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:

$2C_3S + 6H$ tricalcium silicate + water	➔	$C_3S_2H_3 + 3CH$ C - S - H + calcium hydroxide
$2C_2S + 4H$ dicalcium silicate + water	➔	$C_3S_2H_3 + CH$ C - S - H + calcium hydroxide
$C_3A + 3C\overline{S}H_2 + 26H$ tricalcium aluminate + gypsum + water	➔	$C_3A\,(C\overline{S})_3\,H_{32}$ ettringite
$C_3A + C\overline{S}H_2 + 10H$	➔	$C_3AC\overline{S}H_{12}$ 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 monosulphoaluminate 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	92.43	75.0 min
with lime 7 days	1805	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.

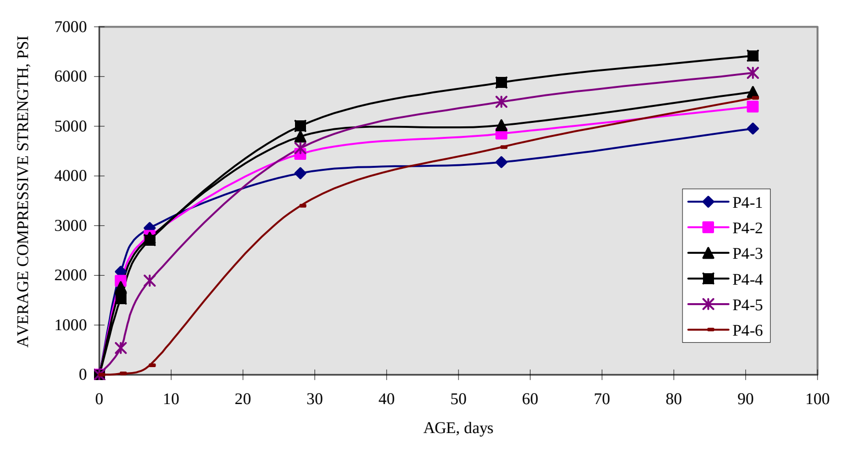

Figure 4–1: Compressive Strength vs. Age Comparison – Mix Nos. P4-1 through P4-6

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	1662	1567	1543	1378	1374	1295	1315	572	576	516	524
1*	1695		1541		1386		1297		577		530	
1*	1576		1521		1358		1353		578		527	
3	2020	2072	1938	1886	1758	1764	1545	1534	572	537	30	26
3	2120		1898		1725		1599		526		24	
3	2076		1822		1810		1459		514		25	
7	2995	2950	2770	2790	2820	2755	2688	2707	1936	1892	202	187
7	3065		2784		2775		2712		1810		176	
7	2789		2817		2670		2723		1931		182	
28	3986	4055	4105	4440	4605	4789	5051	5004	4545	4556	3203	3396
28	4131		4476		4821		5038		4587		3427	
28	4048		4738		4941		4923		4538		3558	
56	4363	4276	4804	4850	4947	5019	5909	5881	5445	5492	4626	4576
56	4350		5011		4877		5811		5457		4811	
56	4115		4735		5234		5923		5575		4290	
91	4960	4953	5160	5393	5850	5687	6400	6417	6080	6073	5630	5567
91	4970		5730		5380		6490		6040		5550	
91	4930		5290		5830		6360		6100		5520	

* After Accelerated Curing, Using Boiling Water Method

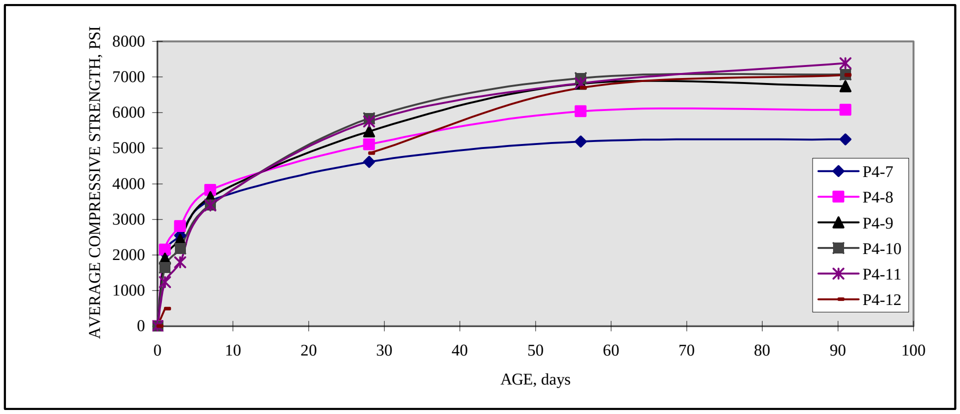

Figure 4–2: Compressive Strength vs. Age Comparison – Mix Nos. P4-7 through P4-12

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.

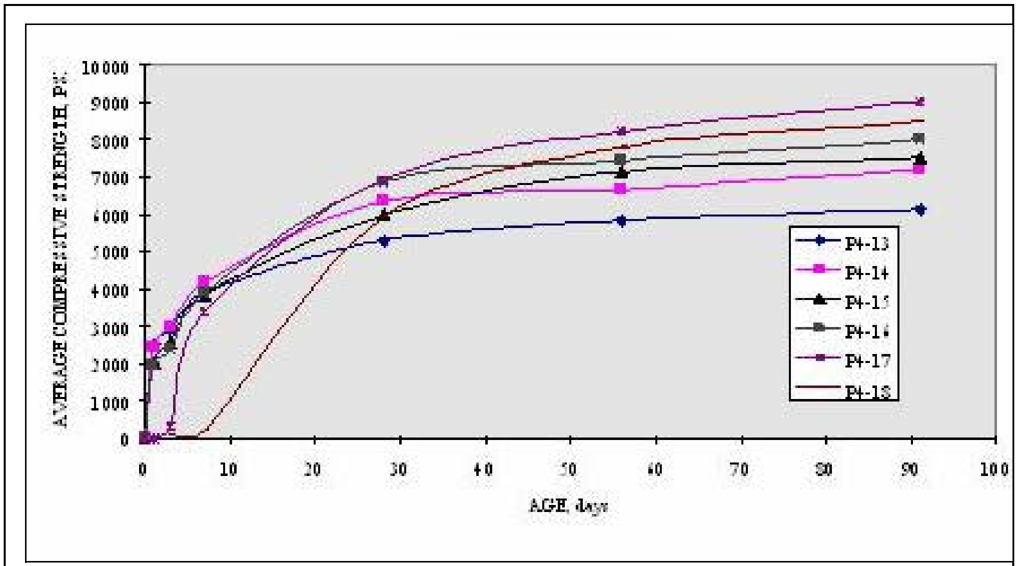

Figure 4-3: Compressive Strength vs. Age Comparison – Mix Nos. P4-13 through P4-18

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	2519	2438	2448	2089	2044	1938	1942	1210	1230	1315	1336
1*	2498		2441		2041		1965		1234		1360	
1*	2481		2465		2003		1924		1246		1332	
3	2839	2904	3115	2987	2570	2591	2390	2390	287**	324**	111**	116**
3	2930		2936		2570		2379		369**		117	
3	2944		2909		2632		2401		285**		120**	
7	3811	3902	4130	4168	3762	3854	3913	3892	3430	3392	203**	205**
7	4028		4220		3935		3811		3409		206**	
7	3868		4154		3864		3952		3338		203**	
28	5002	5300	6412	6353	5839	5993	6851	6864	6919	6935	5795	5931
28	5484		6381		6102		6786		7045		6079	
28	5413		6266		6038		6954		6842		5919	
56	5803	5848	6653	6667	7240	7148	7565	7452	8174	8237	7803	7795
56	5856		6624		7031		7350		8079		7834	
56	5885		6723		7173		7442		8457		7749	
91	5900	6134	7025	7209	7179	7519	8086	8004	9012	9012	8504	8493
91	6315		7400		7835		8133		9016		8274	
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).

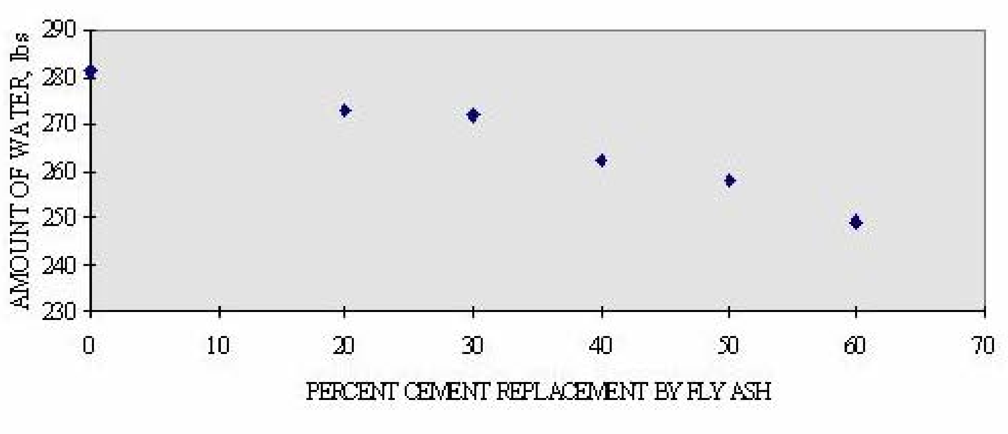

Figure 4-4: Relationship Between Water Demand and Cement Replacement by Fly Ash (3000 psi Concrete with the Same Workability)

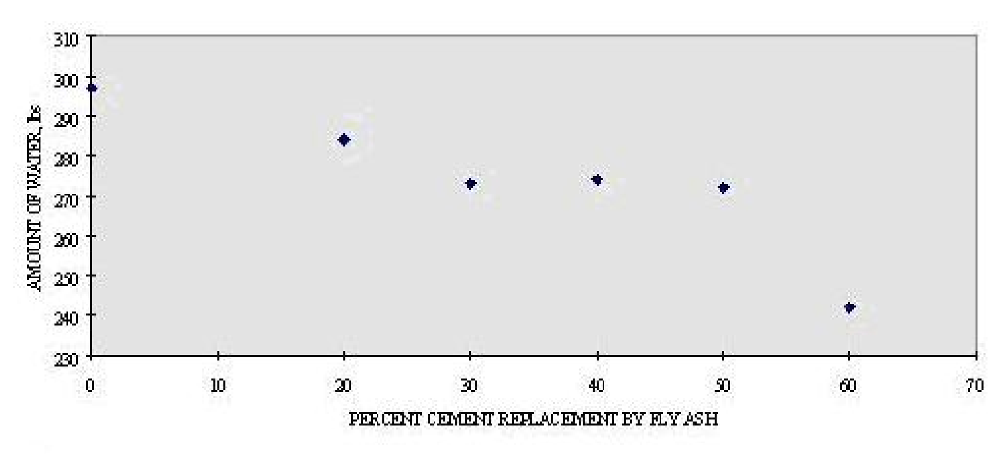

Figure 4-5: Relationship Between Water Demand and Cement Replacement by Fly Ash (4000 psi Concrete with the Same Workability)

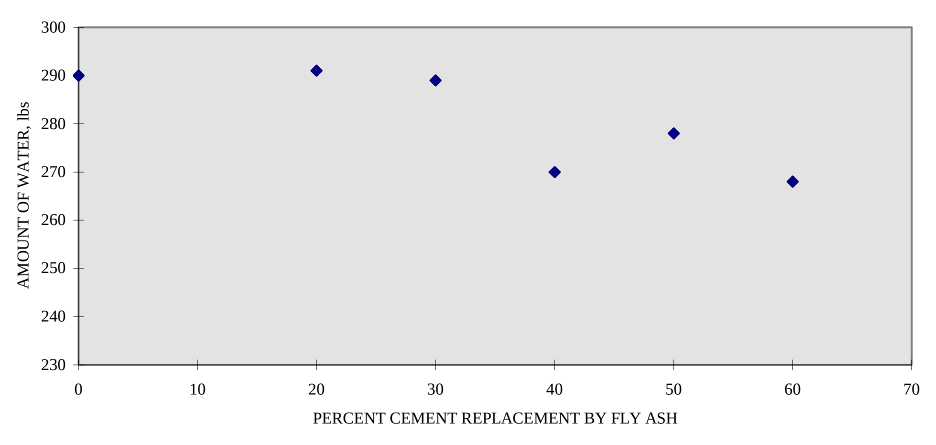

Figure 4–6: Relationship Between Water Demand and Cement Replacement by Fly Ash (5000 psi Concrete with the same Workability)

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.

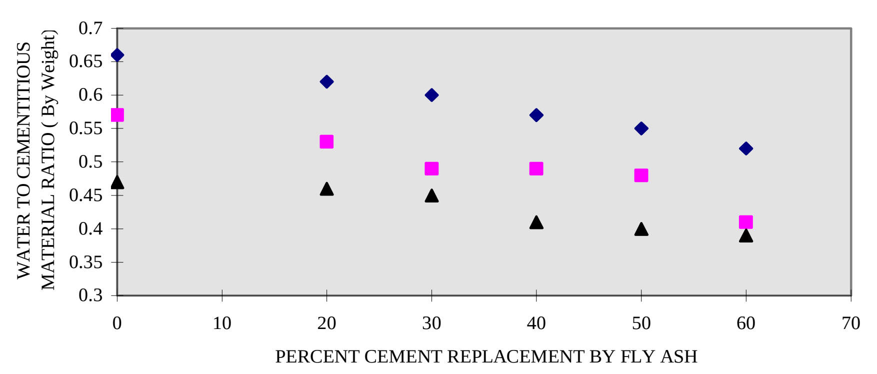

Figure 4–7: Relationship Between Water to Cementitious Ratio and Cement Replacement by Fly Ash (3000, 4000 and 5000 psi Concrete with the same Workability)

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*

NON-AIR-ENTRAINED CONCRETE

Mix No.	Nominal 28-day Compressive Strength, psi	Nominal Percentage of Fly Ash	Time of Setting, HR:MIN	
			Initial	Final
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

Mix No.	Nominal 28-day Compressive Strength, psi	Nominal Percentage of Fly Ash	Time of Setting, HR:MIN	
			Initial	Final
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 √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

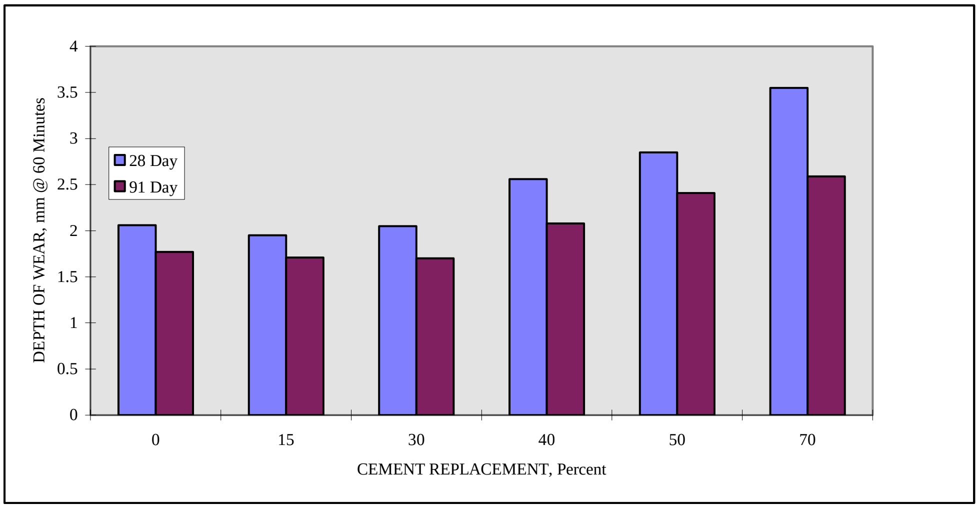

Figure 4–8: Abrasion Resistance vs. Cement Replacement with Class C Fly Ash

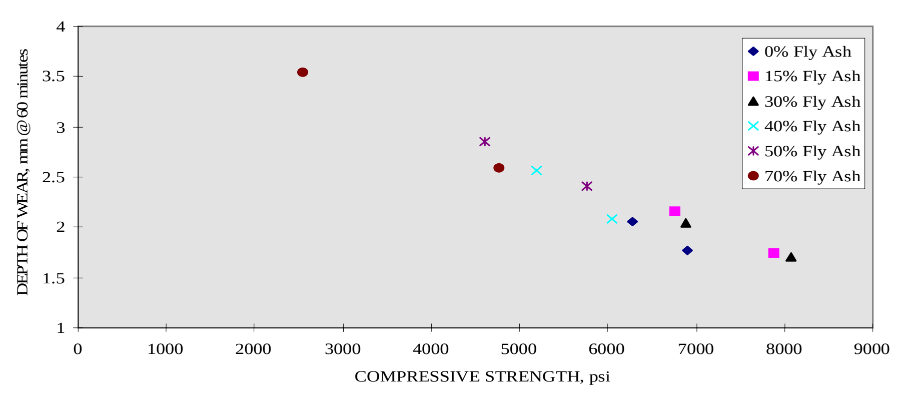

Figure 4–9: Abrasion Resistance vs. Compressive Strength of Concretes Containing Different Percentages of Fly Ash

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.