4-4(S)	55	2,041	1,620	650
P4-7(P)	55	2,200	2,075	430
P4-5(S)	74	2,561	2,750	405
P4-8(P)	74	6,370	2,482	230

Charge Passed (Coulombs) [b]	Chloride Permeability [b]
>4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very low
<100	Negligible

* P = Primary; S= Secondary

** As a percentage of total cementitious materials, FA/(Cement + FA).

*** Test data are average of five test observations. [b] Based on ASTM C1202

The chloride ion permeability showed no major variation with change in air content. It can be concluded from this work that:

1. The optimum ASTM C618, Class C fly ash from We Energies PPPP content is in the range of 35% to 55% with respect to compressive strength, air permeability, water permeability and chloride permeability.
2. Air-entrained high strength concretes can be produced with up to a 35% fly ash to total cementitious material ratio with good resistance to air, water and chloride ion permeability.
3. Concrete mixtures with up to 55% fly ash to total cementitious material ratio showed "good" resistance to air permeability.

4. Concrete mixtures with 35% to 55% fly ash to total cementitious material ratio exhibited excellent resistance to water permeability at 91 day age.
5. The resistance to chloride ion permeability increased as the concrete aged. At the age of one year, all the fly ash mixtures showed very low chloride ion permeability.
6. Air content had little effect on air, water and chloride ion permeability of concrete, within the test limits.

Figure 4–18: Sussex Corporate Center boulevard entrance paved with high-volume fly ash concrete

High-Volume Fly Ash Concrete - Pilot Projects

Several pilot projects were completed as part of the research work to demonstrate and better understand the actual performance of We Energies coal combustion products. All the pilot projects were very successful, and have been in service for several years. The following are examples of such projects.

Sussex Corporate Center Pilot

Pavements at the Sussex Corporate Center, village of Sussex, Wisconsin, were constructed using high-volume fly ash concrete in 1995. Concrete pavements do not require major maintenance for 30 to 50 years, while asphalt pavements typically last only 10-15 years, after which they are generally milled and surfaced or replaced.

Tax Incremental Financing (TIF) was used as a means of encouraging investment on this project. If asphalt pavement is constructed using TIF and it needs replacement in 10 or 15 years, that work will not be funded by most TIF districts. Since the decision to construct concrete pavement using TIF funds was made, there was no reason to worry about finding alternate financing for future pavement maintenance (29).

The Sussex Corporate Center is a 221-acre business park development for small light-industrial business offices and includes approximately 20 commercial parcels. High-volume fly ash concrete was used for paving approximately 4,220 linear feet of dual 28-foot lane divided concrete boulevard and 4210 linear feet of 36-foot wide concrete pavements placed for the corporate center roadways. 9-inch thick concrete pavements were placed over a 6-inch crushed limestone base course.

Concrete Pavement Mixture

The concrete mixture was designed for a minimum of 4,000 psi compressive strength at 28 days. ASTM C618, Class C fly ash from Pleasant Prairie Power Plant was used on the project. Table 4-24 gives the mixture design for the concrete pavement.

Table 4-24: Sussex Corporate Center Concrete Mixture Proportions

Material Description	Quantity Per Cubic Yard
Cement Type 1	360 lbs.
Class C Fly Ash	214 lbs.
Sand	1,410 lbs.
Stone (#1 and #2)	1,800 lbs.
Water (total)	± 21 gal.
Air Entrainment	20 oz.
Water Reducer	As needed for workability

The fly ash used met the standards of ASTM C618 and the cement met ASTM C150 Type 1 standards. Table 4-25 is a comparison between the Wisconsin Department of Transportation pavement specification and this paving mixture containing 40% fly ash.

Table 4-25: Cement vs. Cement Plus Fly Ash Cost Comparison

Description	Cement/Cy (lbs)	Cement cost/Cy @ $85/ton	Fly Ash/Cy (lbs)	Fly Ash Cost/Cy at $26/ton	Cost of Cementitious Material	Savings/Cy with 40% HVFA Concrete
WI State Spec Pavement	480	$20.40	110	$1.43	$21.83	$3.41
40% HVFA Spec Pavement	360	$15.30	240	$3.12	$18.82	

Figure 4-19 : Aerial view of the village of Sussex Corporate Center that was paved with high-volume fly ash concrete.

The Sussex Corporate Center saved $34,000 on this project, which was approximately 5.5% of the pavement cost by using high-volume fly ash concrete. Since the success of this initial project, the village of Sussex has paved additional roads and sidewalks with this same mixture.

Figure 4-20 : Maple Avenue roadway and sidewalk located in the village of Sussex and paved with high-volume fly ash concrete.

Pavement Construction with High-Volume We Energies Class C and Class F Fly Ash Concrete

An existing crushed stone road providing access to an ash landfill was paved using fly ash concrete. Five different concrete mixtures, 20% and 50% ASTM C618, Class C fly ash, and 40, 50, and 60% off-spec ASTM C618, Class F fly ash were used to pave a 6,600 foot (2,012 m) long roadway carrying heavy truck traffic. A 20-foot wide, 8-inch thick concrete pavement with 1/4-inch-per-foot slope from the centerline to the edge of the roadway was placed over the existing crushed stone base. The pavement was designed to comply with the State of Wisconsin Standard Specification for Road and Bridge construction with the exception of using four experimental high-volume fly ash concrete mixtures. A concrete mix with a minimum 28-day compressive strength of 3,500 psi was specified. The air content of fresh concrete was specified to be 5 to 7% by volume (30). The road was opened to traffic within 10 days of paving completion. It has been providing good service after several Wisconsin winters.

Figure 4-21: Another view of Maple Avenue located in the village of Sussex paved with high-volume fly ash concrete.

Figure 4-22: Finishing touch to We Energies' high-volume fly ash concrete demonstration project at Pleasant Prairie Power Plant..

Figure 4-23: High-volume fly ash demonstration road paving at Pleasant Prairie Power Plant. Note the difference between the darker slate colored class F fly ash concrete and lighter tan colored high-volume class C fly ash concrete.

The following observations were made by the contractor during the construction.

- Air entrainment and slump were more difficult to control for the off-spec ASTM C618 Class F fly ash concrete than ASTM C618 Class C fly ash concrete.
- ASTM C618 Class F fly ash concrete was more "sticky" and took a longer time to reach strength at which saw cuts could be made.
- Twenty percent and 50% Class C fly ash concrete showed two shades of tan, earth-tone colors, and 40% Class F concrete had a medium gray slate-tone color when wet.

Off-spec ASTM C618 Class F fly ash obtained from Oak Creek Power Plant and ASTM C618 Class C fly ash obtained from Pleasant Prairie Power Plant were used on this project. ASTM C150, Type I Portland cement was also used. The mixture proportions are shown on Tables 4-26 to 4-27.

Concrete specimens were also made for the following tests:

1. Compressive strength
2. Splitting tensile strength
3. Flexural strength
4. Freezing and thawing resistance
5. Drying shrinkage
6. Deicing salt scaling resistance
7. Chloride ion permeability
8. Abrasion resistance

Table 4-26: Concrete Mixture and Site Test Data for 3500 psi Specified Design Strength Concrete at 28-Day Age

Mixture No.	S1-1	S1-2	S1-3	S2-1	S2-2	S2-3	S3-1	S3-2	S3-3	S3-4
Cement, lbs. *	364	365	364	296	294	296	479	480	479	477
Fly ash, lbs. *	244	245	243	296	296	296	113	110	109	110
Water, lbs. *	164	165	165	155	161	152	172	180	148	183
Sand, lbs. *	1,544	1,538	1,544	1,158	1,294	1,298	1,370	1,366	1,376	1,366
Coarse aggregates, lbs. *	1,848	1,842	1,840	1,710	1,888	1,898	1,932	1,926	1,932	1,930
Slump, inches	4	1-3/4	1-3/4	2-3/4	2-3/4	3	2	1-1/4	1-3/4	3
Air Content, %	6.2	5.2	5.0	5.4	5.0	5.5	5.9	5.2	6.0	6.0
Air Temp, °F	90	98	98	96	76	78	76	76	76	75
Concrete Temp, °F	85	92	91	92	86	86	84	84	84	82
Concrete Density, pcf	144.2	141.9	146.2	145.6	147.0	147.8	146.5	147.7	144.6	136.4

* Mixture proportions data provided by the ready mixed concrete supplier.

Mixture S1: 40% Class F Fly Ash (120 liq. oz superplasticizer and 15 liq. oz air entraining agent)

Mixture S2: 50% Class C Fly Ash (12 liq. oz air entraining agent)

Mixture S3: 20% Class C Fly Ash (7 liq. oz air entraining agent)

Table 4-27: Concrete Mixture and Site Test Data for 3500 psi Specified Design Strength Concrete at 28-Day Age

Mixture No.	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P2-1	P2-2	P2-3
Cement, lbs.*	367	366	367	366	368	367	295	267	293
Fly ash, lbs. *	245	243	244	244	244	245	293	263	296
Water, lbs. *	165	167	162	164	166	164	177	158	158
Sand, lbs. *	1,546	1,546	1,544	1,552	1,548	1,546	1,299	1,169	1,300
Coarse aggregates, lbs. *	1,842	1,846	1,838	1,844	1,844	1,852	1,898	1,712	1,896
Slump, inches	9	5¼	3¼	1½	1¾	2	3	3	3½
Air Content, %	8.5	6.5	6.2	5.6	5.9	5.9	6.0	6.0	6.2
Air Temp, °F	84	92	96	100	102	103	98	96	73
Concrete Temp, °F	83	84	86	85	86	86	86	88	84
Concrete Density, pcf	141.5	141.0	143.4	141.5	142.4	142.8	143.4	134.5	135.5

* Mixture proportions data provided by the ready mixed concrete supplier

Mixture P1: 40% Class F Fly Ash (120 liq. oz superplasticizer and 15 liq. oz. air entraining agent)

Mixture P2: 50% Class C Fly Ash (12 liq. oz. air entraining agent)

Tables 4-28 to 4-40 show the results of the above tests. It can be concluded from this paving project that:

1. Paving grade air-entrained concrete can be produced with 40% of Portland cement replaced with off-spec ASTM C618, Class F fly ash plus a superplasticizer, when the water-to-cementitious materials ratio is maintained around or below 0.36.
2. The 50% ASTM C618, Class C fly ash concrete mixture is suitable for pavement construction.
3. All concrete mixtures gained strength with age. Cores taken from the pavement showed higher compressive strengths than lab-cured concrete cylinders.
4. High-volume fly ash concrete mixtures showed higher freezing and thawing resistance than the WDOT reference mix with 20% ASTM C618, Class C fly ash.
5. High-volume fly ash concrete exhibited lower drying shrinkage when compared to the reference mixture.

6. The high-volume Class C fly ash mixture (50% replacement) showed lower resistance to de-icing salt scaling when compared to the other two mixtures in the laboratory. This has not been observed in the field.
7. All mixtures showed good resistance to chloride ion penetration. High-volume off-spec ASTM C618 Class F fly ash concrete performed better than the other two mixtures, for resistance to chloride ion penetration.
8. The 20% ASTM C618 Class C fly ash mixture showed better resistance to abrasion than the other two mixes.

Table 4-28: Average Compressive Strength Test Results from the Construction Site - Prepared Concrete Cylinders for Specified Design Strength 3500 psi at 28-Day Age

Test Age, Days	Mixture Numbers									
	S1-1	S1-2	S1-3	S2-1	S2-2	S2-3	S3-1	S3-2	S3-3	S3-4
1	1,230	--	--	--	--	1,020	--	1,720	--	--
3	1,770	2,580	1,700	1,920	1,750	1,900	2,690	2,650	2,870	--
7	2,450	--	--	--	--	2,900	--	3,620	--	3,560
28	3,430	5,160	4,460	4,260	4,390	3,900	4,020	4,450	4,860	4,530
56	4,530	5,850	5,260	4,960	5,140	5,270	5,860	6,060	5,890	--
91	4,720	--	--	--	--	5,300	--	6,170	--	--
182	5,310	--	--	--	--	6,020	--	6,320	--	--
365	5,430	7,420	4,810	5,810	5,680	6,400	6,909	6,690	7,060	--

Mix S1: 40% Class F Fly Ash
Mix S2: 50% Class C Fly Ash
Mix S3: 20% Class C Fly Ash

Table 4-29: Average Compressive Strength Test Results From Ready Mix Plant Cylinders for Specified Design Strength 3500 psi at 28-Day Age

Test Age, Days	Mixture Numbers								
	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P2-1	P2-2	P2-3
7	2,550	3,010	3,040	2,790	2,490	3,120	2,250	2,180	2,570
28	3,740	4,640	4,510	2,980	3,720	4,380	3,680	3,640	3,200

Mix P1: 40% Class F Fly Ash
Mix P2: 50% Class C Fly Ash

Table 4-30: Core Strength Test Data ASTM C-42 (Compressive Strength)

Core Number	Average Length (in)			Average Diameter, D	Cross Sectional Area (in^2)	L/D * Ratio	Max. Loads (lbs.)	1- Year Compressive Strength (psi)	
	As Received	After Cutting	After Capping, L					Actual	Average
200 A	8.10	7.38	7.54	3.77	11.16	2.00	71,000	6360	6900
200 B	8.00	7.26	7.47	3.77	11.16	1.98	70,000	6270	
200 C	7.44	7.38	7.51	3.77	11.16	2.00	90,000	8070	
1500 A	7.85	7.25	7.50	3.77	11.16	1.99	76,000	6810	6660
1500 B	8.10	7.30	7.51	3.77	11.16	1.99	75,000	6720	
1500 C	8.69	7.32	7.53	3.77	11.16	2.00	72,000	6450	
3500 A	7.69	7.27	7.49	3.77	11.16	1.99	72,000	6450	6560
3500 B	7.56	7.20	7.44	3.77	11.16	1.97	75,500	6770	
3500 C	7.66	7.13	7.33	3.77	11.16	1.94	72,000	6450	

Core Number	Type of Fracture	Defects in Specimen or Cap	Nominal Age (yr)	Core Moisture Condition as Tested	Nominal Size of Aggregates
200 A	Cone	None	1	Wet	1”
200 B	Cone & Shear	None	1	Wet	1”
200 C	Cone	None	1	Wet	1”
1500 A	Cone	None	1	Wet	1”
1500 B	Cone	None	1	Wet	1”
1500 C	Cone	None	1	Wet	1”
3500 A	Cone & Split	None	1	Wet	1”
3500 B	Cone & Split	None	1	Wet	1”
3500 C	Cone	None	1	Wet	1”

*All cores drilled and tested along direction of placement
200 A, B, C Mix S3: 20% Class C Fly Ash
1500 A, B, C Mix S2: 50% Class C Fly Ash
3500 A, B, C Mix S1: 40% Class F Fly Ash.

Table 4-31: Average Tensile Strength Test Results (psi)

Test Age, Days	Mix Numbers								
	S1-1	S1-2	S1-3	S2-1	S2-2	S2-3	S3-1	S3-2	S3-3
3	230	250	235	250	230	255	300	340	340
7	280	320	260	330	325	360	340	400	410
28	400	400	340	420	370	400	430	440	490
56	510	520	440	530	400	440	440	530	540

Mix S1: 40% Class F Fly Ash
Mix S2: 50% Class C Fly Ash
Mix S3: 20% Class C Fly Ash

Table 4-32: Average Flexural Strength Test Results (psi)

Test Age, Days	S1-1	S2-3	S3-2
3	340	310	490
7	420	370	520
28	580	600	670
56	640	700	700
182	870	780	760

Mix S1: 40% Class F Fly Ash
Mix S2: 50% Class C Fly Ash
Mix S3: 20% Class C Fly Ash

Table 4-33: Summary of Test Results on Concrete Prisms after Repeated Cycles of Freezing and Thawing*

Specimen No	Source of Fly Ash	Percent Replacement	No. of Freeze-thaw Cycles Completed	Resonant Frequency	Weight	Pulse Velocity	Relative Dynamic Modulus of Elasticity, %	Durability Factor, %
2.20.1	P-4	20	300	-13.9	-0.58	-6.65	74.2	74
2.20.2			300	-9.1	-0.12	-5.63	82.7	83
2.20.3			300	-21.9	-0.63	-6.47	61.0	61
F-25	P-4	50	300	-3.4	-0.14	-1.89	93.3	93
F-26			300	-7.2	+0.17	-2.46	86.1	86
F-27			300	-4.4	+0.24	-2.31	91.4	91
F-1	OCPP	40	300	-0.3	-0.42	-1.38	99.3	99
F-2			300	-2.8	-0.44	-3.86	94.4	94
F-3			300	-2.7	-0.41	-2.64	94.6	95

* Freezing and thawing cycles were carried out in accordance to ASTM C666, Procedure A. The number of cycles completed at the termination of the test was 300.

Table 4-34: Changes in Fundamental Longitudinal Resonant Frequency of Test Prisms During Freeze-Thaw Cycling per ASTM C666 Procedure A

Source of Fly Ash	Percent Replacement	Size of Specimen, (in.)	Fundamental Longitudinal Resonant Frequency N, cps						
			Reference Moist-Cured Prisms			Freeze-Thaw Test Prisms			
			Initial	At end of Freeze-Thaw Cycle Time	Percent Change	N *	N **	N ***	Percent Change
P-4	20	3x4x12-1/4	6504 6546 5679	6764 6820 6838	4.0 4.2 3.9	6526 6547 6492	6180 [150] 6103 [150] 6140 [150]	5620 [300] 5954 [300] 5070 [300]	-13.9 -9.1 -21.9
P-4	50	3x4x12-1/4	6431 6340 6400	6778 6645 6722	5.4 4.8 5.0	6412 6350 6379	6178 [150] 6030 [150] 6092 [150]	6194 [300] 5891 [300] 6101 [300]	-3.4 -7.2 -4.4
OCPP	40	3x3x11-1/4	7162 7150 7142	7493 7480 7443	4.6 4.6 4.2	6912 6975 6971	6673 [150] 6805 [150] 6770 [150]	6890 [300] 6780 [300] 6780 [300]	-0.3 -2.8 -2.7
			Weight W, Kg						
			Initial	At end of Freeze-Thaw Cycle Time	Percent Change	W *	W **	W ***	Percent Change
P-4	20	3x4x12-1/4	5.280 5.786 5.807	5.843 5.810 5.832	0.40 0.41 0.41	5.834 5.770 5.827	5.873 [150] 5.763 [150] 5.785 [150]	5.800 [300] 5.763 [300] 5.790 [300]	-0.58 -0.12 -0.63
P-4	50	3x4x12-1/4	5.733 5.647 5.677	5.762 5.675 5.706	0.51 0.50 0.51	5.789 5.763 5.738	5.797 [150] 5.784 [150] 5.759 [150]	5.781 [300] 5.773 [300] 5.752 [300]	-0.14 0.17 0.24
OCPP	40	3x3x11-1/4	3.842 3.826 3.780	3.853 3.837 3.793	0.29 0.29 0.34	3.843 3.850 3.874	3.846 [150] 3.856 [150] 3.878 [150]	3.827 [300] 3.833 [300] 3.858 [300]	-0.42 -0.44 -0.41

Table 4-35: Changes in Ultrasonic Pulse Velocity of Test Prisms During Freeze-Thaw Cycling Per ASTM C666 Procedure A

Specimen No.	Source of Fly Ash	Percent Replacement	Size of Specimen, (in.)	Ultrasonic Pulse Velocity V, m/s						
				Reference Moist-Cured Prisms			Freeze-Thaw Test Prisms			
				Initial	At end of Freeze-Thaw Cycles Time	Percent Change	V*	V**	V***	Percent Change
2.20.4	P-4	20	3x4x12¼	4876	4762	1.84				
2.20.5				4718	4784	1.40				
2.20.6				4769	4821	1.09				
F-28	P-4	50	3x4x12¼	4620	4718	2.12				
F-29				4592	4718	2.74				
F-30				4559	4676	2.57				
F17	OCPP	40	3x3x11¼	4726	4830	2.20				
F21				4582	4734	3.32				
F22				4627	4774	3.18				
2.20.1	P-4	20	3x4x12¼				4704	4473 [150]	4391 [300]	-6.65
2.20.2							4726	4539 [150]	4460 [300]	-5.63
2.20.3							4655	4480 [150]	4354 [300]	-6.47
F-25	P-4	50	3x4x12¼				4599	4473 [150]	4512 [300]	-1.89
F-26							4586	4403 [150]	4473 [300]	-2.46
F-27							4552	4391 [150]	4447 [300]	-2.31
F-1	OCPP	40	3x3x11¼				4481	4453 [150]	4419 [300]	-1.38
F-2							4582	4298 [150]	4405 [300]	-3.86
F-3							4510	4432 [150]]	4391 [300]	-2.64

* Average resonant frequency of prisms after moist curing at the commencement of the freeze-thaw cycling.

** Number in brackets represents the number of freeze-thaw cycles completed at the time of testing.

*** Termination of freeze-thaw test.

Table 4-36: Flexural Strength of Reference Moist Cured and Freeze-Thaw Test Specimens

Source of Fly Ash	Percent Replacement	Size of Specimen, in.	Flexural Strength			
			Reference Moist Cured Prisms		Freeze Thaw Test Prisms	
			psi	MPa	psi	MPa
P-4	20	3×4×12¼	1149 1180 1280	7.8 8.1 8.8	550 100 60	3.8 0.7 0.4
P-4	50	3×4×12¼	1010 930 930	6.9 6.4 6.4	390 450 480	2.7 3.1 3.3
OCPP	40	3×3×11¼	1330 1080 1080	9.1 7.4 7.4	680 710 830	4.7 4.9 5.7

Table 4-37: Shrinkage-Expansion and Moisture Change up to 112 Days for Drying Shrinkage Prisms and Prisms Stored in Water

Curing Conditions	Source of Fly Ash	Percent Replacement	Shrinkage/Expansion Strain, 10^{-6} (After 91-day age)					Weight Change, % of Initial Weight
			7d	**14d**	**28d**	**56d**	**112d**	**112d**
Air-dried at 23°C 50% RH after 91 days in water	P-4 P-4 OCPP	20 50 40	98 107 53	187 213 116	356 338 196	462 444 284	524 516 356	2.76 3.02 2.38
Continuous Water Storage	P-4 P-4 OCPP	20 50 40	+18 9 +17	9 27 +27	9 53 +17	+18 36 +36	+27 +9 +44	+0.17 +0.28 +0.08

Notes:

Prior to air-drying, the specimens were stored in lime-saturated water for 91 days.

Strains were measured on 3x4x11¼ in. specimens.

Positive values indicate expansion.

Testing is to continue up to 448 days, after the 91-day age.

Table 4-38: Results of De-Icing Salt Scaling Tests on High-Volume Fly Ash Concrete Specimens

No. of Cycles	Test Specimens											
	PPPP, 20% Replacement		PPPP, 20% Replacement		PPPP, 50% Replacement		PPPP, 50% Replacement		OCPP, 40% Replacement		OCPP, 40% Replacement	
	Visual Rating	Scaled Residue lb/ft2	Visual Rating	Scaled Residue lb/ft2	Visual Rating	Scaled Residue lb/ft2	Visual Rating	Scaled Residue lb/ft2	Visual Rating	Scaled Residue lb/ft2	Visual Rating	Scaled Residue lb/ft²
11	0+		O+	0.015	2+	0.035	2	0.030	1-	0.017	1	0.030
22	0+	0.039	0+	0.030	3	0.158	3	0.170	2-	0.053	1	0.053
32	1	0.051	1-	0.045	4-	0.234	3+	0.265	2+	0.071	2	0.062
42	1+	0.076	1-	0.081	4	0.342	4-	0.374	2+	0.099	2	0.090
50	2	0.104	1-	0.107	*	*	4-	1.474	2+	0.135	2+	0.116

Notes:

Specimens were subjected to the de-icing salt scaling tests after 3 weeks of moist curing followed by 3 weeks of air cure in the laboratory atmosphere.

A 3% by weight NaCl solution was used as the de-icing salt solution.

Visual ratings shown were made according to the Standard ASTM C-672.

* The specimens failed by the fracture of the dike on the scaling surface.

Visual Rating Per ASTM C-672.

0 = no scaling

1 = very slight scaling (⅛ in. depth), max. no coarse aggregate visible)

2 = slight to moderate scaling

3 = moderate scaling (some coarse aggregate visible)

4 = moderate to severe scaling

5 = severe scaling (coarse aggregate visible over entire surface)

Table 4-39: Results for Chloride Ion Permeability from Cores

Core Designation	Test Slice Location	Maximum Current During Test (Amperes)	Actual Total Charge Passed (Coulombs)	Average Total Charge Passed (Coulombs)	Overall Average Total Charge Passed (Coulombs)	AASHTO Chloride Permeability Equivalent **
600-A	Top Middle Bottom	0.054 0.044 0.041	1132 943 840			
600-B	Top Middle Bottom	0.037 0.035 0.045	772 761 900	Top: 1056 Middle: 798 Bottom: 900	918	Very Low
600-C	Top Middle Bottom	0.064 0.033 0.045	1263 690 961			
1900-A	Top Middle Bottom	0.018 0.019 0.023	365 353 481			
1900-B	Top Middle Bottom	0.018 0.018 0.020	351 363 401	Top: 376 Middle: 372 Bottom: 424	391	Very Low
1900-C	Top Middle Bottom	0.022 0.020 0.020	412 400 391			
3100-A	Top Middle Bottom	0.010 0.009 0.011	181 202 212			
3100-B	Top Middle Bottom	0.010 0.009 0.010	200 180 210	Top: 181 Middle: 184 Bottom: 198	188	Very Low
3100-C	Top Middle Bottom	0.008 0.008 0.009	162 170 172			

Notes:

* Per AASHTO T-277
** > 4,000 = High
2,000 - 4,000 = Moderate
1,000 - 2,000 = Low
100 - 1,000 + Very Low
<100 = Negligible

Cores 600A, B, C are from mixture S3: 20% ASTM C618, Class C Fly Ash Concrete
Cores 1900 A, B, C are from mixture S2: 50% ASTM C618, Class C Fly Ash Concrete
Cores 3100 A, B, C are from mixture S1: 40% ASTM C618 Class F Fly Ash Concrete

Table 4-40: Abrasion Resistance of High-Volume Fly Ash Concrete Specimens

Time of Abrasion, Sec.	Depth of Wear, mm		
	PPPP, 20%	PPPP, 50%	OCPP, 40%
50	0.559	0.581	0.853
100	0.798	0.961	1.318
150	0.961	1.085	1.482
200	1.055	1.237	1.640
250	1.167	1.192	1.680
300	1.273	1.245	1.891
350	1.293	1.318	2.100
400	1.395	1.379	2.211
450	1.452	1.592	2.532
500	1.493	1.680	2.816
550	1.534	1.809	2.950
600	1.562	1.699	3.318
650	1.681	1.850	
700	1.711	1.772	
750	1.753	1.810	
800	1.769	1.879	
850	1.788	1.876	
900	1.811	2.022	
950	1.838	2.296	
1000	1.911	2.416	
1050	1.924	2.403	
1100	1.923	2.624	
1150	1.968	2.535	
1200	2.001	2.527	

Notes:

The specimens used were 12 x 12 x 4 in. slabs.

The specimens were subjected to abrasion testing following eight months of moist curing.

The abrasion testing was done according to ASTM C779, Procedure C.

Long Term Performance of High Volume Fly Ash Concrete Pavement

To evaluate the long-term strength properties and durability of HVFA concrete systems, a study was conducted by the University of Wisconsin – Milwaukee, Center for By-Products Utilization (31). All concrete mixtures developed in this investigation were used in construction of various pavement sections from 1984 to 1991. Core specimens and beams were extracted from in-place pavements for measurement of compressive strength (ASTM C 39), resistance to chloride-ion penetration (ASTM C 1202), and hardened concrete density (ASTM C 642).

Density of Concrete Mixtures

The fresh density values of the concrete mixtures varied within a narrow range for all mixtures. The fresh concrete values were a similar order of magnitude as that of hardened concrete density values for the mixtures. Thus, both the fresh and hardened density values were not significantly influenced by the variations in fly ash content, type, or age within the tested range.

Compressive Strength

The compressive strength of the concrete mixtures increased with age. The rate of increase depended upon the level of cement replacement, type of fly ash, and age. In general concrete strength decreased with increasing fly ash concentration at the very early ages for both types of fly ash. Generally the early-age strength of Class F fly ash concrete mixtures were lower compared to Class C fly ash concrete mixtures. However, the long-term strength gain by the high volume Class F fly ash concrete system was better than comparable Class C fly ash concrete, as shown in Figure 4-24. This is probably due to the fact that Class F fly ash made a greater contribution of pozzolanic C-S-H compared to Class C fly ash. This in turn resulted in a greater improvement in the microstructure of the concrete made with Class F fly ash compared to Class C fly ash, especially in the transition zone. Therefore, the use of Class F fly ash is the most desirable from the long-term perspective for the manufacture of high-performance concrete (HPC) because HPCs are required to possess both long-term high-strength properties and durability. However, Class C fly ash also continued to gain strength over time and is also expected to perform well.

Resistance to Chloride-Ion Penetration

All concrete mixtures tested in this investigation showed excellent resistance to chloride-ion penetration. The general performance trend with respect to resistance to chloride-ion penetration followed a similar trend as indicated by the compressive strength. The highest resistance to chloride-ion penetration for the mixtures containing high volumes of Class F fly ash was due to the same reasons as described for the compressive strength data (i.e., improved microstructure of concrete).

Summary

Based on the data recorded in this investigation, the following general conclusions may be drawn:

(1) Concrete density was not greatly influenced by either the type or the amount of fly ash or the age within the tested range.

(2) The rate of early-age strength gain of the Class C fly ash concrete mixtures was higher compared to the Class F fly ash concrete mixtures. This was primarily attributed to greater reactivity of Class C fly ash compared to Class F fly ash.

(3) Long-term pozzolanic strength contribution of Class F fly ash was greater compared to Class C fly ash. Consequently, long-term compressive strengths of Class F fly ash concrete mixtures were higher than that for Class C fly ash concrete mixtures.

(4) Concrete containing Class F fly ash exhibited higher long-term resistance to chloride-ion penetration compared to Class C fly ash concrete. The best long-term performance was recorded for both the 50% and 60% Class F fly ash concrete mixtures as they were found to be relatively impermeable to chloride-ions in accordance with ASTM C 1202. All fly ash concrete mixtures irrespective of the type and amount of fly ash, showed excellent performance with respect to chloride-ion penetration resistance.

(5) Based on the results obtained in this investigation, it is desirable to use significant amounts of Class F fly ash in the manufacture of low-cost HPC concrete systems for improved long-term performance However, Class C fly ash also continue to gain significant strength over time as well.

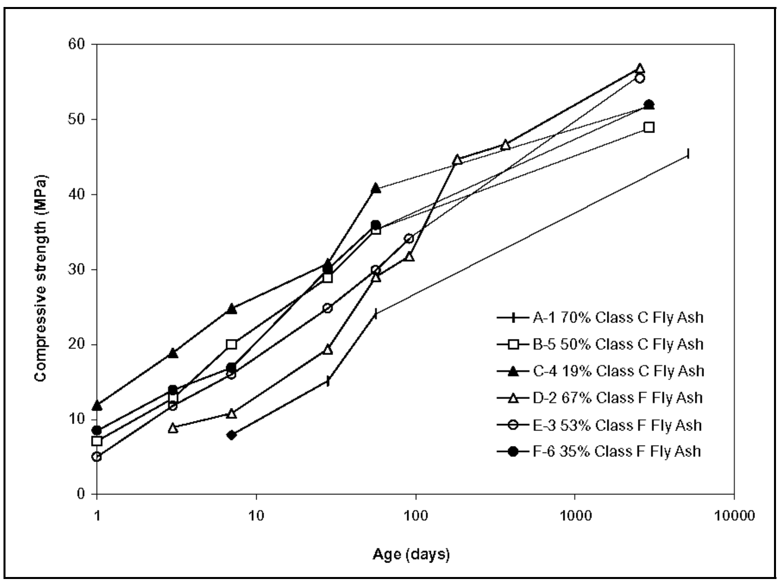


Figure 4–24: Compressive Strength vs. Age

Roller Compacted No-Fines Concrete Containing We Energies Fly Ash for Road Base Course

Many problems associated with pavement failure are due to the pressure of water under rigid surface pavements. When high pressure from heavy traffic is applied on pavements in the presence of water, pumping occurs. Pumping causes erosion of the pavement base, as fines along with water are pumped out. The continued effect of pumping is a loss of support, leading to pavement failure. An open-graded permeable base is used to avoid such problems. The open-graded permeable base pavement system consists of a permeable base, separator layer and edge drainage. Permeable bases can be treated or untreated with cementitious binders.

A demonstration project was designed to use an off-spec ASTM C618, Class F fly ash in the open-graded concrete base course and an ASTM C618 Class C fly ash in the concrete pavement for an internal road at the Port Washington Power Plant located in Port Washington, Wisconsin.

The roadway cross section (see Figures 4-25 and 4-26) consisted of an initial layer of filter fabric installed to prevent fines from the subgrade moving up and blocking drainage in the base course, topped by a 6” thick layer of open-graded concrete base course and a 10 in. thick, high-volume fly ash concrete pavement. This pavement was designed in compliance with Wisconsin DOT standards, with the exception of using high-volume fly ash in the open-graded base, and concrete pavement. Underdrains, manholes and storm sewer piping were also installed as part of this project, to ensure proper functioning of the pavement system (32).

The properties of fly ash and cement used in this project are shown on Table 4-41. The ASTM C618, Class F fly ash used on the project is off-specification with a very high LOI.

The mixture proportions for the open-graded base course were composed of 160 lb./cu. yd. cement, 125 lb./cu. yd. fly ash, 81 lb./cu. yd. water, 2600 lb./cu. yd. ¾ in. coarse aggregate and no fine aggregate.

The mixture proportions for high-volume fly ash concrete pavement included 300 lb./cu. yd. cement, 300 lb./cu. yd. Class C fly ash, 221 lb./cu. yd. water, 1200 lb./cu. yd. sand, 966 lb./cu. yd. ¾” aggregate and 966 lb./cu. yd. 1½” coarse aggregate. The water to cementitious materials ratio was maintained at about 0.37.

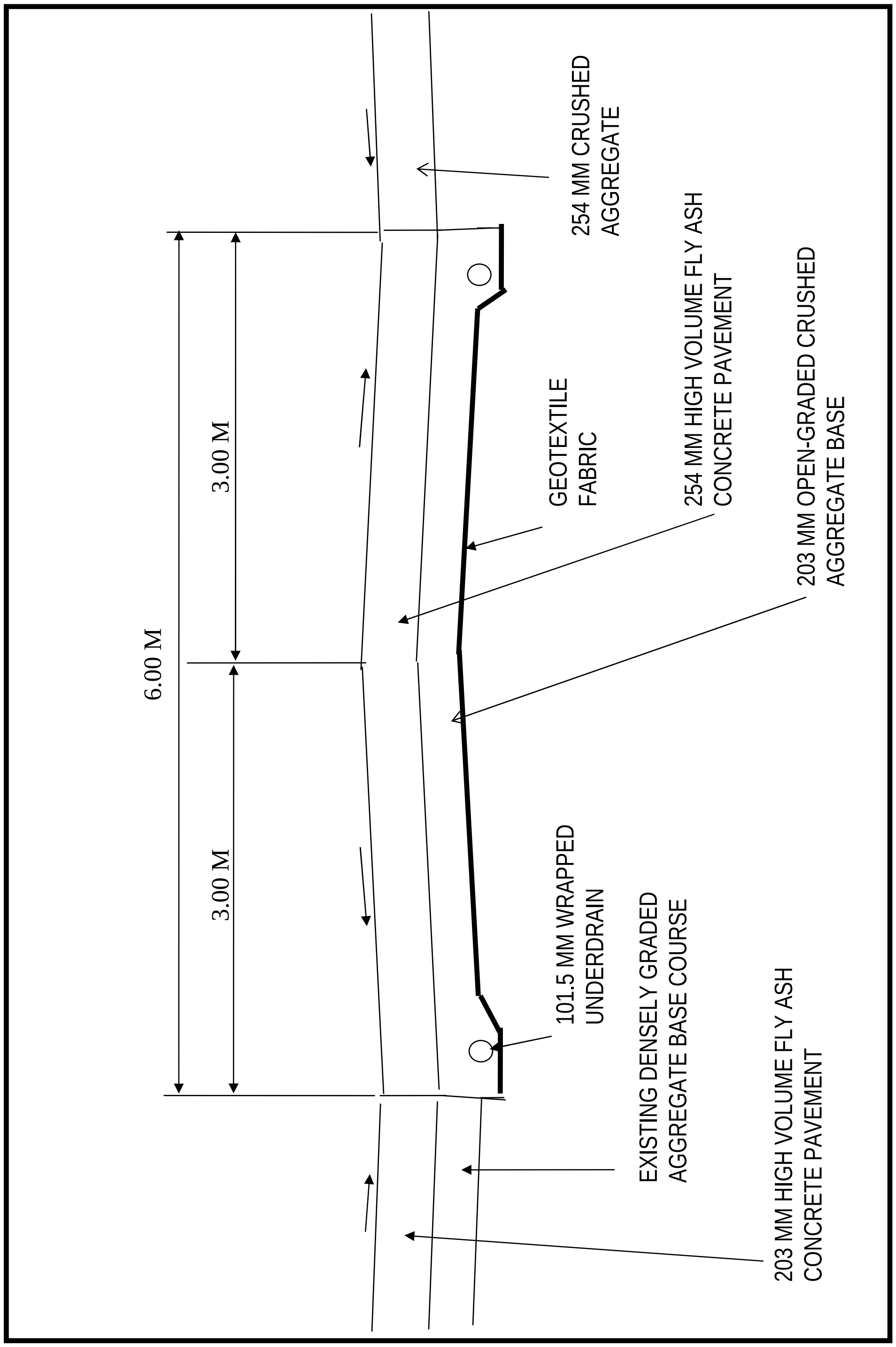


Figure 4-25: Pavement Cross Section

Notes:

1. Pavement slope varies to maintain drainage. Typical slope 20.8 mm per meter.
2. Expansion joints with dowel bars provided at intersection with existing pavement
3. Transverse joints at approximately 6 meter intervals
4. Transverse joints were saw cut to a minimum depth of 762 mm.

Table 4-41: Properties of Cement and Fly Ashes Used

Chemical Composition (%)	Cement Type I	ASTM C150 Type I	Class F Fly Ash	Class C Fly Ash	ASTM C618 Class F	ASTM C618 Class C
Silicon dioxide, SiO_2	20.0	--	36.5	35.4	--	--
Aluminum oxide, Al_2O_3	4.3	--	16.0	23.3	--	--
Ferric oxide, Fe_2O_3	2.5	--	7.0	5.6	--	--
Total, $SiO_2 + Al_2O_3 + Fe_2O_3$	26.8	--	61.5	64.3	70.0 min	50.0 min
Sulfur trioxide, SO_3	2.3	3.0 max	1.5	2.4	5.0 max	5.0 max
Calcium oxide, CaO	64.0	--	2.1	26.7	--	--
Magnesium oxide, MgO	2.0	6.0 max	--	--	5.0 max	5.0 max
Available alkali, Na_2O	0.3	--	0.7	0.9	1.5 max	1.5 max
Moisture content	--	--	1.2	0.13	3.0 max	3.0 max
Loss on ignition	2.0	3.0 max	31.3	0.6	6.0 max	6.0 max
Physical Properties of Cement						
Air content (%)	9.5	12 max			--	
Fineness (m^2/kg)	351	280 min			--	
Autoclave expansion (%)	-0.02	0.8 max			--	
Specific gravity	3.16				--	
Compressive strength (psi) 1-day 3-day 7-day 28-day	1990 3500 4230 5420	-- 1740 min 2760 min --			-- -- -- --	-- -- -- --
Vicat time of initial set (min)	145	45 min 375 max			--	--
Physical Properties of Fly Ashes						
Fineness retained on No. 325 sieve (%)	--	--	25.5	19.4	34 max	34 max
Pozzolanic activity index with cement (% of control) 7-day 28-day	 -- --	 -- --	 64 73	 92.4 99.4	 75 min 75 min	 75 min 75 min
Water requirement (% of control)	--	--	112	93.0	105 max	105 max
Autoclave expansion (%)	--	--	-0.02	-0.02	0.8 max	0.8 max
Specific gravity	--	--	2.02	2.60	--	--

Field testing was performed during the placement of base course and the concrete pavement. Slump measurements were taken on both the base course mixture and concrete mixture. Also, air content (ASTM C231) and temperature (ASTM C1064) measurements were recorded for the concrete mixture.

Compressive strength was also measured on cylinders made from selected batches of base course and paving slab concrete mixtures, in accordance with ASTM procedures.

Results and Discussion

Figure 4-26: Open-graded cementitious base course material being placed over filter fabric at Port Washington Power Plant's high-volume fly ash demonstration project.

- Base Course Material: The compressive strength data is shown in Table 4-42. The permeable base was designed to have a compressive strength in the range of 490 to 990 psi. However, the mixture gave 670 psi at 28-day age and 810 psi at 56-day age.
- Fly Ash Concrete Pavement: Since there already was significant data on high-volume fly ash concrete, only compressive strength of the pavement concrete mixtures was measured. Based on earlier work, it was assumed that a mixture meeting air content and strength requirements would satisfy other durability requirements.

Table 4-43 gives the compressive strength results for the pavement concrete mixtures. The mixture showed a compressive strength of 4870 psi at the 28-day age, which was 20% higher than the design strength of 4000 psi. The pavement was inspected visually to determine its performance over the past several years. No obvious pavement distress was seen during the inspection.

Table 4-42: Open-Graded Base Course Test Results

Test	No. of Tests	Average
Slump	91	7 in.
Compressive Strength (psi)		
3-day	59	290
7 day	59	421
28-day	59	667
56-day	59	812

Table 4-43: High-Volume Fly Ash Concrete Test Results
Specified Strength: 4000 psi at 28-Day Age

Test	No. of Tests	Average
Slump (in.)	174	1/8
Air Content (%)	170	6.0
Concrete Temperature (°F)	174	57
Compressive Strength (psi)		
3-day	62	2170
7-day	62	3320
28-day	62	4870
56-day	62	5550

Bricks, Blocks, and Paving Stones Produced with We Energies Fly Ash

Combustion product applications have shown a substantial increase in the past decade. However, only a limited amount of fly ash and bottom ash are actually used in the production of masonry units, such as bricks, blocks, and paving stones. Since only limited research was done on room-cured and steam-cured ash bricks and blocks, We Energies funded research on a project to investigate the properties of bricks and blocks containing We Energies fly ash at the Center for By-Products Utilization of the University of Wisconsin-Milwaukee.

Testing Program

The testing program consisted of the following stages:

1. Developing mixture proportions for room temperature cured bricks and blocks utilizing ASTM C618 Class C fly ash.
2. Extended testing using different types of (ASTM Class C and Class F) fly ash from different sources, and using bottom ash as a replacement for natural aggregates.
3. Studying the effect of different curing systems.
4. Producing small size blocks using selected mix recipes and testing their properties.

Stage 1 Testing

Fly ash from power plants other than We Energies was also used in this work. However, the data presented here is only information relevant to We Energies products. In the first stage testing, only ASTM C618, Class C fly ash from Dairyland Power Corporation was used. The intent of this work was to develop a suitable and economic brick and block mixture utilizing coal ash.

From the Stage 1 studies, it was concluded that:

1. The dry-cast vibration method is better for obtaining higher compressive strength masonry units.
2. Sufficient strength develops (greater than 2000 psi) when the specimens are cured in a fog room for 28 days. No firing or steam curing is required for this.
3. Most masonry products require only a compressive strength of 2000 psi to 3000 psi. Hence, it is appropriate to raise the aggregate to cementitious ratio and introduce the bottom ash as partial replacement of aggregates in the mixtures.

Stage 2 Testing

Two types of fly ash from We Energies were used in this testing, ASTM C618 Class C (F-2) and an off-spec ASTM C618 Class F (F-4) fly ash. The chemical properties of fly ash used in this project are given in Table 4-44.

Table 4-44: Chemical Properties of We Energies Fly Ash

Compositions Material	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	K_2O	Na_2O	TiO_2	LOI
F-2	32.91	19.36	28.85	4.83	5.38	0.34	1.95	1.58	0.64
F-4	48.21	26.26	2.66	1.14	10.61	1.08	2.26	1.21	7.89

Specimens were made by making semi-dry and wet mixtures and casting them directly into the steel mold for vibrating on a vibration table (33). The molded specimens were cured for one day in the fog room, then removed from molds and placed back in the fog room until the time of test.

Nine 2 inch cubes were made for compressive strength and bulk density tests for each mixture. Three cubes were tested at each test age. Compressive strength tests were performed in accordance with ASTM C192 "Standard Practice for Making and Curing Specimens in the Laboratory". Bulk density tests were performed in accordance with the ASTM C642 "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete" procedures. Mixture proportions are shown in Table 4-45.

Table 4-45: Mix Proportions for Concrete Masonry Units

Mix. No.	Cement (%)	Fly Ash (%)	Aggregate/ Cementitious Material	ASTM C618 Fly Ash
17	0	100	4.5/1	Class C (F-2)
18	20	80	4.5/1	Class C (F-2)
19	40	60	4.5/1	Class C (F-2)
20	60	40	4.5/1	Class C (F-2)
25	20	80	4.5/1	Class F (F-4)*
26	40	60	4.5/1	Class F (F-4)*
27	60	40	4.5/1	Class F (F-4)*
28	80	20	4.5/1	Class F (F-4)*

* LOI = 7.89

The aggregate used throughout this work was ⅜" size natural pea gravel as coarse aggregate and natural sand as fine aggregate. The aggregate in the mixture consisted of 50% fine and 50% coarse aggregate.

Test Results

Table 4-46 shows the compressive strength and bulk density test results. The specimens made with ASTM C618 Class C fly ash gave higher compressive strengths than those with ASTM Class F fly ash for the same fly ash content.

ASTM C618, Class C fly ash generally has a slightly higher specific gravity than Class F fly ash. Hence, Class C fly ash mixtures show a slightly higher bulk density.

Table 4-46: Compressive Strength and Bulk Density

Mix No.	Compressive Strength (psi)			Bulk Density (lb./cu.ft.)
	3-day	7-day	28-day	
17	1650	2320	3340	156.4
18	220	260	2110	155.3
19	1420	2350	4540	152.3
20	2580	4250	6500	155.8
25	340	530	1320	150.1
26	1310	1760	3420	153.3
27	2740	3880	5790	152.8
28	3700	5150	6670	155.0

Stage 3 Testing

After reviewing the work done in Stages 1 and 2, and evaluating the commercial block manufacturing process, modifications were made to the mixture design. Commercial manufacturers use a higher aggregate-to-cement ratio in the mixture than used in the laboratory.

Six blocks measuring approximately 4 × 2.5 × 1.8125 inches with two rectangular 1.25 × 1.25 inch open cells were manufactured. The blocks have a gross area of 10 sq. inches and a net area of 6.25 sq. inches (62.5% of gross area). This size is a proportionately reduced size of block manufactured in the local area for testing purposes.

The mixture design is shown in Table 4-47. Dry material components were first blended with water and then the mixture was tamped into a block mold in three layers. Each layer was compacted by a vibrating pressed bar, then removed from the mold, and stored in the curing tank for steam curing or stored in a fog room.

The blocks were tested for compressive strength and bulk density, water absorption and dimensional stability. All tests were carried out in accordance with ASTM C-140. Table 4-48 shows the compressive strength and bulk density test results and water absorption test results.

Table 4-47: Mix Design for Blocks

Mix No.	Water (%)*	W / C+F	Cementitious (%) **		Aggregate (%) ***		Type of Fly Ash
			Cement	Fly Ash	Sand	Pea Gravel	
1	5.0	0.42	100	0	67	33	None
3	5.2	0.36	40	60	67	33	Class C (F-2)
5	6.3	0.44	40	60	67	33	Class F (F-4)

* Percentage of the total mixture weight

** Percentage of materials by weight of total cementitions (cement + fly ash)

*** Percentage of materials by weight total aggregates (sand + pea gravel)

Table 4-48: Compressive Strength, Bulk Density, and Water Absorption of Blocks

Mix No.	Compressive Strength (psi)		Bulk Density (lb./cu. ft.)		Water Absorption %	
	Individual	Average	Individual	Average	Individual	Average
1	470 480 530	490	154.3 156.0 153.9	154.7	8.0 8.7 7.6	8.1
3	484 448 454	460	151.3 145.9 147.9	148.4	8.0 7.7 8.9	8.2
5	365 408 394	390	152.1 145.1 148.1	148.4	8.3 9.7 9.0	9.0

Note: Tests were performed after 7 days curing (24-hour steam curing plus 6 days fog room curing).

The compressive strength values were somewhat lower than expected even for the no fly ash mixture. The reason is believed to be the size effect. Local block manufacturing companies have also documented such reduction in strength when small blocks are tested. However, mix no. 3 with Class C fly ash showed compressive strength comparable to the control mix.

The bulk density measurements showed that the blocks containing fly ash are slightly lighter. The lower bulk density translates to better insulating properties, improved resistance to freezing and thawing, lower heat losses, and lower dead load in structures.

The water absorption for all the mixes are within the limits of ASTM C-55. Dimensional stability tests did not show any change. These tests should also be performed on full-size blocks to verify the results.

Fly Ash Concrete for Precast/Prestressed Products

We Energies' fly ash was also used to produce precast/prestressed concrete products. We Energies initiated a study to develop mixture proportioning information for the production of high early strength concrete with high fly ash content for precast/prestressed concrete products (34).

Materials

The ASTM C-618 fly ash used in this project was produced by We Energies at the Pleasant Prairie Power Plant. A Type I cement was used and the replacement quantities with Class C fly ash were 0, 10, 15, 20, and 30%. Twelve different mixture proportions were developed based upon a nominal 5000 psi control mixture that contained no fly ash.

Concrete Mixing and Specimen Preparation

Concrete was produced at two different precast/prestressed concrete plants. Standard batching and mixing procedures for ready mixed concrete were followed, in accordance with ASTM C-94. Fresh concrete tests included slump and air content. Cylinders were cured following the actual practice of the individual precast/prestressing plant.

Compressive Strength

The test results indicated that the compressive strength of the concrete mixtures increased with the increase of replacement percentage of cement with Class C fly ash after 3 days (5060 psi) and 28 days (8435 psi) of curing. The maximum compressive strength was obtained for a 25% Class C fly ash replacement. Therefore, Class C fly ash usage increased the early strength of concrete. The strength results also indicated that cement replacement with up to 30% of Class C fly ash increased the early strength relative to the mixture without fly ash.

Workability

Workability was observed and noted throughout the project. All the concrete produced was homogeneous and cohesive. The fly ash replacement did not affect these properties. Slump measurements show variations because of the use of a superplasticizer. Even though the water to cementitious ratio decreased as the fly ash was increased, clearly acceptable workability was maintained.

There are several advantages of using Class C fly ash in the concrete precast/prestressed products:

1. Improved economics are possible as a result of reduced raw material costs resulting in the use of more competitive products over a wider geographical region.
2. Class C fly ash usage in concrete provides higher quality products which include higher density with reduced permeability, increased strength and other properties.
3. Fly ash concrete mixes are handled more easily because of improved workability. Faster release of prestressing tendons is also possible because of increased early age strength with use of Class C fly ash.

Conductive Concrete Containing We Energies High Carbon Fly Ash (US Patent 6,461,424 B1) (35)

Materials

Materials utilized in this project consisted of one source of fly ash, cement, clean concrete sand, crushed quartzite limestone aggregates, steel fibers, and taconite pellets. Materials were characterized for chemical and physical properties in accordance with the appropriate ASTM standards. Table 4-49 shows the mixture proportions.

Type I cement (Lafarge Cement Co.) was used throughout this investigation. Its physical and chemical properties were determined in accordance with applicable ASTM test methods.

One source of fly ash was used for this project (We Energies, Port Washington Power Plant, Units 2 and 3). The ash selected for this project was non-standard (not meeting all requirements of ASTM C 618). This selection was made to develop and encourage additional uses for under-utilized sources of fly ash in Wisconsin.

In one concrete mixture, steel fibers were used to enhance electrical resistance. The steel fibers measured about 2” in length by ¼” wide.

All concrete ingredients were manually weighed and loaded in a laboratory rotating-drum concrete mixer for mixing following the procedures of ASTM C 192. The resulting mixture was then discharged into a pan where the concrete was further tested and test specimens were cast.

Table 4-49: Concrete Mixture Proportions

Mixture No.	40	50	60
Laboratory Mixture Designation	40	50	60
Steel Fiber (lb/yd^3)	0	105	0
Fly Ash (lb/yd^3)	265	260	265
Cement (lb/yd^3)	355	350	350
Fly Ash [FA/(C+FA)], (%)	43	43	43
SSD Fine Aggregate (lb/yd^3)	1285	1275	1265
SSD Coarse Aggregate (lb/yd^3)	1510	1485	1980*
Water, W (lb/yd^3)	39	395	420
[W/(C+FA)]	0.63	0.65	0.68
Air Temperature (°F)	80	78	78
Concrete Temperature (°F)	80	80	76
Slump (in.)	2	3.25	1.75
Air Content (%)	1.5	1.0	4.1
Unit Weight (lb/ft^3)	140.2	142.4	158.6

- Heavyweight aggregate (taconite pellets)

Fresh concrete properties were also measured for the mixtures. Properties measured included: air content (ASTM C 237), slump (ASTM C 143), unit weight (ASTM C 138), and temperature (ASTM C 1064). Air temperature was also measured and recorded. Cylindrical test specimens 6 inches dia. × 12 inches in length were prepared from each mixture for compressive strength (ASTM C 39) and density tests. All test specimens were cast in accordance with ASTM C 192. Concrete specimens were typically cured for one day at about 70±5°F. These specimens were then demolded and placed in a standard moist-curing room maintained at 100% relative humidity and 73±3°F temperature until the time of test (ASTM D 4832).

Electrical Resistance Measurements

In order to test the effect of the moisture on the electrical resistance of the material and the reliability of the measurements, six identical cylinders were made from each concrete mixture. Three specimens were left to air dry after demolding and three were placed in water to remain in a saturated condition for testing. Both the air-dried and saturated specimens were tested at the same ages for electrical properties. Resistance measurements were taken using a Leader LCR-475-01 multimeter at one pre-determined location on all six cylinders for each mixture across its length (Fig. 4-27).

Reactance Measurement and Calculation of Permeability

Reactance of the test cylinder was measured by placing the cylinder in a copper wire coil and measuring the reactance of the coil with air as the core (L_1) and with the test cylinder as the core (L_2). The reactance, L_1 and L_2, were determined using a Leader LCR-475-01 multimeter. The resistance measurements were converted into resistivity values (ohm-cm). The measured reactance values were then used to calculate the permeability values from the relationship:

$$\frac{\mu_0}{\mu_1} = \frac{L_1}{L_2} \Rightarrow \mu_1 = \frac{\mu_0 L_2}{L_1}$$

where:

L_1= Reactance of the coil with air core

L_2= Reactance of the coil with the test cylinder as the core

μ_0= Permeability of air ($4 \pi \times 10^{-7}$ Henry/meter)

μ_1= Permeability of the cylinder

Figure 4–27: Electrical Resistance Measurements

Concrete Compressive Strength

The compressive strength of the three concrete mixtures is shown in Table 4-50. The compressive strength of the mixtures was 2340 to 2535 psi at the age of 28-days. A typical concrete used for foundations and walls construction has a minimum specified 28-day compressive strength of 3000 to 4000 psi. The concrete strengths achieved for the mixtures developed as part of this project are below this usual strength level. The primary focus of this project was to determine the effect of various materials on the electrical properties of the concrete. Therefore, the compressive strength of the mixtures was considered secondary at this stage of the study. Mixtures can be revised in future phases to produce a higher strength material. The compressive strength of the concrete may be increased by increasing the cementitious materials and/or reducing the amount of water in the mixture (reducing the water to cementitious materials ratio). This may also be achieved by using chemical admixtures such as a mid-range or high-range water reducing admixture (superplasticizer). The strength at various ages for these three mixtures is quite similar due to the fact that the cementitious materials and water to cementitious materials ratios are essentially the same.

Table 4-50: Compressive Strength of Concrete Mixtures

Mixture No.	Fly Ash [FA/(C+FA)], (%)	Compressive Strength (psi)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
40	43	1115	1025	1395	1455	1760	1810	2590	2535
		980		1485		1810		2460	
		990		1490		1855		2555	
50	43	1000	970	1425	1380	1960	1850	2390	2385
		965		1300		1785		2370	
		940		1420		1810		2395	
60	43	805	830	1360	1370	1695	1760	2352	2340
		850		1460		1825		2242	
		-		1300		1760		2427	

Electrical Properties of Concrete Mixtures

The electrical properties of the concrete mixtures are shown in Tables 4-51 and Figure 4-28. The electrical resistivity of the air dried concrete prepared in accordance with the invention is in the range of $1\text{-}128\times10^3$ ohm-cm. The air dried conventional concrete typically has a resistivity of the order of 10^6 ohm-cm, with oven dried conventional concrete having a resistivity of the order of 10^{11} ohm-cm. Therefore, it is apparent that the electrical resistivity of concrete in accordance with the invention is less than the electrical resistivity of conventional concrete. In other words, by incorporating high carbon fly ash into a concrete mixture as in the present invention, a more electrically conductive concrete is produced. The permeability of a concrete prepared with high carbon fly ash in accordance with the present invention exceeds that of air, indicating a greater capability to carry an electrical current. The use of fly ash having greater levels of carbon would further decrease the resistivity of the resulting concrete. In addition, the increased concentration of high carbon fly ash in the composition will result in increased conductivity.

Table 4-51: Electrical Properties of Concrete Mixtures

Mixture No.			40	50	60
Fly Ash Content wt., % [FA/(FA+C)]			43	43	43
Fly Ash Content wt., % [FA/(FA+C+S+G)]			7.76	7.72	6.87
Resistivity (ohm-cm)	Air Dried	3	4588.5	1715.8	3152.2
		7	7955.5	3590.8	4628.0
		14	14263	6403.7	9974.8
		28	2733.0	10672	127674
	Saturated	3	1376.5	997.7	1336.4
		7	1875.0	1017.4	1376.5
		14	2793.1	1156.8	1416.6
		28	4069.6	1486.0	1695.5
Relative Permeability	Air Dried	3	1.004	1.082	1.048
		7	1.004	1.082	1.048
		14	1.004	1.082	1.048
		28	1.004	1.082	1.048
	Saturated	3	1.006	1.089	1.051
		7	1.006	1.089	1.051
		14	1.006	1.089	1.051
		28	1.006	1.089	1.051

Conductive Concrete Containing We Energies High Carbon Fly Ash and Carbon Fibers (US Patent 6,821,336)

Testing of concrete using carbon fibers was conducted for concrete mixtures. The goal of this testing work was to determine the feasibility of incorporating high carbon fly ash and carbon fibers in concrete to lower electrical resistance of these construction materials. The lowered electrical resistance of concrete mixtures will reduce the required length of, or entirely replace, the grounding electrodes currently in use for protection of electrical equipment from lightning strikes. Other uses can potentially include grounding, heating bridges, sidewalks or airport runways, and various other applications.

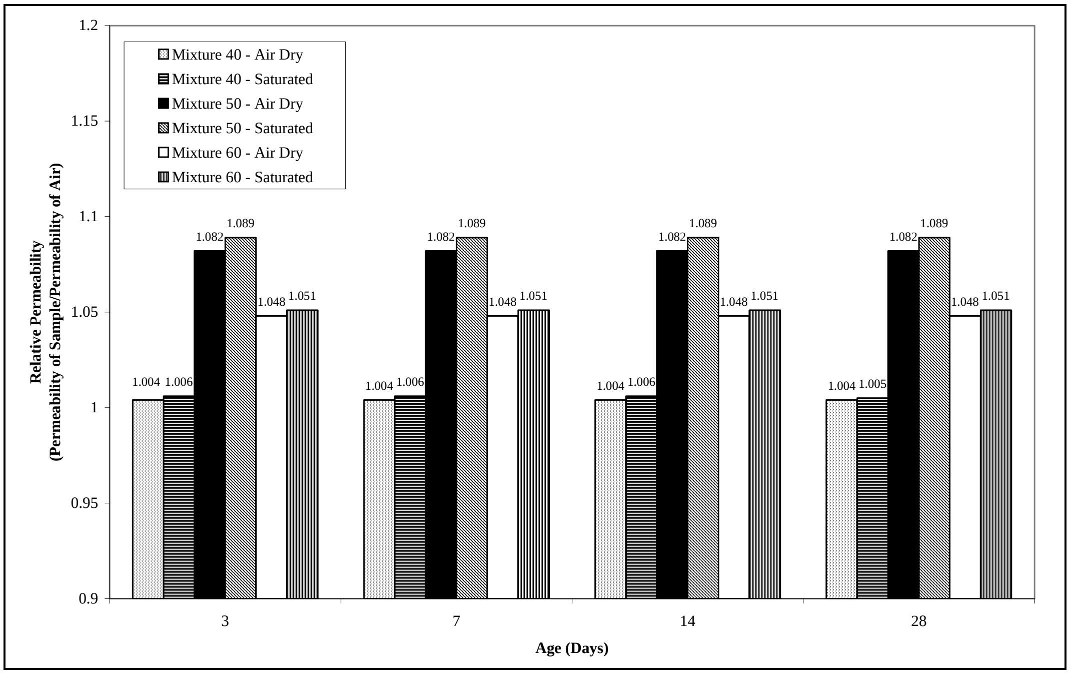


Figure 4–28: Relative Electrical Permeability of Concrete Mixtures

Materials

Materials utilized consisted of one source of fly ash, cement, clean concrete sand, crushed quartzite limestone aggregates, and carbon fibers. One source of clean concrete sand was utilized in this investigation as fine aggregate for concrete mixtures. The aggregate used was a crushed quartzite limestone with a maximum size of ¾” meeting ASTM C33 requirements. Type I cement (Lafarge Cement Co.) was used throughout this investigation. One source of fly ash was used for this project (We Energies, Presque Isle Power Plant). This selection was made to represent a typical high-carbon fly ash available from We Energies.

The fibers used for this project were Panex 33 chopped carbon fibers manufactured by the Zoltek Corporation, St. Louis, MO. The carbon fibers were pan-type fibers ½” long and approximately 0.283 mils (7.2 microns) in diameter. The density of the fibers reported by the manufacturer was 0.065 lb/in^3.

All concrete ingredients were manually weighed and loaded in a laboratory rotating-drum concrete mixer following the procedures of ASTM C 192. The test concrete was also manufactured. A high-range water reducing admixture was used for the concrete mixture to achieve the desired slump.

The amount of carbon fibers incorporated into the concrete mixture was determined by We Energies. Mixture CON-C contained approximately 40%

fly ash by weight of total cementitious materials, a high-range water reducing admixture, and the addition of 14 lb/yd^3 of carbon fibers. Table 4-52 shows the mixture components.

Table 4-52: Concrete Mixtures

Mixture No.	**CON-C**
Laboratory Mixture Designation	WF-C
Mixture Description	High-Carbon Fly Ash Concrete with Carbon Fibers
Fly Ash, FA (lb/yd^3)	240
Cement, C (lb/yd^3)	330
SSD Fine Aggregate, S (lb/yd^3)	1200
SSD Coarse Aggregate, G (lb/yd^3)	1405
Carbon Fibers (lb/yd^3)	14
Fly Ash Content, % [FA/(FA+C)]100	42
Water, W (lb/yd^3)	470
High-Range Water Reducing Admixture (oz/yd^3)	170
[W/(C+FA)]	0.82
Air Temperature (ºF)	73
Fresh Concrete Temperature (ºF)	65
Slump (in.)	1
Air Content (%)	2.0
Unit Weight (lb/ft^3)	135.0
Hardened Concrete Density (lb/ft^3)	130

Mechanical Properties

Compressive strength of the concrete was measured using standard cylinders, 6" diameter × 12" long, following the method of ASTM C 39. The compressive strength of concrete Mixture CON-C is shown in Table 4-53. The compressive strength of the mixture was very low at the early age and could not be measured until the age of 16 days. At the age of 16 days, the compressive strength was only 60 psi. The compressive strength increased at the age of 28 days to 135 days, and then significantly increased at the 42-day age to 1345 psi. This indicates that the setting time of the concrete mixture was significantly delayed, as well as pozzolanic effect of 40% fly ash content contributing to this jump in strength. The delay in setting was attributed to the amount of high-range water reducing admixture (HRWRA) required to be added to the mixture. The amount of HRWRA exceeded the maximum amount recommended by the manufacturer (136 oz/yd^3 versus 170 oz/yd^3 actually used in the laboratory mixture). Another possibility investigated was to determine if the water-soluble sizing of the carbon fibers had any effect on the setting time of the mixtures. The water-soluble sizing is applied to prevent the agglomeration of the fibers.

A test was conducted on cement mortar cubes per ASTM C 109 using water that was obtained from soaking the carbon fibers for 24 hours. The compressive strength of the cement mortar cubes at the age of seven days was 5070 psi. This indicates that the water-soluble sizing probably did not have any time of setting delay effect on the compressive strength of cement mortar. The concrete compressive strength achieved for the Mixture CON-C tested for this project is below its normally expected strength level. The primary focus of this project was to determine the effect of carbon fibers on the electrical properties of the concrete. Therefore, the compressive strength of the mixtures was considered secondary at this stage of the study. The amount of fibers can be revised in the future phases to produce a good-quality structural-grade concrete. The amount of carbon fibers may be reduced and optimized for electrical properties. Compressive strength of the concrete may be increased by increasing the cementitious materials and/or reducing the amount of water in the mixture.

Table 4-53: Compressive Strength of Concrete Mixture

Mixture No.	Fly Ash Content, % [FA/(C+FA)]	Compressive Strength (psi)							
		3-day		16-day		28-day		42-day	
		Act.	Avg.	Act.	Avg	Act.	Avg.	Act.	Avg.
CON-C	42	--	--	80	60	145	135	1265	1345
		--		50		145		1355	
		--		50		120		1410	

Electrical Properties

The electrical resistivities obtained for the concrete Mixture CON-C are given in Table 4-54 and Figure 4-29. Overall, resistivities of both air-dried and saturated specimens were comparable with, approximately 40 to 50 ohms-cm at the age of 16 days and 60 to 70 ohms-cm at the age of 42 days. Although the compressive strengths were much lower for the Mixture CON-C than a typical concrete used for many construction applications, the lower resistivity values achieved through the incorporation of high-carbon fly ash and carbon fibers are very promising for potential grounding applications. Further refinement of the carbon fiber content to optimize the resistivity and strength properties of the concrete is needed as a part of future laboratory studies. The permeability values show only a slight increase between 16 and 28 days. The relative electrical permeability of air-dried and saturated specimens were typically within 1.01.

For CON-C, air-dried specimens also had a higher electrical resistivity at the age of 42 days, but the difference between saturated and air-dried specimens were much less. Typically the difference between air-dried and saturated specimens was 10 ohm-cm or less. This may be attributed to the conductivity of the carbon fibers used in the mixtures.

Table 4-54: Electrical Resistivity of High Carbon Concrete Mixture with Carbon Fibers

Mixture No.	Fly Ash Content, % [FA/(C+S+G)]	Resistivity (Ohm-cm)							
		7-day		16-day		28-day		42-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
		Air-Dried Specimens							
CON-C	93	--	--	42.45	43.1	47.3	47.9	77.2	72.4
		--		43.1		47.9		67.0	
		Saturated Specimens							
		--	--	52.7	48.5	49.7	44.9	65.2	67.6
		--		44.3		40.1		69.4	

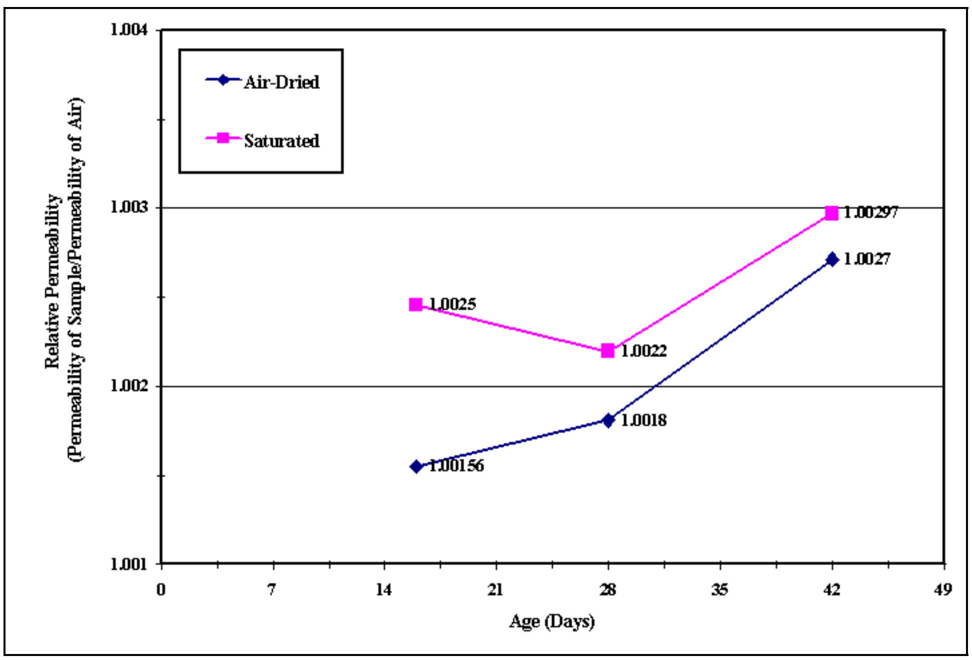


Figure 4–29: Electrical Permeability of High Carbon Fly Ash Concrete Contained Carbon Fibers, Mixture CON-C

Chapter 5

Controlled Low-Strength Material (CLSM) Containing We Energies Fly Ash

Introduction

During the past two decades fly ash has been increasingly used in the manufacture of controlled low-strength material (CLSM). CLSM is defined by ACI Committee 229 as a "self-compacted cementitious material used primarily as a backfill material in lieu of compacted fill with a compressive strength of 1200 psi or less." However, where future excavation is anticipated, the ultimate compressive strength of CLSM should be less than 300 psi. This level of strength is very low, compared to concrete, but very strong when compared to soils. The composition of CLSM can vary depending on the materials used in the mixture. CLSM has the unique advantage of flowing and self-leveling. Hence, in applications like filling abandoned underground tanks or voids under pavements, CLSM may be the only viable method of completely filling the void. Additionally, there is no cost associated with vibrating or compacting the material in place.

CLSM may be known by such names as: unshrinkable fill, controlled density fill, flowable mortar, plastic soil-cement, soil-cement slurry and K-Krete (36). We Energies uses the registered trademark, Flo-Pac® for its CLSM. The range of strength required varies with the type of application. However, CLSM is normally designed to develop a minimum of at least 20 psi strength in 3 days and 30 psi at 28 days (ASTM C403 penetration resistance numbers of 500 to 1500).

A compressive strength of 100 psi is equivalent to the load bearing capacity of a well compacted soil with a capacity of 14,400 psf which is comparable to a densely compacted gravel or hard pan type soil. Where CLSM is used as a support layer for foundations, a compressive strength of 300 psi to 1200 psi is sometimes used. However, applications involving CLSM with strength in this range are very limited and often not necessary.

The CLSM mixture selected should be based on technical and economic considerations for a specific project. The desired strength level and flowability are two significant considerations for CLSM. Permeability, and shrinkage or expansion of the final product (hardened CLSM) are additional considerations.

We Energies CLSM Developments

The development of CLSM containing We Energies fly ash has been a long process involving manufacturing several trial mixes and studying their properties. Various parameters were considered; however, compressive strength and excavatability are primary considerations. In the early trials a wide variety of sample strengths were developed, some of which were higher than normally recommended for CLSM.

Several CLSM mix designs were developed and tested using We Energies fly ash at the Center for By-Products Utilization (CBU) at the University of Wisconsin-Milwaukee (UWM). The scope of these tests was to evaluate fly ash, the properties of the mixes and study potential field applications. The mixes were prepared using various percentages of Class C and Class F fly ash with various proportions of other ingredients. It is important to note that Class F fly ash can be used in much higher proportions (sometimes replacing aggregate) than cementitious Class C fly ash which is introduced primarily as a binder.

CLSM production is an excellent use for fly ash that does not meet all of the ASTM C618 requirements for use in concrete. The strength level required for CLSM is low when compared to concrete and can be easily obtained with off-spec fly ash. High carbon content can be a reason for concern in air-entrained concrete where air entraining admixtures are absorbed yielding inadequate or variable concrete air content. In CLSM, air content is often not a requirement and hence the presence of carbon particles do not affect its properties.

CLSM Produced with We Energies High-Lime (ASTM C618 Class C) Fly Ash

The mixtures shown in Table 5-1 were developed using ASTM C618 Class C fly ash produced at We Energies's Pleasant Prairie Power Plant from burning western United States sub-bituminous coal. The chemical and physical properties of the PPPP fly ash are listed in Chapter 3, Tables 3-1 and 3-2. The mixtures were produced at a commercial batch plant using standard procedures that were monitored to assure homogeneity of the products.

Table 5-1: Mixture Proportions and Field Test Data for CLSM (and Low-Strength Concrete) Produced With Class C Fly Ash

Mix No.	C-1	C-2	C-3	C-4	C-5	C-6	C-7
Specified Strength at 28-Day Age, psi	500	1000	1200	500	750	1000	500
Cement, lb./cu yd.	74	89	104	70	81	96	129
Fly Ash, lb./cu yd.	128	158	189	118	159	195	239
Water, lb./cu. yd.	332	293	283	345	337	338	351
SSD Sand, lb./cu. yd.	1763	1671	1609	1728	1611	1641	1543
SSD Pea Gravel, lb./cu. yd.	1773	1832	1863	1778	1761	1813	1721
Slump, inches.	1-3/4	3/4	1-1/4	7-1/2	6-1/4	6-1/2	9-1/4
Air Content, Percentage	3.2	2.7	2.6	2.1	2.3	2.2	1.0
Air Temperature, Fahrenheit	40	45	49	37	40	38	32
Concrete Temperature, Fahrenheit	64	62	58	55	60	60	58
Concrete Density, pcf	150.7	149.8	149.9	149.6	146.3	151.2	147.5
Concrete Weight, lb./cu. yd.	4070	4044	4048	4039	3969	4083	3983
W/(C+FA)	1.64	1.19	0.97	1.84	1.16	1.16	0.95

The first three mixtures were produced with low cement content and relatively low water content.

Mixtures C-1 to C-3 showed very low slump and did not flow as desired in a flowable slurry. Hence, new mixtures were developed, taking into consideration the drawbacks of previous mixes. (37)

The new mixes C-4 to C-7 showed good to very good flowability. A detailed discussion of the research can be obtained from reference 37.

Figure 5-1 is a graph showing compressive strength vs. age for these mixtures. Figure 5-2 shows 28-day compressive strength vs. total cementitious material, and Figure 5-3 shows 28-day compressive strength vs. water to cementitious ratio for these mixtures. Table 5-2 shows the CLSM compressive strength test results.

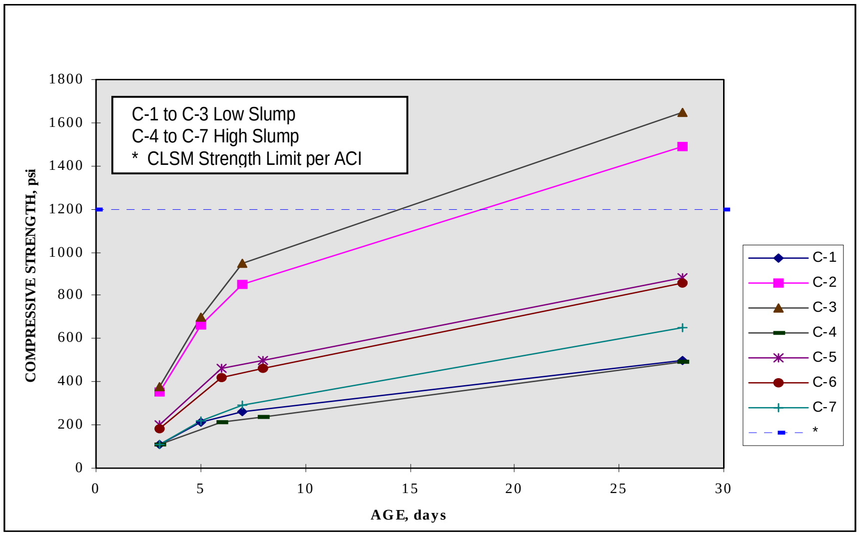


Figure 5-1: CLSM Compressive Strength vs. Age Comparison (Class C Fly Ash)

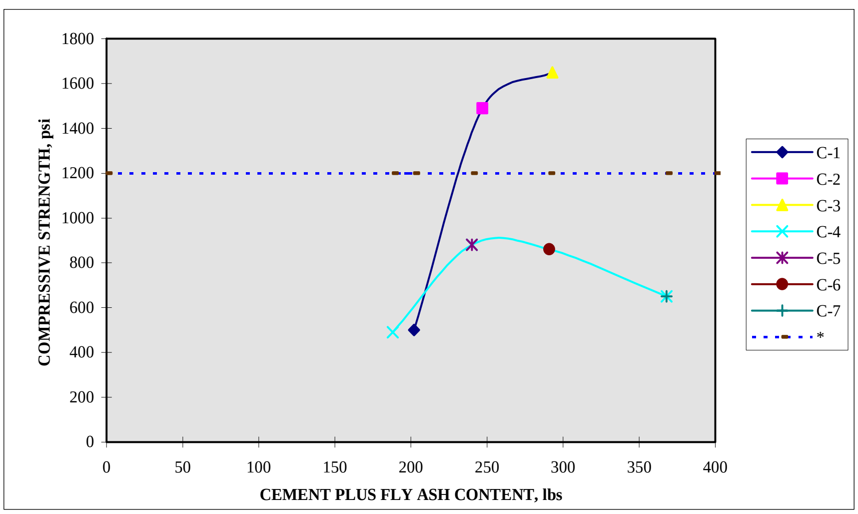


Figure 5-2: CLSM 28-Day Compressive Strength vs. Total Cementitious Material (Class C Fly Ash)

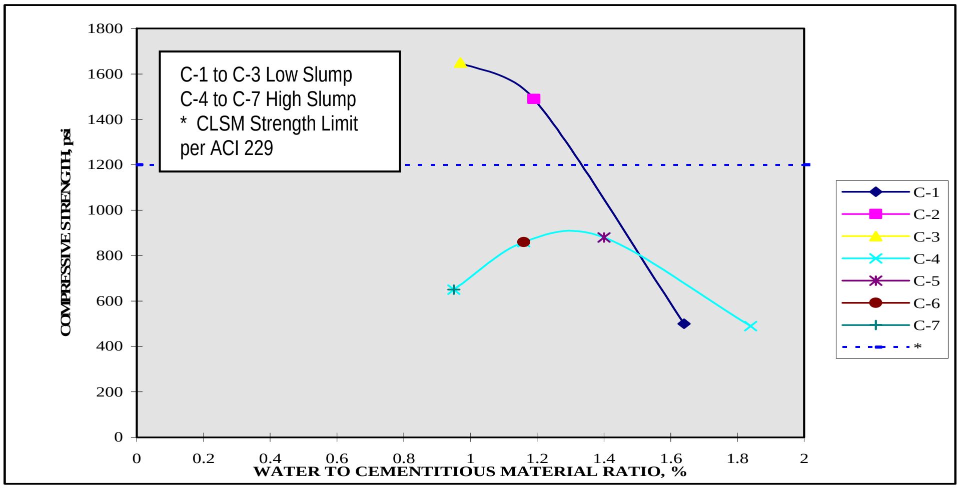


Figure 5-3: CLSM 28-Day Compressive Strength vs. Water to Cementitious Material Ratio

Table 5-2: High Fly Ash CLSM Test Data
500-1200 psi Specified Strength Range at 28-Day Age

MIX No.	C-1	C-2	C-3	C-4	C-5	C-6	C-7
Specified Strength, psi	500	1000	1200	500	750	1000	500
Class of Ash	C	C	C	C	C	C	C
Slump, in	1-3/4	3/4	1-1/4	7-1/2	6-1/4	6-1/2	9-1/4
TEST AGE, Days	COMPRESSIVE STRENGTH, psi						
3	110	350	375	110	200	180	110
5	210	660	700				220
6				210	460	420	
7	260	850	950				290
8				240	500	460	
28	500	1490*	1650*	490	880	860	650

* Exceeds CLSM strength cap of 1200 psi specified by ACI 229.

It can be concluded from these test results that:

1. As the water to cementitious materials ratio increases, the compressive strength decreases for the low slump mixtures.
2. The compressive strength did not change significantly for the higher slump mixtures as the water to cementitious materials ratio increased between 1.0 and 2.0.

3. All mixtures behaved well and can be used as a basis for selection of mixtures for CLSMs or low-strength high fly ash content concrete for non-structural applications.
4. The compressive strength results for all these trial mixtures are at a level where easy excavatability will not be possible.

CLSM Containing We Energies Valley Power Plant Off-Spec (ASTM C618 Class F) Fly Ash

The mixture proportions used in this project were designed to have a compressive strength of 500 psi to 1500 psi. This strength level is similar to the strength levels of many natural rock formations and can be used as foundation support, capable of distributing the load uniformly.

The CLSM mixtures were produced at a commercial batch plant in New Berlin, Wisconsin. The mixtures contained ⅜" (maximum size) pea gravel, in addition to fly ash, cement, sand and water. The final mixtures were designed with high slump (7" to 9".).

From each concrete mixture, 6" diameter by 12" high cylinders were prepared for compressive strength and other tests. Cylinders were tested from each mixture at the ages of 3, 5, 7 and 28 days. Shrinkage was noted to be very low, ranging from 0 to 1/32" for the 12" high cylinders. A detailed discussion of this research can be obtained from reference 38.

Table 5-3 gives the chemical and physical test data for mixtures produced with off-spec ASTM C618 Class F fly ash from Valley Power Plant. Tables 5-4 and 5-5 show mixture proportions, field test data, and compressive strength data for the various mixtures.

Figure 5-4 is a graph showing compressive strength vs. age for these mixtures. Figure 5-5 shows compressive strength vs. total cementitious material for the same mixtures, and Figure 5-6 shows compressive strength vs. water to cementitious material ratio for the above mixtures.

Table 5-3: Chemical and Fineness Test Data for Class F Fly Ash from Valley Power Plant

Chemical Composition	No. of Samples	Range, %	Average, %	ASTM C-618
Silicon Oxide, SiO_2	4	50.06-50.20	50.14	-
Aluminum Oxide, Al_2O_3	4	25.24-25.36	25.27	-
Iron Oxide, Fe_2O_3	4	14.66-15.39	14.93	-
Total, SiO_2+Al_2O_3+ Fe_2O_3	4	89.96-90.82	90.36	50 Min
Sulfur Trioxide, SO_3	4	0.20-0.33	0.26	5.0 Max
Calcium Oxide, CaO	4	1.18-1.44	1.27	-
Magnesium Oxide, MgO	4	0.70-0.74	0.71	5.0 Max
Carbon	4	3.59-6.94	5.08	6.0 Max
Available Alkalis as Na_2O	4	1.61-1.70	1.65	
Sulfur	4		0.22	
Physical Tests				
Fineness: % Retained on #325 Sieve	1	25		34.0 max

Table 5-4: Mixture Proportions and Field Test Data for Class F Fly Ash CLSM

Mix No.	F-1	F-2	F-3	F-4	F-5	F-6
Specified Strength at 28-Day Age, psi	1000	1500	2000	1500	1500	1500
Cement, lb./cu. yd.	102	151	229	138	211	263
Fly Ash, lb./cu. yd.	499	519	500	452	459	446
Water, lb./cu. yd.	439	375	422	323	294	320
SSD Sand, lb./cu. yd.	1206	1198	1111	1090	1053	1060
SSD Pea Gravel, lb./cu. yd.	1614	1697	1680	1783	1774	1688
Slump, inches	9	7-3/4	8-1/4	9	7-1/4	8-1/4
Air Content, Percentage	1.0	1.8	1.9	0.5	1.4	1.7
Air Temp., Fahrenheit	38	36	35	32	33	33
Concrete Temperature, Fahrenheit	65	64	64	58	60	62
Concrete Density, pcf	143.0	145.9	146.0	140.2	140.4	139.5
Concrete Weight, lb./cu. yd.	3861	3940	3942	3786	3791	3777
W/C	4.3	2.5	1.8	2.34	1.39	1.22
W/(C+FA)*	0.73	0.56	0.58	0.55	0.44	0.45

* May not be meaningful because all of the Type F fly ash probably should not be accepted as cementitious

Table 5-5: Class F Fly Ash CLSM Test Data

Mix No.	F-1	F-2	F-3	F-4	F-5	F-6
Specified Strength, psi	500	1000	1500*	500	1000	1500*
Class of Ash	F	F	F	F	F	F
Slump, inches	9	7¾	8¼	9	7¼	8¼
Test Age, days	Compressive Strength, psi					
3	110	270	500	123	263	420
5				200	383	630
6	210	470	820			
7				237	443	693
8	220	510	880			
28	490	930	1640*	677	900	1210*

* Exceeds CLSM strength cap specified by ACI 229 of 1200 psi

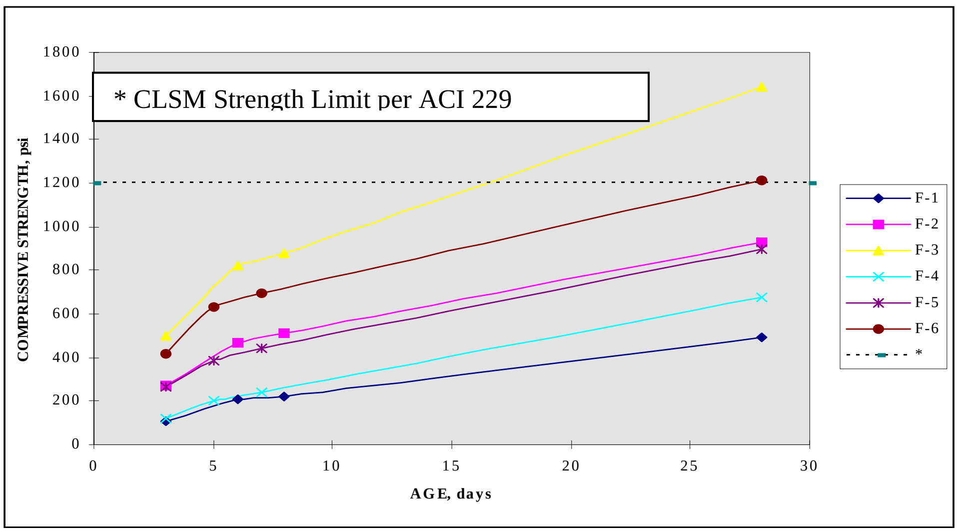


Figure 5-4: CLSM Compressive Strength vs. Age Comparison (Class F Fly Ash)

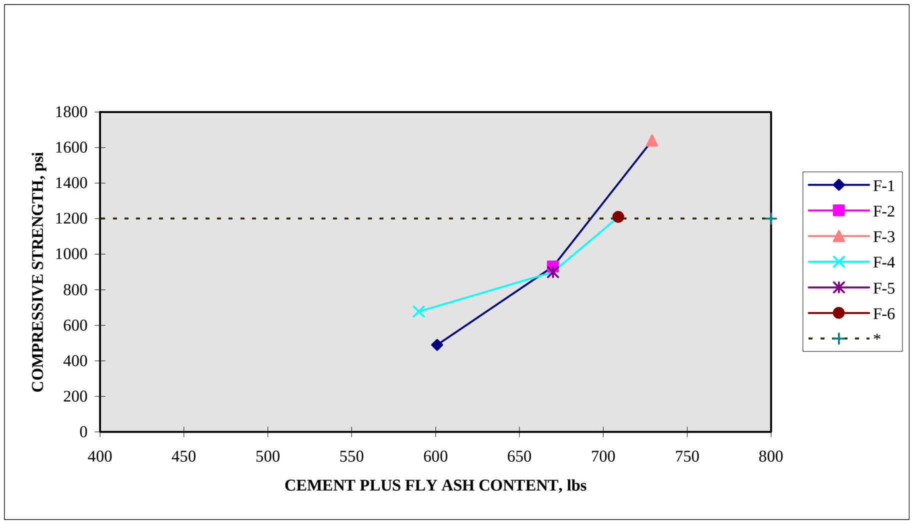


Figure 5-5: CLSM 28-Day Compressive Strength vs. Total Cementitious Material

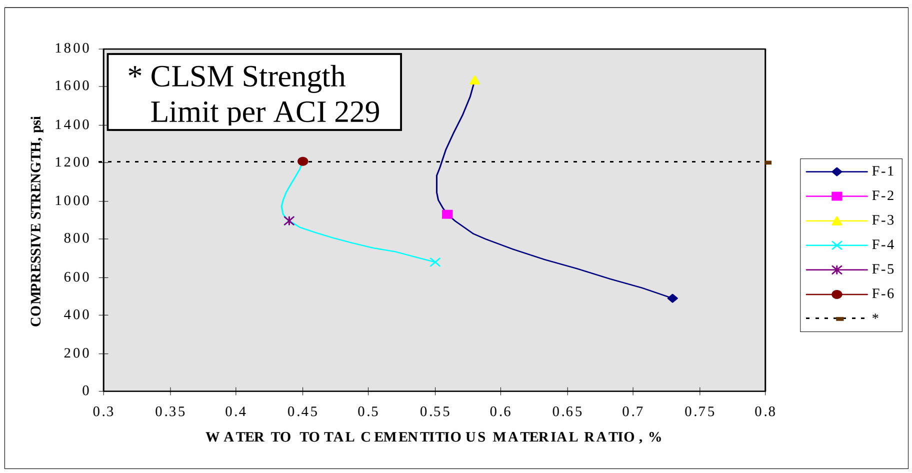


Figure 5-6: CLSM 28-Day Compressive Strength vs. Water to Cementitious Material Ratio

The following conclusions were made from this research (38).

1. The compressive strength decreased as water to cementitious material ratio increased.
2. All mixtures showed good flowability and workability.
3. Shrinkage was minimal.
4. The mixture designs developed performed well and can be used as a basis for selecting mixture proportions for CLSMs or low-strength concrete with high slump for non-structural applications, using the same materials.
5. All of these mixtures <u>will not</u> be easily excavatable.

CLSM Made with We Energies Port Washington Power Plant Off-Spec (ASTM C618 Class F) Fly Ash

This study was conducted by We Energies with a local ready mix firm to determine various properties of CLSM material containing off-spec ASTM C618 Class F fly ash from Port Washington Power Plant (PWPP). CLSM fly ash slurry was initially used for limited applications in filling abandoned underground facilities and voids such as tunnels, manholes, vaults, underground storage tanks, sewers and pipelines. Another obvious application is the backfilling of trenches for underground utility lines. For this application it is important that the backfill material be compatible with the underground utility line material. Also, the material should be easily excavatable and also provide for special needs such as high thermal conductivity for underground high-voltage transmission lines.

ASTM C618 chemistry tests were not performed on PWPP fly ash at the time of this research because this fly ash was not used for the production of concrete. However, fly ash from Valley Power Plant that used the same coal was tested. The chemical composition is shown in Table 5-3 for reference purposes. The physical properties of PWPP fly ash are shown in Table 5-6.

Table 5-6: Physical Properties of Port Washington Power Plant Class F Fly Ash

Test	Class F Fly Ash	ASTM C618 Min	ASTM C618 Max
Fineness % Retained on #325 Sieve	28.8 30.2	- -	34
Pozzolanic Activity Index With Cement (28 days), % With Lime (7 days), psi	 99.4 *	 75 800	 - -
Water Requirement, % of Control	109	-	105
Autoclave Expansion, %	0.05	-	0.8
Specific Gravity	2.33 2.34	- -	- -
Variation from Mean Specific Gravity, % Fineness, %	 0.214 2.290	 - -	 5 5

* Not enough material was available to do this test

CLSM laboratory trial mixtures using PWPP fly ash were also developed at the Center for By-Products Utilization (CBU) at the University of Wisconsin-Milwaukee (UWM) laboratory in November of 1991. The mixture proportions and corresponding compressive strength test results are shown in Table 5-7 (laboratory tests) and Table 5-8 (ready-mix plant production tests). Figure 5-7 is a graph showing compressive strength vs. age for these mixtures.

Table 5-7: Laboratory CLSM Mixture Proportions for PWPP Class F Fly Ash and Compressive Strength Data

Ingredient	Actual Weight	Cubic Yard Basis
Cement (Type 1)	2.2 lbs	69 lbs
Fly Ash	44.2 lbs	1389 lbs
Water	34.0 lbs	1069 lbs
Water/Cement Ratio	15.45	15.45 lbs
Water/Cementitious Material ratio	0.73	
Compressive Strength Data		
Test Age	Max. Load, lb	Compressive Strength, psi
7 day	640	23
28 day	1150	41
56 day	1090	38

Table 5-8: Ready Mix CLSM Mixture Proportions for PWPP Class F Fly Ash and Compressive Strength Data

Mix No.	1	2	3	4
Cement (Type 1), lbs	94	94	94	94
Fly Ash*, lbs	1731	1329	1153	699
Water, lbs	853	644	617	372
Sand (SSD), lbs	-	1000	-	1200
¾" Aggregate (SSD), lbs	-	-	1000	1700
Slump, in	9	9	10	8 3/4
Average Compressive Strength, psi				
1 Day	0	6	5	43
3 Day	7	22	17	96
4 Day	4	10	11	117
7 Day	16	36	30	162
28 Day	39	62	50	276

* Dry Weight

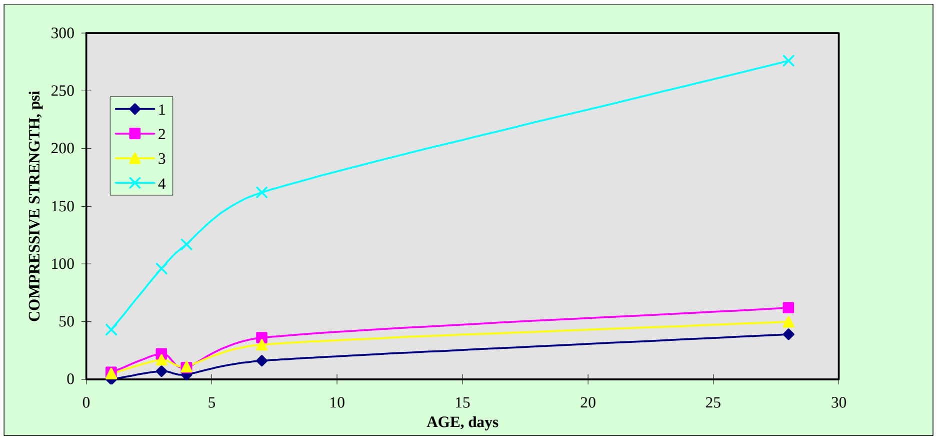


Figure 5-7: Compressive Strength vs. Age Comparison (Class F Fly Ash with One Bag Cement)

The compressive strength test results for mixtures 1 – 3 at a 28-day age ranged from 39 – 62 psi and are comparable to many undisturbed or recompacted soils, which makes it suitable as a backfill material. Mixture 4, with a 28-day compressive strength of 276 psi, may be suitable in applications below foundations where future excavatability concerns are not important. It is important to note that all four mixtures contained only one bag of Portland cement and that mixture 4 contained both coarse and fine aggregates.

Electric Resistivity, Thermal Conductivity and Plastics Compatibility Properties of CLSM Produced with We Energies Fly Ash

Figure 5-8: CLSM flows into place and completely filled this underground equipment vault.

Electric resistivity, thermal conductivity and plastics compatibility evaluations were performed on solidified CLSM fly ash slurry produced from a mixture of 1,275 lbs. of Valley Power Plant fly ash, 150 lbs. of Type 1 Portland cement and 1,050 lbs. of water per cubic yard (39).

Compressive strength tests were also performed per ASTM C39 for comparison of these special properties. Electrical resistivity tests were performed in accordance with California Test 643-1978. Moisture content in the selected samples varied from 20% to 100%. Thermal conductivity tests were conducted using the thermal needle test method (Mitchell and Kao, 1978). Electrical resistivity test values are used to predict corrosiveness of soils. The electrical resistivity values obtained from the tests indicate that CLSM fly ash slurry is not considered corrosive. Table 5-9 shows commonly used soil corrosivity vs. resistivity values.

Table 5-9: Electrical Resistivity vs. Soil Corrosivity

Resistivity (ohm-cm)	Corrosivity
Below 500	Very Corrosive
1,000 - 2, 000	Moderately Corrosive
2,000 - 10,000	Mildly Corrosive
Above 10,000	Progressively Less Corrosive

Thermal conductivity results exhibited a near linear relationship with moisture content. Thermal conductivity increases with an increase in moisture content and dry density. In applications like backfill for underground power cables where high thermal conductivity is desired, high-density, low porosity mixtures are preferable. Thermal conductivity values of high-volume flowable fly ash slurry are typically lower than sand, silt and clays but higher than peat.

A study conducted by Dr. Henry E. Haxo, Jr. of Matrecon, Inc., Alameda, California, concluded that high-density polyethylene-coated steel gas pipe, medium-density polyethylene gas pipe and low-density polyethylene jacketed cable would not be adversely affected by CLSM fly ash slurry (39).

Figure 5-9: Excavating hardened CLSM with a backhoe at We Energies' Valley Power Plant in downtown Milwaukee, Wisconsin.

Tables 5-10 and 5-11 show the electrical resistivity test results and thermal conductivity test results respectively.

Table 5-10: Resistivity Test Results
CLSM Fly Ash Slurry (ohm-cm)

Moisture Content %	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
20	213606	-	-	-	-	-
30	133504	-	-	-	-	-
40	13478	-	-	-	-	-
50	73427	-	-	150859	173555	106803
60	60077	140847	94788	134171	146854	101463
70	56739	126161	120821	108138	140179	100128
80	60077	108138	118151	97458	132169	92118
90	60077	95455	120154	86778	120154	86778
100	60077	94120	120154	87445	120154	86778
Dry Wt. (pcf)	50.74	54.81	50.74	52.28	55.73	68.29

Table 5-11: Thermal Conductivity Test Results
CLSM Fly Ash Slurry (BTU/hr-ft-°F)

Moisture Content, %	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
0.0	0.08	0.08	0.08	0.1	0.09	0.09
2.6	-	0.09	-	-	-	-
3.0	0.08	-	-	-	-	-
16.0	-	-	0.19	-	-	-
16.1	-	-	-	-	-	0.18
17.7	-	-	-	0.22	-	-
25.0	-	-	-	-	0.2	-
62.9	-	0.53	-	-	-	-
65.0	0.42	-	-	-	-	-
66.9	-	-	0.46	-	-	-
75.3	-	-	-	-	0.47	-
76.0	-	-	-	0.49	-	-
77.4	-	-	-	-	-	0.46
Dry Density, pcf	55.6	55.9	55.1	50.6	50.2	50.4

It can be concluded from this research that:

1. Good quality CLSM fly ash slurry for utility trench backfill can be produced with off-spec Class F fly ash produced at PWPP and VAPP.
2. CLSM fly ash slurry using PWPP or VAPP fly ash has less corrosion potential than typical soil used for trench backfill.
3. High-density, very low porosity CLSM should be used where high thermal conductivity is desired, such as backfill around underground power cables.
4. CLSM fly ash slurry has no adverse effect on polyethylene plastics used for underground gas lines and power cables.

Conductive CLSM Containing We Energies High Carbon Fly Ash (US Patent 6,461,424 B1) (35)

Materials

Materials used in this project consisted of one source of fly ash, cement, clean concrete sand, crushed quartzite limestone aggregates, and taconite pellets. Materials were characterized for chemical and physical properties in accordance with the appropriate ASTM standards. Table 5-12 shows the mixture proportions.

Type I cement (Lafarge Cement Co.) was used throughout this investigation. One source of fly ash was used for this project (We Energies, Port Washington Power Plant, Units 2 and 3).

The CLSM mixtures were proportioned to maintain a practical value of flow that would not have excessive segregation and bleeding. The flow was reduced for mixtures containing sand and gravel to maintain the cohesiveness and the workability of the mixture.

Fresh CLSM properties such as air content (ASTM D 6023), flow (ASTM D 6103), unit weight (ASTM D 6023), and setting and hardening (ASTM D 6024) were measured and recorded. All test specimens were cast in accordance with ASTM D 4832. These specimens were typically cured for one day in their molds at about 70 ± 5ºF. The specimens were then demolded and placed in a standard moist-curing room maintained at 100% relative humidity and 73 ± 3ºF temperature until the time of test (ASTM D 4832).

Table 5-12: CLSM Mixtures with We Energies High Carbon Fly Ash

Mixture No.	100	100S	100SG
Laboratory Mixture Designation	100-5	100S-5	100SG-5
Fly Ash, FA (lb/yd^3)	1365	665	660
Cement, C (lb/yd^3)	100	65	45
SSD Fine Aggregate, S (lb/yd^3)	0	1335	865
SSD Coarse Aggregate, G (lb/yd^3)	0	0	1430
Fly Ash Content, % [FA/(FA+C+S+G)]	93	32	22
Water, W (lb/yd^3)	1045	525	480
Air Temperature (ºF)	78	79	78
Fresh CLSM Temperature (ºF)	77	77	84
Flow (in.)	11-1/4	10-1/4	6-3/4
Air Content (%)	1.7	1.2	0.9
Unit Weight (lb/ft^3)	92.8	95.7	129.2

Mechanical Properties of CLSM with We Energies High Carbon Fly Ash

The CLSM strength increased with increasing age. In general, the rate of strength increase was the highest for the mixtures containing aggregates (sand and/or stone) content. Compressive strength for Mixture 100 (fly ash and cement) was 50 psi at the 28-day age. Compressive strength of Mixture 100S and 100SG were higher, 140 psi and 130 psi, respectively, even with reduced cement content, as shown in Table 5-13.

Table 5-13: Compressive Strength of CLSM Mixtures with We Energies High Carbon Fly Ash

Mixture No.	Fly Ash Content, % [FA/(C+S+G)]	Compressive Strength (psi)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
100	93	15	15	35	35	60	60	60	50
		15		35		60		40	
		15		30		65		45	
100S	32	30	30	105	100	130	120	135	140
		30		100		115		135	
		30		95		115		140	
100SG	22	15	17	140	110	105	110	135	130
		15		95		110		115	
		20		100		110		145	

The compressive strength of Mixture 100S and 100SG at the age of 28-days indicates that a backhoe may be required to excavate these mixtures in the future. However, standard excavation practices typically do utilize a backhoe for excavations for efficiency. Therefore, the 28-day strength levels of the 100S and 100SG mixtures should not be expected to pose a problem for future excavations with mechanical equipment.

Electrical Properties of CLSM with We Energies High Carbon Fly Ash

The electrical properties of the CLSM mixtures are shown in Table 5-14. The electrical resistivity of the air dried CLSM prepared is in the range of 3-6×10^3 ohm-cm. The resistivity value of the saturated specimens were lower than that obtained for air dried specimens. The permeability of most CLSM specimens prepared with high carbon fly ash exceeds that of air, indicating a greater capability to carry an electrical current. The use of fly ash having greater levels of carbon would further decrease the resistivity of the resulting CLSM. In addition, the increased concentration of high carbon fly ash in the composition will result in increased conductivity. The most significant decrease in resistivity occurs when increasing the high carbon fly ash content in the controlled low-strength materials from 22%–32%. This is evident in the high carbon fly ash controlled low-strength material mixtures for both the saturated and air dry specimens.

Table 5-14: Electrical Properties of CLSM Mixtures

Mixture No.			100	100S	100SG
Fly Ash Content wt., % [FA/(FA+C)]			93	91	93.6
Fly Ash Content wt., % [FA/(FA+C+S+G)]			93	32	22
Resistivity (ohm-cm)	Air Dried	3	40.1	65.8	151.4
		7	225.6	309.4	863.6
		14	837.9	911.5	1430.4
		28	3890.1	3417.9	5824.9
	Saturated	3	40.1	65.8	151.4
		7	40.1	85.6	161.6
		14	40.1	103.5	168.8
		28	48.5	101.7	183.7
Relative Permeability	Air Dried	3	1.001	1.004	1.006
		7	1.001	1.004	1.006
		14	1.004	1.004	1.006
		28	1.012	1.004	1.006
	Saturated	3	1.001	1.004	0.999
		7	0.999	1.004	1.008
		14	1.001	1.004	1.005
		28	1.012	1.004	1.006

Conductive CLSM Containing We Energies High Carbon Fly Ash and Carbon Fibers (US Patent 6,821,336)

Electrically conductive CLSM is advantageous where lower electrical resistance is sought, such as for use in structures where it is necessary to protect electrical equipment from lighting strikes. Electrically conductive CLSM has the following features:

(1) Provides low inductance, low resistance and subsequently low impedance values for all frequencies up to 1 MHz,

(2) Conducts energy efficiently across and through its surface without damage while providing true equalized ground potential rise values,

(3) Conducts energy efficiently into the earth quickly and seamlessly by providing the lowest impedance-coupling path,

(4) Compatible with copper, aluminum and galvanized steel products, and

(5) Fully excavatable, without heavy equipment

Conductive CLSM is made by using electrically conductive materials in close contact with each other throughout the CLSM. Electrically conductive additives include carbon fibers, steel fibers, steel shavings, carbon black, coke breeze, and other similar types of materials.

Since high carbon content fly ash is readily available as a coal combustion product, and carbon is known to be highly conductive, its use as an additive to CLSM to lower electrical resistance has been investigated. The goal of this testing work was to determine the feasibility of incorporating carbon fibers in the CLSM to lower electrical resistance of these construction materials. The lower electrical resistance of these construction materials will reduce the required length, or entirely replace, the grounding electrodes currently in use for protection of electrical equipment from lightning strikes.

Materials

Materials utilized in this project consisted of one source of fly ash, cement, and carbon fibers. One source of fly ash was used for this project (We Energies, Presque Isle Power Plant). This selection was made to represent a typical high-carbon fly ash available from We Energies. Type I cement (Lafarge Cement Co.) was used throughout this investigation. Carbon fibers were used in one CLSM mixture (Mixture CLSM-B) to attempt to enhance the electrical resistance characteristics.

All CLSM ingredients were manually weighed and loaded in a rotating-drum concrete mixer. The CLSM was mixed using the rotating-drum mixer. Fresh CLSM properties such as air content (ASTM D 6023), flow (ASTM D 6103), and unit weight (ASTM D 6023) were measured and recorded. Air and CLSM temperature was also measured and recorded. CLSM test specimens were prepared from each mixture for compressive strength (ASTM D 4832) and density. Compressive strengths of the CLSM mixtures were evaluated at the designated ages of 3, 7, 14, and 28 days. All test specimens were cast in accordance with ASTM D 4832. Three CLSM test specimens were tested at each test age. These specimens were typically cured for one day in their molds in the University of Wisconsin at Milwaukee – Center for By-Products Utilization laboratory at about 70°± 5°F. After setting, the test specimens were then demolded and placed in a standard moist-curing room maintained at 100% relative humidity and 73°± 3°F temperature until the time of test.

Mixture Proportions

Two different types of CLSM mixtures were tested. CLSM mixture proportions and fresh CLSM test results are shown in Table 5-15. The CLSM mixtures were proportioned to maintain a "practical" value of flow that would not lead to excessive segregation and bleeding.

Table 5-15: CLSM Mixtures

Mixture No.	CLSM-A	CLSM-B
Laboratory Mixture Designation	W-1	WF
Mixture Description	High-Carbon Fly Ash CLSM	High-Carbon Fly Ash CLSM with Carbon Fibers
Fly Ash, FA (lb/yd^3)	1250	490
Cement, C (lb/yd^3)	97	95
Carbon Fibers (lb/yd^3)	--	23
Fly Ash Content, % [FA/(FA+C)]100	93	82
Water, W (lb/yd^3)	1010	1370
[W/(C+FA)]	0.75	2.3
Air Temperature (ºF)	79	72
Fresh CLSM Temperature (ºF)	76	60
Flow (in.)	11	8
Air Content (%)	1.7	0.6
Unit Weight (lb/ft^3)	87.2	73.6
Hardened CLSM Density (lb/ft^3)	85	90

Mechanical Properties

The compressive strength data for the CLSM mixtures are presented in Table 5-16. Compressive strength of the high-volume fly ash CLSM mixture (Mixture CLSM-A, fly ash and cement) increased slightly between the ages of 3 and 28 days. Compressive strength for Mixture CLSM-A was 70 psi at the 3-day age, and increased to 85 psi at the 28-day age. When carbon fibers were introduced into the CLSM mixture, compressive strength was significantly reduced, to approximately 10 psi. The 28-day strength levels achieved for the CLSM-A and CLSM-B mixtures should not be expected to pose a problem in case of future excavation.

Due to the addition of carbon fibers, the flowability of the CLSM was significantly reduced for Mixture CLSM-B. In order to obtain flow characteristics for a typical CLSM, water for Mixture CLSM-B needed to be increased by approximately 30% over the amount used for Mixture CLSM-A (CLSM without fibers). Reduced flowability is to be expected since the fibers would tend to interlock and restrict the flow of the mixture.

Table 5-16: Compressive Strength of CLSM Mixtures

Mixture No.	Fly Ash Content, % [FA/(C+FA)]	Compressive Strength (psi)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
CLSM-A	93	75	70	85	75	80	75	85	85
		70		70		70		80	
		65		70		75		90	
CLSM-B	82	--	--	10	10	10	10	10	10
		--		5		10		10	
		--		10		10		10	

Electrical Properties of CLSM Mixtures

The electrical resistivity values of the CLSM mixtures shown in Table 5-17 and Figure 5-10 are for air-dried specimens and Table 5-18 and Figure 5-11 for saturated specimens. Electrical resistivity of high-carbon fly ash mixture, CLSM-A, increased from 162.8 ohm-cm at the age of three days to over 55000 ohm-cm at the age of 28 days. Saturated specimens increased from 162.2 ohm-cm to only 535.7 ohm-cm at the age of 28 days. A significant improvement in the electrical resistance of CLSM occurred when carbon fibers were incorporated in Mixture CLSM-B. Both air-dried and saturated specimens exhibited very low rsistivity of approximately 13.2 ohm-cm or less when tested at ages between three and 28 days. These results illustrate that using carbon fibers in CLSM has a greater positive effect on lowering the resistivity above that normally achieved through the use of high-carbon fly ash alone. Electrical permeability decreased slightly when carbon fibers were used (Mixture CLSM-B).

Table 5-17: Electrical Resistivity of CLSM Mixtures – Air-Dried Specimens

Mixture No.	Fly Ash Content, % [FA/(C+S+G)]	Resistance (Ohm-cm)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
CLSM-A	93	167.0	165.0	456.6	597.5	3357.4	4967.6	44706.0	55458.6
		159.8		544.0		4500.5		43568.9	
		168.2		791.8		7050.0		78100.8	
CLSM-B	82	6.6	6.4	7.8	7.8	9.0	8.8	13.2	13.4
		6.0		7.8		8.4		13.2	
		6.6		7.8		9.0		13.8	

Table 5-18: Electrical Resistivity of CLSM Mixtures - Saturated Specimens

Mixture No.	Fly Ash Content, % [FA/(C+S+G)]	Resistance (Ohm-cm)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
CLSM-A	93	159.8	164.0	239.4	263.9	350.1	383.4	482.4	535.0
		168.2		293.3		420.7		583.5	
		164.0		259.1		379.4		541.0	
CLSM-B	82	10.2	10.8	7.2	7.6	9.0	8.8	9.6	9.2
		9.0		7.8		8.4		9.6	
		13.2		7.8		9.0		8.4	

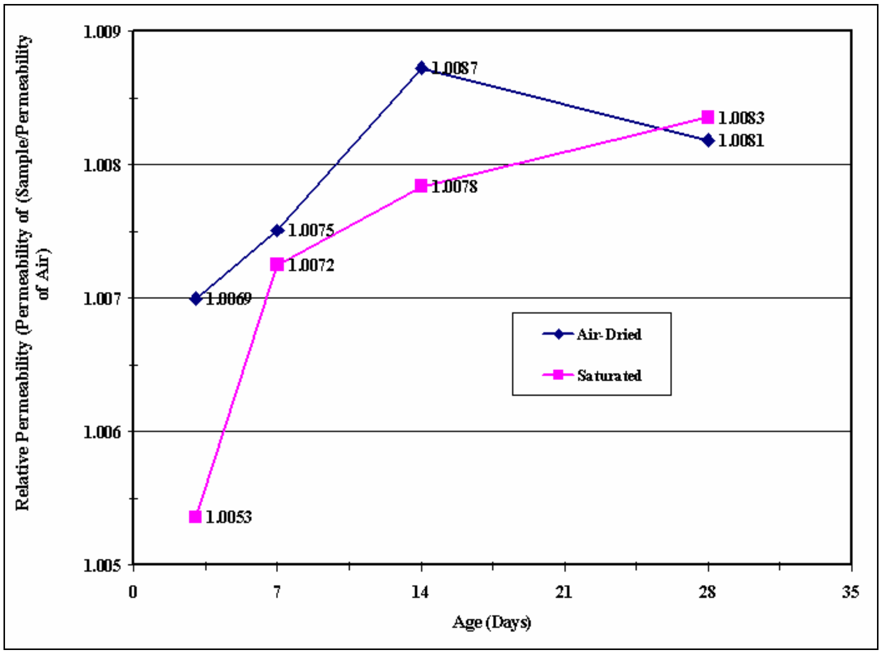


Figure 5-10: Electrical permeability of High Carbon Fly Ash CLSM Mixture CLSM-A

Dried vs. Saturated Specimens

Measurements taken for saturated CLSM specimens produced significantly smaller resistivity values compared to the air-dried specimens when tested without carbon fibers (Mixture CLSM-A). For the dried specimens, the aging process affected the resistivity significantly; the older the specimens, the higher the resistivity. The aging process affected the dried specimens more than the saturated ones. This indicates adding moisture to the material in place improves its conductivity. For the mixture containing carbon fibers, Mixture CLSM-B, air-dried specimens also had a higher electrical resistivity, but the difference between saturated and air-dried specimens were much less. Typically the difference between air-dried and saturated specimens was one ohm-cm or less. This may be attributed to the conductivity of the carbon fibers used in the mixtures.

Commonly-Used CLSM Mixtures

We Energies has been testing and utilizing controlled low-strength materials containing fly ash for construction for over 15 years. Though several mixture proportions have been tried, a few mixtures are commonly used that are re-excavatable by ordinary methods. These mixtures usually are required to be self-leveling and essentially free from shrinkage after hardening. The mixtures that are most commonly used are designed to reach a state of hardening such that they can support the weight of a person in less than 24 hours.

We Energies has developed and currently markets three different CLSM mixtures under the commercial name Flo-Pac. Flo-Pac is placed to lines and grades shown on the construction plans. Table 5-19 shows the mix designs for Flo-Pac 1, Flo-Pac 2 and Flo-Pac 5.

Table 5-19: Commonly Used High Carbon* Class F Fly Ash Mixtures and Proportions

Mixtures (lbs./Cu. ft.)	Flo-Pac 1	Flo-Pac 2	Flo-Pac 5**
Portland Cement	100	70	200
PWPP or VAPP Class F Fly Ash	1450	925	700
SSD Stone	0	0	1500
SSD Sand	0	1175	750
Water	950	832	533
Total Weight	2500	3002	3683

* Carbon content exceeds ASTM C618 requirements

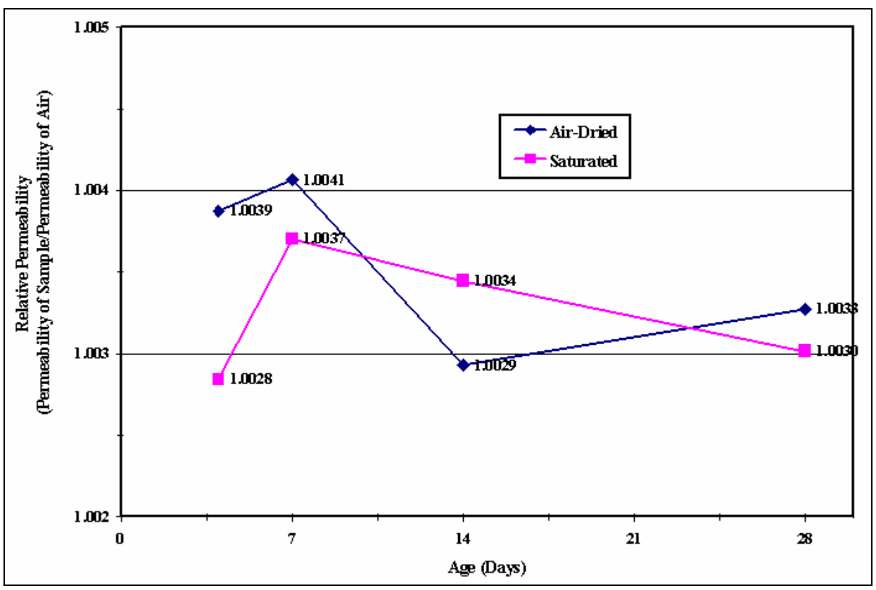


Figure 5-11: Electrical Permeability of High Carbon Fly Ash CLSM Mixture Containing Carbon Fiber CLSM

** Not excavatable

Pilot Projects Using We Energies CLSM

We Energies has utilized CLSM fly ash slurry on the following projects, where low strength and flowability were essential.

Abandoned Steam Service Tunnels

This was the first documented We Energies pilot project utilizing CLSM fly ash slurry. The project involved filling two obsolete brick lined steam service tunnels in downtown Milwaukee in December 1983. One tunnel was 6 ft. in diameter by 290 ft. long and the other had a 5 ft. by 4 ft. wide ellipsoid cross section.

Figure 5-12: ASTM D6103, Standard Test for CLSM Flow Consistency

Over 420 cubic yards of CLSM slurry material were produced from a typical mixture of 2,152 pounds of dry Class F fly ash, 859 pounds of water, and 88 pounds of Type I Portland cement. The fly ash was loaded directly into the ready-mix truck. The cement and water were also added directly and the drum was rotated at least 60 times during transit.

The CLSM flowable fly ash slurry was pumped into the tunnel. The maximum distance of CLSM flow was approximately 130 ft. Cylinders measuring 6” × 12” was prepared, and unconfined compression tests were run on the cylinders after 7 and 28 days, showing strengths between 50 and 100 psi, and greater than 100 psi, respectively. The project was completed over 15 years ago and no problems have been detected.

Figure 5-13: CLSM flowing through a funnel to fill an underground tunnel in downtown Milwaukee, Wisconsin.

Figure 5-14: We Energies' Flo-Pac CLSM being placed in a direct buried steam pipe trench in downtown Milwaukee, Wisconsin.

Sidewalk Cavity

This project was undertaken in 1984 and involved filling a hollow sidewalk cavity containing former locker room facilities in downtown Milwaukee. The CLSM flowable fly ash fill covered a length of about 80 ft., width of 14 ft. and a depth of 7 ft. The final top leveling layer was filled with sand (40).

About three hundred cubic yards of CLSM slurry was prepared using 1,950 lb. of dry Class F fly ash, 1,000 lb. of water and 128 lb. of Type 1 Portland cement. This mixture was placed directly into the cavity from ready mix trucks. Though minor shrinkage cracks were observed the following day, no voids or settlement was noticed.

Figure 5-15: CLSM being placed in lifts to manage the load on basement walls.

The site was excavated, using a tractor mounted backhoe, after several months to install a water supply lateral. The hardened slurry was easily rippable and the excavation had straight walls on each side. CLSM slurry with a compressive strength of less than 300 psi at 28 days worked well for this type of an application.

WisDOT Low Permeability CLSM with We Energies Fly Ash (41)

To ensure containment of contaminated soils and groundwater, WisDOT developed a CLSM with low permeability for use as a migration/contamination barrier during normal construction and construction emergencies. Strict physical requirements were specified for the WisDOT low permeability CLSM. The material needed to be flowable, with a maximum compressive strength of 100 psi, a maximum permeability of 1×10^{-6} cm/s and less than a 24-hour set.

Class C fly ash from We Energies' Pleasant Prairie Power Plant (PPPP) was used extensively during WisDOT low permeability CLSM mixture design study. The mixture using We Energies' PPPP Class C fly ash was one of two mixture designs which meet the above engineering properties requirement, as shown in Table 5-20.

Table 5-20: WisDOT Low Permeability CLSM Mixture Design with We Energies Class C Fly Ash

Weight (lbs/yd^3)	Material
50	Type I Portland Cement
700	Class C Fly Ash from We Energies Pleasant Prairie Power Plant
2640	Fine Aggregate per section 501.3.6.3 of the Wisconsin Standard Specifications
390	Water per section 501.3.5 of the Wisconsin Standard Specifications

Precautions to be Taken When Using CLSM Flowable Fly Ash Slurry

When properly mixed and placed, CLSM can provide construction savings by eliminating the need for labor intensive compaction efforts with standard granular materials. However, the following important construction considerations must be followed for success.

Figure 5-16: CLSM compression test cylinders. Note the color difference between those CLSMs based on Class F (dark) and Class C (light).

1. CLSM is placed as a liquid. Hence it exerts fluid pressure. If CLSM is placed against basement walls or other structures, verify that the

structure is capable of taking this lateral pressure. If the structure is not capable of handling this pressure, it can be braced externally until the CLSM slurry solidifies, or the CLSM slurry may be poured in multiple lifts so that one lift hardens before the next is poured.

2. Secure tanks, pipes and cables so they don't float in the excavation.

3. Fresh CLSM flowable fly ash slurry that is placed in deep excavations behaves like "quick-sand" so it must be protected from accidental entry until it hardens.

4. Low-strength CLSM material where re-excavation may be required at a later age should be specified with a maximum strength (or a range of strength) that will allow for easy re-excavation with normal equipment. The addition of coarse aggregate to the mixture generally makes re-excavation more difficult.

5. When transporting CLSM flowable slurry in a ready-mix truck, the driver should be aware of the liquid nature of the material being transported. CLSM may spill out of the back of a ready mix truck with quick stops or while travelling up hills. It is better to transport CLSM stiff and add water at the job site for high flow requirements.

Advantages of Using CLSM Fly Ash Slurry

CLSM fly ash slurry has several advantages when compared to conventional compacted backfill. The slurry mixture can be designed to meet the requirements of particular applications. The following are the major advantages:

Figure 5-17: Filling a tunnel with twin 30" diameter steam mains in Milwaukee, Wisconsin

1. CLSM fly ash slurry is flowable. The flowability can be increased or decreased by varying the water content. Hence, it can be used to fill inaccessible areas like retired sewer mains and tunnels where conventional ways of backfilling are difficult or economically not feasible. The flowable slurry fills voids completely, thus avoiding future settlement.

2. The level of strength can be increased or decreased depending on the application. Where re-excavation is required, the strength may be limited to the range of 50 to 300 psi maximum. Where higher strength is specified, such as base

material for foundations, changing the cementitious and aggregate proportions may increase the strength.

3. Unlike conventional backfilling methods, no tamping or vibration is required to place CLSM.
4. Long-term settlement is virtually nonexistent. Except for the initial shrinkage settlement of less than ⅛ inch per foot, there is no additional settlement after hardening. Hence, on pavement repairs and similar applications, a smoother ride can be expected.
5. There are substantial cost savings in using CLSM slurry, when compared to labor intensive conventional methods of backfilling. Fly ash slurry does not need compaction or vibration.
6. Utilizing fly ash for this application is making beneficial use of a coal combustion product, which is helpful to the environment. It preserves sand and gravel pits, crushed stone quarries, valuable landfill space; saves land that would be otherwise dedicated for these uses; and contributes to sustainable development by completely utilizing this resource and preserving virgin materials for future generations.

Figure 5-18: Volumetric mixer used for production of fast setting and excavatable CLSM in the Chicago area.

Chapter 6

Commercial Applications of We Energies Bottom Ash

Introduction

We Energies bottom ash can be beneficially utilized in a variety of manufacturing and construction applications. These applications include both confined and unconfined geotechnical uses, as an ingredient for the production of soil products and as an aggregate for concrete products. When using bottom ash, it is important to compare the applications and material properties to local and state regulations and specifications. In order to evaluate potential applications, We Energies has studied the properties and performance of the material with the assistance of several consulting firms and research institutions. We Energies bottom ash is predominantly used for the following applications:

1. Road base and sub-base
2. Structural fill
3. Backfill
4. Drainage media
5. Aggregate for concrete, asphalt and masonry
6. Abrasives/traction
7. Manufactured soil products

Road Base and Sub-Base

STS Consultants, Ltd. conducted a study for We Energies to evaluate the potential use of Pleasant Prairie Power Plant bottom ash as a base course in road construction (42). The study evaluated potential applications, and initiated durability and structural testing of bottom ash from We Energies Pleasant Prairie Power Plant.

The following tests were performed:

- Particle size analysis (ASTM D-422)
- Moisture-density relationship test - to establish maximum dry density (ASTM D-698-78, Method A).
- California Bearing Ratio (CBR) test - to develop a basis for comparison of bottom ash material with conventional base course aggregates (ASTM D-1883).
- Laboratory permeability test (ASTM D-2434)
- Direct shear test - to determine the angle of internal friction (ASTM D-3080)

The scope of this study included establishing an equivalent thickness of bottom ash compared to conventional aggregates in road construction. To address frost susceptibility in a meaningful manner, a sample of bottom ash was compacted into a 6” mold at its optimum moisture content. The mold with its perforated base was placed in a container of water for three (3) days to allow the sample to absorb water. The sample was then frozen and subsequently thawed. Volume change measurements were made after both freezing and thawing.

The gradation of bottom ash tested was comparable to a silty fine to coarse sand with little gravel. However, bottom ash was considerably finer grained than the conventional gradation for fine aggregate.

The PPPP bottom ash exhibited a maximum dry density of 88.5 pounds per cubic foot and optimum water content of 28%. Conventional aggregates have maximum densities in the range of 105 to 120 lb/cu ft. at optimum moisture contents typically in the range of 8% to 16%.

The CBR test results showed PPPP bottom ash had a CBR value on the order of 30% of that of conventional aggregate. In general, more coarsely graded and more angular materials tend to exhibit greater stiffness and tend to distribute load more evenly. The results showed that when used in a comparable thickness, bottom ash exhibits less favorable load distribution characteristics and would be more flexible, i.e., greater surface deformation under a load, than for conventional aggregates.

However, based on accepted pavement design principles, it was estimated that bottom ash used at approximately 1.5 times the thickness of conventional aggregates achieves a comparable stress level in the underlying clay subgrade. For equivalent deformation, it was estimated that the thickness of bottom ash should be two times the thickness of conventional aggregates to maintain similar deflection at the surface of the base course layer (42). Figure 6-1 shows the stress penetration CBR curve for PPPP bottom ash.

The report also evaluated frost susceptibility, since bottom ash contains more fine-grained particles than conventional aggregates. The permeability study of compacted bottom ash was in the same range as conventional base course aggregates, i.e., 8×10^{-4} to 5×10^{-5} cm/sec. However, due to the presence of slightly higher fines when compared to conventional materials, it is recommended that bottom ash be used at locations with reasonably good drainage.

The direct shear test indicated an angle of internal friction of 40 degrees and cohesion of 750 psf, for the ash tested. The friction angle is consistent with this type of material. Figure 6-2 is a graph showing the normal stress vs. shearing stress relationship. However zero cohesion was expected due to its similarity to silty sand. Freeze-thaw test results showed a volumetric expansion of the compacted ash of 0.4% upon freezing. But after thawing, the net volumetric expansion was 0.1%.

Table 6-1 shows the gradation for PPPP bottom ash and crushed aggregate base course (crushed gravel) per the 1996 Wisconsin DOT Standard Specification for Highway and Structure Construction at the time of testing. A comparison of We Energies' bottom ash to crushed aggregate base course in 2003 Wisconsin DOT Standard Specifications can be found in Chapter 3.

Table 6-1: Grain Size Distribution (ASTM D422) PPPP Bottom Ash and Comparison with WDOT Crushed Gravel Specification for Crushed Aggregate Base Course

Sieve Size	PPPP Bottom Ash % Passing	Gradation No. 1 Crushed Gravel % Passing	Gradation No. 2 Crushed Gravel % Passing	Gradation No. 3 Crushed Gravel % Passing
1.5"	100.00	100	-	-
1"	98.15	75 - 100	100	100
.75"	94.09	-	-	95 - 100
.50"	85.29	-	-	-
.375"	78.28	40 - 75	50 - 85	50 - 90
#4	57.78	30 - 60	35 - 65	35 - 70
#8	41.51	-	-	-
#10	36.99	20 - 45	25 - 50	20 - 55
#16	27.92	-	-	-
#30	17.72	-	-	-
#40	13.10	10 - 30	10 - 30	10 - 35
#50	10.56	-	-	-
#100	6.05	-	-	-
#200	3.05	3 - 10*	3 - 10*	8-15

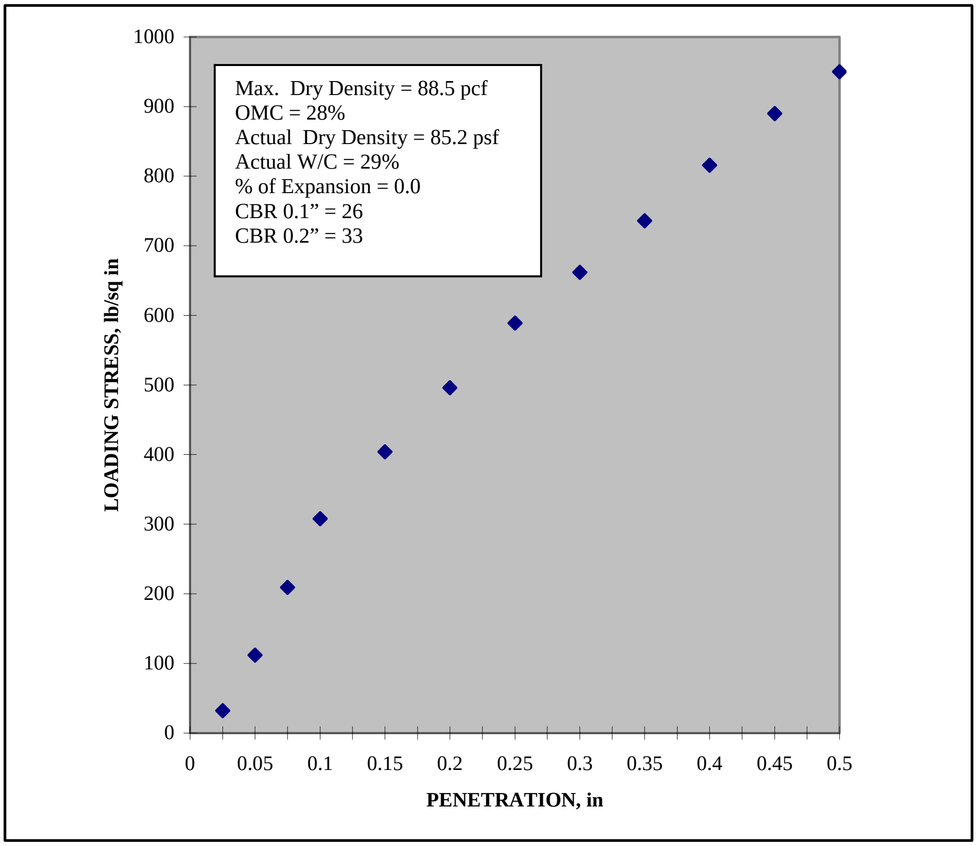


Figure 6–1: Loading Stress vs. Penetration (California Bearing Ratio) Curve for PPPP Bottom Ash

* Limited to a maximum of 8% in the base course placed between old and new pavement

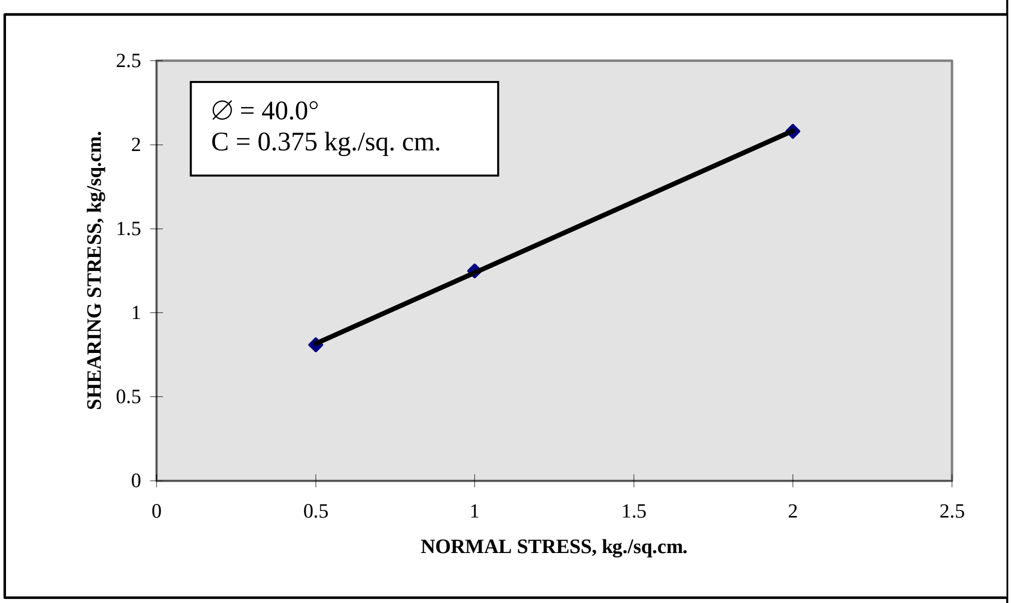


Figure 6–2: Normal Stress vs. Shearing Stress PPPP Bottom Ash

Field Study

Following the initial study conducted on the suitability of bottom ash from PPPP as a base course, another study was commenced with field observation and testing on the performance of bottom ash during construction of another roadway in the Lakeview Corporate Park (43). The purpose of the testing was:

1. To further evaluate the equivalency ratio using field plate load bearing tests.
2. To evaluate frost susceptibility during a winter season by level survey techniques.
3. To observe the general performance of the road subgrade for various thickness of base course.

Plate Load Test

As part of the road subgrade preparation, crushed limestone was placed in thicknesses varying from 0" to 6". Bottom ash was placed above the proof rolled subgrade and leveled with a Caterpillar 14G grader. Bottom ash was then compacted close to its Modified Proctor maximum dry density, in the range of 83 to 95 lb/cu ft. Crushed stone and gravel were placed in a parallel stretch of roadway and compacted to approximately 100% of its Modified Proctor maximum dry density. Plate load tests were performed in accordance with Military Standard 621A (Method 104).

Based on the test performed, a subgrade reaction modulus of 380 pounds per cubic inch (pci) was calculated. A similar test performed at the surface of the native subgrade gave a reaction modulus of approximately 212 pci. This gives a modular ratio of bottom ash to subgrade of approximately 1.9. Originally, a modular ratio of approximately 3 had been calculated. Conservatively, a modular ratio of 2 is appropriate.

Level Survey

The road surface was initially surveyed to establish a baseline for the determination of freeze-thaw effects. The level survey conducted on February 9, 1989, recorded a maximum surface heave of 0.6", but after the spring thaw, the surface elevations were within ± 0.24". These heaves were observed on both surfaces with and without bottom ash base course. The survey did not find any distinct pattern of response with the bottom ash experiencing neither greater nor lesser net heave during freeze-thaw cycles.

General Road Performance

The surface of the concrete road was inspected initially and found to be in competent condition, free of substantial ruts, cracking and other signs of pavement distress. The pavement was observed again after spring thaw and found to be in good condition. This indicated that the subgrade performed satisfactorily through the first winter.

It was concluded that the PPPP bottom ash materials are well suited for use as general structural fill in road subgrade preparations or below structural elements. Based on field observations, it was recommended to use bottom ash in a 2 to 1 thickness ratio compared to conventional base course material, to enhance the performance of the pavements. The reason for this recommendation is the lesser degree of stiffness of the bottom ash. It was concluded that in well-drained pavement sections, bottom ash base course (in the recommended thickness) should perform well.

Bottom Ash as Base Course Aggregate for Flexible Pavement Sections

The earlier study evaluated the performance of bottom ash as a base course material for a rigid pavement section. Though the pavement section performed well, a rigid pavement was used in that study and the performance of that section cannot be assumed to represent the behavior of less rigid pavement sections. Hence, a second pilot study was undertaken to evaluate the use of bottom ash for conventional base course aggregate in a flexible pavement section, such as parking lots and bituminous-paved roads (44).

A.W. Oakes & Son had observed that the actual performance of bottom ash in constructed haul roads was excellent. From this experience, they suggested that the ash might be effective at lesser thicknesses than recommended in the original study performed by STS Consultants, Ltd. A.W. Oakes & Son suggested that a pavement section consisting of 4” – 6” of bottom ash over 4” – 6” of open-graded crushed stone would serve as an excellent base for a heavy duty asphalt pavement.

Pavement Construction

A failed section of pavement 24 ft. wide by 55 ft. long located at the entrance drive of A.W. Oakes & Son Land Reclamation Landfill Facility in Racine, Wisconsin, was replaced with 4¾” of bituminous concrete pavement placed over 4½” – 6½” of bottom ash which was over 8” of an open-graded crushed stone base layer. The test section was constructed in November and December of 1993. Field density tests were performed by STS Consultants on the in-place bottom ash and on the in-place bituminous pavement using a nuclear density meter (44).

Figure 6-3: Bottom ash base course for concrete building slab in Racine, Wisconsin

Pavement Performance

The test pavement was evaluated by STS Consultants, Ltd. on March 21, 1994; November 22, 1994; April 20, 1995 and April 22, 1997. The field observations revealed that the pavement section performed well with only minor rutting in wheel traffic areas. The depth of rutting increased slightly over the years, but was not considered abnormal. The asphalt surface showed no signs of alligator cracking.

No direct correlation can be made with the adjoining pavement, since the age and construction of this pavement is unknown. However, from field observations, it was concluded that the pavement section appeared to be comparable to or better than the adjacent pavement. Recent evaluation of the pavement by We Energies staff confirmed that the pavement is in good condition.

We Energies Bottom Ash Backfill

We Energies bottom ash has been successfully used as a backfill material on numerous projects. PPPP bottom ash is a clean, durable, torpedo sand-like material. Other We Energies bottom ashes are finer or include gravel size gradation particles as well.

The suitability of bottom ash as a backfill material can be understood from its close resemblance to commonly used natural granular backfill materials. In most cases, the most critical factor is the gradation of backfill material.

Sieve analyses indicated that bottom ash from PPPP and PIPP (Units 7–9) meets the gradation requirements for a granular backfill material by both the WDOT and the MDOT. The bottom ash from PIPP Units 1-6 does not meet the specifications because over 23% of fines passed the No. 200 sieve. However this ash from PIPP can be blended, washed or screened to meet the requirements. Other analyses have shown that bottom ash from OCPP also meets the WDOT gradation requirement for granular backfill.

Figure 6-4: Bottom ash structural backfill being used for building construction in Racine, Wisconsin

Permeability of the backfill is a common concern, especially in applications where the backfill material is subjected to a moist environment. Permeability is also one of the major reasons that sand is a preferred backfill material when compared to clay.

Since the gradation of bottom ash and sand are similar, they tend to exhibit similar permeability. Clean fine sand has a coefficient of permeability (K) in the range of 0.004 to 0.02 cm/sec (45). The drainage characteristics associated with the above K values are considered good. Most We Energies bottom ashes have a coefficient of permeability in this range and can be considered to provide good drainage when used as a backfill material.

Table 6-2 gives the coefficient of permeability for We Energies bottom ash and conventional backfill materials.

Table 6-2: Permeability and Drainage Characteristics of Backfill Material

Type	Approximate Coefficient of Permeability K, cm/sec	Drainage Characteristics
Clean Gravel	5 - 10	Good
Clean Coarse Sand	0.4 - 3	Good
Clean Medium Sand	0.05 - 0.15	Good
VAPP Bottom Ash	0.0054	Good
OCPP Bottom Ash	0.001	Good
PIPP 1-6 Bottom Ash	0.0048	Good
PPPP Bottom Ash	0.0049	Good
PWPP Bottom Ash	0.0046	Good
Clean Fine Sand	0.004 - 0.02	Good
Silty Sand and Gravel	10^{-5} - 0.01	Poor to Good
Silty Sand	10^{-5} - 10^{-4}	Poor
Sandy Clay	10^{-6} - 10^{-5}	Poor
Silty Clay	$l0^{-6}$	Poor
Clay	10^{-7}	Poor
Colloidal Clay	10^{-9}	Poor

Bottom ash has a lower density when compared to conventional backfill materials. Conventional backfill materials (like sand) typically have a maximum dry density of 105 to 120 lb/cu ft. We Energies bottom ash has a maximum dry density in the range of 49 to 89 1b/cu ft. VAPP bottom ash showed the lowest dry density of 49 lbs./cu ft., and PPPP bottom ash had the highest density of 89 lbs/cu ft.

Bottom ashes from VAPP and MCPP have a higher percentage of fines and are more sensitive to moisture changes. However, bottom ash from other power plants performed well when compacted at the optimum moisture content. Soil generally exhibits lateral earth pressure. Structures like retaining walls have to be designed, considering the lateral pressure exerted by soil retained by the structure. The angle of internal friction for various backfill materials is shown in Table 6-3.

Table 6-3: Approximate Friction Angle

Soil Type	Ø Degrees	Tan Ø
Silt or Uniform Fine to Medium Sand	26 to 30	0.5 to 0.6
Well-Graded Sand	30 to 34	0.6 to 0.7
Sand and Gravel	32 to 36	0.6 to 0.7

The friction angle of bottom ash is very similar to that of well-graded sand and gravel. The lateral earth pressure on the structure can be reduced because of the lower material density. Assume that the dry unit weight of a specific bottom ash in such a situation is only ⅔ of the dry unit weight of conventional backfill material. Because the friction angle value remains more or less the same, the lateral earth pressure will also be reduced to ⅔ of regular fill. Due to the reduced lateral pressure on the wall, it can be designed as a thinner section, with less reinforcement, or with a higher safety factor.

Bottom Ash as an Anti-Skid Material

Bottom ash performs as an excellent anti-skid material when spread on ice or snow covered roads. Bottom ash does not have the corrosivity of salt, as only a very small fraction of it is soluble. The performance of bottom ash as an anti-skid material is not temperature dependent. For this reason, bottom ash can be considered a better anti-skid material than road salt. The WisDOT recommends the following rate of application (46):

1. A rate of 500 pounds per mile on average snowy and icy roads.
2. A rate of 800 pounds per mile at intersections, hills, curves and extremely icy areas.

Used tires are sometimes burned with coal in some power plants in the United States. Bottom ash produced from plants that burn tires may contain steel wires that are left from the steel belted radial tires. Bottom ash containing steel wires is not suitable for use on roads as steel can puncture tires of vehicles traveling on these roads.

We Energies power plants do not burn used tires with coal. Hence, the bottom ash will not contain such steel wires and is acceptable for use as an anti-skid material on roads. Bottom ash will usually require screening to meet anti-skid material gradation requirements.

Bottom Ash as an Aggregate in Asphaltic Concrete

A.W. Oakes & Son replaced fine aggregates with bottom ash in asphaltic concrete mixtures for paving projects. Since bottom ash particles are porous, the consumption or absorption of asphalt binder is higher than when the conventional fine aggregate is used. Hence, from a purely economical point of view, We Energies bottom ash is not best suited as an aggregate for asphaltic concrete. However, other bottom ash sources have been extensively used by West Virginia Department of Transportation for asphalt roads, particularly for secondary roads (47).

Bottom Ash as a Bike Trail Base and Surface Material

Bottom ash has been successfully used as a base and surface material for bike trails and as a surface course material in parks and for running tracks.

In several states in the United States, bottom ash has been used as a finish grade surfacing material. The New River Trail in Virginia surfaced a portion of its 57-mile route with bottom ash. This project demonstrated significant savings in cost compared to a similar crushed stone surface (47).

We Energies Bottom Ash as a Manufactured Soil Ingredient

During the past several years, We Energies studied the properties of bottom ash and its use as a soil-amending agent to heavy clayey soils to increase its workability and porosity. Studies conducted at the University of Wisconsin-Madison (48) revealed that land application of bottom ash had no negative effect on the crops or soil during the five-year period of study.

Bottom ash from the OCPP and PPPP were used on farms in Kenosha County, Wisconsin, at a rate ranging from 100 to 200 tons per acre. Bottom ash was tilled into the soil to a depth of approximately 10”.

Corn was grown on this field for two years and soybeans were grown for one year. Chemical analysis conducted on the soil throughout the three-year study revealed that there was no appreciable movement of nutrients or heavy metals below the 10” plow layer. Chemical analysis of corn and soybean seed and edible tissue for heavy metals and nutrient uptake indicated no adverse effect. Crop yield at the bottom ash treated soils was generally higher than from the non-treated soils.

The Scott’s Company of Maryville, Ohio, studied the properties of We Energies bottom ash and determined that it is suitable as an ingredient in manufactured soil products. The bottom ash from Milwaukee County Power Plant, Port Washington Power Plant and Valley Power Plant were used in their studies.

Figure 6–5: "Before" grass growing on We Energies' landscaping with Scott's 10% bottom ash topsoil blend at We Energies' Milwaukee County Power Plant.

Their investigation has determined that the addition of 10–15% (weight basis) of bottom ash provides desired soil porosities. In addition, the ash blended soils exhibit excellent micronutrient composition.

The mixture also meets all of the state and federal limits for trace elements in composted soils. Bottom ash has been blended with peat, compost and manure to manufacture about 300 cubic yards of manufactured topsoil for We Energies landscaping projects with excellent results.

Figure 6–6: "After" grass is growing on landscaping with Scott's Hyponex 10% bottom ash topsoil blend at We Energies' Milwaukee County Power Plant.

Table 6-4 shows the summary of total elemental analysis results for fly ash and bottom ash and comparison to Wisconsin DNR, NR 538 standards, together with various naturally occurring materials. Table 6-5 shows ASTM water leach test data, in a similar fashion.

Additional information on environmental considerations is provided in Chapter 9.

Table 6-4: Total Elemental Analysis
Comparison of Sample We Energies Fly Ash, Bottom Ash and Natural Materials

Parameter	Units	NR 538 Category 1 Criteria	NR 538 Category 2 Criteria	Fly Ash	Bottom Ash	Road Gravel	Sand	Pea Gravel	Crushed Limestone	Garden Top Soil	Recycled Concrete
Antimony	mg/kg	6.3									
Arsenic	mg/kg	0.042	21	31	4.2	2.8	1.1	2.1	1.0	4.0	2.3
Barium	mg/kg	1100		2000	410						
Beryllium	mg/kg	0.014	7	11	1.4	0.2	0.2	0.3		0.8	0.8
Boron	mg/kg	1400		690	60						
Cadmium	mg/kg	7.8		2.3	0.059						
Chromium	mg/kg	14.5 as Cr+6			65.5	22.4	34.1			59.1	33.2
Lead	mg/kg	50			23.6	14.1				43.3	
Mercury	mg/kg	4.7			0.11						
Molybdenum	mg/kg	78		12	1.6						
Nickel	mg/kg	310		40.4	28.1	6.4					6.2
Selenium	mg/kg	78									
Silver	mg/kg	9400									
Strontium	mg/kg	9400				71.7	65.5	74.3	25.6	129.4	113.4
Thallium	mg/kg	1.3									
Vanadium	mg/kg	110		201							
Zinc	mg/kg	4700		111	49.7	16.0	11.2	9.8	5.3	162	23.3

Note: Concentrations not shown are below the analytical detection levels

Table 6-5: ASTM D3987 Water Leach Test Data
Comparison of Sample We Energies Fly Ash, Bottom Ash and Natural Materials

Parameter	Units	NR 538 Category 1 Criteria	NR 538 Category 2 Criteria	Fly Ash	Bottom Ash	Road Gravel	Sand	Pea Gravel	Crushed Limestone	Mequon Clay	Garden Top Soil	Recycled Concrete
Aluminum	mg/l	1.5	15	9.7	3.6	0.128	0.18	0.091	0.032	0.086	0.138	2.9
Antimony	mg/l	0.0012	0.012			0.0055		0.0032	0.0052	0.0026	0.0047	0.002
Arsenic	mg/l	0.005	0.05	0.003	0.004					0.0017	0.0016	
Barium	mg/l	0.4	4	0.76	0.25	0.0021	0.0017	0.0024	0.0018	0.0071	0.0135	0.146
Beryllium	mg/l	0.0004	0.004	0.0031		0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003
Cadmium	mg/l	0.0005	0.005									
Chloride	mg/l	125		0.57								
Chromium	mg/l	0.01	0.1	0.11	0.0013							0.019
Copper	mg/l	1.3			0.0096							
Iron	mg/l	0.15			0.1					0.033	0.092	0.008
Lead	mg/l	0.0015	0.015		0.0016			0.0012				0.0012
Manganese	mg/l	0.025	0.25		0.0033					0.003		0.003
Mercury	mg/l	0.0002	0.002									
Molybdenum	mg/l	0.05		0.23	0.014							
Nickel	mg/l	0.02										
Selenium	mg/l	0.01	0.1	0.034	0.0013							
Sulfate	mg/l	125	1250	35	68						28.1	11
Thallium	mg/l	0.0004	0.004									

Note: Concentrations not shown are below the analytical detection levels

We Energies Bottom Ash as a Soil Ingredient for Green Roofs

We Energies bottom ash was also used experimentally as a portion of a soil ingredient in green roofs. Green roofs involve growing plants on rooftops, thus replacing the vegetated footprint that was destroyed when the building was constructed. Establishing plant material on rooftops provides numerous ecological and economic benefits including stormwater management, energy conservation, mitigation of the urban heat island effect, increased longevity of roofing membranes, as well as providing a more aesthetically pleasing environment to work and live. Examples of green roofs are shown in Figures 6-7 and 6-8.

Additional loading is one of the main factors in determining both the viability and the cost of a green roof installation, especially when a green roof is not part of the initial design of the building. Bottom ash is a lightweight material.

Figure 6–7: Green Roof at ABC Supply Company, Inc.

Blending bottom ash with the soil provides a lightweight growing media for the plants of the green roofs. We Energies' bottom ash was used for a small portion of the green roof (as a blended soil ingredient) by ABC Supply Company, Inc. in Beloit, Wisconsin. Additional information can be found on website at: http://www.greengridroofs.com/Pages/system.htm

Figure 6–8: Green Roof at ABC Supply Company, Inc.

We Energies Recovered Ash and Reburning

Coal Ash Recovery (U.S. Patent # 6,637,354) (49)

As part of We Energies' continued effort to find innovative applications for its coal combustion products, and to preserve valuable licensed landfill capacity, We Energies has patented a process for recovery of coal combustion products from the PPPP ash landfill. The PPPP ash landfill occupies an area of approximately 163 acres and is located north of Bain Station road and south of Highway 50.

The landfill was placed in operation in 1980 and consists of 25 cells with a total licensed capacity of 3,012,155 cubic yards of coal combustion products. Cell 1 was constructed with a natural 5 ft. thick clay liner and cells 2–4 were constructed with a 5 ft. thick recompacted clay groundwater separation liner. Currently only cells 1–3 are filled and cell 4 is partially filled. Since demand for bottom ash and fly ash has continued to increase since the 1980's, the quantity of material that goes into these landfills is limited. Since 1998, more material has been recovered from the landfill than placed in it.

The coal combustion materials landfilled in cells 1–4 consist primarily of bottom ash, solidified fly ash and wastewater treatment system solids. We Energies ash reclamation plan is to excavate the landfilled material, crush and

Figure 6-9: Coal ash recovery from the Pleasant Prairie Power Plant ash landfill for use as granular base course material

screen if necessary, test and store for reuse in compliance with the criteria defined in NR 538, plus boron as an additional leachable parameter in

Figure 6-10: Recovered coal ash from the Pleasant Prairie Power Plant ash landfill

accordance with a Cooperative agreement signed with the Wisconsin DNR (50). Any material that is found to be unsuitable for beneficial application such as miscellaneous debris or soil is separated and properly placed in designated areas within the current active cell.

The first pilot project to reprocess landfilled combustion products were carried out in July 1998 and the second in October 1998. An earthwork contractor who was very experienced in landfill and ash management performed the work. A state certified material testing laboratory was also hired to monitor and sample the processed material, during the first operation. The contractor's engineer collected samples during the second operation. Samples were collected every 30 minutes from the transfer point where the ash fell onto the stacker conveyor during the entire operation per ASTM sampling procedure D2234. A composite sample was prepared for every 5000 tons processed and tested.

Both ash recovery operations worked very smoothly, and were dust free due to the residual moisture and low fines content of the material processed.

Figure 6-11 shows the grain size distribution range of the recovered ash. It is important to mention that the samples tested had excellent grain size distribution and a small amount of material passing the #200 sieve. Tests run

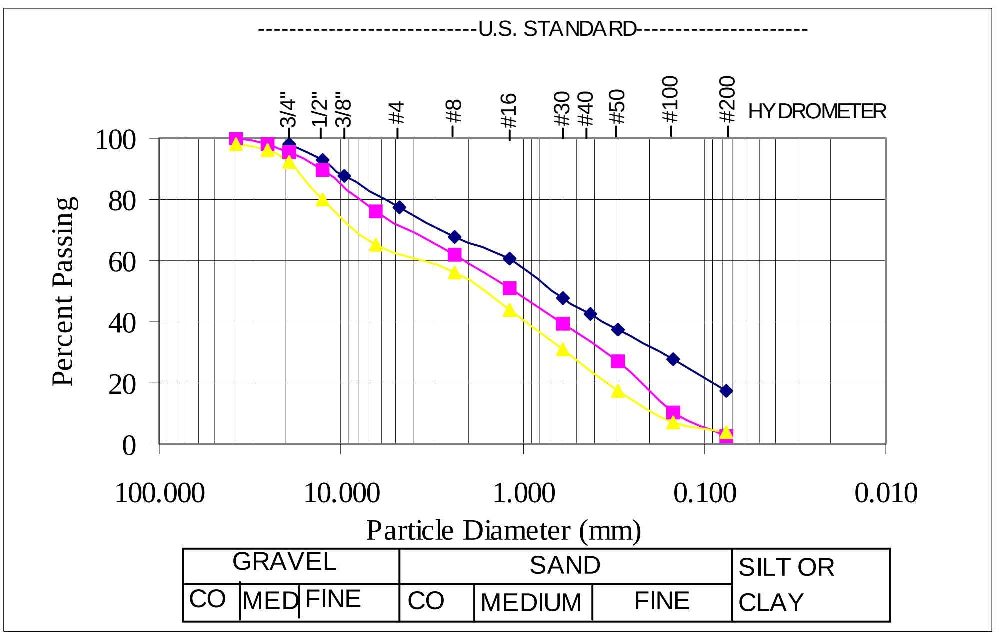


Figure 6–11: Gradation Distribution Range of Recovered Ash

to evaluate the environmental effects of this material also gave encouraging results. The ash met all of the NR538 category 2 criteria with the exception of dissolved aluminum. However the concentration of aluminum was only slightly above the limits (18 to 22 mg/l vs. 15 mg/l criteria).

The only other compounds detected that were within one order of magnitude of the category 2 criteria were antimony, barium, chromium and sulfate. The remaining elements were either non-detectable or were several orders of magnitude below the category 2 criteria.

The first 10,000 tons of recovered ash was used as a sub-base material under pavements. This practice has continued due to the excellent sub-base and base performance of the interlocking angular shaped recovered ash particles for this application. This is an application meeting NR538.10 (5) category 4 standards. However the recovered ash test results meet most of the NR 538 category 2 requirements.

In February 2001, Wisconsin DNR and We Energies entered into an agreement in which an ash sampling and testing procedure was specified. In order to determine the chemical consistency of the coal combustion materials recovered from the landfill, the ash will be excavated, processed, and stored in a designated area in the landfill in no larger than 50,000 cubic yard piles. A representative sample will be obtained per each 10,000 tons of reclaimed material for testing using guidelines presented in ASTM D2234. A minimum of five discrete samples of at least 25 pounds each will be collected from different locations on the storage pile. These discrete samples will be composited, mixed, and volume reduced by manual riffling to develop the analysis sample. Testing will be performed to measure category 2 parameters (described in ch. NR 538, Wis. Adm. Code), as well as boron as an additional leachable parameter, for use as sand/gravel/and crushed stone replacement materials. These recovered materials will be used in category 4 or 5 applications (described in ch. NR 538, Wis. Adm. Code).

Reburning of Coal Ash (U.S. Patent # 5,992,336) (51)

If coal ash has a significant amount of unburned carbon, it cannot be utilized directly in applications such as concrete, and concrete products. According to ASTM C618, an ash must have a LOI value no higher than 6% for use in concrete. An upper limit of 3% is more realistic. Higher LOI ash cannot be used because of color problems and concerns for durability under freezing and thawing conditions.

We Energies is utilizing an innovative technique, reburning of coal ash, to treat high carbon coal ash using existing capital installations, and particularly the existing pulverized coal boilers. Coal ash, either fly ash or bottom ash or a mixture of both, is added in a fine particle condition to the furnace of a pulverized coal boiler in a small proportion to the pulverized coal fed to the furnace. The ash is burned with the pulverized coal. The proportion of coal ash is preferably in the range of 1% – 3.5%, by weight of the pulverized coal.

The high carbon coal ash generally results from burning bituminous coal while sub-bituminous coal will typically result in a low carbon ash with an LOI of less than 1%. The high LOI fly ash and bottom ash formed from a pulverized coal furnace burning bituminous coal can be rendered into a usable fly ash and bottom ash having very low LOI such as produced in a pulverized coal furnace using subbituminous coals. This can be achieved by adding the high LOI coal ashes to the coal stream which normally produces low LOI coal ashes.

The bottom ash and fly ash may be handled separately. The bottom ash typically has a larger particle size and may require grinding to reduce it to the size of the pulverized coal stream. The preferred approach for handling of the bottom ash is to add it to the store of coal prior to the coal being ground.

For instance in original tests conducted in 1996, bottom ash having an LOI of 37.9% and a moisture content of 60.0% was added to loaded coal cars using a front end loader. The bottom ash was added at a ratio of 5% of the coal prior to unloading in a rotary car unloader. The coal cars were then unloaded in a normal manner and the coal was transported by a conveyor system to one of five coal silos. The bottom ash and coal mixture was then milled and injected into the boiler with the fuel stream during normal operation in the furnace along with coal from the other four silos and mills that did not contain bottom ash. Thus, the actual ratio of bottom ash to coal transported for combustion was 1% of the overall fuel being burned. The addition of the 1% of bottom ash was not significant from an operational viewpoint. There was no discernable difference in emissions, and the bottom ash coal fuel blend had adequate fineness for combustion. The fly ash from the reburning of the bottom ash exhibited a LOI of between 0.2% and 0.4% and has a slightly reduced calcium oxide content. Bottom ash typically represents less than 20% of the coal ash.

High LOI fly ash can be introduced using four approaches: (1) introduced with the pulverized coal stream entering the pulverizer classifiers. This has the advantage of thorough mixing upstream of the burners and would require only a slight additional volume of air to transport the fly ash; (2) introduced with the pulverized coal stream at each burner location; (3) introduced with the secondary air flow stream as it enter the furnace. The secondary air flow with the fly ash provides sufficient mixing; (4) introduced through heat-resistant or stainless pipes; and (5) introduced into the furnace either above or adjacent to the existing burner level through separate pipes. Injection points through a waterwall could be used, although this may require modifications of the waterwalls in the boilers.

For instance in original tests conducted in 1996, a fly ash having an LOI of 26.5% and a moisture content of 0.3% was introduced into a coal pulverized furnace through injection pipes. The fly ash was stored in a horizontal silo from which it was pumped through stainless steel pipes extending through the furnace wall immediately above two coal burners. The hose was connected to a reducer splitter where the 5" diameter hose was reduced to two 2" diameter hoses. The fly ash was pumped at a rate of approximately 1% –2% of the coal flow into the furnace. The addition of the fly ash to the combustion did not affect combustion. The resulting fly ash from the reburning had an LOI of between 0.2% and 0.5% based upon samples taken at intervals over four days. Reburning of high carbon bituminous coal ash in sub-bituminous pulverized fuel furnaces is now a regular procedure at We Energies Pleasant Prairie Power Plant in Wisconsin and Presque Isle Power Plant in upper Michigan with excellent results.

We Energies Bottom Ash as Fine Aggregate in Concrete Masonry Products

Natural volcanic combustion products have been used in the manufacture of masonry products since ancient times. Several decades ago cinders, a combustion product of lump coal combustion, were used as a lightweight aggregate in the manufacture of masonry blocks. However, not much technical data was available on these products. Today, fly ash and bottom ash have been extensively investigated to determine performance.

We Energies has investigated the suitability of its bottom ash and fly ash in the manufacture of concrete bricks, blocks and paving stones. The following data is from research conducted at the Center for By-Products Utilization (CBU) of the University of Wisconsin-Milwaukee for We Energies at two local manufacturing plants (52).

Concrete masonry products can be manufactured either by the wet-cast process or the dry-cast process. Several mixes were designed at the CBU for the manufacture of concrete bricks, blocks and paving stones using the dry-cast method. Actual manufacture of the dry-cast test products was performed at Best Block Company in Racine, Wisconsin, using standard manufacturing equipment.

Tables 6-6 – 6-8 show the mixture design data for bricks, blocks and paving stones using the dry-cast method. Tables 6-9 – 6-11 show the compressive strength data for the above-mentioned products. The three mixtures for each product have varying amounts of fly ash and bottom ash. Each of the three products also has a control mixture with no fly ash and no bottom ash.

Table 6-6: Dry-Cast Concrete Brick Mixtures Using OCPP Bottom Ash and Fly Ash

Mix No.	BR-1	BR-2	BR-3	BR-4
Field Mix Designation	1	3	8	10
Fly Ash, [A/(C+A)](%)	0	29	29	41
Bottom Ash, [BA/S+BA)](%)	0	0	23	33
Cement, C (lb/yd^3)	345	260	245	215
Fly Ash, A (lb/yd^3)	0	110	100	150
Net Water, W (lb/yd^3)	145	160	190	260
[W/(C+A)]	0.43	0.43	0.55	0.72
SSD Fine Aggregate, S (lb/yd^3)	2335	2365	1655	1455
SSD Bottom Ash, BA (lb/yd^3)	0	0	490	705
SSD ⅜" Crushed Limestone Aggregate (lb/yd^3)	795	805	750	750
Moisture Content of Mixture, %	5.6	5.9	7.8	10.1
Unit Weight (lb/ft^3)	134.0	137.0	127.0	131.0
Test Batch Yield (yd^3)	0.60	0.60	0.60	0.60

The dry-cast concrete brick mixture BR-1 (control mix) had a 56-day strength that was lower than that of BR-2, a similar mix containing fly ash. Twenty-five percent cement was replaced with fly ash at a 1 – 1.3 replacement ratio. The exact proportions can be seen in Table 6-6.

Brick mixtures BR-3 and BR-4 containing bottom ash and fly ash showed lower compressive strengths at the 56-day age. The compressive strengths obtained were all above 3,000 psi. This level of strength is good for most applications. Similar strength patterns are also seen for blocks and paving stones.

Long-term behaviors of these masonry products are currently being studied at CBU. When this information is available, a better conclusion can be made about these products. However, based on available data, it can be seen that concrete bricks, blocks and paving stones with reasonable strength can be made using fly ash and bottom ash.

Table 6-7: Dry-Cast Concrete Block Mixtures

Mix No.	BL-1	BL-2	BL-3	BL-4
Field Mix Designation	13	14	16	18
Fly Ash, [A/(C+A) (%)	0	30	29	40
Bottom Ash, [BA/(S+BA)] (%)	0	0	23	33
Cement, C (lb/yd^3)	345	265	245	215
Fly Ash, A (lb/yd^3)	0	110	100	150
Net Water, W (lb/yd^3)	161	160	190	260
[W/(C+A)]	0.36	0.43	0.54	0.71
SSD Fine Aggregate, S (lb/yd^3)	2300	2355	1775	1430
SSD Bottom Ash, BA (lb/yd^3)	0	0	495	715
SSD 3/8" Crushed Limestone Aggregate (lb/yd^3)	795	815	755	765
Moisture Content of Mixture, %	5.9	5.9	6.5	10.1
Unit Weight (lb/ft^3)	137	137	127	131
Test Batch Yield (yd^3)	0.60	0.60	0.60	0.60

Table 6-8: Dry-Cast Concrete Paving Stone Mixtures

Mix No.	PS-1	PS-2	PS-3	PS-4
Field Mix Designation	2	4	6	11
Fly Ash, [A/(C+A)] (%)	0	18	18	30
Bottom Ash, [BA/(S+BA)] (%)	0	0	24	33
Cement, C (lb/yd^3)	650	560	510	425
Fly Ash, A (lb/yd^3)	0	125	115	180
Net Water, W (lb/yd^3)	16	180	195	190
[W/(C+A)]	0.25	0.26	0.31	0.31
SSD Fine Aggregate, S (lb/yd^3)	2205	2235	1540	1255
SSD Bottom Ash, BA (lb/yd^3)	0	0	475	605
SSD 3/8" Crushed Limestone Aggregate, (lb/yd^3)	750	760	695	650
Moisture Content of Mixture, %	5.7	6.1	7.6	8.0
Unit Weight (lb/ft^3)	139	143	131	122
Test Batch Yield (yd^3)	0.62	0.61	0.66	0.70

Table 6-9: Compressive Strength of Dry-Cast Concrete Bricks

Mixture No.	Field Mix No.	Fly Ash %	Bottom Ash %	Compressive Strength (psi)					
				5 Day		28 Day		56 Day	
				Act.	Avg.	Act.	Avg.	Act.	Avg.
BR-1	1	0	0	3255	3660	4005	4530	4480	4750
				3830		4345		4730	
				3895		4485		4735	
				--		4525		5055	
				--		4850		--	
				--		4935		--	
BR-2	3	29	0	2740	3360	3855	4650	490	5300
				3365		4645		5025	
				3970		4659		5220	
				--		4780		5550	
				-		4880		5785	
				--		5065		--	
BR-3	8	29	23	2260	2360	2530	2740	2600	3210
				2360		2610		3285	
				2460		2705		3305	
				--		2810		3375	
				--		2880		3480	
				--		2930		--	
BR-4	10	41	33	1690	1870	2835	3130	2650	3490
				1770		3130		3570	
				2140		3175		3635	
				--		3190		3700	
				--		3225		3910	
				--		3230		--	

ASTM C90 requirement for compressive strength is 1900 psi minimum average of 3 units and 1700 psi minimum individual brick.

Table 6-10
Compressive Strength of Dry-Cast Concrete Blocks

Mixture No.	Field Mix No.	Fly Ash %	Bottom Ash %	Compressive Strength (psi) based on average net area							
				7 Day		14 Day		28 Day		91 Day	
				Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
BL-1	13	0	0	2605	2780	2825	3150	2850	3290	3240	3350
				2775		3290		3415		3360	
				2955		3345		3610		3460	
BL-2	14	30	0	2830	2990	2805	2880	3405	3690	4200	4240
				3055		2880		3545		4215	
				3080		2950		4115		4300	
BL-3	16	29	23	2075	2150	2875	2960	3030	3100	3130	3260
				2190		2875		3110		3225	
				2195		3125		3150		3435	
BL-4	18	40	33	1315	1410	1790	1810	2040	2220	2075	2340
				1405		1805		2220		2260	
				1520		1825		2390		2695	

ASTM C90 requirement for compressive strength is 1900 psi minimum average of 3 units and 1700 psi minimum individual brick.

Table 6-11: Compressive Strength of Dry-Cast Concrete Paving Stones

Mixture No.	Field Mix No.	Fly Ash %	Bottom Ash %	Compressive Strength (psi)									
				5 Day		8 Day		28 Day		56 Day		91 Day	
				Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
PS-1	2	0	0	3820	5550	7100	7610	4460	4900	5515	7040	7050	7595
				5805		7630		4855		5745		7495	
				7025		8095		4950		7515		8235	
				--		--		5020		8075		--	
				--		--		5040		8365		--	
				--		--		5085		--		--	
PS-2	4	18	0	7745	7800	7020	7410	5640	6880	7120	8020	7700	7790
				7770		7265		5645		7895		7735	
				7880		7950		6645		8075		7790	
				--		--		6655		8985		7920	
				--		--		8195		--		8385	
				--		--		8520		--		--	
PS-3	6	18	24	3250	3840	3575	3870	5005	5310	5390	5740	5420	6050
				3935		3750		5015		5660		5775	
				4065		4295		5080		5725		6030	
				--		--		5565		5935		6035	
				--		--		5865		5975		6975	
PS-4	11	30	33	2080	2270	2945	2760	2865	3190	2820	3290	3435	3690
				2440		2815		3080		3245		3545	
				2295		2520		3155		3285		3675	
				--		--		3215		3350		3875	
				--		--		3385		3765		3925	
				--		--		3445		--		--	

Chapter 7

Fly Ash Stabilized Cold In-Place Recycled Asphalt Pavements, Stabilized Soils, and Stabilized Coal Ash

Introduction

We Energies conducted studies in cooperation with Bloom Consultants, LLC and the Center for Highway and Traffic Engineering at Marquette University in Milwaukee, Wisconsin to evaluate the potential application of fly ash in asphalt pavement construction. In a typical cold in-place recycled (CIR) application, existing hot mix asphalt (HMA) layers are pulverized, graded, compacted and used as a base layer for a new hot mix asphalt surface. In most CIR applications, the existing HMA layers are pulverized to the full thickness, and in some cases through the top 2” or 3” or the entire depth of aggregate base. The CIR material is sprayed with water to get the desired moisture content. The material is graded and then compacted with vibrating steel drums and pneumatic tired rollers.

In recent years, stabilizers have been added into the CIR materials to improve the structural capacity of the CIR layers. In these studies self cementing Class C fly ash was used to bond with CIR materials and the long-term performance of the final pavement section is being studied.

In addition, Class C fly ash was used by We Energies to stabilize a coal ash land fill to construct a commercial office building parking lot.

Case Study I: Highland Avenue, Mequon

A 1.5 mile long section of West Highland Avenue, between Wauwatosa Avenue and Farmdale Road, was resurfaced in 1997. The existing pavement had a 5½” thick asphaltic surface with an aggregate base varying in thickness from 7” – 18”. This stretch of road is a two-lane cross section with an average annual daily traffic (AADT) of 1150. The pavement was constructed over a natural cohesive soil subgrade material.

Through a 1.5 mile length of the pavement was resurfaced, two 800 ft. long test sections were stabilized with a fly ash binder and an asphalt emulsion binder respectively. The project was undertaken in August of 1997. The existing HMA surface was pulverized to a total depth of 8", then graded and compacted using standard procedures.

The 800 ft. asphalt emulsion stabilized test section was constructed by repulverizing the upper 4" of the CIR base, and incorporating emulsified asphalt at a rate of 1½ gallons per square yard. The base was then graded and compacted. The 800-ft. length of fly ash stabilized CIR section was constructed by applying 35 lbs./yd^2 of Pleasant Prairie ASTM C618, Class C fly ash over the pulverized CIR base and repulverizing the top 5" of CIR base. The pulverized layer was shaped with the grader and moistened with surface applied water, at the rate of 8 gal/yd^2. The stabilized base was graded and compacted similar to the other test section.

The asphalt emulsion stabilized test section received a 3½" HMA surface, and the fly ash stabilized test section received a 4" HMA surface. The remaining portion of the pavement received a 4" HMA surface without repulverization of the base. Due to the lack of established procedures and equipment to transfer fly ash from the supply tank to the spreader truck and in spreading fly ash, some delays and dusting problems occurred. This problem has now been solved by using a vein feeder spreader for the fly ash and by addition of water to the reclaimer mixing chamber.

Pavement Performance

Representative sections, 500 ft. each in length, were selected from the asphalt emulsion stabilized, fly ash stabilized and control sections. Visual inspections performed on these three sections do not show any surface distress (i.e., cracking, rutting or raveling). Nondestructive deflection testing using the Marquette Falling Weight Deflectometer (FWD) was conducted prior to the construction, after initial pulverization, after one year, and after six years of service to establish structural integrity of each test section. This data was used to back calculate in-situ subgrade resilient moduli and the structural number of the pavement (53).

The preconstruction and post pulverization structural number (SN) results (back calculated) indicate general between section uniformity of the upper pavement layers. The post construction testing and back calculation of SN shows that the fly ash stabilized section gave an 8.6% increase in SN (2.53 vs. 2.33) when compared to the control section. Also the fly ash stabilized section gave a 4.6% increase in SN (2.53 vs. 2.42) compared to the asphalt stabilized section, after making adjustments for the difference in thickness of the HMA surface.

Using the back-calculated SN values of the pavement sections, the structural coefficients of the stabilized and unstabilized CIR base material were calculated. The structural coefficient was found to be 0.11 for the untreated CIR base layer, 0.13 for the asphalt emulsion stabilized layer and 0.15 for the fly ash stabilized base layer.

Based on the 1993 edition of the AASHTO Guide for Design of Pavement, an estimate of the allowable number of 18,000 lb. equivalent single axle loads (ESALs) was determined. In this calculation a design reliability of 85%, an overall standard deviation of 0.35 and a design serviceability loss due to traffic of 2.0 were used. Figure 7-1 shows the allowable ESALs vs. SN (structural number) for the range of subgrade resilient moduli exhibited within the test sections. By holding the subgrade resilient modulus constant and adjusting the asphalt layer coefficient to 0.44, the structural numbers were recalculated. The revised values of SN are as follows:

Control section = 2.65

Emulsion stabilized section = 2.74

Fly ash stabilized section = 2.85

The allowable traffic estimate based on the revised SN provided a more meaningful comparison. Based on the revised SN, the fly ash test section provided a 58% increase in the allowable traffic compared to the control section and a 28% increase in the allowable traffic compared to the asphalt emulsion test section. Long term testing of the pavement is required to understand its behavior. However from the studies completed to date, the fly ash stabilized CIR appears to have good potential.

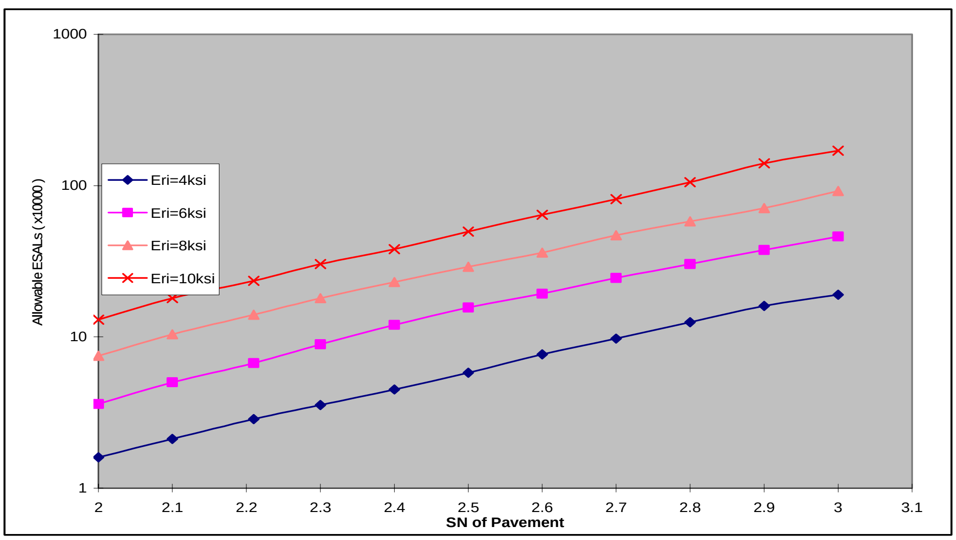


Figure 7-1: Allowable Traffic Estimates

Figure 7-2: Fly ash being placed uniformly on the pulverized pavement.

Figure 7-3: Pavement being repulverized after fly ash application.

Falling Weight Deflectometer tests were conducted again in October 2003, approximately six years after construction, within the control section, the emulsion stabilized section, and the fly ash stabilized section. Surface deflections were used to backcalculate subgrade and pavement parameters including the flexural rigidity of the upper pavement layers and the effective structural number of the pavement (54).

Figure 7-4 provides a summary of the backcalculated effective structural number (Sneff.) As shown, the Sneff of the fly ash stabilized section is greater than comparable control or emulsion stabilized sections with the exception of the westbound emulsion stabilized section with a stronger subgrade.

In general, after six years of service the structural integrity of fly ash stabilized section of Highland Road appears to be equal or better than both the control and emulsion stabilized sections. From a condition standpoint, all sections are performing well with no observed surface cracking.

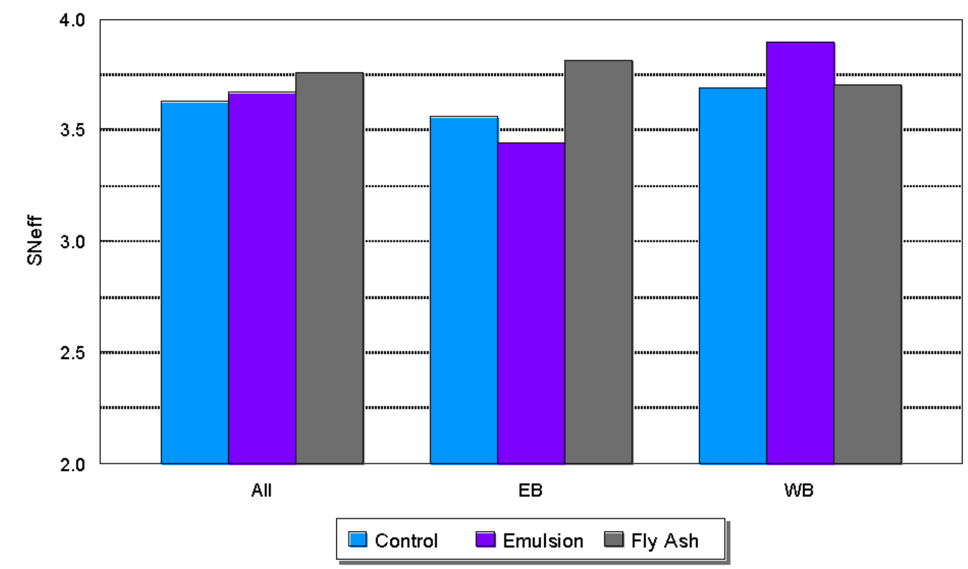


Figure 7-4: Comparison of Effective Structural Numbers (Sneff.) (54)

Case Study II: CTH JK, Waukesha

County Trunk Highway JK is located in Waukesha County, Wisconsin and the project segment runs between County Trunk Highway KF and County Trunk Highway K, with a project length of 3,310 ft. It is a two-lane road with an average daily traffic (ADT) count of 5,050 vehicles in year 2000 and a projected ADT of 8,080 in design year 2021. The existing pavement structure consisted of approximately a 5” asphalt concrete surface layer and a 7” granular base course.

The project scope included construction of a reinforced concrete pipe culvert. The contractor completed this task prior to starting the paving. The base course of the pavement section at the culvert for a length of approximately 50 feet was constructed using crushed aggregate, instead of fly ash stabilized CIR materials. Prior to construction of the road, undercutting was performed at places where severe pavement distresses existed. The pavement was excavated to a depth of 2 feet underneath the existing base course and was filled with breaker run stone. Initial pulverization started on October 9, 2001. The existing HMA pavement was first pulverized to a depth of 5”. After spraying water on the surface of pulverized materials, the pavement was repulverized to a depth of 12” and was graded and compacted by a Sheep’s Foot Roller.

Fly ash was placed on October 11, 2001. Fly ash was transferred from the supply tanker to the vein feeder spreader truck through a hose, which significantly reduced dusting. The vein feeder spreader truck applied the fly ash at an application rate of 8% by weight. The feed gates from the spreader truck provided a six ft. wide surface application. Water was sprayed to obtain the water content of the stabilized CIR materials to the desired 5.0% moisture content. The fly ash and moisture content was controlled by an operator, based on field experience. The mixing operation commenced immediately after distribution of fly ash over a length of approximately 100 feet and was completed within one hour, using the pulverizer. Compaction of the mixture began immediately after mixing and was completed within one hour following spreading of fly ash. The compaction of the base course included 6 passes of the Sheep’s Foot Roller followed by 2 passes of the Vibratory Drum Compactor.

A laboratory mix analysis to evaluate the stabilization potential of recycled pavement material with Class C fly ash was conducted. A field sample of existing asphalt pavement and underlying aggregate bases was obtained from CTH JK. The results of the grain size analysis on the CIR material indicated a sand and gravel mixture with trace fines. The analysis showed that the sample contained 68% gravel (larger than #4 sieve), 26% sand (between #4 and #200 sieves) and 6% silt (between #200 sieve and size of 0.005 mm) and clay (between 0.005 and 0.001 mm) size particles. Evaluation of fly ash stabilized CIR material was performed at two fly ash contents, 6% and 8% by dry weight of total mix. Laboratory analysis of the fly ash stabilized materials was in accordance with ASTM C593, where the Moisture-Density (ASTM D1557) and Moisture-Strength (ASTM D1633) relationship of specimens compacted in a 4” diameter mold was obtained. Results of the moisture density relationship test on the recycled asphalt pavement indicated a maximum dry density of 141.7 pcf at an optimum moisture level of 5.0%. In addition, moisture density relationship tests on the recycled asphalt pavement material with 6%and 8% fly ash added indicated a maximum dry density of 142.3 and 142.9 pcf at optimum moisture contents of 5.5%, respectively. A maximum unconfined compressive strength of 1250 psi and 380 psi at optimum moisture contents of 5% were also obtained after seven day curing, respectively.

Pavement Performance

Pavement performance of CTH JK was evaluated using the FWD test in October 2001, 2002, and 2003. The results of the testing indicate that the strength of fly ash stabilized CIR recycled asphalt base course developed significantly and the modulus increased from 179.7 ksi in 2001, to 267.91 ksi in 2002, and to 328.82 ksi in 2003. The layer coefficient of fly ash stabilized CIR recycled asphalt base course was 0.23 at time of FWD testing in 2002 and 0.245 in 2003, compared to 0.16 in 2001. No cracking and rutting was identified in the pavement distress survey. Compared to the pavement of CTH VV with untreated CIR recycled asphalt base course, the structural capacity of fly ash stabilized CIR recycled asphalt base course in CTH JK, with a layer coefficient of 0.245, is appreciably higher than that of untreated CIR recycled asphalt base course, with a layer coefficient of 0.13 (55). Figure 7-5 shows the structural number of CTH JK pavement since the construction.

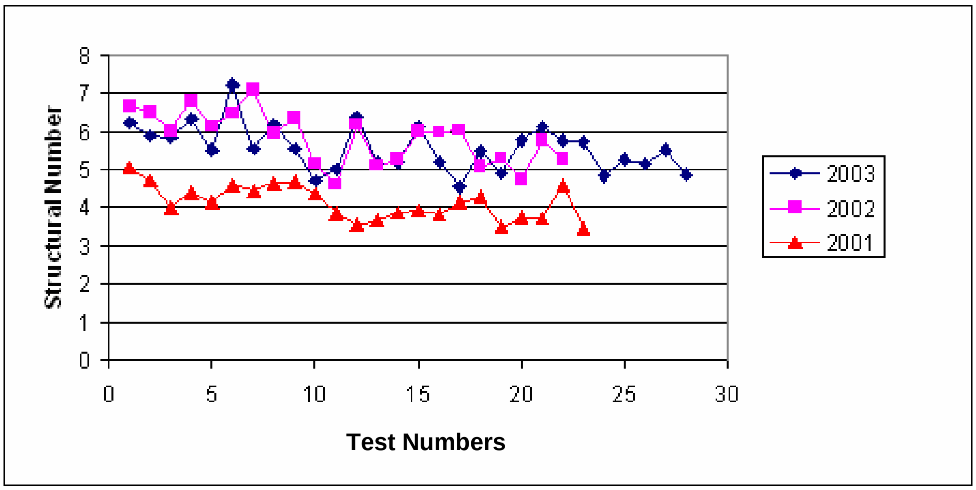


Figure 7-5: Structural Numbers of Pavement in CTH JK

Case Study III: Commercial Office Building Parking Lot

The surface parking lot is located at 3600 S. Lake Drive, St. Francis, Wisconsin. The lot area contained a capped coal ash fill. The coal ash was placed there more than 30 years ago by We Energies. The Class F fly ash and bottom ash were byproducts from the former Lakeside Power Plant operation. Due to the large quantity of coal ash, the cost and time to remove and transport the coal ash is prohibitive. Therefore, it was decided to build the parking lot on the existing coal ash fill. Because the coal ash fill did not contain any Class C fly ash, the coal ash was graded and stabilized with Class C fly ash to a depth of 12”. Upon compaction, a 5” asphalt pavement was placed directly on top of the compacted self-cementing fly ash mixture, without the need to use crushed aggregate base course. For the parking lot ramp, a 12” Class C fly ash stabilized sandy clay was used as subbase directly underneath the asphalt pavement. The construction was done in August 2002.

A significant cost savings of approximately $400,000 was achieved by avoiding the costs associated with removal and hauling of the existing coal ash off site and the need to import crushed aggregate for base course. The life expectancy of the parking lot using the Class C fly ash stabilization is expected to be equal to or better than the standard practice of using a crushed aggregate base course material. The performance of the parking lot is monitored annually using a FWD. Figure 7-6 shows parking lot.

Figure 7-6: Commercial Office Building Parking Lot

Chapter 8

Fly Ash Metal Matrix Composites

Introduction

Metal matrix composites (MMCs) are engineered materials formed by the combination of two or more materials, at least one of which is a metal, to obtain enhanced properties. MMCs tend to have higher strength/density and stiffness density ratios, compared to monolithic metals. They also tend to perform better at higher temperatures, compared to polymer matrix composites.

Though MMCs have been in existence since the 1960s, their commercial applications have been limited due to their higher cost and lack of proper understanding. More recently developed MMCs, especially cast aluminum-fly ash composites, have the potential of being cost effective, ultra light composites, with significant applications (56). Such composites, if properly developed, can be applied for use in automotive components, machine parts and related industries.

Figure 8-1: Brake drum cast with aluminum ash alloy material in Manitowoc, Wisconsin

Aluminum and magnesium are lightweight materials, when compared to iron and steel. However, they do not have the strength requirements necessary for several applications. Metal matrix composites manufactured by dispersing coal fly ash in common aluminum alloys improve mechanical properties such as hardness and abrasion resistance.

Processed fly ash is estimated to cost about $0.10 per pound (including the cost of mixing the ash into the aluminum melt). Aluminum alloy 380 costs approximately $0.70 per pound. An alloy blend containing 40% fly ash would cost about $0.50 per pound, compared to $2.40 to $2.60 per pound for similar conventional aluminum-silicon carbide composites (57).

Preparation of Ash Alloy Metal Matrix Composites

Ash alloy metal matrix composites can be prepared using various techniques. The following methods were studied at the University of Wisconsin-Milwaukee to prepare ash alloys using We Energies fly ash.

- Stir Casting
- Powder Metallurgy
- Pressure Infiltration

Stir Casting

Aluminum-silicon alloys (A356.2 and Al 6061) were used in this work which was conducted at the University of Wisconsin-Milwaukee. In the stir casting process, the alloy is melted at a controlled temperature and the desired quantity of fly ash is added to the molten aluminum alloy. The molten alloy is stirred continuously to create a vortex to force the slightly lighter particles into the melt. Stirring continues to disperse the fly ash particles as uniformly as possible in a short time.

The matrix is then transferred into a preheated and precoated transfer ladle. The material is stirred again and then poured into preheated permanent molds. It is then cooled, cut to shape, and surface cleaned.

Photomicrographs of aluminum alloy (A356.2), with a 10% volume of precipitator fly ash showed that fly ash particles tend to segregate along the aluminum dendrite boundary due to particle pushing. Fly ash particles tend to float to the top of the cast ingots due to their lower density. However, the distribution is reasonably uniform except for the top layer.

Powder Metallurgy

Commercially pure aluminum (99.9%) and We Energies fly ash were used in this work. Oven-dried at 110°C, aluminum and fly ash powders were well-blended by using a rotating drum. The amount of fly ash varied from 5 to 10 percent by weight in the mixtures.

Aluminum fly ash samples were compacted at different pressures (20,000 psi to 60,000 psi) using a uniaxial hydraulic press (58). Aluminum and aluminum fly ash compacts were sealed in a transparent silica tube under pure nitrogen and sintered at 625°C and 645°C for 2.5 and 6 hours at both temperatures.

The green density of the aluminum fly ash powder compacts increased with the increase in compacting pressure and decrease in fly ash content. Fly ash particles did not change shape significantly even when sintered at 625°C for 2.5 hours.

The morphology of aluminum powders changes during compaction due to plastic deformation. When the quantity of fly ash in the composite increased

Figure 8-2: Connecting rods produced at the University of Wisconsin-Milwaukee with aluminum ash alloy material.

above 10% by weight, the hardness significantly decreased, and thus it was concluded that powder metallurgy did not seem very promising for producing ash alloy composite parts.

Pressure Infiltration

Commercial aluminum-silicon alloy (A356.2) and We Energies fly ash were used in this study. Preforms were prepared by mixing cenospheres and precipitator ash with MAP (mono-aluminum phosphate). The slurry was poured into a mold, dried at 204°C for 24 hours and then cured at 815°C for five hours. The preforms were placed in a graphite die followed by preheating at 815°C for two hours. The aluminum alloy was poured into the die at 840°C. A pressure of 1,500 to 2,500 psi was applied on top of the molten alloy for a period of 10 minutes.

When higher percentages of fly ash are used in ash alloy materials, the pressure infiltration casting technique is preferred. The distribution of fly ash particles is uniform in the pressure-infiltrated casting. The volume percentage of fly ash in the composite can be controlled by controlling the porosity in the fly ash preform, which can again be controlled by adjusting the quantity of foaming agent in the preform. The pressure infiltration method gave better castings than the other techniques developed earlier.

Properties of Ash Alloy

In order to determine the suitability of fly ash composites in the manufacture of various automobile and other components, abrasive wear behavior and forging characteristics of composites containing We Energies fly ash were also studied at the University of Wisconsin-Milwaukee.

Abrasive Wear Behavior

Standard Al - 7Si casting alloy (A356) and We Energies fly ash were used in wear tests in the laboratory. Composites were prepared in the lab by stir casting containing 3% fly ash by volume, and composites were also prepared by the squeeze casting technique containing 56 % fly ash by volume. Wear tests were carried out on a FALEX machine. The details of the test procedure can be obtained from reference 50.

The study concluded that:

1. Fly ash improves the abrasive wear resistance of aluminum alloy. Specific abrasive wear rate of aluminum alloy with 3% fly ash composites was decreased with increasing load and increasing sliding velocity.
2. The aluminum alloy - 3% fly ash composite showed better resistance than base alloy up to 24N.
3. Specific abrasive wear rates of the composite (aluminum alloy with 3% fly ash by volume) decreased with decreasing size of the abrading particles.
4. Friction coefficients of the above composites decreased with increasing time, load and size of the abrading particles.
5. Observation of wear surface and wear debris shows that fly ash particles in the composite tend to blunt the abrading SiC particles, thus reducing the extent of ploughing.

Forging Characteristics

The hot forging behaviors of Al 6061- fly ash composites were compared with that of the Al 6061 matrix alloys, Al 6061-20% (by volume) SiC and Al 6061 - 20% Al_2O_3 composites made by Duralcan and Comalco, respectively.

The Al 6061 - fly ash composites were made at the University of Wisconsin-Milwaukee using sieved precipitator fly ash particles obtained from We Energies and cenospheres from another source. The fly ash composites were made using the stir casting and squeeze casting techniques. Table 8-1 is a list of alloys and samples tested in the laboratory.

Table 8-1: Alloy Samples Tested in the Laboratory

No.	Type	Description
1.	Al 6061	Matrix alloy only
2.	Al 6061	20% SiC (14-20 um) Duralcan)
3.	Al 6061	20% SiC $A1_2O_3$ (14-20 um) (Comalco)
4.	Al 6061	5% Cenosphere fly ash (100 um)
5.	Al 6061	10% Cenosphere fly ash (100 um)
6.	Al 6061	10% Precipitator fly ash (44 - 75 um) squeeze cast
7.	Al 6061	20% Precipitator fly ash (44 - 75 um) squeeze cast
8.	Al 6061	30% Cenosphere fly ash (110 um) squeeze cast

Three-inch thick blocks were cut from the ingots and slightly turned to clean up imperfections. The blocks were then coated with either boron nitride or graphite paste to lubricate the ends.

The pieces were then forged in a 150-ton (1.34 MN) hydraulic press at a forging rate of 0.5 in/minute, under a vacuum of 13MPa (97508 torr). The forgings were made at The Ladish Co., Inc., in Milwaukee, Wisconsin. Table 8-2 lists the defects found in each forging.

The study at the University of Wisconsin-Milwaukee led to the following conclusions:

1. The A1 6061 fly ash composites containing 5% or 10% fly ash performed similar to the A1 matrix alloys containing no fly ash during forging.
2. All castings had porosity which affected forgeability.
3. The A1 6061 alloy containing 5% and 10% fly ash forged without cracking. Under similar conditions, A1 6061- 20% SiC and A1 6061- 20% $A1_2O_3$ showed peripheral cracking. A1 6061- 20% fly ash composite showed some cracking. This may be due to non-uniform distribution of fly ash.
4. A1 6061- fly ash composites, had significant segregations in the forgings due to segregations in the billets. Despite the non-uniformity in the microstructure, these composites can be forged.
5. The fly ash particles remained integrated to the alloy particles, showing good microstructure and no debonding. However, during forging some cenospheres collapsed leading to a layered structure of aluminum and collapsed cenospheres.

The University of Wisconsin-Milwaukee study suggests that We Energies fly ash can be used to make composites suitable for forging. However, additional work is being conducted to perfect this technology.

Table 8-2: Defects of Forging Samples Tested

Serial No.	Material	Forging Temperature F (C)	Initial Dimension Height/Dia. (mm)	Forged Thickness	Remarks
4199 4201	Matrix alloy Al 6061	800 (427) 800 (427)	74.7/50.3	9.91	No cracking
4202 4203 4205 4206 4211	Duralcan Al 6061-20 Vol % SiC (14-20 µm)	800 (427) 800 (427) 800 (427) 800 (427) 800 (427)	69.9/50.5 72.6/50.5 72.6/50.3 74.4/50.5 68.1/50.3	10.9 10.7 11.2 11.4 11.4	All five forgings cracked quite severely under a strain greater than 80% forging strain
4207 4208 4209 4210	Comalco Al 6061-20 Vol % Al_2O_1 (14-20 µm)	800 (427) 800 (427) 800 (427) 800 (427)	73.9/50.0 73.7/50.0 81.2/50.5 68.8/50.5	10.9 10.7 11.7 11.4	All four forgings cracked, more or less similarly to the Duralcan forgings
4189 4190 4198	UWM Al 6061-5 Vol % cenosphere fly ash (110 µm)	900 (482) 900 (482) 800 (427)	76.2/49.3 73.7/50.3 76.2/50.0	9.14 9.14 10.2	All three forgings are crack free
4186 4188	UWM Al 6061-10 Vol % cenosphere fly ash (110 µm)	900 (482) 900 (482)	76.7/50.3 75.9/50.0	10.9 9.65	Both forgings are crack free
4194	UWM Al 6061-10 Vol % precipitator fly ash, squeeze cast (44-75 µm)	800 (427)	75.4/50.5	8.89	No transverse edge crack
4191	UWM Al 6061-20 Vol % precipitator fly ash, squeeze cast (44-75 µm)	900 (482)	45.7/50.5	11.9	A little cracking. However, the strain was about 75%

Cenospheres

Cenospheres are hollow, gas-filled glassy microspheres, which normally represent a small portion of fly ash. Cenospheres are formed when CO_2 and N_2 fill the semi-molten material in a coal-fired boiler.

Cenospheres are generally less than one percent of the total mass of CCPs produced. They are generally gray to buff in color and primarily consist of silica and alumina. Cenospheres have valuable applications as fillers in the manufacture of paints, plastics, ceramics, adhesives and metal alloys. Cenospheres are also excellent insulators, which is a direct result of their low density (59).

We Energies, along with the Electric Power Research Institute (EPRI) and several other agencies, have been funding research projects aimed at developing technology for manufacturing ash-alloy automobile components.

We Energies and EPRI have patented a manufacturing method of ash-alloy (U.S Patent 5,897,973). The first step in the method is to prepare a solid, porous, reinforcing phase preform combined with an aqueous medium comprising a binder, such as sodium silicate and polyvinyl alcohol. The ratio of reinforcing phase to aqueous medium ranges is from 1:1 to 3:1. The ratio of binder to water in the aqueous medium generally ranges from 1:1 to 1:9, more usually 1:1 to 1:2. Following introduction into the mold, the slurry produced by the combination of the aqueous medium and reinforcing phase is dried to produce a porous, reinforcing material preform at temperatures ranging from 194ºF to 482ºF for one hour or two. The molten metal is then infiltrated into the porous preform by pressure ranging from about 2000 to 2500 psi. After infiltration, the resultant metal matrix composite is cooled using air drying or low temperature.

Ash alloys containing a volume of over 40% hollow cenospheres are extremely light. It is possible to develop magnesium composites with the density of plastics by proper addition of cenospheres and the use of controlled processes.

Advantages of Using Ash Alloys

The significance of developing and marketing ash alloys can be fully understood only if we consider the overall benefit to various industries and to the environment. The process of developing an ash alloy matrix with excellent properties is very involved, expensive and lengthy. The following are a few of the benefits that will have a significant impact on the community:

1. **Economics:** Ash alloys are at least 10-30% lower in cost than other alloys available in the market. Hence foundries and auto part manufacturers can potentially realize significant savings which can be shared with consumers.

2. **Reduced Energy Consumption:** With a projected annual displacement of 225,000 tons of aluminum with ash, the savings in energy costs for aluminum production is about $156 million annually.
3. **Availability of Lightweight Material:** The U.S. auto industry has a goal to reduce vehicle weight. Ash alloys are significantly lighter when compared to steel.
4. **Improved Gas Mileage:** Due to the projected significant weight reductions, the gas mileage of U. S. vehicles will improve and the savings will be significant. The Department of Energy's Light-Weight Materials Program has predicted that a 25% weight reduction of current vehicles would result in a 13% (750,000 barrels/day) reduction in U.S. gas consumption.
5. **Avoided Ash Disposal Cost:** Electric utilities generate approximately 60 million tons of coal fly ash per year, which are landfilled. If fly ash can be sold as a metal matrix filler, utilities would avoid disposal costs and simultaneously generate revenue from the sale of ash. The anticipated market value of processed fly ash is $100/ton.
6. **Reduced Greenhouse Gases:** Greenhouse gases are produced during the two stages of aluminum production; bauxite processing and alumina reduction. Carbon dioxide (CO_2) and perfluorocarbons (PFCs) are generated in significant amounts during these processes. Decreasing the production of aluminum or other metals by fly ash substitution will significantly reduce the production of these gases. CO_2 emissions would also be reduced by approximately 101 million tons per year.
7. **U.S. Competitiveness:** The U.S. auto parts manufacturers are losing market share to overseas competitors who benefit from low-cost labor. The competitive edge of the United States is its research and development facilities and technical expertise. Development and commercial use of a superior ash alloy matrix at less than half the cost of conventional materials can boost the competitive edge of U.S. parts manufacturers.

These benefits are not limited to the automotive industry. The commercial applications of lighter weight materials, if properly exploited, can benefit foundries, manufacturers, transportation, construction, electrical and consumer goods industries.

Chapter 9

Environmental Considerations of We Energies Coal Combustion Products and Regulatory Requirements

Introduction

Fly ash and bottom ash consist of residual inorganic components in coal that are not vaporized or emitted as volatile gases when coal is burned. The ash contains other non-combustible constituents that are not inorganic. The most common mineral elements found in coal ash in the form of oxides are primarily silicon, aluminum, iron, calcium and magnesium (46).

Oxidation takes place in the furnace due to the heat of combustion. Coal ash contains trace quantities (in the parts-per-million/billion range) of other naturally occurring elements in their oxidized form. Coal ash composition and mineralogy, including their trace element contents, vary primarily based on the source of coal and the combustion conditions.

The major chemical components of both fly ash and bottom ash obtained from the same plant are essentially the same. However, the availability of minor and trace elements are often quite different between fly ash and bottom ash. The chemistry of coal ash is very similar to many naturally occurring soils and natural aggregates. The availability of trace elements from all of these materials is directly related to the particle size. Therefore, the leaching potential of fly ash is higher than bottom ash due to the exponentially higher total surface area available in samples of the same mass.

After reviewing research work on the environmental and health risks associated with coal ash utilization, the U.S. EPA has determined that coal ash is nonhazardous. However, current regulations require protective measures when either fly ash or bottom ash is placed in solid waste disposal sites or other non-contained applications to prevent trace elements from reaching drinking water sources. The use of a respirator is also recommended when handling dry fly ash, which is the same for other finely divided siliceous materials.

Fly ash does not possess any threat to people who do not handle dry unprocessed ash for extended hours. Studies have also proved that there are no inhalation risks from manufactured products containing fly ash. Precautions are generally taken to prevent ash from blowing or dusting during handling. [We Energies material safety data sheet (MSDS) for coal ash is shown in Appendix A]

The utilization of CCPs has several added benefits that are not directly visible. For example, the controlled emissions from a typical cement plant producing 245,000 tons of cement (which is similar to the quantity of We Energies fly ash used as a cementitious material) are 12,000 lbs. of HCl; 54 lbs. of Hg; 220 lbs. of HF; 171 lbs. of Pb; and 49 lbs. of Se. This is in addition to approximately one ton of CO_2 emissions for every ton of cement produced.

Hence, if the entire 245,000 tons of cement is replaced by Class C fly ash (produced anyway from coal combustion), we are reducing CO_2 emissions into the atmosphere by 490,000,000 pounds. This is a large step in reducing greenhouse gas emissions and preserving our virgin raw materials for future generations (sustainable development).

Chemical Elements in Coal Ash

Coal ash may contain nearly all of the naturally-occurring chemical elements, most of them in trace quantities. Table 9-1 gives the list of commonly found chemical elements in coal ash.

Table 9-1: Chemical Elements in Coal Ash

Group 1 (Major) 25% to 1%	Group 2 (Intermediate) 1% to 10 ppm	Group 3 (Minor) 50 to 5 ppm	Group 4 (Minor) 10 ppm to BDL	Group 5 (Usually Minor) 100 to 1 ppm
Silicon	Barium	Silver	Mercury	Carbon
Aluminum	Strontium	Arsenic	Chloride	Cesium
Iron	Manganese	Cadmium	Fluoride	Rubidium
Calcium	Boron	Chromium	Selenium	Germanium
Magnesium	Molybdenum	Copper	Beryllium	Tin
Sodium	Vanadium	Nickel	Antimony	Cobalt
Potassium	Sulfur	Lead	Uranium	Gold
Titanium	Phosphorus	Zinc	Thorium	Platinum

The type and quantity of trace elements in the ash primarily depends on the source of coal. The presence of trace elements in coal ash is a reason that good judgment is required for new applications. State regulations provide guidelines for safe utilization practices.

Leaching From Coal Ash Land Applications

We Energies fly ash and bottom ash has been successfully used in several varieties of land applications. Bottom ash is commonly used as a road base and sub-base, in parking lots as a base material, structural fill, backfill and in top soil. Fly ash is also sometimes used as a road base or structural fill material.

We Energies performs total elemental analysis by the Test Method for Evaluating Solid Waste Physical/Chemical Methods (SW-846) and Proton Induced X-ray Emission Spectroscopy (PIXE) methods and leaching tests of ash samples in accordance with the ASTM distilled water method (ASTM D3987). These tests are used to assess the elemental composition and leaching potential of the ashes as well as to categorize each combustion product source for permitted applications under state rules.

The Wisconsin Department of Natural Resources (WDNR) adopted NR 538 in January, 1998, with the purpose of encouraging the beneficial use of industrial by-products. NR 538 also requires generators to provide certification information on their by-products to the WDNR. The results of the total elemental analysis by SW-846 and PIXE methods on We Energies fly ash and bottom ash are shown in Tables 9-2 and 9-4, respectively. The results of the ASTM D3987 extraction analysis on We Energies fly ash and bottom ash are shown in Tables 9-3 and 9-5. NR 538 has defined limits for several categories of industrial by-products based on the concentration of certain specified parameters.

There are five categories in total with Category 1 having the lowest concentration of the listed parameters. Category 1 by-products have the lowest level of regulatory requirements in terms of beneficial utilization. It can be seen from the following tables that the concentration of elements leaching from fly ash and bottom ash is very low. We Energies fly ash and bottom ash contain only very limited quantities of the trace elements.

Most of these parameters meet the requirements set for Category 1 or Category 2 material. The WDNR can grant an exemption to be classified in a particular category if the concentration of one or two elements is slightly in excess of the set limits. However, this is done on a case-by-case basis. If no exemptions are granted, We Energies bottom ash is primarily a Category 2 material and fly ash is primarily a Category 4 material (with a few exceptions for both fly ash and bottom ash). MCPP mixed ash is also a Category 4 material.

Table 9-2: NR 538 Fly Ash Analysis - Bulk Analysis Data Summary

Parameter	Units	NR538 Category 1 Standard	NR538 Category 2 Standard	VAPP Flyash AC33525	PWPP 1 Flyash AC33526	PWPP 2&3 Flyash AC33527	PIPP 1-4 Flyash AC33528	PIPP 5&6 Flyash AC33529	PIPP 7-9 Flyash AC33530
Total Antimony	ppm	6.3		<0.68	2.7	2.3	2	1.5	<0.53
Total Boron	ppm	1400		480	290	290	760	820	730
Total Barium	ppm	1100		530	150	180	910	930	4000
Total Cadmium	ppm	7.8		<0.22	1.3	1.3	<0.21	1	2.4
Total Lead	ppm	50		4	20	25	17	12	15
Total Molybdenum	ppm	78		8.2	15	16	16	18	13
Total Nickel	ppm	310		34	49	58	59	70	60
Total Vanadium	ppm	110		120	120	140	220	260	210
Total Zinc	ppm	4700		12	59	78	34	25	100
Total Arsenic	ppm	0.042	21	7.4	110	110	19	10	23
Total Beryllium	ppm	0.014	7	0.92	5.2	5.7	2.8	1.9	3.9
Total Thallium	ppm	1.3		<0.50	2.4	2.6	<0.51	<0.53	<0.39
Total Mercury	ppm	4.7		0.21	0.8	1.2	0.35	0.17	0.0007
Hexavalent Chromium	ppm	14.5		0.57	2	5.1	2.9	2.9	28
1-Methylnaphthalene	ppm	8.8		<0.014	0.21	0.62	0.05	<0.014	<0.007
2-Methylnaphthalene	ppm	8.8		<0.015	0.15	0.65	0.075	<0.015	<0.0075
Acenaphthene	ppm	900		<0.022	<0.022	0.029	<0.022	<0.022	<0.011
Acenaphthylene	ppm	8.8		<0.036	<0.036	<0.036	<0.036	<0.036	<0.018
Anthraceme	ppm	5000		<0.022	0.053	<0.022	<0.022	<0.022	<0.011
Benzo(a)anthracene	ppm	0.088	44	<0.012	<0.012	0.041	<0.012	<0.012	<0.006
Benzo(a)pyrene	ppm	0.0088	4.4	<0.012	<0.012	0.097	<0.012	<0.012	<0.006
Benzo(b)fluoranthene	ppm	0.088	44	<0.013	<0.013	0.06	<0.013	<0.013	<0.0065
Benzo(g,h,I)perylene	ppm	0.88		<0.024	<0.024	<0.024	<0.024	<0.024	<0.012
Benzo(k)fluoranthene	ppm	0.88		<0.018	<0.018	0.039	<0.018	<0.018	<0.009
Chrysene	ppm	8.8		<0.014	<0.014	0.041	<0.014	<0.014	<0.0069
Dibenzo(a,h)anthracene	ppm	0.0088	4.4	<0.015	<0.015	<0.015	<0.015	<0.015	<0.0074
Fluoranthene	ppm	600		<0.016	<0.016	<0.016	<0.016	<0.016	<0.008
Fluorene	ppm	600		<0.012	<0.012	0.02	<0.012	<0.012	<0.006
Indeno(1,2,3-cd)pyrene	ppm	0.088	44	<0.022	<0.022	<0.022	<0.022	<0.022	<0.011
Naphthalene	ppm	600		<0.015	0.37	0.95	0.027	<0.015	<0.0075
Phenanthrene	ppm	0.88		<0.016	0.057	0.11	<0.016	<0.016	<0.008
Pyrene	ppm	500		<0.026	<0.026	<0.026	<0.026	<0.026	<0.013
Total PAH's	ppm		100	<0.33	0.84	2.66	0.152	<0.33	<0.17

NR 538 Table 1B exceedances are highlighted in *bold* type.

Table 9-2: NR 538 Fly Ash Analysis - Bulk Analysis Data Summary *(Continued)*

Parameter	Units	NR538 Category 1 Standard	NR538 Category 2 Standard	OCPP Flyash AC33531	PPPP Flyash AC33532	P4 Landfill 1st 10000 AC27609	P4 Landfill 2nd 10000 AC33540	P4 Landfill 3rd 10000 AC33541
Total Antimony	ppm	6.3		<0.63	1.4	28	<0.51	<0.63
Total Boron	ppm	1400		670	950	230	310	290
Total Barium	ppm	1100		4800	4400	3300	3700	3500
Total Cadmium	ppm	7.8		2.6	2.2	1.4	1.6	0.91
Total Lead	ppm	50		31	29	9.6	<6.6	<7.0
Total Molybdenum	ppm	78		7.8	13	5.2	5.5	4.4
Total Nickel	ppm	310		49	96	7.5	39	40
Total Vanadium	ppm	110		190	330	140	150	150
Total Zinc	ppm	4700		75	73	36	27	24
Total Arsenic	ppm	0.042	21	17	25	5.1	6.6	6.8
Total Beryllium	ppm	0.014	7	4.2	5.4	5.7	3	3.2
Total Thallium	ppm	1.3		<0.47	<0.58	<0.69	<0.37	<0.47
Total Mercury	ppm	4.7		0.36	0.22	0.06	0.0069	0.0087
Hexavalent Chromium	ppm	14.5		26	17	5.8	0.58	0.76
1-Methylnaphthalene	ppm	8.8		<0.007	<0.007	<0.0082	0.0076	0.0082
2-Methylnaphthalene	ppm	8.8		<0.0075	<0.0075	<0.0088	0.01	0.0076
Acenaphthene	ppm	900		<0.011	<0.011	<0.013	<0.011	<0.011
Acenaphthylene	ppm	8.8		<0.018	<0.018	<0.021	<0.018	<0.018
Anthraceme	ppm	5000		<0.011	<0.011	<0.013	<0.011	<0.011
Benzo(a)anthracene	ppm	0.088	44	<0.006	<0.006	<0.0071	<0.006	<0.006
Benzo(a)pyrene	ppm	0.0088	4.4	<0.006	<0.006	<0.0071	<0.006	<0.006
Benzo(b)fluoranthene	ppm	0.088	44	<0.0065	<0.0065	<0.0077	<0.0065	<0.0065
Benzo(g,h,l)perylene	ppm	0.88		<0.012	<0.012	<0.014	<0.012	<0.012
Benzo(k)fluoranthene	ppm	0.88		<0.009	<0.009	<0.011	<0.009	<0.009
Chrysene	ppm	8.8		<0.0069	<0.0069	<0.0081	<0.0069	<0.0069
Dibenzo(a,h)anthracene	ppm	0.0088	4.4	<0.0074	<0.0074	<0.0087	<0.0074	<0.0074
Fluoranthene	ppm	600		<0.008	<0.008	0.011	<0.008	0.0094
Fluorene	ppm	600		<0.006	<0.006	<0.0071	<0.006	<0.006
Indeno(1,2,3-cd)pyrene	ppm	0.088	44	<0.011	<0.011	<0.013	<0.011	<0.011
Naphthalene	ppm	600		<0.0075	<0.0075	0.013	0.022	0.014
Phenanthrene	ppm	0.88		<0.008	<0.008	<0.0094	<0.008	0.0099
Pyrene	ppm	500		<0.013	<0.013	<0.015	<0.013	<0.013
Total PAH's	ppm		100	<0.17	<0.17	0.024	0.04	0.049

Table 9-3: NR 538 Fly Ash Analysis - ASTM D3987 Leachate Test Result Summary

Parameter	Units	NR538 Category 1 Standard	NR538 Category 2&3 Standard	NR538 Category 4 Standard	Extraction Blank AC33823	VAPP Flyash AC33824	PWPP Unit 1 Flyash AC33825	PWPP Unit 1 F/A Dupl. AC33826	PWPP 2&3 Flyash AC33827	PIPP 1-4 Flyash AC33828	PIPP 5&6 Flyash AC33829
Dissolved Aluminum	mg/l	1.5	15		0.029	2.6	0.2	0.16	47	7.9	8.2
Dissolved Antimony	mg/l	0.0012	0.012		<0.0019	0.0054	0.04	0.039	0.0069	0.014	0.009
Dissolved Arsenic	mg/l	0.005	0.05		<0.0012	0.004	0.062	0.04	0.0078	0.0067	0.0035
Dissolved Barium	mg/l	0.4	4		<0.0010	0.5	0.11	0.11	0.11	1	1
Dissolved Beryllium	mg/l	0.0004	0.004		<0.00005	<0.00005	<0.00005	<0.00005	0.021	<.00010	0.00005
Dissolved Boron	mg/l				<0.0077	7.6	10	10	11	21	24
Dissolved Cadmium	mg/l	0.0005	0.005	0.025	<0.00004	0.000065	0.00015	0.00014	0.019	<0.00004	0.00051
Chloride	mg/l	125			<0.039	1.5	208	207	2.2	0.65	0.96
Dissolved Chromium	mg/l	0.01	0.1	0.5	<0.00020	0.0027	0.0024	0.0038	0.018	0.049	0.024
Dissolved Copper	mg/l	0.13			<0.00054	<0.00054	0.00067	<0.00054	0.043	0.0017	0.0006
Dissolved Iron	mg/l	0.15			0.0041	0.0032	<0.0012	<0.0012	1.9	0.0059	0.0027
Dissolved Lead	mg/l	0.0015	0.015		<0.0014	<0.0014	0.0035	0.0038	0.0038	<0.0014	<0.0014
Dissolved Manganese	mg/l	0.025	0.25		<0.00042	<0.00042	0.084	0.083	1.8	<0.00042	<0.00042
Mercury	mg/l	0.0002	0.002		0.000007	0.000007	0.000004	0.000004	0.000005	<0.000002	<0.000002
Dissolved Molybdenum	mg/l	0.05			<0.0062	0.12	0.49	0.49	0.026	0.5	0.56
Dissolved Nickel	mg/l	0.02			<0.00056	<0.00056	0.0078	0.0079	0.41	<0.00056	<0.00056
Nitrate-Nitrite as N	mg/l	2			<0.095	<0.095	<0.095	<0.095	<0.095	<0.095	<0.095
Dissolved Selenium	mg/l	0.01	0.1	0.25	<0.0015	0.041	0.17	0.16	<0.0015	0.21	0.16
Dissolved Silver	mg/l	0.01	0.1	0.25	<0.00004	<0.00004	0.00021	0.00025	<0.00004	<0.00004	<0.00004
Sulfate	mg/l	125	1250	2500	<0.10	96	2650	2730	1340	244	192
Dissolved Thallium	mg/l	0.0004	0.004		<0.0014	<0.0014	0.004	<0.0014	0.0057	<0.0014	<0.0014
Dissolved Zinc	mg/l	2.5			<0.0016	<0.0016	0.003	0.0056	0.69	0.0057	0.011

Note: A value highlighted in bold exceeds the NR 538 Category 1 Standard.

Table 9-3: NR 538 Fly Ash Analysis - ASTM D3987 Leachate Test Result Summary *(Continued)*

Parameter	Units	NR538 Category 1 Standard	NR538 Category 2&3 Standard	R538 Category 4 Standard	Extraction Blank AC33823	PIPP 7-9 Flyash AC33830	OCPP Flyash AC33831	PPPP Flyash AC33832	P4 Landfill 1st 10000 AC27750	P4 Landfill 2nd 10000 AC33841	P4 Landfill 3rd 10000 AC33842
Dissolved Aluminum	mg/l	1.5	15		0.029	55	34	64	10	4.8	7.2
Dissolved Antimony	mg/l	0.0012	0.012		<0.0019	<0.0019	<0.0019	<0.0019	<0.0019	<0.0019	<0.0019
Dissolved Arsenic	mg/l	0.005	0.05		<0.0012	<0.0012	<0.0012	<0.0012	<0.0012	0.0013	0.0024
Dissolved Barium	mg/l	0.4	4		<0.0010	2.2	42	6.6	0.24	0.21	0.22
Dissolved Beryllium	mg/l	0.0004	0.004		<0.00005	0.00011	0.00017	0.000089	<0.00005	<0.00005	<0.0005
Dissolved Boron	mg/l				<0.0077	0.16	4.3	0.44	1	1.5	1.5
Dissolved Cadmium	mg/l	0.0005	0.005	0.025	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004
Chloride	mg/l	125			<0.039	1.9	0.61	0.34	0.16	0.34	<0.039
Dissolved Chromium	mg/l	0.01	0.1	0.5	<0.00020	0.45	0.00024	0.2	<0.0025	0.0021	0.0014
Dissolved Copper	mg/l	0.13			<0.00054	<0.00054	0.0018	0.00074	0.0012	0.00089	<0.00054
Dissolved Iron	mg/l	0.15			0.0041	0.016	<0.0012	0.027	0.011	0.0031	0.0025
Dissolved Lead	mg/l	0.0015	0.015		<0.0014	<0.0014	0.0015	<0.0014	<0.00083	<0.0014	<0.0014
Dissolved Manganese	mg/l	0.025	0.25		<0.00042	<0.00042	<0.00042	<0.00042	<0.00045	<0.00042	<0.00042
Mercury	mg/l	0.0002	0.002		0.000007	0.000011	0.000004	<0.000002	<0.00016	0.000006	0.000004
Dissolved Molybdenum	mg/l	0.05			<0.0062	0.16	<0.0062	0.12	<0.012	0.013	<0.0062
Dissolved Nickel	mg/l	0.02			<0.00056	<0.00056	<0.00056	<0.00056	<0.00056	<0.00056	<0.00056
Nitrate-Nitrite as N	mg/l	2			<0.095	<0.095	<0.095	<0.095	<0.027	<0.095	<0.095
Dissolved Selenium	mg/l	0.01	0.1	0.25	<0.0015	0.045	0.0027	0.011	<0.0015	0.0033	0.0016
Dissolved Silver	mg/l	0.01	0.1	0.25	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004
Sulfate	mg/l	125	1250	2500	<0.10	180	<0.10	26	112	180	138
Dissolved Thallium	mg/l	0.0004	0.004		<0.0014	<0.0014	0.0018	<0.0014	<0.0014	<0.0014	<0.0014
Dissolved Zinc	mg/l	2.5			<0.0016	0.0025	0.031	0.0099	<0.0042	0.0092	<0.0016

Table 9-4: NR 538 Bottom Ash Analysis - Bulk Analysis Data Summary

Parameter	Units	NR538 Category 1 Standard	NR538 Category 2 Standard	MCPP Mixed Ash AC33533	PWPP Bottom Ash AC33534	VAPP Bottom Ash AC33535	PIPP 1-6 Bottom Ash AC33536	PIPP 7-9 Bottom Ash AC33537
Total Antimony	ppm	6.3		4	<0.80	0.76	<0.51	<0.58
Total Boron	ppm	1400		94	32	190	76	220
Total Barium	ppm	1100		240	36	400	180	3200
Total Cadmium	ppm	7.8		0.46	<0.20	0.37	<0.20	1
Total Lead	ppm	50		53	<3.1	<3.2	<3.1	<3.3
Total Molybdenum	ppm	78		12	2.6	1.7	2.5	2.6
Total Nickel	ppm	310		52	11	8.6	11	27
Total Vanadium	ppm	110		67	22	28	33	99
Total Zinc	ppm	4700		100	9.4	12	3.4	24
Total Arsenic	ppm	0.042	21	47	16	5	1.6	4.2
Total Beryllium	ppm	0.014	7	6.6	1.1	0.8	0.58	2
Total Thallium	ppm	1.3		2.9	<0.59	<0.54	<0.37	<0.43
Total Mercury	ppm	4.7		0.067	0.17	0.063	0.0024	0.007
Hexavalent Chromium	ppm	14.5		0.47	0.28	0.67	<0.20	0.95
1-Methylnaphthalene	ppm	8.8		0.022	0.26	<0.0093	<0.014	0.007
2-Methylnaphthalene	ppm	8.8		0.029	0.39	<0.010	<0.015	0.0097
Acenaphthene	ppm	900		<0.011	<0.015	<0.015	<0.022	<0.011
Acenaphthylene	ppm	8.8		<0.018	<0.024	<0.024	<0.036	<0.018
Anthraceme	ppm	5000		<0.011	<0.015	<0.015	<0.022	<0.011
Benzo(a)anthracene	ppm	0.088	44	<0.006	0.0088	<0.008	<0.012	<0.006
Benzo(a)pyrene	ppm	0.0088	4.4	<0.006	<0.008	<0.008	<0.012	<0.006
Benzo(b)fluoranthene	ppm	0.088	44	<0.0065	<0.0087	<0.0087	<0.013	<0.0065
Benzo(g,h,I)perylene	ppm	0.88		<0.012	<0.016	<0.016	<0.024	<0.012
Benzo(k)fluoranthene	ppm	0.88		<0.009	<0.012	<0.012	<0.018	<0.009
Chrysene	ppm	8.8		<0.0069	0.014	<0.0092	<0.014	<0.0069
Dibenzo(a,h)anthracene	ppm	0.0088	4.4	<0.0074	<0.0099	<0.0099	<0.015	<0.0074
Fluoranthene	ppm	600		<0.008	0.014	<0.011	<0.016	<0.008
Fluorene	ppm	600		<0.006	0.013	<0.008	<0.012	<0.006
Indeno(1,2,3-cd)pyrene	ppm	0.088	44	<0.011	<0.015	<0.015	<0.022	<0.011
Naphthalene	ppm	600		0.02	0.23	<0.010	<0.015	0.0095
Phenanthrene	ppm	0.88		0.012	0.099	<0.011	<0.016	<0.008
Pyrene	ppm	500		<0.013	<0.017	<0.017	<0.026	<0.013
Total PAH's	ppm		100	0.083	1.03	<0.22	<0.33	0.026

NR 538 Table 1B exceedences are highlighted in bold type.

Table 9-4: NR 538 Bottom Ash Analysis - Bulk Analysis Data Summary *(Continued)*

Parameter	Units	NR538 Category 1 Standard	NR538 Category 2 Standard	OCPP Bottom Ash AC33538	PPPP Bottom Ash AC33539	OCPP Grounds BA/Asphalt AC29510	OCPP Grounds BA/Asphalt Increased 1/3	CemRock w/P4 Flyash AC33542
Total Antimony	ppm	6.3		<0.53	<0.66	<20	<Detect	<0.74
Total Boron	ppm	1400		250	260	41	54.530	710
Total Barium	ppm	1100		3300	2500	100	133.000	4000
Total Cadmium	ppm	7.8		<0.49	0.73	2.4	3.192	1.9
Total Lead	ppm	50		<7.4	<6.4	16	21.280	20
Total Molybdenum	ppm	78		4.4	4.2	5.8	7.714	11
Total Nickel	ppm	310		130	45	15	19.950	66
Total Vanadium	ppm	110		110	140	22	29.260	230
Total Zinc	ppm	4700		18	14	100	133.000	61
Total Arsenic	ppm	0.042	21	3.4	5.3	6.6	8.778	18
Total Beryllium	ppm	0.014	7	2.6	2.9	0.67	0.891	3.8
Total Thallium	ppm	1.3		<0.39	<0.48	0.48	0.638	<0.54
Total Mercury	ppm	4.7		0.0049	0.0022	<0.038	<Detect	0.16
Hexavalent Chromium	ppm	14.5		1.1	0.27	3.2	4.256	11
1-Methylnaphthalene	ppm	8.8		<0.007	<0.007	0.15	0.200	<0.007
2-Methylnaphthalene	ppm	8.8		<0.0075	<0.0075	0.18	0.239	<0.0075
Acenaphthene	ppm	900		<0.011	<0.011	0.008	0.011	<0.011
Acenaphthylene	ppm	8.8		<0.018	<0.018	0.0089	0.012	<0.018
Anthraceme	ppm	5000		<0.011	<0.011	0.031	0.041	<0.011
Benzo(a)anthracene	ppm	0.088	44	<0.006	<0.006	0.077	0.102	<0.006
Benzo(a)pyrene	ppm	0.0088	4.4	<0.006	<0.006	0.097	0.129	<0.006
Benzo(b)fluoranthene	ppm	0.088	44	<0.0065	<0.0065	0.083	0.110	<0.0065
Benzo(g,h,I)perylene	ppm	0.88		<0.012	<0.012	0.067	0.089	<0.012
Benzo(k)fluoranthene	ppm	0.88		<0.009	<0.009	0.074	0.098	<0.009
Chrysene	ppm	8.8		<0.0069	<0.0069	0.089	0.118	<0.0069
Dibenzo(a,h)anthracene	ppm	0.0088	4.4	<0.0074	<0.0074	0.024	0.032	<0.0074
Fluoranthene	ppm	600		0.0094	<0.008	0.1	0.133	<0.008
Fluorene	ppm	600		<0.006	<0.006	0.022	0.029	<0.006
Indeno(1,2,3-cd)pyrene	ppm	0.088	44	<0.011	<0.011	0.058	0.077	<0.011
Naphthalene	ppm	600		0.034	<0.0075	0.086	0.114	<0.0075
Phenanthrene	ppm	0.88		0.0084	<0.008	0.18	0.239	<0.008
Pyrene	ppm	500		0.014	<0.013	0.14	0.186	<0.013
Total PAH's	ppm		100	0.066	<0.17	1.47	1.955	<0.17

Table 9-5: NR 538 Bottom Ash Analysis - ASTM D3987 Leachate Test Result Summary

Parameter	Units	NR538 Category 1 Standard	NR538 Category 2&3 Standard	R538 Category 4 Standard	Extraction Blank AC33823	MCPP Mixed Ash AC33823	PWPP Bottom Ash AC33534	VAPP Bottom Ash AC33535	PIPP 1-6 Bottom Ash AC33536	PIPP 1-6 B/A Dupl. AC33837	PIPP 7-9 Bottom Ash AC33537
Dissolved Aluminum	mg/l	1.5	15		0.029	0.07	0.68	1.2	0.54	0.67	9
Dissolved Antimony	mg/l	0.0012	0.012		<0.0019	0.026	<0.0019	0.0052	<0.0019	<0.0019	<0.0019
Dissolved Arsenic	mg/l	0.005	0.05		<0.0012	<0.0012	0.051	0.012	0.0046	0.0044	<0.0012
Dissolved Barium	mg/l	0.4	4		<0.0010	0.33	0.017	0.48	0.15	0.14	0.67
Dissolved Beryllium	mg/l	0.0004	0.004		<0.00005	0.00019	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005
Dissolved Boron	mg/l				<0.0077	1.9	0.17	4	0.44	0.4	0.71
Dissolved Cadmium	mg/l	0.0005	0.005	0.025	<0.00004	0.0042	<0.00004	<0.00004	<0.00004	<0.00004	0.000042
Chloride	mg/l	125			<0.039	2.2	0.62	1.1	0.71	0.74	0.38
Dissolved Chromium	mg/l	0.01	0.1	0.5	<0.00020	<0.00020	0.00063	0.0024	0.00028	0.00023	0.0048
Dissolved Copper	mg/l	0.13			<0.00054	0.0038	<0.00054	0.00075	<0.00054	<0.00054	<0.00054
Dissolved Iron	mg/l	0.15			0.0041	<0.0012	0.01	0.0035	0.02	0.014	0.0052
Dissolved Lead	mg/l	0.0015	0.015		<0.0014	<0.0014	<0.0014	<0.0014	<0.0014	<0.0014	<0.0014
Dissolved Manganese	mg/l	0.025	0.25		<0.00042	0.26	0.0006	<0.00042	<0.00042	<0.00042	<0.00042
Mercury	mg/l	0.0002	0.002		0.000007	<0.000002	0.000012	0.000003	0.000005	0.000003	<0.000002
Dissolved Molybdenum	mg/l	0.05			<0.0062	0.058	0.008	0.028	0.019	0.013	<0.0062
Dissolved Nickel	mg/l	0.02			<0.00056	0.37	0.00093	<0.00056	<0.00056	<0.00056	<0.00056
Nitrate-Nitrite as N	mg/l	2			<0.095	<0.095	<0.095	<0.095	<0.095	<0.095	<0.095
Dissolved Selenium	mg/l	0.01	0.1	0.25	<0.0015	0.002	<0.0015	0.015	0.0022	0.0022	<0.0015
Dissolved Silver	mg/l	0.01	0.1	0.25	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004
Sulfate	mg/l	125	1250	2500	<0.10	372	44	47	28	30	65
Dissolved Thallium	mg/l	0.0004	0.004		<0.0014	0.0031	<0.0014	<0.0014	<0.0014	<0.0014	<0.0014
Dissolved Zinc	mg/l	2.5			<0.0016	0.88	<0.0016	<0.0016	0.0031	0.0019	<0.0016

Note: A value highlighted in bold exceeds the NR538 Category 1 standard.

Table 9-5: NR 538 Bottom Ash Analysis - ASTM D3987 Leachate Test Result Summary *(Continued)*

Parameter	Units	NR538 Category 1 Standard	NR538 Category 2&3 Standard	R538 Category 4 Standard	Extraction Blank AC33823	OCPP Bottom Ash AC33538	PPPP Bottom Ash AC33539	OCPP Grounds BA/Asphalt AC29510	OCPP Grounds BA/Asphalt Increased 1/3	CemRock w/P4 Flyash AC33542
Dissolved Aluminum	mg/l	1.5	15		0.029	17	12	0.44	0.5852	27
Dissolved Antimony	mg/l	0.0012	0.012		<0.0019	<0.0019	<0.0019	<0.0019	<Detect	0.0022
Dissolved Arsenic	mg/l	0.005	0.05		<0.0012	<0.0012	0.0015	0.004	0.00532	<0.0012
Dissolved Barium	mg/l	0.4	4		<0.0010	0.47	0.54	0.053	0.07049	0.8
Dissolved Beryllium	mg/l	0.0004	0.004		<0.00005	<0.00005	0.000053	0.000058	0.00007714	0.00008
Dissolved Boron	mg/l				<0.0077	0.79	0.85	0.02	0.0266	2.7
Dissolved Cadmium	mg/l	0.0005	0.005	0.025	<0.00004	0.00004	0.000055	0.00024	0.0003192	0.00006
Chloride	mg/l	125			<0.039	0.37	0.74	6.8	9.044	2
Dissolved Chromium	mg/l	0.01	0.1	0.5	<0.00020	0.0049	0.003	<0.0025	<Detect	0.22
Dissolved Copper	mg/l	0.13			<0.00054	0.0038	<0.00054	<0.0022	<Detect	0.2
Dissolved Iron	mg/l	0.15			0.0041	0.016	0.0069	0.027	0.03591	0.011
Dissolved Lead	mg/l	0.0015	0.015		<0.0014	<0.0014	<0.0014	<0.00083	<Detect	<0.0014
Dissolved Manganese	mg/l	0.025	0.25		<0.00042	<0.00042	<0.00042	0.0008	0.001064	<0.00042
Mercury	mg/l	0.0002	0.002		0.000007	0.000051	0.000005	<0.00016	<Detect	0.000004
Dissolved Molybdenum	mg/l	0.05			<0.0062	0.0065	<0.0062	<0.012	<Detect	0.12
Dissolved Nickel	mg/l	0.02			<0.00056	<0.00056	<0.00056	<0.0035	<Detect	0.029
Nitrate-Nitrite as N	mg/l	2			<0.095	<0.095	<0.095	0.98	1.3034	0.11
Dissolved Selenium	mg/l	0.01	0.1	0.25	<0.0015	<0.0015	0.0028	<0.0015	<Detect	0.028
Dissolved Silver	mg/l	0.01	0.1	0.25	<0.00004	<0.00004	<0.00004	<0.00004	<Detect	<0.00004
Sulfate	mg/l	125	1250	2500	<0.10	34	70	7.7	10.241	76
Dissolved Thallium	mg/l	0.0004	0.004		<0.0014	<0.0014	<0.0014	<0.0011	<Detect	<0.0014
Dissolved Zinc	mg/l	2.5			<0.0016	<0.0016	<0.0016	<0.0042	<Detect	0.0028

Leaching From Products Containing Coal Combustion Products

Fly ash has found great applications in construction products like concrete, CLSM and in the manufacture of Portland cement. It is well established that leaching of trace elements from concrete is negligible. Concrete is very dense and impermeable, making it hard for water to penetrate into the interior of a concrete structure. The reaction products in concrete are stable, dense and do not leach significantly in the natural environment.

The composition of CLSM material is different from that of concrete. It is a low-strength material, often with a compressive strength of less than 300 psi. When prepared with large amounts of fly ash, the permeability is also very low. However, the potential for future removal and handling could allow the material to be broken up into smaller particles with more leachable surface area. Hence, ASTM D-3987 Extraction Analysis has been performed on this material to determine the amount of trace elements leached out of high fly ash content CLSM.

Table 9-6 shows the total results of total elemental analysis for CLSM produced with PWPP Units 2 and 3 fly ash. Table 9-7 gives the results of ASTM D-3987 Extraction Analysis for the same material. The extract meets all requirements for Category 2 per NR 538.

Table 9-6: Total Elemental Analysis – CLSM Produced with Port Washington Power Plant Units 2 & 3 Fly Ash

Parameter	Detection Level	Units	NR 538 Category 1 Standard	NR 538 Category 2 & 3 Standard	Collected 11/19/97 AB 59506	Collected 11/19/97 AB 59507
Antimony – PIXE	166	Mg/kg	6.3		<166	<199
Arsenic - SW-846	0.06	mg/kg	0.042	21	57	58
Barium - SW-846	0.056	mg/kg	1100		168	160
Beryllium - SW-846	0.06	mg/kg	0.014	7	3.3	3.6
Boron - SW-846	0.014	mg/kg	1400		200	180
Cadmium - SW-846	0.005	mg/kg	7.8		1.3	0.92
Chromium - PIXE	39.8	mg/kg	14.5 as Hex		171	239
Lead - PIXE	41.6	mg/kg	50		212	160
Mercury - SW-846	0.0037	mg/kg	4.7		<0.0037	<0.0037
Molybdenum - SW-846	0.19	mg/kg	78		12	9.2
Nickel	13.1	mg/kg	310		103	94.7
Thallium - PIXE	33.5	mg/kg	1.3		<33.5	<25.5
Vanadium - PIXE	80.6	mg/kg	110		<80.6	<81.1
Zinc - PIXE	14.6	mg/kg	4700		179	173

PIXE - Proton Induced X-Ray Emission Spectroscopy
SW-846 - Test Methods for Evaluating Solid Waste Physical/Chemical Methods

Table 9-7: ASTM D3987 Extraction Analysis – CLSM Produced With Port Washington Power Plant Units 2 & 3 Fly Ash

Parameter	Detection Level	Units	NR 538 Category 1 Standard	NR 538 Category 2 & 3 Standard	Collected 11/19/97 AB 59630	Collected 11/19/97 AB 59631
Aluminum	0.011	mg/l	1.5	15	6	5.5
Antimony	0.0015	mg/l	0.0012	0.12	0.0051	0.005
Arsenic	0.0006	mg/l	0.005	0.05	0.03	0.031
Barium	0.0009	mg/l	0.4	4	0.041	0.047
Beryllium	0.0002	mg/l	0.0004	0.004	<0.0002	<0.0002
Cadmium	0.0001	mg/l	0.0005	0.005	0.0001	<0.0001
Chloride	0.15	mg/l	125		2	3.2
Chromium	0.0005	mg/l	0.01	0.1	0.029	0.03
Copper	0.0012	mg/l	0.13		0.0047	0.0053
Iron	0.0007	mg/l	0.15		0.0013	0.002
Lead	0.0007	mg/l	0.0015	0.015	<0.0007	<0.0007
Manganese	0.0015	mg/l	0.025	0.25	0.0015	<0.0015
Mercury	0.00067	mg/l	0.0002	0.002	<0.00067	<0.00067
Molybdenum	0.0029	mg/l	0.05		0.2	0.25
Nickel	0.0044	mg/l	0.02		<0.0044	<0.0044
Nitrate-Nitrite as N	0.02	mg/l	2		0.05	0.03
Selenium	0.0007	mg/l	0.01	0.1	0.049	0.051
Silver	0.00014	mg/l	0.01	0.1	<0.00014	<0.00014
Sulfate	0.09	mg/l	125	1250	52	63
Thallium	0.0014	mg/l	0.0004	0.004	<0.0014	0.0017
Zinc	0.0013	mg/l	2.5		0.0061	0.0046

Radioactivity of Coal Ash (60)

The radioactivity levels in coal ash do not constitute a safety hazard. Based on the concentration process as a result of coal combustion, the Ra-226 concentrations in ash could be on the order of 1-30 pCi/g. Analyses of various ashes and ash products produced at We Energies plants in 1993 and 2003 found Ra-226 concentrations in the range of 1 – 3 pCi/g. This is comparable to the concentrations in soil (0.2 – 3 pCi/g) and within the range of 1 – 8 pCi/g found in ash from analyses of other fly ash in the US (Cement and Concrete Containing Fly Ash, Guideline for Federal Procurement, Federal Register, Vol. 48 (20), January 28, 1983, Rules and Regulations; Zielinski and Budahn, Fuel Vol. 77 (1998) 259-267).

Given that the ash may be landfilled or may be used in building materials as a cement substitute, the doses resulting from these applications have been studied to determine if there is any risk. The British Nuclear Radiation Protection Board conducted a detailed evaluation of the doses from fly ash released to the air to people living within 500 meters (547 yards) of a plant stack, to landfill workers burying fly ash, to workers manufacturing building products from fly ash, and to people living in a house built with fly ash building products. The maximum doses determined from this evaluation were 0.15 mrem/yr for the person living near the plant, 0.13 mrem/yr from releases from the ash landfill, 0.5 mrem/yr for workers manufacturing building products, and 13.5 mrem/yr to a resident of a home constructed with fly ash building materials. The latter is not that different from the 13 mrem/yr from living in a conventional brick/masonry house mentioned earlier.

The levels of radioactivity are within the range found in other natural products. The doses resulting from using the ash in various products are comparable to doses from other human activities and from other natural sources. These doses from the radionuclides in ash are much less than the 300 mrem/yr received from normal background radiation. See Appendix B for the report prepared by Dr. Kjell Johansen for We Energies.

Coal Ash Exemptions

The WDNR monitors the beneficial utilization of CCPs. NR 538 was adopted to categorize by-products and to recommend self-implementing rules to be followed for utilization. However, CCPs have been beneficially utilized for a long time and the WDNR has granted We Energies specific exemptions for many proven applications such as use in concrete, asphalt, CLSM, soil amendment and various aggregate applications.

With increased understanding of coal combustion products and their relationships with the natural environment, We Energies continues to perform research and seek exemptions for additional beneficial use applications.

Table 9-8: Typical Heavy Metals Found in Fly Ash and Soil

Element	Fly Ash Mean ppm	Fly Ash Range ppm	Soil Mean ppm	Soil Range ppm
Aluminum	128,000	106,990 - 1,139,700	71,000	10,000 – 300,000
Arsenic	28	11 – 63	6	0.1 - 40
Barium	1278	73 - 2,100	500	100 - 3,000
Cadmium	1.8	0.68 – 4.4	0.06	0.01 - 0.7
Chromium	86	34 – 124	100	5 - 3,000
Copper	94	18 – 239	20	2 – 100
Iron	33,000	17,050 – 45,910	38,000	3,000 – 550,000
Lead	89	63 – 111	10	2 – 200
Manganese	171	54 – 673	850	100 - 4,000
Mercury	0.01	0.00008 - 0.1	0.03	0.01 - 0.3
Nickel	41	8-65	40	10 - 1,000
Selenium	9.9	3 – 16	0.3	0.01 - 2
Vanadium	246	184 – 268	100	20 – 500
Zinc	63	9 – 110	50	10 – 300

Regulations of Ash Utilization - Wisconsin Department of Natural Resources

The Wisconsin Department of Natural Resources has the authority to regulate the utilization of individual by-products, including coal combustion products, in the State of Wisconsin. Until recently, there was no single guideline that governed the beneficial utilization of industrial by-products. The NR 538 sets rules for 12 predefined industrial by-product utilization methods.

According to the WDNR, the purpose of Chapter NR 538 is “to allow and encourage to the maximum extent possible, consistent with the protection of public health and the environment and good engineering practices, the beneficial use of industrial by-products in a nuisance-free manner.” NR 538 does not govern hazardous waste and metallic mining waste, nor does this apply to the design, construction or operations of industrial waste water facilities, sewerage systems and waterworks treating liquid wastes.

Figures 9-1 to 9-5 give flowchart guidance for beneficial use of industrial by-products in accordance with NR 538. This flowchart can be used as a ready-reference to understand the various requirements and beneficial applications governed under NR 538. WDNR NR538 can be found on the website at:

http://www.legis.state.wi.us/rsb/code/nr/nr538.pdf

Regulations of We Energies Ash Utilization - Michigan Department of Environmental Quality

The Michigan Department of Environmental Quality (MDEQ) is responsible for regulating ash utilization in Michigan. The regulations in Michigan are different than in Wisconsin. Fly ash has been used in concrete widely. However, other land applications have been limited. The readers are referred to the following websites for Michigan statues and rules:

http://www.deq.state.mi.us/documents/deq-wmd-swp-part115.pdf

http://www.deq.state.mi.us/documents/deq-wmd-swp-pt115rls.pdf

Environmental Protection Agency (EPA) Guidelines and C^2P^2 Program

The EPA regulates the ash utilization program in the United States, together with many other environmental issues. Based on the studies conducted by various power plants, universities and research institutions, EPA has determined that large volume wastes from coal-fired electric utilities pose minimal risk to human health and the environment.

On January 28, 1993, the EPA issued a guideline for purchasing cement containing fly ash. This guideline requires that all federal agencies and all state and local government agencies, and contractors that use federal funds to purchase cement and concrete, must implement a preference program favoring the purchase of cement and concrete containing coal fly ash (61). Additional preference guidelines have recently been issued for CLSM and car stops produced with CCPs as well.

EPA recognizes the significant environmental, economic, and performance benefits from using CCPs in a number of applications and sponsors the Coal Combustion Products Partnership (C^2P^2) program. The C^2P^2 program is a cooperative effort between EPA and various organizations to help promote the beneficial use of CCPs and the environmental benefits which can result from that beneficial use. The initiative includes three primary activities:

(1) A challenge program;

(2) Development of environmental effects and benefits booklets focusing on coal ash use in the highway and building construction industries; and

(3) Support for the development of CCP use workshops.

The voluntary C_2P_2 Challenge Program focuses on the beneficial use of CCPs and encourages organizations to participate as Champions for generators and users of CCPs and Leaders for federal agencies, professional groups, and trade associations. EPA is developing two booklets outlining the environmental effects and benefits from the beneficial use of coal fly ash and other CCPs in certain applications: one for highway construction and the other for cast-in-place concrete building construction. EPA is working with Federal Highway Administration, the Department of Energy, and the American Coal Ash Association to develop a series of workshops for users of CCPs. EPA C^2P^2 program can be found on the website at: http://www.epa.gov/c2p2/

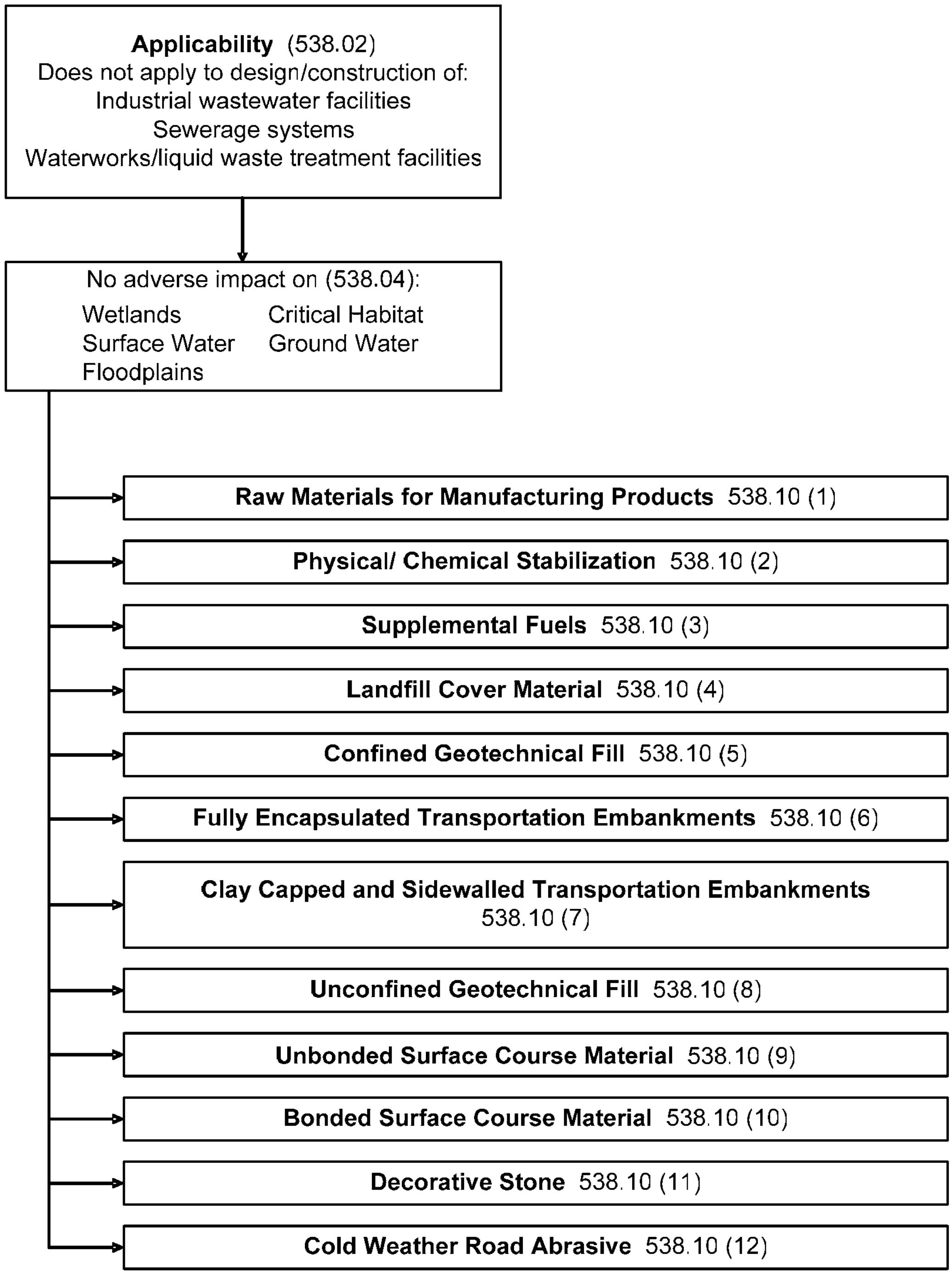
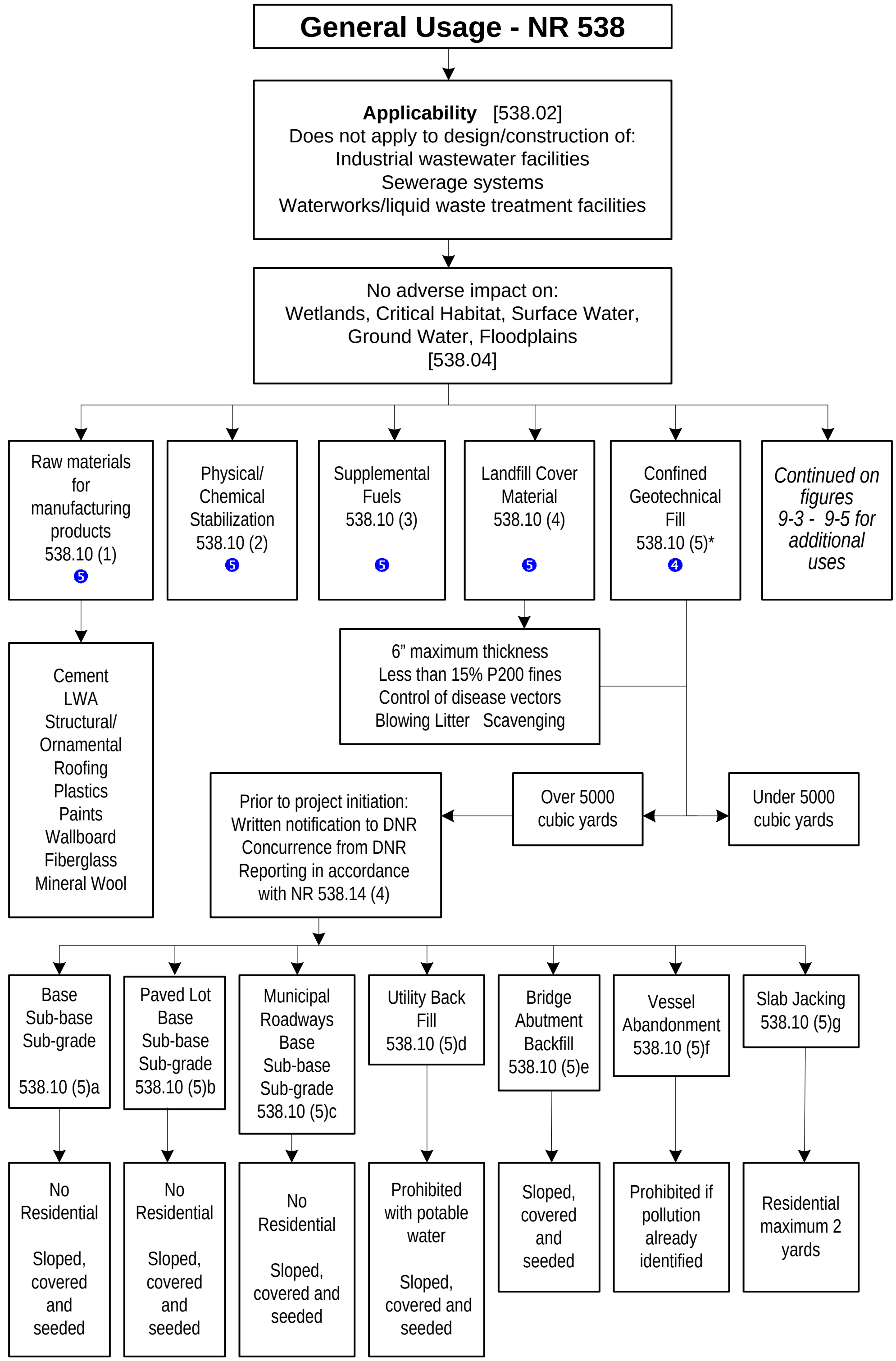
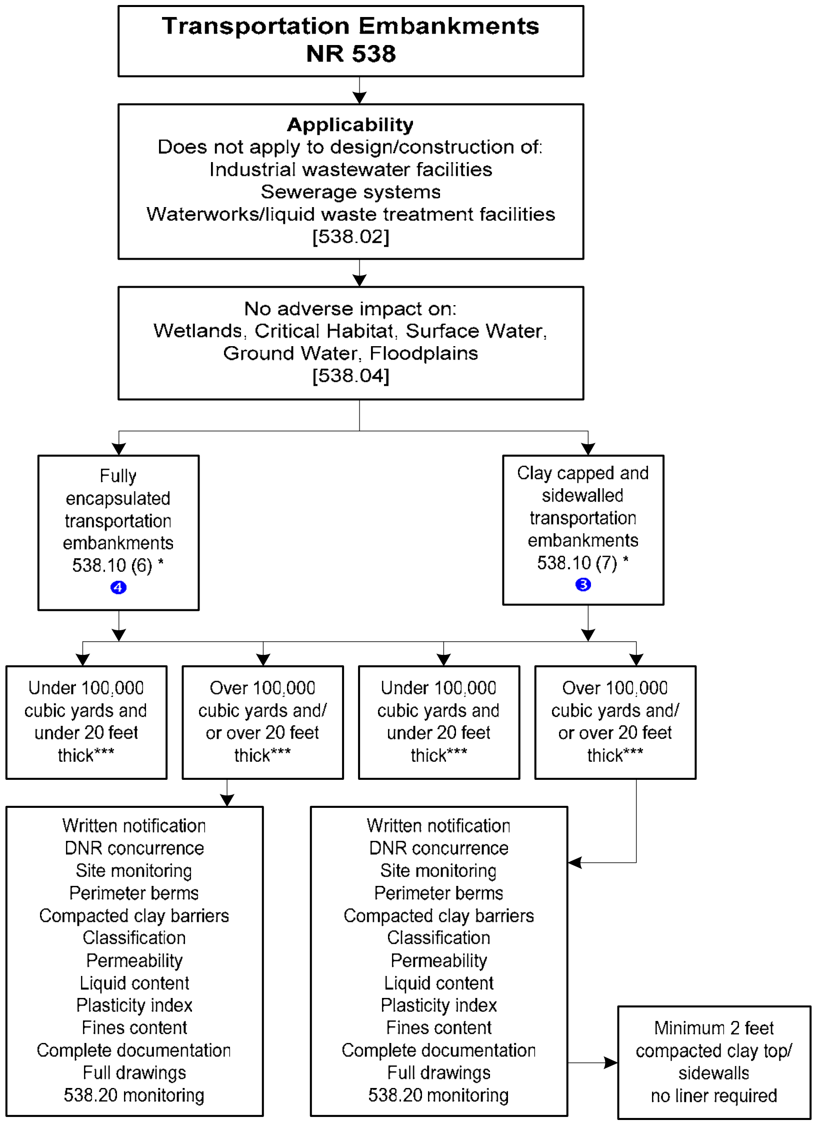


Figure 9-1: NR 538 Beneficial Use of Industrial By-Products



*Use Property Owner Notification – form 4400-199 Wisconsin DOT
**See attachments for details ***Use affidavit – form 4400-200 Wis. DOT
⓿ Industrial By-product Category – By-product must have category number equal or lower than the one shown

Figure 9-2: Flow Chart for General Usage of Industrial By-Products



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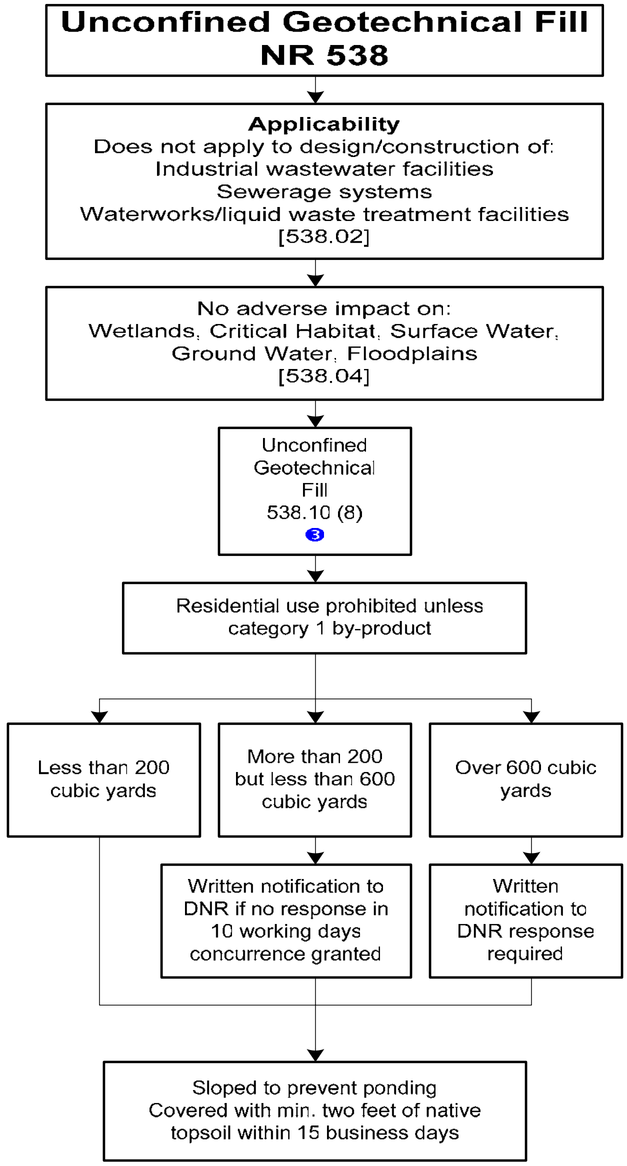
*** Use affidavit – form 4400-200 Wis. DOT

0 Industrial By-product Category – By-product must have category number equal or lower than the one shown

Figure 9-3: Flow Chart for Application of Industrial By-Products in Transportation Embankments



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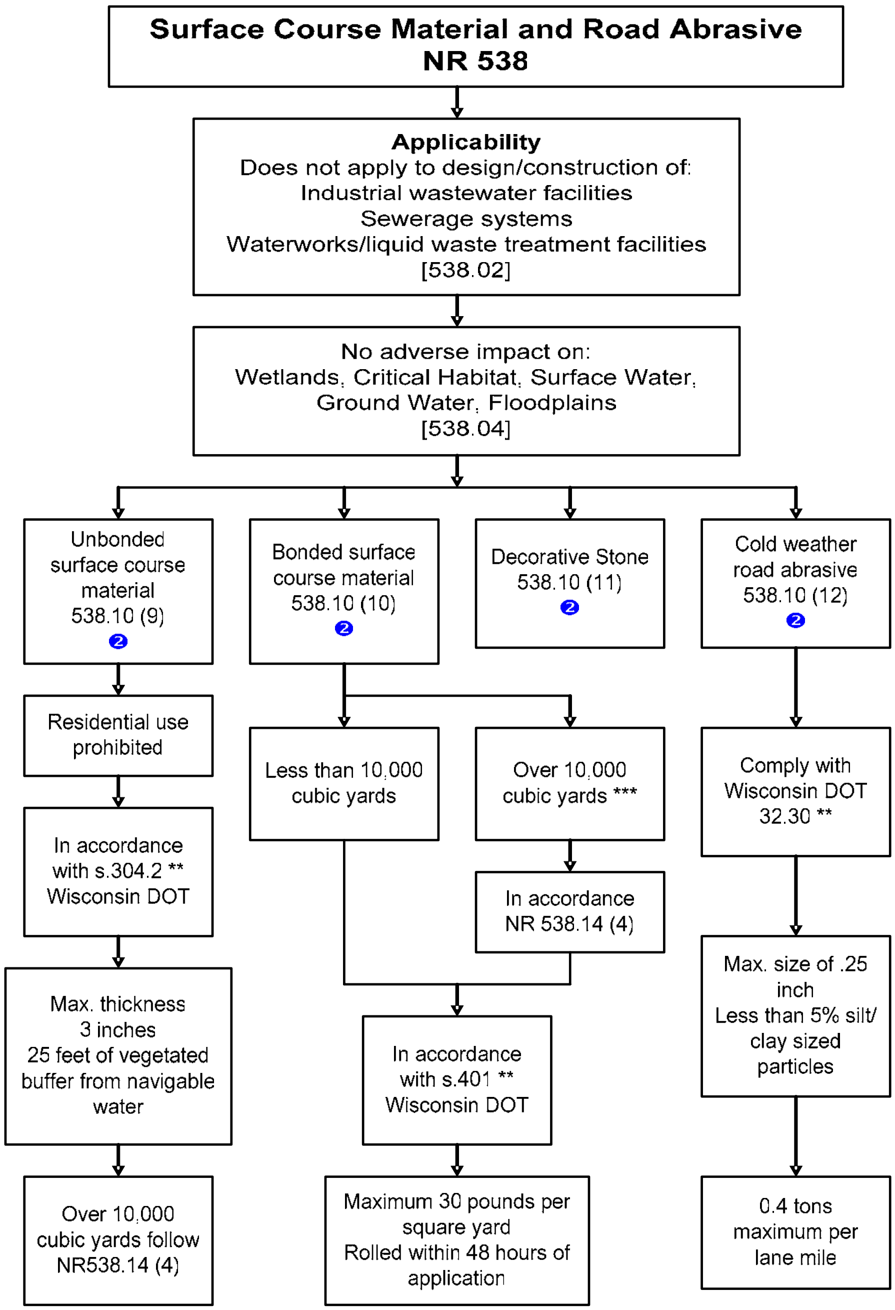
*** Use affidavit – form 4400-200 Wis. DOT

❶ Industrial By-product Category – By-product must have category number equal or lower than the one shown

Figure 9-4: Flow Chart for Application of Industrial By-Products in Unconfined Geotechnical Fill.



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**See attachments for complete details
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0 Industrial By-product Category – By-product must have category number equal or lower than the one shown

Figure 9-5: Flow Chart for Application of Industrial By-Products as Surface Course Material and Road Abrasive

Mercury Removal-Ash Beneficiation (Patent Pending)

The emission of mercury compounds from all sources, including coal-fired power plants, has drawn national and international attention due to the fact that certain forms of mercury have deleterious effects on wildlife and can be toxic to humans. Activated carbon injection (ACI) is by far the most effective and widely accepted technology to remove mercury from the flue gas of power plants. However, the implementation of ACI ahead of the primary electrostatic precipitator (ESP) or baghouse will inevitably increase the mercury concentration and carbon content in coal ash and is expected to affect the value of the ash.

We Energies conducted a study to develop and demonstrate a technology to liberate and recapture the mercury adsorbed onto activated carbon and fly ash, and provide high quality fly ash for reuse in concrete applications or recycle sorbent used in mercury removal (62).

A bench scale study was done to select an optimum combination of temperature and retention time to maximize mercury (Hg) recovery. Fly ash samples taken from Presque Isle Power Plant (PIPP) were used in the experiments. The total Hg concentration in the sample was determined by cold-vapor generation atomic fluorescence spectroscopy (AFS). Samples were treated in a muffle furnace in an inert atmosphere at different temperatures ranging from 371ºC to 538ºC for retention times of one to five minutes. A nitrogen atmosphere was maintained to keep the carbon from igniting. The percent of Hg liberated from the ash samples was determined by measuring the total Hg left in the ash after thermal treatment. PIPP fly ash Units 5 & 6 was derived from western bituminous coal and colleted using a precipitator. The original total Hg concentration in the sample was 0.42 ppm. The results indicated that both temperature and retention time are important parameters in the thermal desorption process. At temperatures lower than 482ºC, the maximum Hg removal was 40% even with prolonged thermal treatment. More Hg can be removed with higher temperature and longer treatment. At 538ºC, 90% of the Hg was liberated from the fly ash within four minutes. Figure 9-6 shows the rate of Hg removal from PIPP fly ash in the muffle furnace using different combinations of temperature and retention time.

Based upon the test results obtained from the bench scale study, a test program was designed to generate experimental data from a pilot apparatus

The pilot test apparatus is comprised of seven main components: a cone-shaped hopper, air slide, baghouse, burner, collector underneath the air slide, Hg condenser, and wet scrubber. During each fly ash processing run, samples were fed into the air slide through the cone-shaped hopper. The speed of sample going through the system was controlled by a rotary feeder. Inside the

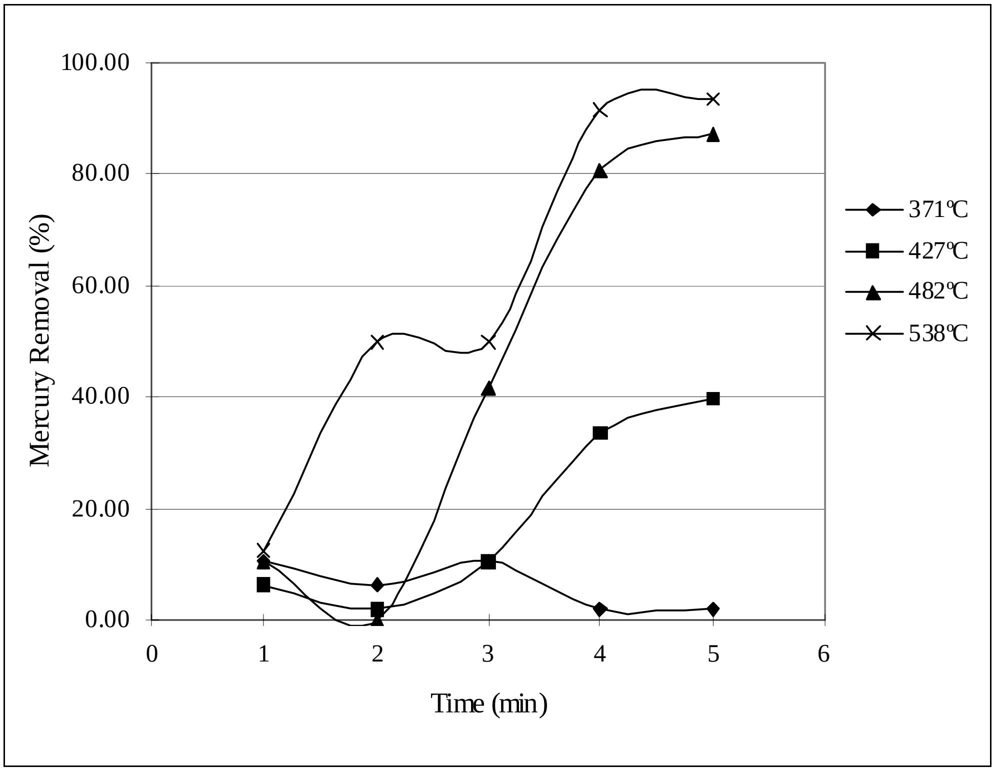

Figure 9-6: Effect of temperature and retention time on mercury removal from PIPP fly ash.

air slide, samples were heated by hot air coming from the burner. The temperature inside the air slide was controlled by adjusting the air flow rate of the burner. A data logger connected to five thermocouples located at the burner, baghouse inlet, and the inlet, midpoint and outlet of the air slide, were used to record the temperature readings. After traveling through the air slide, part of the sample went to the collector at the discharge end of the air slide and the rest of the sample went to the baghouse. Hot air that exited the baghouse passed through a mercury condenser and wet scrubber before being emitted into the ambient environment. Fly ash samples from Presque Isle Power Plant (PIPP), Valley Power Plant (VAPP) and Pleasant Prairie Power Plant (PPPP) were used for the pilot study. Hg concentration and carbon content were measured before and after thermal treatment for comparative purposes. Loss on ignition was used as the indicator of carbon content.

A total of ten fly ash samples from three different power plants were used in the pilot study. The pilot study was conducted in two phases: first, ash samples (two from PIPP, one from PPPP and one from VAPP) were treated in the pilot scale apparatus under fixed temperature and rotary feeding rate (retention time); second, fly ashes (three split samples from PIPP and three split samples from PPPP) were tested under different temperatures and rotary feeding speed. The Hg concentrations in these fly ash samples ranged from 0.11 ppm to 1.00 ppm. For each test in phase one, the initial temperature of the air slide inlet was set at 538ºC and the rotary feeding speed was set at 1000 rpm. The results of these tests are shown in Table 9-9 and Figure 9-7. All four initial tests indicated that Hg could be liberated from various ash samples at 538ºC using the pilot scale apparatus. The majority of the sample passing through the air slide discharged to the collector under the air slide with very low concentrations of Hg detected in these samples. A small proportion of the sample passed with the air flow to the baghouse and contained a higher Hg content.

Table 9-9: Pilot test data for PIPP, PPPP and VAPP samples at 538ºC and 1000rpm

Sample Description		PIPP-I	PPPP	VAPP	PIPP-II
Samples collected before Experiment					
	Hg Content (ppm)	0.18	0.97	0.20	0.15
	Loss on ignition	26.7	3.2	33.5	21.7
Samples collected under the air slide					
	Hg content (ppm)	0.05	0.14	0.03	0.03
	Hg Removed (%)	74.4	85.6	84.5	79.3
	Loss on Ignition	38.1	9.8	36.9	26.1
Samples collected under the Baghouse					
	Hg content (ppm)	0.38	1.00	0.38	0.32
	Hg Increased (%)	111.1	3.1	90.0	113.3
	Loss on Ignition (%)	22.6	10.5	26.9	22.0

Further experiments were performed to determine how temperature and rotary feeding speed would impact the Hg desorption process using PIPP and PPPP samples. Three experiments were run with the rotary feeder speed set at 800, 1000 and 1200 rpm and the air slide inlet temperature set at 538ºC using PIPP samples. The initial Hg content in these samples was around 0.14 ppm. PPPP samples were treated with different heating temperatures, 538ºC, 593ºC and 649ºC and the rotary feeder speed fixed at 1000 rpm. The results are shown in Table 9-10.

Data analysis shows no obvious correlation between the rotary feeding speed and Hg removal. The Hg content in fly ash samples collected under the air slide was 77.3% to 89.3% lower than that found in the original samples. It is possible that rotary feeder speed does not significantly impact the retention time of samples in the air slide.

Table 9-10: Effects of temperature and retention time on mercury liberation

Sample Description			PIPP			PPPP	
Experiment Sequence		1st	2nd	3rd	4th	5th	6th
Rotary Feeder Speed (RPM)		800	1000	1200	1000	1000	1000
Temperature (ºF)		538	538	538	538	593	649
Samples collected before Experiment							
	Hg Content (ppm)	0.14	0.14	0.11	0.69	0.62	1.00
	LOI (%)	25.7	25.3	26.6	2.7	2.6	2.7
Samples collected under the air slide							
	Hg content (ppm)	0.025	0.015	0.025	0.10	0.054	0.055
	Hg Removal (%)	82.14	89.29	77.27	85.51	91.29	94.50
	LOI (%)	42.3	31.3	14.6	3.2	1.9	1.8
Samples collected in the Baghouse							
	Hg content (ppm)	0.38	0.40	0.36	0.81	1.2	1.4
	Hg Increased (%)	171.43	185.71	227.27	17.39	93.55	40.00
	LOI (%)	22.7	20.9	20.5	5.3	3.9	4.0

Ammonia Removal-Ash Beneficiation (US Patent 6,755,901)

Coal-fired power plants are utilizing several proven technologies to improve the quality of air emissions through the reduction of nitrogen oxides (NO_x). These include Low NO_x burners, Selective Catalytic Reduction (SCR), Selective Non-Catalytic Reduction (SNCR), and Amine Enhanced Lean Gas Reburn (AEFLGR). These modifications and additions to coal-fired combustion systems normally result in additional residual carbon and/or ammonia compounds. We Energies has developed the ammonia liberation process (ALP) as a way to overcome the far reaching effects that the installation of NO_x reduction technologies may have. The process developed by We Energies employs the application of heat to liberate the ammonia compounds from the ash, consume undesirable carbon and render the ash a marketable product. The process design employs few moving parts to keep wear and maintenance low. The system is adaptable to meet the different ash characteristics generated by the various NO_x reduction systems as well as the quantity of ash needing beneficiation.

Ammonia Removal Process

The type of NO_x reduction process used typically determines the type and characteristics of the ammonia contaminants. In general the most common and abundant species are the bisulfate and sulfate forms. These species have the required removal temperatures of 813ºF and 808ºF, respectively. The ammonia liberating process preheats the ash and then feeds it to a processing bed where its temperature is increased to about 1,000ºF with hot fluidizing air. The fluidizing air is supplied by a burner and forced through a porous metal media. This high temperature media provides support for the ash and distribution for the air flow. The heat breaks down or consumes the contaminants and the air flow carries the contaminants away from the ash. The ash leaves the processing bed and is cooled with a heat exchanger. This reclaimed heat can be used to preheat the incoming untreated ash. The clean ash is transferred to storage for subsequent use. The contaminated air flow leaving the processing bed is passed through a baghouse where any fugitive ash is captured and returned to the ash exiting the processing bed. The dust free ammonia laden gas may then be passed into a wet scrubber for removal of the contaminants for disposal or passed back into the combustion process or NO_x reduction process.

ALP Pilot Plant Test

We Energies has assembled and tested a small-scale prototype ALP unit. The unit is operated under the parameters described above. Figure 9-10 shows the properties of fly ash before and after the tests. The amount of ammonia in the ash was significantly reduced. The resulting fly ash is a marketable ash that could be beneficially utilized as a "green" construction material.

ASTM C 618 Class F Fly Ash
Ammonia Removal Results

Base Case - Ammonia Before Processing	160 mg/kg
Baghouse Ash – Ammonia After Processing	16 mg/kg
Product Bin Ash – Ammonia After Processing	Less than 2 mg/kg

ASTM C 618 Class F Fly Ash
Loss on Ignition Results

Base Case - LOI Before Processing	2.7%
Baghouse Ash - LOI After Processing	2.6%
Product Bin Ash – LOI After Processing	2.8%

High Carbon Bituminous Coal Fly Ash *
***(No Ammonia Present in Fly Ash)**
Loss on Ignition Results

Base Case - LOI Before Processing	16.2%
Baghouse Ash - LOI After Processing	9.9%
Product Bin Ash – LOI After Processing	7.2%

Chapter 10

Minergy LWA – Structural, Masonry, and Geotechnical Lightweight Aggregates

Introduction

The unique process developed by Wisconsin Electric and its affiliate Minergy Corp. (both companies are subsidiaries of Wisconsin Energy Corporation), in which fly ash, municipal wastewater sludge, and paper mill sludge are converted to an environmentally inert structural lightweight aggregate for use in the construction market was closed in 2000 thus ending five years of quality lightweight aggregate production.

Wisconsin Electric's lightweight aggregate plant, which was located in Oak Creek, Wisconsin, started production in 1994 and was the world's only commercial-scale facility that produced structural-grade lightweight aggregate from coal combustion fly ash and wastewater sludge. The stone-like end product, Minergy LWA™, was suitable for use in a broad range of concrete products and geotechnical applications.

Minergy LWA was sold to concrete producers throughout the Midwest. It is used to reduce dead loads and improve fire ratings of concrete in numerous construction projects. For example, past projects include office buildings in the Chicago area; a student commons facility at St. Olaf College in Minnesota; a hospital in Ft. Wayne, Indiana; Michigan Tech University's Environmental Sciences Building; and in Wisconsin, VA Hospital in Madison, 8th Street Bridge in Sheboygan, and Miller Park, Midwest Express Center and the Hilton Hotel in Milwaukee.

Minergy LWA was also used to produce lightweight concrete masonry. Compared to conventional masonry units made with sand and stone, lightweight concrete masonry has higher fire ratings and higher R-values.

Since lightweight concrete masonry is about 20% lighter than conventional masonry, it is easier to install and transport. Many users report fewer back injuries and fewer complaints due to repetitive motion ailments. Lightweight masonry units are slightly more expensive than conventional concrete masonry, but the cost of a typical wall made of lightweight masonry is generally less, due to increased productivity and lower transportation costs. The life cycle costs are less due to energy savings.

Minergy LWA was also used for geotechnical applications. Lightweight backfill reduces the loads on poor sub-soils thus minimizing settlement. Lightweight backfill behind retaining walls exerts lateral pressures that are 3 to 4 times less than conventional sand, stone or clay backfill. Typical backfill projects include highway embankments, bridge abutments, fill for road construction, segmental retaining walls, and lightweight fill for building structures.

Minergy LWA was also used to produce lightweight soils for roof top gardens and parks such as McArthur Square in Milwaukee, Wisconsin and Monona Terrace in Madison, Wisconsin. The thermal resistivity of Minergy LWA was about 4 times higher than sand or stone and is often used to backfill water mains that do not have adequate cover or to insulate other frost susceptible structures. Lightweight aggregate can be used for perimeter insulation for slabs on grade and building foundations.

The Minergy LWA manufacturing process had numerous environmental benefits. Historically, fly ash and sludge were landfilled at a substantial economic and environmental cost. By utilizing recycled ingredients, the Minergy LWA process not only prevents needless land filling but also eliminates the need for raw material extraction.

Unlike conventional lightweight aggregate manufacturing processes that rely on a large amount of energy to power the process, the ash and sludge provided fuel for most of the plant's energy needs – minimizing the need to consume other resources. Since LWA concrete’s R-value (thermal resistivity) is two times higher than normal weight concrete, it can improve the energy efficiency of buildings in which it is applied.

The plant was closed in November 2000 due to competitive pressures for sewage sludge, higher value uses for the fly ash, and to make room for additional generating facilities at the Oak Creek Power Plant.

Chapter 11

Sample Specifications

11.1 Specification for We Energies Cast-in-Place Concrete

Part 1 - General

1.01 Section Includes

A. Furnish and install all cast-in-place concrete.

1.02 References

A. American Concrete Institute (ACI):

1. *ACI 301 - Specifications for Structural Concrete for Buildings.*
2. *ACI 305 - Hot Weather Concreting.*
3. *ACI 306 - Cold Weather Concreting.*
4. *ACI 309 - Recommended Practice for Consolidation of Concrete.*

1.03 Submittals

A. Submit Portland cement and fly ash test reports at least 14 days prior to placement of concrete.

B. Submit manufacturer’s data for concrete admixtures, liquid curing material, floor joint filler, finishing compounds, and bonding agents.

C. Submit concrete aggregate test reports and concrete mix designs at least 14 days prior to placement of concrete.

D. Submit results of concrete strength tests.

1.04 Quality Assurance

A. Comply with ACI 301, except as modified in this Section.

B. Hire an independent testing laboratory, approved by the Engineer, to perform the work listed below. All costs for this testing shall be paid by the Contractor.

1. *Test proposed aggregate.*
2. *Test proposed fly ash.*

3. *Design concrete mixes for each type of concrete specified*

4. *Cast concrete cylinders for strength tests.*

5. *Test concrete cylinders.*

C. Aggregate Tests:

1. *Test aggregates for compliance with ASTM C33.*

D. Concrete Mix Design:

1. *Prepare mix designs for each type of concrete specified.*

2. *Design concrete mixes in accordance with ACI 301.*

E. Concrete Strength Tests:

1. *Mold and cure three specimens from each sample in accordance with ASTM C31. Any deviations from the requirements of ASTM C31 shall be recorded in the test report.*

2. *Test specimens in accordance with ASTM C39. Two specimens shall be tested at 28 days for acceptance and one shall be tested at seven days for information. The acceptance test results shall be the average of the strengths of the two specimens tested at 28 days.*

3. *Make at least one strength test for each 100 cu. yds., or fraction thereof, of each mixture design of concrete placed in any one day.*

4. *A copy of the test results shall be furnished to the Engineer as soon as available.*

5. *All costs of concrete cylinder testing shall be paid by the Contractor.*

6. *Mold and field cure additional specimens for early form removal.*

F. Concrete Slump Tests:

1. *The Independent Testing Laboratory will determine slump of concrete from each truck in accordance with ASTM C143.*

2. *If the slump does not meet specifications, remove batch from work and return to supplier.*

G. Concrete Air Content Tests:

1. *The Independent Testing Laboratory will determine air content of concrete from each truck in accordance with ASTM C231.*

2. *If air content does not meet specifications, remove batch from work and return to supplier.*

3. *Air content will be tested prior to and after adding superplasticizer.*

H. Concrete Temperature:

1. *The Independent Testing Laboratory will determine temperature of concrete from each truck.*

1.05 Product Handling

A. Do not store forms, shores, reinforcing, equipment or other material on finished slab surfaces.

Part 2 – Products

2.01 Concrete Materials

A. Cement: Conform to ASTM C150, Type I. Provide cement from one source of supply.

B. Fly ash: Conform to ASTM C618, Class C from We Energies Pleasant Prairie or Presque Isle Power Plants.

C. Aggregate: Conform to ASTM C33. Provide aggregate from one source of supply.

D. Water: Clean, potable, and free from deleterious amounts of oil, acid, alkali or other foreign matter.

2.02 Admixtures

A. Air Entraining Admixture: Conform to ASTM C260.

B. Water Reducing Admixture: Conform to ASTM C494, Type A.

C. High Range Water-Reducing Admixtures (Superplasticizer): Conform to ASTM C494, Type F and contain no chlorides.

2.03 Miscellaneous Material

A. Burlap-Polyethylene Sheet: Burlap polyethylene sheeting shall consist of burlap weighing not less than 10 oz./linear yard, 40 in. wide impregnated on one side with white opaque polyethylene 0.006 in. thick. Sheeting shall conform to ASTM C171.

B. Liquid Curing Compound: Conform to ASTM C309, Type 1-D, Class B clear or translucent with fugitive dye. Not to be applied to floor slabs.

C. Expansion Joint Material: Bituminous fiber type conforming to ASTM D1751 with bituminous or paraffin binder.

D. Interior Joint Filler: One part, self leveling, polymer reinforced joint filler, Everjoint manufactured by L&M Construction Chemicals, Inc., or approved equal.

E. Exterior Joint Sealant: Two part, self leveling, polyurethane sealant, Sonolastic SL2 manufactured by Sonneborn, or approved equal.

F. Concrete Finishing Compound: Thoroseal cement based coating manufactured by Thoro System Products, or approved equal.

G. Bonding Agent: Acryl 60 manufactured by Thoro System Products, or approved equal.

2.04 Concrete Mix Proportions

A. 3000 PSI Concrete - 40% fly ash @ 1:1.25, cement to fly ash replacement ratio.

Coarse Aggregate Size	ASTM C33 No. 67
Minimum Compressive Strength at 28 days	3000 psi
Minimum Cement Content	255 lbs/cu. yd.
Minimum Class C Fly ash Content	208 lbs/cu. yd.

Air Entraining Agent	Compatible with cement and as needed for air content to provide required air for exposure condition

B. 4000 PSI Concrete - 40% fly ash @ 1:1.25, cement to fly ash replacement ratio.

Coarse Aggregate Size	ASTM C33 Size No. 67
Minimum Compressive Strength at 28 days	4000 psi
Minimum Cement Content	310 lbs/cu. yd.
Minimum Class C Fly ash Content	251 lbs/cu. yd.
Air Entraining Agent	Compatible with cement and as needed for air content to provide required air for exposure condition

C. 5000 PSI Concrete - 40% fly ash @ 1:1.25, cement to fly ash replacement ratio

Coarse Aggregate Size	ASTM C33 No. 67
Minimum Compressive Strength at 28 days	5000 psi
Minimum Cement Content	367 lbs/cu. yd.
Minimum Class C Fly Ash	265 lbs/cu. yd.
Air Entraining Agent	Compatible with cement and as needed for air content to provide required air for exposure condition

D. 6000 PSI Concrete - 40% fly ash @ 1:1.25 cement to fly ash replacement ratio.

Coarse Aggregate Size	ASTM C33 No. 67
Minimum Compressive Strength @ 28 days	6000 psi
Minimum Cement Content	445 lbs/cu. yd.
Minimum Flyash Content	239 lbs/cu. yd.
Slump	6½ in.
Superplasticizer	Compatible with cement and as needed for workability
Air Entraining Agent	Compatible with cement and as needed for air content to provide required air for exposure condition

Part 3 – Execution

3.01 Concrete Production

A. Batch, mix, and transport ready-mixed concrete in accordance with ASTM C94.

B. Mix concrete only in quantities for immediate use. Discard concrete which has set. Do not retemper.

C. Discharge concrete from truck within 60 minutes after cement is added to the mix.

D. Do not add water at the site without the permission of the Engineer.

E. Add superplasticizer to the concrete at the project site. Add superplasticizer and mix concrete in accordance with manufacturer's recommendations.

3.02 Embedded Items

A. All sleeves, inserts, anchors, and embedded items required for adjoining work or for its support shall be placed prior to placing concrete.

B. All embedded items shall be positioned accurately and supported against displacement.

C. Voids in sleeves, inserts and anchor slots shall be filled temporarily with readily removable material to prevent the entry of concrete into the voids.

3.03 Preparation Before Placing

A. Formwork shall be completed and all reinforcement and embedded items shall be secured in place.

B. All snow, ice, and mud shall be removed prior to placing concrete.

C. Do not place concrete on frozen ground.

D. Do not place concrete on ground with standing water or when upper 2" of ground is saturated.

E. Do not place concrete during rain, sleet, or snow.

3.04 Concrete Conveying

A. Handle concrete from the mixer to the place of final deposit as rapidly as practical by methods, which will prevent segregation or loss of ingredients.

3.05 Concrete Depositing

A. Deposit concrete continuously or in layers of such thickness that no concrete will be deposited on concrete which has hardened sufficiently to cause the formation of seams or planes or weakness within the section.

B. Place concrete at such a rate that the concrete which is being integrated with fresh concrete is still plastic.

C. Concrete, which has partially hardened or has been contaminated by hardened materials, shall not be deposited.

D. Remove rejected concrete from the site.

E. Deposit concrete as nearly as practicable in its final position to avoid segregation due to handling or flowing.

F. Free fall of concrete shall not exceed five feet. Use chutes equipped with hopper heads for placing where a drop of more than five feet is required.

3.06 Placing Concrete Slabs

A. Deposit and consolidate concrete slabs in a continuous operation.

B. Consolidate concrete placed in slabs by vibrating bridge screeds, roller pipe screeds or other methods acceptable to the Engineer. Bring slab surfaces to the correct level with a straight edge and then strike off. Use bullfloats or darbies to smooth the surface, leaving it free from bumps and hollows.

C. Do not leave screed stakes in concrete.

D. Do not sprinkle water on the plastic surface. Do not disturb the slab surfaces prior to start of finishing operations.

3.07 Cold Weather Placing

A. Do not place concrete when the air temperature is less than 40^{o}F without the specific approval of the Engineer.

B. Comply with ACI 306 to protect all concrete work from physical damage and reduced strength caused by frost or low temperatures.

C. The temperature of the concrete delivered at the site shall conform to the following limitations.

Air Temperature	Minimum Concrete Temperature
30^o to 45^{o}F	60^{o}F
0^o to 30^{o}F	65^{o}F
Below 0^{o}F	70^{o}F

D. If water or aggregate is heated above 100^{o}F, the water shall be combined with the aggregate in the mixer before cement is added. Cement shall not be mixed with water or with mixtures of water and aggregate having a temperature greater than 100^{o}F.

E. When the mean daily temperature is less than 40^{o}F, the temperature of the concrete shall be maintained between 50^{o}and 70^{o}F for the required curing period.

F. Arrangements for heating, covering, insulation, or housing the concrete work shall be made in advance of placement and shall be adequate to maintain the required temperature without injury due to concentration of heat.

G. Combustion heaters shall not be used during the first 24 hours unless precautions are taken to prevent exposure of the concrete to exhaust gases.

3.08 Hot Weather Placing

A. Comply with ACI 305 when hot weather conditions exist.

B. Maintain concrete temperature at time of placement below 90^{o}F.

C. When the temperature of the steel is greater than 120^{o}F, steel forms and reinforcement shall be sprayed with water prior to placing concrete.

D. Keep all surfaces protected from rapid drying. Provide windbreaks, shading, fog spraying, sprinkling, ponding, or wet covering in advance of placement.

3.09 Consolidation

A. Consolidate all concrete in accordance with provisions of ACI 309.

B. Consolidate each layer of concrete immediately after placing, by use of internal concrete vibrators. Maintain a frequency of not less than 8,000 vibrations per minute for each internal vibrator.

C. Provide adequate number of units and power source at all times. Use a minimum of two vibrators for all work and maintain spare units to ensure adequacy.

D. Insert the vibrator so as to penetrate the lift immediately below the one being placed. Do not insert the vibrator into lower courses, which have begun to set.

E. Spacing between insertions of the vibrator shall generally be from 12” to 18” and shall not exceed twice the radius of action as shown in ACI 309 or eighteen (18) inches.

F. Do not use vibrators to transport concrete inside the forms.

G. Vibration shall be adequate and properly carried out to minimize entrapped air and surface voids on formed surfaces.

3.10 Concrete Slab Finishing

A. Float Finish:

1. *Apply float finish to all slab surfaces.*
2. *After placing and screeding concrete slabs, do not work the surface until ready for floating. Begin floating when the surface water has disappeared and when the concrete has stiffened sufficiently to permit operation of a power-driven float.*
3. *Consolidate the surface with power-driven float, or by handfloating if the area is small or inaccessible to power units.*
4. *Check and level the surface plane to a tolerance not exceeding ¼ inch in ten (10) feet when tested with a ten-foot straight-edge placed on the surface at not less than two different angles.*
5. *Immediately after leveling, refloat the surfaces to a smooth, uniform, granular texture.*

B. Trowel Finish:

1. *Apply steel trowel finish to all interior floor slabs, topping, and stair treads.*
2. *Apply float finish to slabs as described above in part 3.10.A.*
3. *After floating, begin the first trowel finish operation using a power-driven trowel. Begin final troweling when the surface produces a ringing sound as the trowel is moved over the surface.*
4. *Consolidate the concrete surface by the final hand troweling operation, free from trowel marks, uniform in texture and appearance, and with a surface plane tolerance not exceeding ⅛ inch in 10 feet when tested with a ten foot straight-edge.*

C. Broom Finish:

1. *Apply non-slip broom finish to all exterior sidewalks and aprons.*
2. *Apply float to slabs as described above in part 3.10A.*
3. *Immediately after floating, slightly roughen the concrete surface by sweeping in the direction perpendicular to the main traffic route. Use a fiber-bristle broom.*

3.11 Finishing Formed Surfaces

A. Smooth Form Finish: Provide a smooth formed surface to all formed surfaces not exposed to view unless otherwise noted in paragraph B. Smooth formed finish shall consist of the following:

   1. *Construct formwork in exact dimension of the concrete member poured.*
   2. *Patch all tie holes and defects.*
   3. *Remove all fins, concrete "buttons", and protrusions completely.*

B. Special Wall Finish: Provide a special wall finish to all formed surfaces exposed to view.

   1. *Provide a smooth form finish in accordance with paragraph 3.11.A.*
   2. *Thoroughly clean wall surface and remove all dirt, loose mortar particles, paint, films, protective coatings, efflorescence and other foreign material.*
   3. *Dampen surface with clean water just prior to application of finishing compound.*
   4. *Mix one part bonding agent to three parts clean water for mixing liquid.*
   5. *Mix concrete finish compound with mixing liquid as specified by the manufacturer.*
   6. *Apply first coat to concrete with brush at 2 lbs. per square yard.*
   7. *Apply second coat to concrete with brush at 2 lbs. per square yard after the first coat has set.*
   8. *When the second coat has set, float it to a uniform texture with a sponge float.*
   9. *Prepare three test samples of various textures for approval by the Engineer. Each sample shall be approximately 6' x 6' in size and located on an unexposed wall surface as directed by the Engineer.*

3.12 Curing

A. Immediately after placement, all concrete shall be damp cured for a minimum of seven days.

B. All slabs shall be covered with approved burlap-polyethylene film and kept in place throughout the curing period.

C. Walls, beams, columns, and other formed surfaces shall be covered with burlap-polyethylene film or sprayed with an approved curing compound.

D. All burlap-polyethylene film shall be adequately anchored at the edges to prevent moisture loss.

E. Rewet all slab surfaces at least once a day during the curing period.

3.13 Patching

A. Repair honeycomb and other defective areas, fill surface voids and fill form tie holes and similar defects in accordance with Chapter 9 of ACI 301.

B. Reinforce or replace deficient work as directed by the Engineer and at no additional cost to the Owner.

3.14 Cleaning

A. Upon completion and prior to any painting, all exposed or painted concrete surfaces shall be thoroughly cleaned of all concrete spatters, from oil or other foreign material detrimental to appearance or painting.

END OF SECTION

11.2 Specification for We Energies Bottom Ash Structural Backfill

Part 1 – General

1.01 Section Includes

A. Furnish bottom ash structural fill material and backfill excavation (for bridges, culverts, retaining walls, structural plate pipes, pipe anchors, and/or around building basements).

1.02 References

A. WDOT - Standard Specifications for Highway and Structure Construction Section 210.

B. ASTM E1861 - Standard Guide for Use of Coal Combustion By-Products in Structural Fills.

1.03 Submittals

A. Submit Sieve Analysis Test and Reports.

1.04 Quality Assurance

A. Chapter NR 538 - Beneficial Use of Industrial By-Products - Department of Natural Resources (Wisconsin Administrative Code).

B. Comply with ASTM E1861, except as modified in this section.

C. Hire an independent testing laboratory, approved by the Engineer to perform the work listed below. All costs for the testing shall be paid by the Contractor.

1. *Perform Sieve Analysis Test on the bottom ash.*
2. *Measure field density of the bottom ash.*

Part 2 – Products

2.01 Bottom Ash Structural Fill

A. Bottom Ash: Meet ASTM E1861 requirements.

B. Water: Clean, potable, and free from deleterious amounts of oil, acid, alkali or other foreign matter.

Part 3 – Execution

3.01 Bottom Ash Material

A. Bottom ash used for backfill shall be of a quality acceptable to the Engineer and free from frozen lumps, wood or other extraneous or deleterious material.

3.02 Limitations on Placing Backfill

A. Bottom ash shall not be placed against concrete masonry retaining wall or abutment until the masonry has been in place 14 days or until tests show the strength of masonry strong enough to take lateral pressure from the fill.

B. Structural backfill shall not be placed against any portion of any substructure until the required curing and protection, surface finishing, damp proofing and waterproofing of the work to be covered by structural fill has been completed.

C. When backfilling against retaining walls, fill uniformly and simultaneously on both sides to the elevations of the front ground surface immediately after removal of the forms.

D. Abutments for rigid frame structures and abutments not designed as self-sustaining shall not be backfilled until concrete in the superstructure has been poured and cured.

E. Backfill only after the area has been cleared of all false work, sheet piling, cribbing, shoring, bracing, forms and rubbish.

3.03 Bottom Ash Transporting and Placing

A. Bottom ash shall be transported in a truck or other vehicle and shall be so unloaded such that contents of each vehicle are gradually deposited instead of simultaneously emptying the entire content as one mass.

B. Backfill shall be placed in continuous horizontal layers not more than eight inches thick and brought up uniformly. Compact each layer to at least 95% of proctor density or 90% of modified proctor density (ASTM D1557) before the next layer is placed, by means of approved rollers or portable mechanical or pneumatic tampers or vibrators.

C. Backfilling along front face of abutments, retaining walls and wing walls shall extend to within six inches of weep holes, unless otherwise specified.

3.04 Cleaning

A. Upon completion of placing structural fill, the area shall be thoroughly cleaned of all foreign material.

END OF SECTION

11.3 Specification for We Energies Bottom Ash as Granular Backfill

Part 1 – General

1.01 Section Includes

A. Furnish bottom ash granular material and backfill trenches for pipe culverts, storm sewers, underdrains and similar structures.

1.02 References

A. WDOT - Standard Specifications for Highway and Structure Construction-Section 209.

B. ASTM D422 - Test Method for Particle Size Analysis of Soils

C. Chapter NR 538 - Beneficial Use of Industrial By-Products - Department of Natural Resources (Wisconsin Administrative Code).

1.03 Submittals

A. Submit Sieve Analysis Test results.

1.04 Quality Assurance

A. Comply with WDOT - Standard Specification for Highway and Structure Construction Section 209.2 for particle size distribution, except as modified in this section.

B. Hire an independent testing laboratory, approved by the Engineer to perform the work listed below. All costs for the testing shall be paid by the Contractor.

1. *Perform Sieve Analysis Test on the aggregate.*
2. *Measure field density of the backfill.*

Part 2 – Products

2.01 Bottom Ash Granular Fill

A. Bottom Ash: Particle size distribution shall meet job requirements.

B. Water: Clean potable and free from deleterious amounts of oil, acid, alkali or other foreign matter.

Part 3 – Execution

3.01 Bottom Ash Material

A. Bottom ash used for backfill shall be of a quality acceptable to the Engineer and free from frozen lumps, wood or other extraneous or perishable material.

3.02 Bottom Ash Placing and Compacting

A. Bottom ash shall be unloaded from the truck or other vehicles so that the contents of each vehicle are gradually deposited instead of emptying the entire contents as one mass.

B. The bottom ash shall be spread and leveled in layers generally not exceeding eight inches in thickness before compaction.

C. Compact each layer to the degree that no further appreciable consolidation is evident under the actions of the compaction equipment. The required compaction shall be attained before any material for a succeeding layer is placed thereon.

D. Compaction shall be performed by specialized compaction equipment in addition to hauling and leveling equipment routed and distributed over each layer of the fill.

E. The fill material shall be compacted to at least 90% of modified proctor maximum density (ASTM D1557) for their full depth.

3.04 Cleaning

A. Upon completion of placing granular fill, the area shall be thoroughly cleaned of all foreign material. The compaction area shall be free from bottom ash debris and suitable for placement of topsoil or next course of road construction.

END OF SECTION

11.4 Specification for We Energies Flowable Fly Ash Slurry Controlled Low Strength Material (CLSM)

Part 1 - General

1.01 Section Includes

A. Furnish and place controlled low strength material as backfill in trenches for culverts, conduit, storm sewers, utilities or similar structures, as a backfill behind bridge abutments or as a fill for retirement of sewers, tunnels, tanks, culverts or pipes.

1.02 References

A. ACI 229R-94 Report: Controlled Low Strength Materials (CLSM)

B. ACI 304 - Guide for measuring, mixing, transporting and placing concrete.

C. Chapter NR 538 - Beneficial use of industrial by-products - Department of Natural Resources (Wisconsin Administrative Code).

1.03 Submittals

A. Submit fly ash test results.

B. Submit CLSM flow and compressive strength test results.

C. Submit documentation that the fly ash used in this mixture meets the requirements of Industrial By-Products Categories 1, 2, 3 or 4 in NR 538 of the Wisconsin Administrative Code for use as a confined geotechnical fill.

1.04 Quality Assurance

A. Comply with ACI 229R, except as modified in this section.

B. Hire an independent testing laboratory, approved by the Engineer, to perform the work listed below. All costs for testing shall be paid by the Contractor.

1. *Design CLSM mixes for each type of CLSM specified.*
2. *Cast CLSM cylinder for compressive strength test.*
3. *Measure flow of CLSM.*
4. *Test CLSM cylinders.*

C. CLSM Mix Design

1. *CLSM shall consist of a designed mixture of cement and We Energies' Valley Power Plant or Port Washington Power Plant bituminous coal fly ash and sometimes aggregate.*
2. *The designed mixture shall be self-leveling and shall be essentially free from shrinkage after hardening. The mixture shall be designed to reach a state of hardening such that it can support the weight of a person in no more than 24 hours.*

3. *The CLSM shall meet the following criteria:*

Test	Method	Valve
Flow	ASTM D6103	10" (250 mm) ± 3"
Compressive Strength	ASTM D4832	20-200psi @ 28 days (140 - 1400 kPa)

(The compressive strength values shown are guideline targets and actual cylinder breaks may vary considerably while still providing an acceptable and re-excavatable fill material. 100psi is 14,400 psf in soil terms, which is comparable to very compacted gravel to hard pan material.)

D. CLSM Strength Tests

1. *Mold and cure three specimens from each sample in accordance with ASTM D4832. Any deviations from the requirements of ASTM D4832 shall be recorded in the test report.*
2. *Test specimens in accordance with ASTM D4832. Two specimens shall be tested at 28 days for acceptance and one shall be tested at seven days for information. The acceptance test results shall be the average of the strength of the two specimens tested at 28 days.*
3. *Make at least one strength test for each 100 cu. yd., or fraction thereof, of each mixture design of CLSM placed in any one day.*
4. *A copy of the test results shall be furnished to the Engineer as soon as possible.*
5. *The Contractor shall pay all costs of CLSM cylinder testing.*

F. CLSM Flow Tests

1. *The testing laboratory will determine the flow of CLSM from each truck in accordance with ASTM D6103.*
2. *If flow does not meet specifications, remove batch from work and dispose of off site.*
3. *The Contractor will pay all costs of flow testing.*

G. Hardening Time

1. *On projects where hardening time is critical, the Owner/Engineer may at his/her discretion measure the hardening time in accordance with ASTM C403.*
2. *When measured in accordance with ASTM C403, the CLSM shall give a penetration number in the range of 500 to 1500.*
3. *All costs for measuring hardening time shall be paid by the Contractor.*

Part 2 – Products

2.01 CLSM Material

A. Cement: Conform to ASTM C150, Type 1. Provide cement from one source.

B. Aggregate: Conform to ASTM C33 unless approved by the Engineer.

C. We Energies Class F Fly Ash: Not necessarily conforming to ASTM C 618.

D. Water: Clean, potable, and free from deleterious amounts of oil, acid, alkali or other matter.

2.02 CLSM Mixture Proportions

A. CLSM mixtures shall be proportioned to meet project requirements. The following mixture proportions shall be considered as a guideline for CLSM mixtures. The mixture proportion shall be modified to meet specific project requirements.

1. *Flo-Pac 1 – (Excavatable) trench backfill applications:*

Portland Cement	:	100 lb/cu. yd.
Class F Fly ash	:	1450 lb/cu. yd.
Water	:	950 lb/cu. yd.
Total Weight	:	2500 lb/cu. yd

2. *Flo-Pac 2 (Excavatable)*

Portland Cement	:	70 lb/cu. yd.
Class F Fly ash	:	925 lb/cu. yd.
Sand (SSD)	:	1175 lb/cu. yd.
Added Water	:	785 lb/cu. yd.
Total Weight	:	3002 lb/cu. yd.

3. *Flo-Pac 5 (Not easily excavatable)*

Portland Cement	:	200 lb/cu. yd.
Class F Fly ash	:	700 lb/cu. yd.
Stone (SSD)	:	1500 lb/cu. yd.
Sand (SSD)	:	750 lb/cu. yd.
Added Water	:	480 lb/cu. yd.
Total Weight	:	3683 lb/cu. yd.

4. *Flo-Pac 6 (Excavatable)*

Portland Cement	:	50 lb/cu. yd.
Class C Fly Ash	:	50 lb/cu. yd.
Sand (SSD)	:	3100 lb/cu. yd.
Added Water	:	500 lb/cu. yd.
Total Weight	:	3700 lb/cu. yd.

Part 3 – Execution

3.01 CLSM Production and Conveyance

A. CLSM shall be batched, mixed and transported in accordance with ACI 229.

B. CLSM shall be mixed only in quantities for immediate use. CLSM, that has set, shall be discarded and shall not be retempered.

C. Discharge CLSM from truck within 90 minutes after cement and fly ash is added to the mix.

D. CLSM shall be handled from the mixer to the place of final deposit as rapidly as practical by methods, which will prevent segregation or loss of ingredients.

3.02 CLSM Depositing

A. CLSM shall be placed to the lines and grades as shown on the plans.

B. Materials shall be proportioned in accordance with the specified mix design. The product shall be of consistent texture and flow characteristics. The Engineer may reject any materials exhibiting a substantial change in properties, appearance or composition.

C. CLSM, which has partially hardened or has been contaminated by hardened material, shall not be deposited.

D. Deposit CLSM as soon as practical, so it can flow to any irregular area and fill completely.

E. CLSM shall be placed in accordance with Wisconsin DNR Chapter NR538 and no CLSM material shall be allowed to enter any stream, lake, or storm sewer system.

F. If the official Weather Bureau forecast for the construction site predicts temperatures at or below freezing within the next 24 hours after placement of CLSM, the Contractor shall protect the material placed from freezing during that time period. If the temperature is not forecast to rise above 40^{o}F (4^{o}C) for 72 hours after placement, the Engineer may require protection from freezing for up to 72 hours.

G. When CLSM is used for pipe bedding, it shall be placed in lifts to prevent floating the pipe.

H. When backfilling existing basement walls, or walls not designed for full lateral pressure from CLSM, CLSM shall be placed in lifts to prevent overstressing.

I. Allow CLSM to self-level. Barricade the site or protect by other means, till CLSM hardens to avoid accidental entry.

3.03 Construction Cautions

A. CLSM is placed as a liquid. Hence, it exerts fluid pressure. If CLSM is placed against basement walls or other structures, verify that the structure is capable of taking this lateral pressure. If the structure is not capable of handling this pressure, it can be braced externally until the CLSM slurry solidifies, or the CLSM slurry may be poured in multiple lifts so that one lift hardens before the next is poured.

B. Fresh CLSM flowable fly ash slurry that is placed in deep excavations behaves like “quick-sand” and must be protected from accidental entry until it hardens.

C. Low strength CLSM material (where re-excavation may be required at a later age) should be specified with a maximum strength (or a range of strength) that will allow for easy re-excavation with normal equipment. The addition of coarse aggregate to the mixture generally makes re-excavation more difficult.

D. When transporting CLSM flowable slurry in a ready-mix truck, the driver should be aware of the liquid nature of the material being transported. CLSM may spill out of the back of a ready mix truck with quick stops or traveling up hills. It is better to transport CLSM stiff and add water at the job site for high flow requirements.

3.04 Cleaning

A. Upon completion of placing CLSM, clean the surrounding area of all CLSM spatters, or other foreign material detrimental to appearance.

END OF SECTION

11.5 Sample Specification for We Energies Class C Fly Ash Stabilized Cold In-place Recycled (CIR) Asphaltic Concrete Pavement

Part 1 - General

1.01 Section Includes

A. Pulverize and relay the existing asphaltic surface and stabilize the recycled materials with Class C fly ash.

1.02 References

A. WisDOT – Standard Specifications for Highway and Structure Construction-Section 325.

B. ASTM C-618 – Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete

C. Chapter NR 538 – Beneficial Use of Industrial By-Products - Department of Natural Resources (Wisconsin Administrative Code)

D. ASTM D-698 – Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort

E. ASTM D-5239 – Standard Practice for Characterizing Fly Ash for Use in Soil Stabilization

1.03 Submittals

A. Submit fly ash test results.

1.04 Quality Assurance

A. Comply with WisDOT - Standard Specification for Highway and Structure Construction Section 325 for particle size distribution, except as modified in this section.

B. Required moisture contents will be established by the Engineer based on laboratory tests with the site materials and specific fly ash to be used for the treatment.

Part 2 – Products

2.01 Materials

A. Fly Ash

Fly ash shall comply with the physical requirements of ASTM D-5239 6.4 maintaining a minimum compressive strength of 3.45 MPa (500 psi) at 7 days and the chemical requirements of ASTM C-618. Table 1, for Class “C” fly ash. Self-cementing ashes not meeting the above requirements can be used provided that the sulfur trioxide content does not exceed 10% and the self-cementing properties have been demonstrated to provide the required degree of stabilization. The source of the ash shall be identified and approved in advance of stabilization operations so that laboratory tests can be completed prior to commencing work.

B. Water

The water used in the stabilized mixture shall be clean, clear, free of sewage, vegetable matter, oil, acid and alkali. Water known to be potable may be used without testing. All other sources shall be tested in accordance with A.A.S.H.T.O. T-26 and approved by the Engineer.

Part 3 – Execution

3.01 Reprocessed Asphaltic Base

A. Description

The work under this item shall consist of cutting out, grading and windrowing the existing gravel shoulders and pulverizing and relaying the existing asphaltic surface as shown on the plans and as hereinafter provided.

B. Construction Methods

The milling machine used shall be capable of pulverizing the existing asphaltic surface to a width of 12'6". The milling machine shall be equipped with a spray bar capable of adding 8% by volume of water to the pulverized material. The amount of water added shall be determined by the Engineer.

The existing asphaltic surface shall be pulverized to a depth as shown on the plans and to a maximum size of 1½ inches. A milling machine intended for this pulverizing operation shall be utilized. The milling machine shall be self propelled and equipped with electronic devices which will provide accurate depth, grade and slope control. Contractor shall furnish necessary extra trucks, loaders and graders to transfer reprocessed material where needed and to balance the material. Surplus reprocessed material from the project shall remain the property of the Owner.

Contractor shall grade the pulverized material to a width and slope as shown on the plans.

The grader used to distribute the reprocessed material shall be equipped with an approved automatic control system capable of automatically controlling the elevation and slope of the blade. Crown slope shown in the typical section is after compaction. Slope at lay down or rolling technique shall be adjusted to achieve desired final cross slope.

C. Method of Measurement

This item will be measured as provided in the contract by the area in square yards. The quantity to be measured for payment shall be the area of the pavement before being removed and then redistributed, graded and compacted. Crushed Aggregate Base Course added shall be measured by the ton, delivered and spread prior to the reprocessing operation.

D. Basis of Payment

This item, measured as provided above, will be paid for at the contract unit price per square yard, which price shall be full compensation for removing, redistributing, adding moisture and blending aggregate, shaping and compacting the materials and for furnishing all labor, equipment, water, tools and incidentals necessary to complete the work.

3.02 Specifications for Stabilization of Pavement Subgrades with Self-Cementing Coal Fly Ash

A. Description

This item shall consist of the addition of self-cementing fly ash to the reprocessed asphaltic base, mixing, and compacting the material to the required density to develop a stabilized subgrade section. This item shall be constructed as specified herein and in conformity with the typical sections, lines, and grades as shown on the plans or as established by the Engineer.

B. Equipment

1. The machinery, tools and equipment necessary for proper execution of the work shall be on the project and approved by the Engineer prior to beginning construction operations. Blending of the reprocessed asphaltic base-fly ash mixture shall be accomplished by a Bomag MPH 100 pulvamixer or equivalent. Compaction shall be achieved using a ***vibratory padfoot roller***. Rubber-tired rollers will not be permitted except for finish rolling of the stabilized section.

   All machinery, tools and equipment used shall be maintained in a satisfactory and workmanlike manner.

2. Fly ash shall be stored and handled in closed weatherproof containers until immediately before distribution.

3. Fly ash is furnished in trucks, each truck shall have the weight of fly ash certified on public scales or the Contractor shall place a set of standard platform truck scales or hopper scales at a location approved by the Engineer.

C. Construction Methods

1. General

   It is the primary purpose of this specification to secure a completed section of treated material which contains a uniform fly ash/reprocess asphaltic base mixture with no loose or segregated areas; which has a uniform density and moisture content; and which is well bound for its full depth. It shall be the responsibility of the Contractor to regulate the sequence of work; to process a sufficient quantity of material to provide a completed section as shown on plans; to use the proper amounts of fly ash; to achieve final compaction within the specified time; to maintain the work; and to rework the lifts as necessary to meet the above requirements. Soil temperature shall be at or above 35ºF. at the time ash is incorporated.

2. Preparation of Subgrade

   Before other construction operations are begun, the area where the fly ash stabilized material will be placed shall be cut and shaped in conformance with the lines and grades shown on the plans.

   All areas shall be firm and able to support, without displacement, the construction equipment and the compaction hereinafter specified. Soft or yielding subgrade shall be corrected and made stable by scarifying, adding fly ash, and compacting until it is of uniform stability.

   Where the stabilized section is to extend below the cut surface, the ash shall be distributed uniformly across the surface in a quantity sufficient to provide the specified ash content. The ash shall be incorporated with a pulvamixer with water being added to achieve the specified moisture content.

3. Moisture Control

   Moisture control shall be achieved through use of a pulvamixer equipped with a spray bar in the mixing drum capable of applying sufficient quantities of water to achieve the required moisture content for the soil-fly ash mixture. The system shall be capable of being regulated to the degree necessary to maintain moisture contents within the specified range.

   Required moisture contents will be established by the Engineer based on laboratory tests with the site reprocessed asphaltic base and specific fly ash to be used for the treatment. Final moisture content of the mix immediately prior to compaction shall not exceed the specified range of moisture contents. If moisture contents exceed the specified limits, additional fly ash may be added to lower moisture contents to the required limits. Lowering moisture contents by aeration following addition of fly ash will not be allowed.

4. Application of Fly Ash

   Immediately prior to application of fly ash, the area shall be bladed to provide uniform distribution of fly ash.

   The fly ash shall be spread in an approved manner at the rates shown on the plans or as directed by the Engineer.

   The fly ash shall be distributed at a uniform rate and in such manner to reduce the scattering of fly ash by wind to a minimum. Fly ash shall not be applied when wind conditions, in the opinion of Engineer, are such that blowing fly ash will become objectionable to adjacent property owners.

   Mixing operations shall commence within one hour after distribution of the fly ash.

5. Mixing

   The RAB and fly ash shall be thoroughly mixed by approved mixers or other approved equipment, and the mixing continued until, in the opinion of the Engineer, a homogeneous, friable mixture of reprocessed asphaltic base and fly ash, free from all clods or lumps, is obtained.

If the reprocessed asphaltic base-fly ash mixture contains clods, they shall be reduced in size by additional pulverization.

6. Compaction

   Compaction of the mixture shall begin immediately after mixing of the fly ash and be completed within two hours, (one or two hours depending upon the degree of stabilization required and experience level of the stabilization contractor), following incorporation of fly ash. Compaction of the mixture shall begin at the bottom and shall continue until the entire depth of mixture is uniformly compacted to the specified density using padfoot or similar rollers.

   All non-uniform (too wet, too dry or insufficiently treated) areas which appear shall be corrected immediately by scarifying the areas affected, adding or removing material as required and remixing and recompacting.

   The stabilized section shall be compacted to a minimum of 95% of the material's maximum dry density as determined by ASTM D-698 (Standard proctor compaction). Moisture content of the reprocessed asphaltic base fly ash mixture shall be in the range developed from the laboratory compaction and strength tests.

   In addition to the requirements specified for density, the full depth of the material shown on the plans shall be compacted to the extent necessary to remain firm and stable under construction equipment. After each section is completed, tests will be made by the Engineer. If the material fails to meet the density or moisture content requirements, the Engineer may require it be reworked as necessary to meet those requirements or require the Contractor to change his construction methods to obtain required density on the next section. Additional fly ash will be added to areas that are reworked and amount required will be established by the Engineer. Should the material, due to any reason or cause, lose the required stability, density and finish before the work is accepted, it shall be reprocessed, recompacted and refinished at the sole expense of the Contractor. Reprocessing shall follow the same pattern as the initial stabilization including the addition of fly ash.

7. Finishing and Curing

   After the stabilized layer has been compacted, it shall be brought to the required lines and grades in accordance with the typical sections.

   a. After the fly ash treated course has been finished as specified herein, the surface shall be protected against rapid drying by either of the following curing methods for a period of not less than three (3) days or until the pavement is placed :

      1) Maintain in a thorough and continuously moist condition by sprinkling.

      2) Binder course shall be applied within ***three to seven calendar days.***

D. Measurement

FLY ASH will be measured by the ton (2,000 pounds), dry weight. MIXING reprocessed asphaltic base and FLY ASH will be measured by the square yard in place.

E. Payment

Work performed and materials furnished as prescribed by this item and measured as provided under “Measurement” will be paid for as follows:

FLY ASH will be paid for at the unit price bid per ton (2,000 pounds) which price shall be full compensation for furnishing all fly ash.

MIXING reprocessed asphaltic base and FLY ASH will be paid for at the unit price per square yard in place, which shall include placing of fly ash, mixing reprocessed asphaltic base, fly ash, and water, compacting the mixture, grading to required cross slope, and final compaction. Contractor shall supply water necessary to achieve optimal density and the cost shall be incidental to this item.

3.03. Temporary Pavement Marking, 4 inch, Removable Tape

This work shall be in accordance with the pertinent requirements of Section 649 of the Standard Specifications and as hereinafter provided.

A. General

This item of work shall consist of furnishing and application of temporary pavement marking to all intermediate courses or layers and final surfaces of asphaltic pavement on the same day that such course, layers, or surfaces are placed, in order to delineate the traffic centerline.

B. Basis of Payment

The item of Temporary Pavement Marking, 4 inch removable tape will be considered incidental to the item Asphaltic Concrete Pavement.

Chapter 12

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Appendix A

Product Data Sheets

Minergy LWA; Durolite Lightweight Aggregate

Bituminous & Sub-Bituminous Ash

NFPA

F: 0 | R: 0 | H: 1 | S:

Wisconsin Energy Corporation

C.H.E.S. - Chemical Hazard Evaluation System

PRODUCT DATA SHEET

CHES#: 3432

REVISION: 04

DATE: 07/18/02

SUPERCEDES: 5/23/2001

I General Information

Trade Name: MINERGY LWA; DUROLITE LIGHTWEIGHT AGG REGATE

Chemical Name: Not reported

Manufacturer: Wisconsin Electric Power Co., Minergy LWA
333 W. Everett St.
Milwaukee, WI 53209

Information Phone No.: 2625421440

Identical Products: Expanded Shale, Clay, Slate

Container: SOLD IN BULK; BAGS

Use: Lightweight Aggregate Abrasive Thermal Insulation

II Ingredients

CHEMICAL	%	CAS	TLV	PEL	STEL	CEIL	TRI
ALUMINO SILICATE MINERAL							☐
IRON MINERAL							☐
AMORPHOUS SILICA		7631-86-9		80 mg/m3/%SiO			☐
CRYSTALLINE SILICA MOST FREE SILICA IS AN AMORPHOUS GLASS	*	14808-60-7	0.05 mg/m3	0.1 mg/m3			☐
CALCIUM SILICATE		1344-95-2	10 mg/m3	15 mg/m3			☐

III Health Hazard Data

Routes/Effects of Acute Overexposure

Skin Little hazard from intermittent contact.

Eyes May cause mild irritation and a burning sensation.

Inhalation Little hazard produced by normal operations in open or well ventilated areas.

Ingestion Mild irritation of throat and G.I. tract.

Chronic Overexposure Effects

Chronic overexposure unlikely. Lung damage. IARC possible human carcinogen.

Warning Properties

Eye, nose, and/or throat irritation.

First Aid

Skin Wash with mild soap and water.

Eyes Flush with large amount of water for at least 15 minutes -- Seek medical attention, if irritation persists.

Inhalation Remove to fresh air -- Seek medical help promptly -- Use artificial respiration, if necessary.

Ingestion Give milk or water - DO NOT induce vomiting - Seek medical attention promptly.

IV Exposure Controls / Personal Protection

Engineering Controls

Assure adequate general dilution ventilation.

Personal Protective Equipment

Eyes/Face Safety glasses or dust goggles recommended.

Skin None normally required.

Respiratory Half-face resp./HEPA if above TLV/PEL.

Personal Protective Equipment

Special Clothing or Equipment	Change/wash contaminated clothing before reuse.

V Fire/Explosion Data

Flash Point (N/A)	N/A	**Flammable (Explosive) Limits (%)**	**- Upper**	N/A
Auto Ignition	N/A		**- Lower**	N/A

Extinguishing Media

SUITABLE AGENT FOR SURROUNDING FIRE TYPE

Extinguishing Agents to Avoid

None known.

VI Physical Data

Boiling Point	N/A	N/A	**Appearance**	Brown Or Gray STONE-LIKE Pellets
Melting Point	2300 F	1260 C	**Odor**	None
Vapor Density	N/A		**Vapor Pressure (mmHg)**	N/A
Specific Gravity	> 1.3		**Percent Volatile**	N/A
Bulk Density	N/A		**pH**	> 100
Solubility (H2O)	Insoluble		**Corrosivity on Metal**	N/A

VII Reactivity

Chemical Stability

Stable.

Hazardous Polymerization

May not occur.

VIII Environmental/Handling/Storage

Spill Or Leak Procedure

Control dust, dispose of according to local regulations.

Storage Procedures

Label all unlabeled containers with a CHES label (L/N 138-2010).

Is This Product Listed Or Does It Contain Any Chemical Listed For The Following:

1. Disposal Of Product Or Any Residue A Hazardous Waste? No

   Hazardous Waste Code:

2. An Extremely Hazardous Substance Under Emergency Planning And Community Right-To-Know?

Substance Name:	Threshold Planning Quantity (lbs.):
No	N/A

3. An EPA Hazardous Substance Requiring Spill Reporting?

Listed Substance:	Reportable Quantity (lbs.):
No	N/A

4. An OSHA Hazardous Chemical? Chemical Name: CRYSTALLINE SILICA

Does It Contain Any Materials Regulated As Hazardous Materials Or Hazardous Substances By The Department C Transportation?

Proper Shipping Name:	Not Regulated		
Hazard Class:	None	Packaging Group:	
UN/NA Code:	None	Quantity Required for Placarding:	N/A
Labels Required:	None		

IX Other

This information was based upon current scientific literature. Information may be developed from time to time which may render this document incorrect; therefore, the Wisconsin Energy Corporation nor any of it's subsidiaries makes any warranties to it's agents, employees, or contractors as to the applicability of this data to the user's intended purpose.

NFPA		
F: 0, R: 0, H: 1, S:	Wisconsin Energy Corporation C.H.E.S. - Chemical Hazard Evaluation System PRODUCT DATA SHEET	CHES#: 14468 REVISION: 05 DATE: 03/18/04 SUPERCEDES: 3/8/2004

I General Information

Trade Name: ASH; WISCONSIN ELECTRIC COAL COMBUSTION PRODUCTS - FLY ASH OR BOTTOM ASH

Chemical Name: Mixture

Manufacturer: We Energies
333 W. Everett St.
Milwaukee, WI 53201

Information Phone No.: 414-221-2345

Emergency Phone: 262-542-1440

Identical Products: Fly Ash (Eastern/Western Coal), BITUMINOUS AND SUB-BITUMINOUS ASH (ALL PLANTS)

Container: Various

Use: Fly Ash: Pozzolans in concrete; cementious material; soil amendment; sorbents
Bottom Ash: Construction aggregates; soil amendment

Locations: PIPP, PPPP, OCPP, VAPP, PWPP, MCPP, FO

II Ingredients

CHEMICAL	%	CAS	TLV	PEL	STEL	CEIL	TRI
AMORPHOUS SILICA	20 - 60	7631-86-9		80 mg/m3/%SiO			☐
ALUMINUM OXIDE	10 - 33	1344-28-1	10 mg/m3	10 mg/m3			☑
IRON OXIDE	4 - 30	1309-37-1	5 mg/m3	10 mg/m3			☐
CRYSTALLINE SILICA**	0 - 10	14808-60-7	0.05 mg/m3	0.1 mg/m3			☐
CALCIUM OXIDE	1 - 30	1305-78-8	2 mg/m3	5 mg/m3			☐
AMMONIA (PPPP Ash only)	0 - 300 ppm	7664-41-7	25 ppm		35 ppm		☐
MAGNESIUM OXIDE	0 - 4	1309-48-4	10 mg/m3	10 mg/m3			☐
TITANIUM DIOXIDE	0 - 3	13463-67-7	10 mg/m3	10 mg/m3			☐
SODIUM OXIDE	0 - 10	12401-86-4					☐
POTASSIUM OXIDE	0 - 3	12136-45-7					☐
CARBON	0 - 50	7440-44-0					☐
MANY TRACE METALS	ALL < 1						☐

III Health Hazard Data

Routes/Effects of Acute Overexposure

Skin May be abrasive and or irritating.

Eyes May be irritating and abrasive.

Inhalation Little hazard produced by normal operations in open or well ventilated areas. Dust may irritate the mucous membrane.

Ingestion Mild irritation of throat and G.I. tract.

Chronic Overexposure Effects

Lung damage. Specifically silicosis/**also see section IX**.

Warning Properties

Eye, nose, and/or throat irritation. Skin redness or burning.

First Aid

Skin Wash with mild soap and water.

First Aid

Eyes	Flush with large amount of water for at least 15 minutes -- Seek medical attention.
Inhalation	Remove to fresh air -- Seek medical help promptly -- Use artificial respiration, if necessary.
Ingestion	Give milk or water - DO NOT induce vomiting - Seek medical attention promptly.

IV Exposure Controls / Personal Protection

Engineering Controls

Consider on a case-by-case basis/usually not required. Local exhaust above the TLV/PEL limits.

Personal Protective Equipment

Eyes/Face	Safety glasses or dust goggles recommended.
Skin	Gloves recommended if irritating to skin. Appropriate for the task-e.g. cloth/leather/synthetic.
Respiratory	Lot No. 742-5848/6135 (Magenta) HEPA filter if needed with full/half respirator.
Special Clothing or Equipment	Cover skin areas as needed/flyash can be irritating. Avoid creating dust, vacuum or dampen area if possible.

V Fire/Explosion Data

Flash Point	NONE
Auto Ignition	N/A

Extinguishing Media

Suitable for surrounding fire.

VI Physical Data

Boiling Point	N/A	N/A	**Appearance**	Fine tan or gray colored powder
Melting Point	N/A	N/A	**Odor**	Odorless
Vapor Density	N/A		**Vapor Pressure (mmHg)**	N/A
Specific Gravity	2 - 3		**Percent Volatile**	N/A
Bulk Density	N/A		**pH**	N/A
Solubility (H2O)	Slight		**Corrosivity on Metal**	N/A

VII Reactivity

Chemical Stability

Stable.

Hazardous Decomposition

None established.

Hazardous Polymerization

May not occur.

VIII Environmental/Handling/Storage

Spill Or Leak Procedure

Collect and dispose per local, state and fed. regs..

Storage Procedures

Contain as appropriate to minimize dusting. Label all unlabeled containers with a CHES label (L/N 138-2010).

Is This Product Listed Or Does It Contain Any Chemical Listed For The Following:

1. Disposal Of Product Or Any Residue A Hazardous Waste? No
   Hazardous Waste Code:

2. An Extremely Hazardous Substance Under Emergency Planning And Community Right-To-Know?

Substance Name:	Threshold Planning Quantity (lbs.):
No	N/A

3. An EPA Hazardous Substance Requiring Spill Reporting?

Listed Substance:	Reportable Quantity (lbs.):
No	N/A

4. An OSHA Hazardous Chemical? Chemical Name: AMMONIA

4. An OSHA Hazardous Chemical? Chemical Name: AMORPHOUS SILICA
CRYSTALLINE SILICA**

Does It Contain Any Materials Regulated As Hazardous Materials Or Hazardous Substances By The Department C Transportation?

Proper Shipping Name:	Not Regulated		
Hazard Class:	None	Packaging Group:	N/A
UN/NA Code:	N/A	Quantity Required for Placarding:	N/A
Labels Required:	N/A		

IX Other

**LISTED BY IARC As A Possible Human Carcinogen Based On Laboratory Animal Test DATA-No Evidence Of Human Carcinogenicity.

Note: PIPP = Presque Isle Power Plant; PPPP= Pleasant Prairie Power Plant; OCPP= Oak Creek Power Plant;VAPP= Valley Power Plant; MCPP= Milwaukee County Power Plant; PWPP= Port Washington Power Plant

This information was based upon current scientific literature. Information may be developed from time to time which may render this document incorrect; therefore, the Wisconsin Energy Corporation nor any of it's subsidiaries makes any warranties to it's agents, employees, or contractors as to the applicability of this data to the user's intended purpose.

Appendix B

Radioactivity in Coal and Fly Ash

by Kjell Johansen, Ph.D.*

*Dr. Johansen is a Sr. Chemist at the Point Beach Nuclear Plant in Two Rivers, WI, where he is responsible for air and water related effluent compliance issues. He received an MS in Radiological Health Physics from North Dakota State University, an MS in Environmental Health Sciences from the University of Michigan, and a PhD in Oceanography from the University of Michigan. He spent 12 years at the UM Great Lakes Research Division as a radiolimnologist measuring NORM and fallout radionuclides in Great Lakes' sediments to determine the fate and historical inputs of pollutants to the Great Lakes. While a Radiological Engineer at We Energies from 1983 - 2000, he was responsible for Point Beach's radiological effluent and environmental monitoring programs. During that time, he also served as the Radiation Safety Officer for the use of radioactive level gauges at We Energies' fossil plants.

Radioactivity in Coal and Fly Ash

A. We live in a radioactive world. The naturally occurring radioactive atoms, or radionuclides, in the earth, the air, the vegetation, and our bodies constantly irradiate us. Each second naturally occurring radioactive atoms in the earth bombard us with 15,000 photons. Photons are a form of electromagnetic radiation given off by the radioactive atoms as they transform into stable atoms. When the nuclear transformations occur in the form of emitted particles, the original atom is transformed into a different element, which also may be radioactive. These radioactive transformations or decays continue until a stable element is formed. The earth contains two main classes of natural radioactive elements: primordial and cosmogenic.

B. Primordial radionuclides have been present since the formation of the earth. Uranium and thorium, the most well-know primordial radionuclides, have no stable isotopes. (Isotopes are atoms of the same element that have the same chemical property but differ slightly in atomic weight due to the number of neutrons in the nucleus.) In contrast, normal, non-radioactive potassium has one radioactive, primordial isotope, potassium-40 or K-40. Out of every one million potassium atoms, 119 will be primordial K-40 atoms. Whereas K-40 decays directly to a stable element, uranium and thorium decay to stable lead isotopes via a series of decays that produce numerous other radioactive elements, such as radium and radon, in the process.

C. Cosmogenic radionuclides are continually being made by the cosmic ray bombardment of the earth's atmosphere. There are 22 different cosmogenic radionuclides that become incorporated into plants and other living material to varying degrees based upon their chemical properties. The most important cosmogenic radionuclides are carbon-14 (C-14), hydrogen-3 (H-3), and beryllium-7 (Be-7).

D. The common unit for the decay rate, or transformations per unit time, is the curie or Ci (named for the Polish scientist, Marie Curie). One curie equals 2.22 trillion decays (2,220,000,000,000) per minute. Not all radionuclides decay at the same rate. The more unstable the nucleus, the faster the decay rate. Two properties directly follow from the variation in decay rates. One, it takes more atoms of a low decay rate radionuclide to produce one curie than it does for a high decay rate radionuclide to produce one curie. Two, atoms with a high decay rate will disappear faster than atoms with a low decay rate. Therefore, just because there are equal curie amounts of radionuclides present does not mean that there are an equal number of atoms present

E. Inversely related to the decay rate is the atoms half-life. One half-life is the time it takes the initial number of atoms to decay to half that number. The C-14 half-life is 5760 years where as that of Be-7 is 53.3 days. The half-life of H-3 is in between these two, 12.28 years. By comparison, the half-lives of the primordial radionuclides uranium, thorium, and K-40 are the order of a billion years. One of the radionuclides formed by the decay of uranium has a half-life on the order of microseconds.

F. Based on their known cosmic ray production rates, atoms per unit area per unit time (National Council on Radiation Protection and Measurements, Report #94, p. 39. 1987) and their known decay rates, we calculate the annual number of curies of each of the major cosmogenic radionuclides produced in the air over Wisconsin (56,154 square miles) to be as follows: 11.9 Ci of C-14, 552 Ci of H-3, and 15,100 Ci of Be-7.

G. While you may remember NORM as a character from the TV sitcom "Cheers," in the field of environmental radioactivity NORM is an acronym for **N**aturally **O**ccurring **R**adioactive **M**aterial. The air, soil, water, vegetation, and even our bodies are NORM because they contain varying amounts of naturally occurring radioactive atoms. The most common NORM radionuclides are uranium, thorium, radium, potassium-40, and carbon-14. Because of the low radionuclide concentrations in NORM, the unit used to express these values is the picoCurie or pCi. A pCi is a very small number, one-trillionth of a curie. As mentioned above, a curie is 2.22 trillion disintegrations per minute. Hence, one pCi equals 2.22 disintegrations per minute.

H. The standard 70 kilogram (154 pound) adult contains the following amounts of the aforementioned radionuclides: 30 pCi of uranium, 3 pCi of thorium, 30 pCi of radium, 110,000 pCi of K-40, and 400,000 pCi of C-14 (International Commission of Radiation Protection – Publication 39 and National Council on Radiation Protection and Measurements –Report No. 94).

I. Radioactive elements enter our bodies through the food we eat and the air we breathe. C-14 and K-40 react chemically in the same manner as the stable or non-radioactive isotopes of these elements and are continually being incorporated into the plants and animals in the food chain. Because the chemical composition of our bodies is internally regulated with respect to the amount of stable carbon and potassium present, the concentrations of C-14 and K-40 are regulated as well. Uranium, thorium, and radium also enter our bodies through the food chain, but to a lesser extent as evidenced by the pCi quantities of NORM in our bodies mentioned in the preceding paragraph. Because radium is chemically similar to calcium, long-lived radium-226 (half-life = 1600 years) will build up in the skeleton. Uranium and thorium exhibit a lesser degree of build up. Because of the relative chemical inactivity of Ra, Th, and U compared to the C and K, it takes a longer time to remove the Ra, Th, and U once they are incorporated in our bodies.

J. The amount of NORM you consume each day depends upon the foods you eat. Norm has been measured in many food items. Foods high in potassium have a correspondingly higher amount of K-40. For example, a serving of dried apricots has 409 pCi of K-40; a fresh banana, 368 pCi; a glass of orange juice, 409 pCi; bran flakes, 155 pCi; a glass of skim milk, 285 pCi; a medium potato, 690 pCi; spinach, 97 pCi; substituting lite salt (potassium chloride) for 1.2 grams of common table salt, 499 pCi; and 3 oz. of chicken breast, 180 pCi. (If you know the grams of potassium in your food, multiply by 818 to get the number of pCi of K-40). Because the body's K-40 is chemically regulated along with non-radioactive potassium, K-40 will not build up in the body but vary as stable potassium varies as a function of muscle mass and age.

K. The most common mode of radium ingestion is via drinking water. As recently noted in the Journal-Sentinel, 53 Wisconsin communities will have to reduce the radium content of their drinking water because it contains more than the EPA allowable concentration of 5 pCi/liter, (about 19 pCi per gallon).

A person drinking the recommended 8 glasses of water a day would consume about 10 pCi of radium per day, of which about 30% would be absorbed into the body (International Commission on Radiation Protection, Report of Committee 2, 1963). The food highest in radium is the Brazil nut. Brazil nuts selectively concentrate calcium family elements such as barium and radium (R. L. Kathren, 1984, Radioactivity in the Environment, Harwood Academic Publishers, p. 67). This concentration process gives Brazil nuts a radium concentration of 1-7 pCi per gram or, in a comparison to water on a weight basis, 1000 – 7000 pCi per liter. All other foods contain, on average, 1/1000th of the radium found in Brazil nuts. The US Nuclear Regulatory Commission sets the annual ingestion limit for Ra-226 at 2,000,000 pCi/yr (Title 10, Code of Federal Regulations, Part 20, Appendix B).

L. Radon, a chemically inert, radioactive gas produced by the decay of radium, is a normal constituent of air and enters the body by breathing. Radon generated by the decay of radium diffuses into the soil pore water where it can reach concentrations of 100 – 1000 pCi/liter. The pore water radon then diffuses out of the ground into the air to yield concentrations on the order 0.1 – 0.2 pCi/liter in the northern hemisphere (NCRP Report No. 94). The amount and rate of radon entering the air from the ground depends not only upon the amount of radium in the soil but also on the physical condition of the soil containing the radium. Frozen soil and snow cover slow down the transfer of radon to the air. Radon diffuses out of porous soils more quickly than out of rock or compacted soil. Meteorological conditions like wind speed and the air pressure also affect the transfer of radon from the soil to the air. Unlike the other elements, radon does not react chemically with the body and so is readily exhaled as well as inhaled. The concentration of radon in our lungs is normally in equilibrium with the concentration in the air that we breathe.

M. The energy released by radioactive elements can be measured. The amount of energy deposited in the human body from radioactive decay is called dose. As mentioned above, radionuclides enter the body through air and foods we eat. Energy deposited in our bodies from the radioactive isotopes in our bodies is called internal dose. External doses result from gamma rays emitted by terrestrial NORM sources such as the ground and building materials and from cosmic rays. Roughly 1,000,000 photons per minute are responsible for the terrestrial component of the total NORM dose. About 500,000 decays per minute in our bodies contribute to our internal NORM dose (M. Eisenbud, Environment Vol.26 (10): 6-33, 1984). This internal NORM acts as an external radiation source to people around us. Based on the amount of K-40, the standard 154-pound adult emits about 24,400 photons per minute, which contributes dose to nearby individuals.

N. The standard dose unit in the United States is the rem. Because doses from NORM are small, these doses are reported in millirem (mrem), or 1/1000th of a rem. In the US, the average annual NORM dose is 300 mrem. The largest part of this dose, 200 mrem, comes from the radon in the air. When we say the dose is from the radon in air, this actually is shorthand for radon and the radionuclides to which the radon decays. It is the decay products that produce most of the dose because these decay products, as opposed to a noble gas, are particulates that remain in the lungs for a longer period of time. Two of these decay products, lead-210 (22.3 yr half-life) and polonium-210 (138 day half-life) contribute most of the dose. The remaining 100 mrem is divided among cosmic (30 mrem), internal (40 mrem), and terrestrial sources (30 mrem). In the case of human-to-human irradiation mentioned above, the K-40 dose from spending 8 hours a day at 1 foot from an adult emitting 24,400 photons per minute is about 0.4 mrem/yr.

O. Cosmic ray doses increase with elevation above sea level. Typical doses in Wisconsin are around 27 mrem/yr. In Denver, the mile-high city, the cosmic ray dose is 50 mrem/yr. The highest cosmic ray dose in the US, 125 mrem/year, occurs in Leadville, CO. La Paz, Bolivia has a cosmic ray dose of 202 mrem/yr. A passenger in a New York to Los Angles flight at an altitude of 39,000 feet would get 2.5 mrem for the 5-hour flight.

P. The major contributor to the annual internal dose is K-40 (18 mrem). Lesser contributions result from two radon decay products, Pb –210 and Po-210 (14 mrem), from Ra-226 (1 mrem), and from C-14 (0.1 mrem). Note that even though the human body contains 400,000 pCi of C-14, roughly four times the pCi content of K-40, the resulting dose is very much less than that from K-40. This happens because the energy emitted per decay of C-14 is much less than that per disintegration of K-40. [United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1993; NCRP Report #94; Medical Effects of Ionizing Radiation, F.A. Mettler and R.D. Mosely, 1985; D.C. Kocher, Radioactive Decay Data Tables, Dept. of Energy TIC-11026, 1981]

Q. Scientists have determined the NORM terrestrial doses in many parts of the world. These doses vary depending upon the geology of the area. Regions with high amounts of uranium and thorium in the soil and bedrock also have higher radium and radon concentrations. The US average is 30 mrem. The highest US terrestrial dose is 88 mrem. The highest measured terrestrial dose, 26,000 mrem/yr, occurs in Ramsar, Iran. Other high annual terrestrial doses occur in areas of Brazil and India (3,500 mrem), China (1,000 mrem), Norway (1,050 mrem), and Italy (438 mrem). The areas in Iran, India, and Brazil are associated with high concentrations of uranium and thorium in the soil. Epidemiological studies of the people in these areas have been made to determine, what, if any, affect these high radiation dose levels have on health. To date, no radiation related health effects have been found. [UNSCEAR 1993; NCRP Report #94]

R. Consumer products also generate NORM radiation exposures. The most common and highest consumer product exposure results from cigarettes. Smoking 30 cigarettes a day for a year delivers a lung dose of 16,000 mrem/yr, which is equivalent to a whole body dose of 1,300 mrem. By comparison to cigarettes, a chest X-ray delivers 20-30 mrem to the same tissues. Masonry buildings typically contribute 13 mrem/yr to its occupants from the uranium, thorium, and K-40 in the building material. Some electrodes used for arc welding contain thorium in order to produce greater arc stability and less weld metal contamination. Using these rods on an occasional basis results in less the 1 mrem/yr, most of which is in the form of external radiation (NCRP Reports #94 & 95).

S. Carbon based fuels also are NORM. Natural gas contains 10 – 20 pCi of radon per liter. [A liter is slightly larger than a quart with 1 gallon = 3.785 liters.] As a result, cooking with natural gas produces a dose of 0.4 mrem/yr (NCRP Reports #94 & 95). Coal contains numerous radionuclides. The US

Geological Survey maintains a large database of uranium and thorium data on coal from various US coal fields. Based on more than 5000 coal samples from all the major coal regions in the US, the average U content of 1.3 parts per million (ppm) equals 0.44 pCi/g. The average thorium (3.32 ppm) concentration is 0.37 pCi/g. These concentrations are not that much different from soil: 1.0 pCi/g for uranium (range 0.12 – 3.8 pCi/g) and 0.98 pCi/g for thorium (range 0.1 – 3.4 pCi/g). Both uranium and thorium decay to stable Pb and along the way produce radioactive isotopes of uranium, thorium, radium, radon, bismuth, lead, and polonium. Ra-226 analyses of coal indicate concentrations in the range of 0.2 – 3 pCi/g [J. Tadmore, J. of Environmental Radioactivity 4(1986) 177-204]. Lignite, a low-grade coal, has slightly higher concentrations: U-238, 8.26 pCi/g; Ra-226, 9.34 pCi/g; Th-232, 0.51 pCi/g; K-40, 4.67 pCi/g [Rouni *et. al*., Sci. Total Environment 272(2001) 261-272]. In coal-fired power plants, some of the NORM is released via the stack whereas most is trapped in the resulting ash. Studies in Great Britain (K. R. Smith et. al., Radiological Impact of the UK Population of Industries Which Use or Produce Materials Containing Enhanced Levels of Naturally Occurring Radionuclides, Part I: Coal-fired Electricity Generation, National Radiation Protection Board report, NRPB-R327, 2001) and the United States (EPA, Study of Hazardous Air Pollutant Emissions from Electric Utility Steam Generating Units – Final Report to Congress, EPA-453/R-98-004a, Feb. 1998) conclude that NORM emissions from coal-fired plants do not pose a health problem. A United Nations group of experts reached a similar conclusion (UNSCEAR, 1993).

T. The NORM concentration in coal ash is higher than in the coal because most of the radionuclides stay in the ash as compared to being released to the air during the combustion process. Therefore, burning off the organic content of the coal results in about a 10-fold increase in U, Th, and Ra concentrations in the ash as compared to the coal (UNSCEAR, 1993; USGS Fact Sheet FS-163-97). Based on the concentration process, the Ra-226 concentrations in ash could be on the order of 1-30 pCi/g. Analyses of various ashes and ash products produced at WE-Energies plants in 1993 and 2003 found Ra-226 concentrations in the range of 1 – 3 pCi/g. This is comparable to the concentrations in soil (0.2 – 3 pCi/g) and within the range of 1 – 8 pCi/g found in ash from analyses of other fly ash in the US (Cement and Concrete Containing Fly Ash, Guideline for Federal Procurement, Federal Register, Vol 48 (20), January 28, 1983, Rules and Regulations; Zielinski and Budahn, Fuel Vol.77 (1998) 259-267).

U. Given that the ash may be land filled or may be used in building materials as a cement substitute, the doses resulting from these applications have been studied to determine if there is any risk. The British Nuclear Radiation Protection Board (Smith *et. al*. 2001) conducted a detailed evaluation “Radiological Impact on the UK Population of Industries Which Use or Produce Materials Containing Enhanced Levels of Naturally Occurring Radionuclides, Part I: Coal-fired Electricity Generation” (NRBP-R327) of the doses from fly ash released to the air to people living within 500 meters (547 yards) of a plant stack, to landfill workers burying fly ash, to workers manufacturing building products from fly ash, and to people living in a house built with fly ash building products. The maximum doses determined from this evaluation were 0.15 mrem/yr for the person living near the plant, 0.13 mrem/yr from releases from the ash landfill, 0.5 mrem/yr for workers manufacturing building products, and 13.5 mrem/yr to a resident of a home constructed with fly ash building materials. The latter is not that different from the 13 mrem/yr from living in a brick/masonry house mentioned earlier.

V. Based on the preceding discussion, the radioactivity levels in coal and the slightly enhanced levels in coal ash do not constitute a safety hazard. The levels of radioactivity are within the range found in other natural products. The doses resulting from using the ash in various products are comparable to doses from other human activities and from other natural sources. These doses from the radionuclides in ash are much less than the 300 mrem/yr received from normal background radiation.

Appendix C

Field Guide for Recycling HMA Pavement (CIR) with Self-Cementing Class C Fly Ash

Prepared in cooperation with Lafarge North America and Bloom Consultants, LLC.

What is Fly Ash Stabilization?

Enhancing the strength of recycled asphalt pavement is simply applying controlled amounts of class ‘C’ fly ash to the CIR surface, thoroughly blending the ash with the recycled material and water, usually with a reclaimer or pulverizer, grading the material blend and compacting it. The stabilized material is now ready for paving.

Why is stabilization done?

Stabilizing CIR materials with fly ash makes them dry, stronger, very stable and easy to grade. The self-cementing fly ash makes the recycled asphalt hard, strong and allows for interim traffic operations. Subsequent construction operations can proceed.

What types of equipment are required?

Essential pieces of equipment include a distributor truck, a reclaimer [pulverizer] for blending, a grader, a pad-foot roller, a drum roller and a water truck. A bucket loader is also helpful.

Who controls the work activities?

Ideally, the recycling contractor is in charge of operations and controls the work flow. Others involved are the fly ash supplier, engineers and contractors who are in charge of related work such as storm sewer or other utility work. The stabilizing contractor in any case is in charge of the operation and controls work flow.

Is the process difficult?

Stabilizing CIR materials with self-cementing Class ‘C’ fly ash is easy, but there are several very critical elements in the operation.

Is the sequence of work activities important?

The success of any stabilizing project depends on having the component activities planned and closely controlled throughout the process. The preferred sequence of activities follows:

- Prepare the site either by pre-pulverizing the existing HMA pavement and base course.
- Spread the fly ash in predetermined concentrations on the prepared surface.

  The preferred distributor is a vane feeder truck.

- Blend the fly ash and prepared materials with the reclaimer and add a pre-determined amount of water to the mixture. A reclaimer equipped with an injection manifold is ideal for the addition of water.
- Compact the blended material with a pad-foot roller in vibratory mode if the site will tolerate it and grade the surface to comply with design requirements.
- Complete final grading and roll with the drum roller. The surface is now ready for paving.

Are there any cautions in the process?

Plan the work and layout the site before the work starts. Make sure all equipment operators understand the importance of controlling the operation. Control the distribution of fly ash so the vane feeder does not get too far ahead of the blending operation. Be sure to have an adequate supply of ash on site and in delivery. Control the transfer of ash to the distributor truck.

During ash material transfer operations and other activities, it is crucial to keep trucks and equipment from running through the newly placed ash. The material will not be influenced too much by wind unless it is disturbed. Preserving environmental integrity is critical.

Since fly ash undergoes a change through hydration [much like cement does in concrete] it is very important to begin grading operations as soon as the fly ash is distributed and blended. Open time during warm weather is 2-3 hours. After that, achieving good surface results becomes more difficult. Keep in mind, Class C fly ash enhanced materials will get hard and gain strength.

The contractor should carefully watch the yield of the fly ash during distribution. Pace or measure the remaining work and estimate volume requirements. Compare the data with fly ash supply. Avoid over or under treating any of the work areas.

The reclaimer operator must assure that no areas where ash is distributed are not properly mixed or blended. Some overlap is better than leaving strips or other areas unmixed. Care needs to be taken to keep fly ash out of roadside ditches and off adjacent private property.

About the Authors

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Bruce W. Ramme is Manager-Land Quality in the Environmental Business Unit of We Energies in Milwaukee, Wisconsin. He is a registered Professional Engineer in Wisconsin and has a BS, MS and EMBA degrees from the University of Wisconsin—Milwaukee in structural, civil engineering, and business administration. He has worked as an engineer and manager for over 25 years in various design engineering, project management, operations, and research positions. Part of his present work assignment is to develop high value uses and maintain full utilization of We Energies' coal combustion products. Prior to joining We Energies, Bruce worked in plant engineering at A.O. Smith's Powder Metallurgy Division, and as a structural engineer at Industrial Consulting Engineers, Inc. and Lakeside Bridge and Steel Company.

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