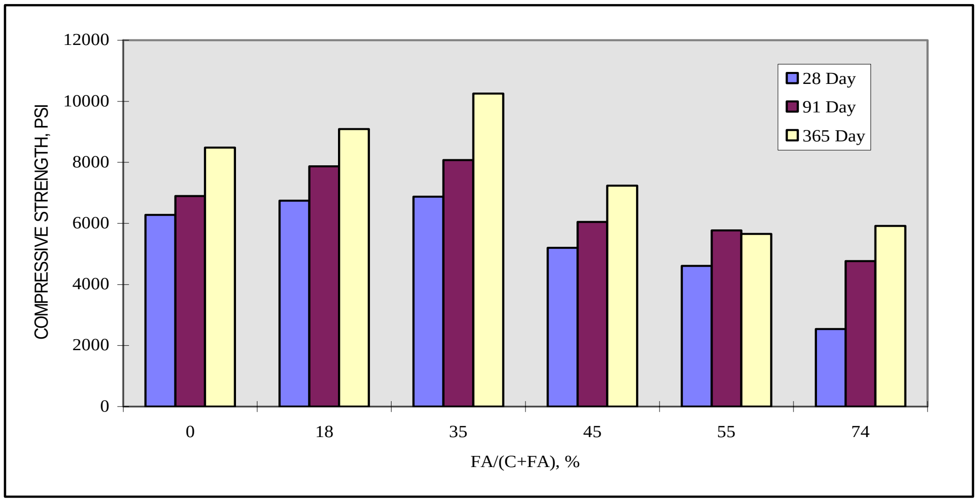

Figure 4–10: Compressive Strength of Concrete made with and without Fly Ash for Primary Mixtures

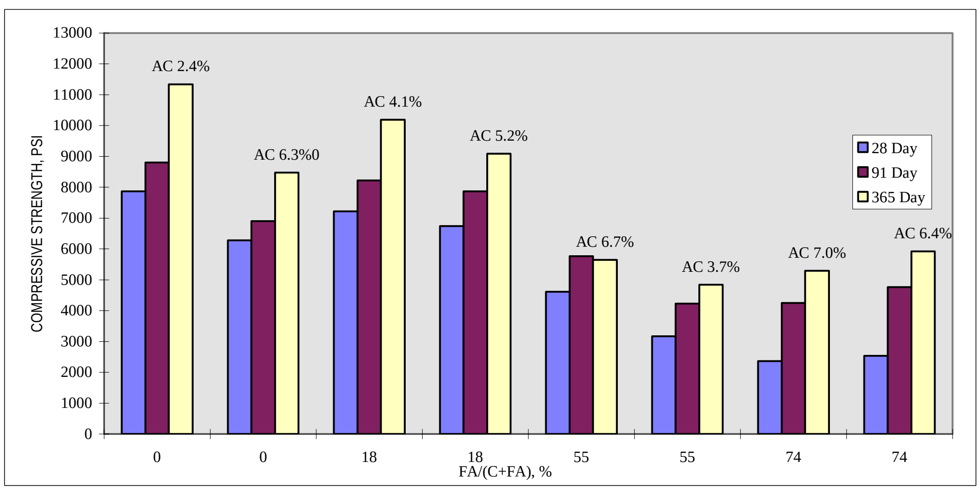

Figure 4–11: Compressive Strength of Concrete made with and without Fly Ash having Different Percentage of Air Content

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.

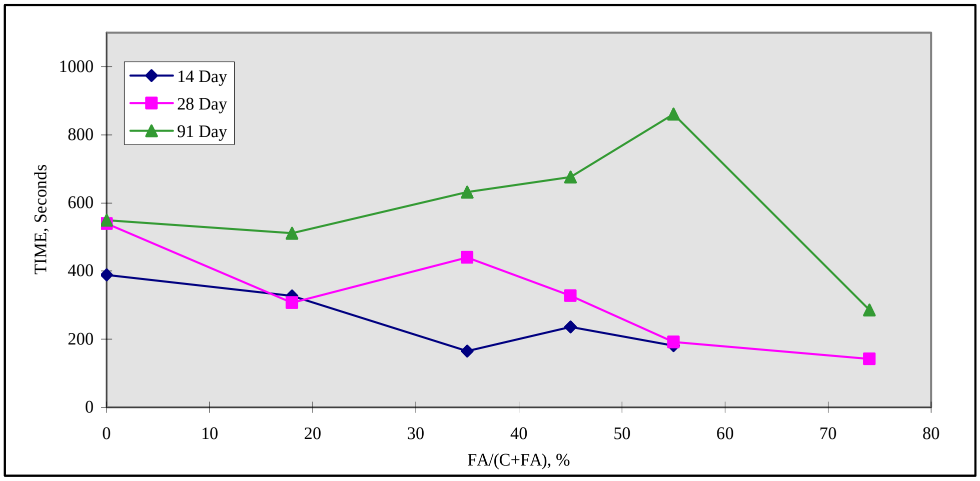

Figure 4–12: Air Permeability (Time) vs. Fly Ash Content for Primary Mixtures

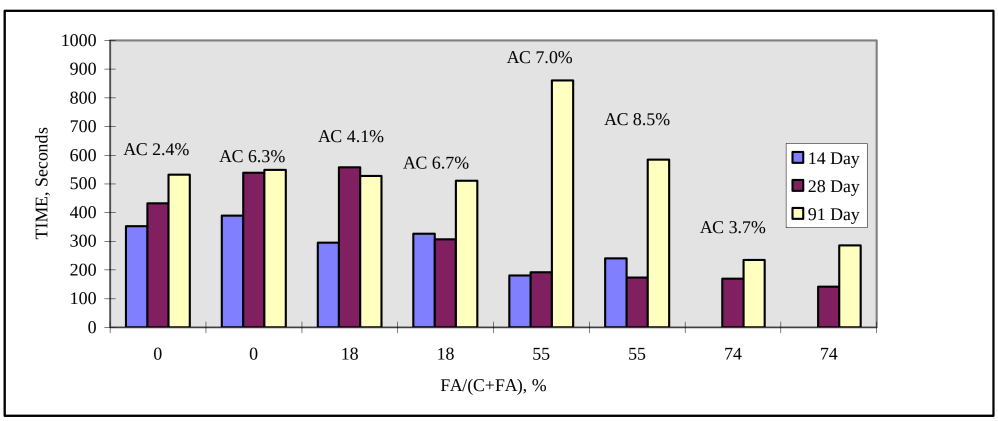

Figure 4–13: Air Permeability of Concrete with and without Fly Ash having Different Percentages of Air Content

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.

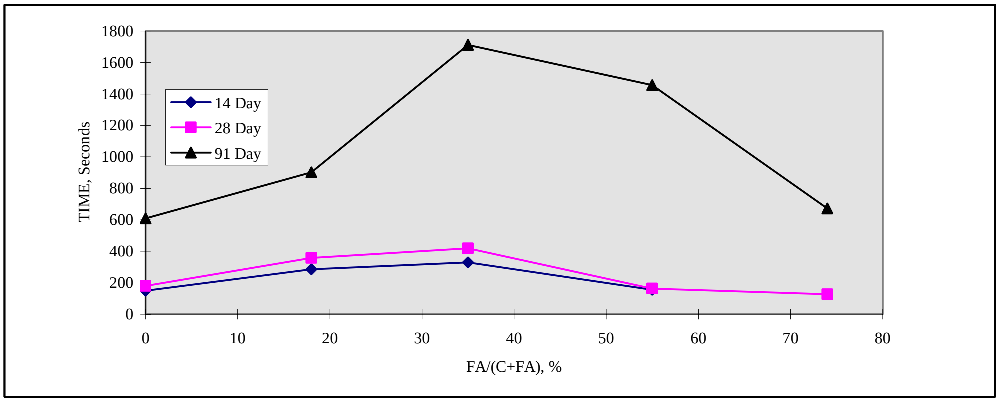

Figure 4–14: Water Permeability (Time) vs. Fly Ash Content for Primary Mixtures

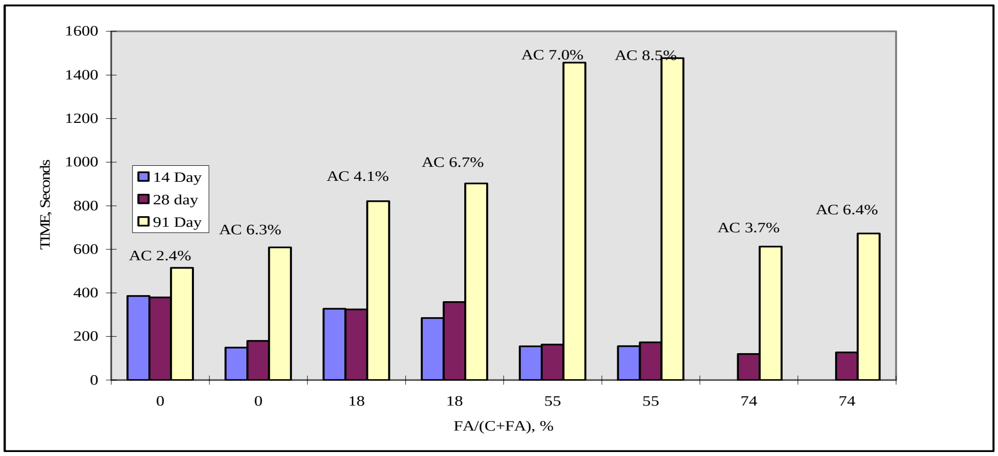

Figure 4–15: Water Permeability of Concrete with and without Fly Ash having Different Percentages of Air Content

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.

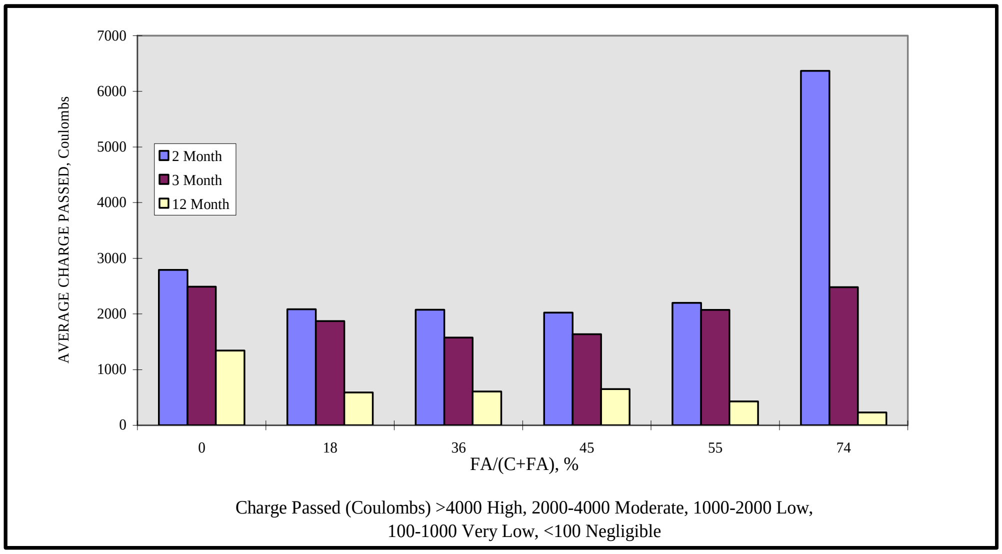

Figure 4–16: Chloride Permeability vs. Fly Ash Content for Primary Mixtures

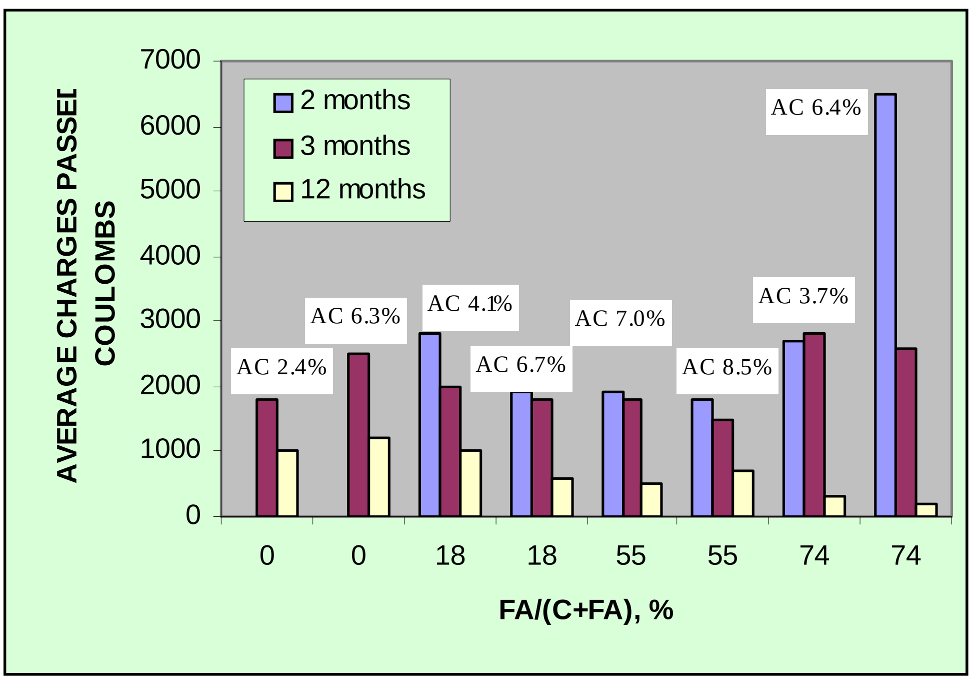

Figure 4–17: Water Permeability of Concrete with and without Fly Ash having Different Percentages of Air Content

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 (in²)	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 2.20.5 2.20.6	P-4	20	3x4x12¼	4876 4718 4769	4762 4784 4821	1.84 1.40 1.09				
F-28 F-29 F-30	P-4	50	3x4x12¼	4620 4592 4559	4718 4718 4676	2.12 2.74 2.57				
F17 F21 F22	OCPP	40	3x3x11¼	4726 4582 4627	4830 4734 4774	2.20 3.32 3.18				
2.20.1 2.20.2 2.20.3	P-4	20	3x4x12¼				4704 4726 4655	4473 [150] 4539 [150] 4480 [150]	4391 [300] 4460 [300] 4354 [300]	-6.65 -5.63 -6.47
F-25 F-26 F-27	P-4	50	3x4x12¼				4599 4586 4552	4473 [150] 4403 [150] 4391 [150]	4512 [300] 4473 [300] 4447 [300]	-1.89 -2.46 -2.31
F-1 F-2 F-3	OCPP	40	3x3x11¼				4481 4582 4510	4453 [150] 4298 [150] 4432 [150]]	4419 [300] 4405 [300] 4391 [300]	-1.38 -3.86 -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.

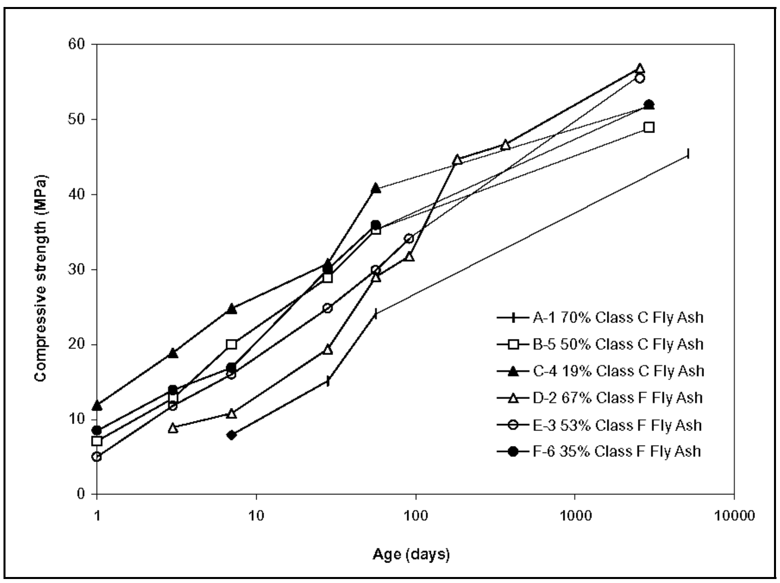

Figure 4–24: Compressive Strength vs. Age

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.

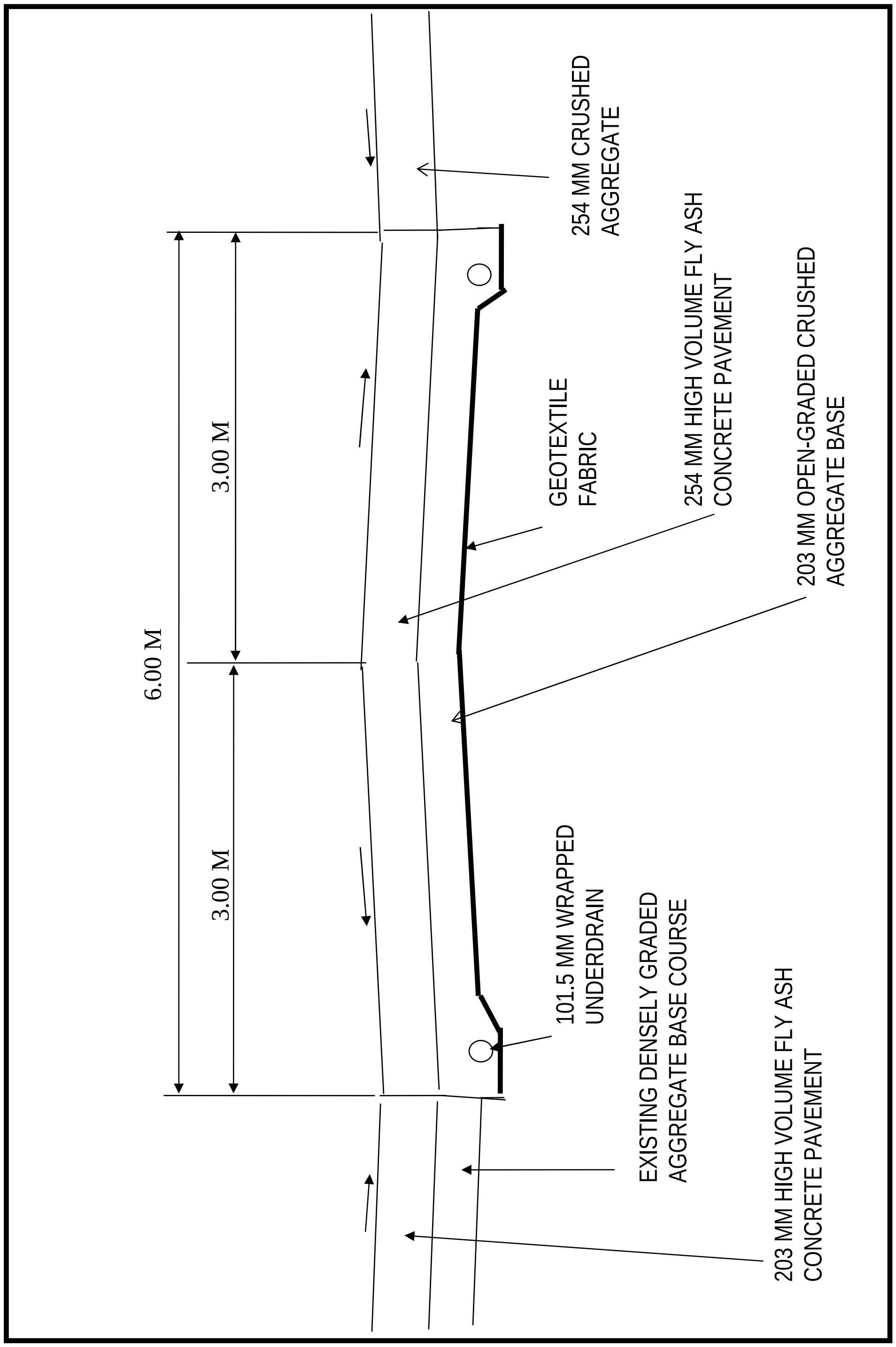

Figure 4-25: Pavement Cross Section

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.

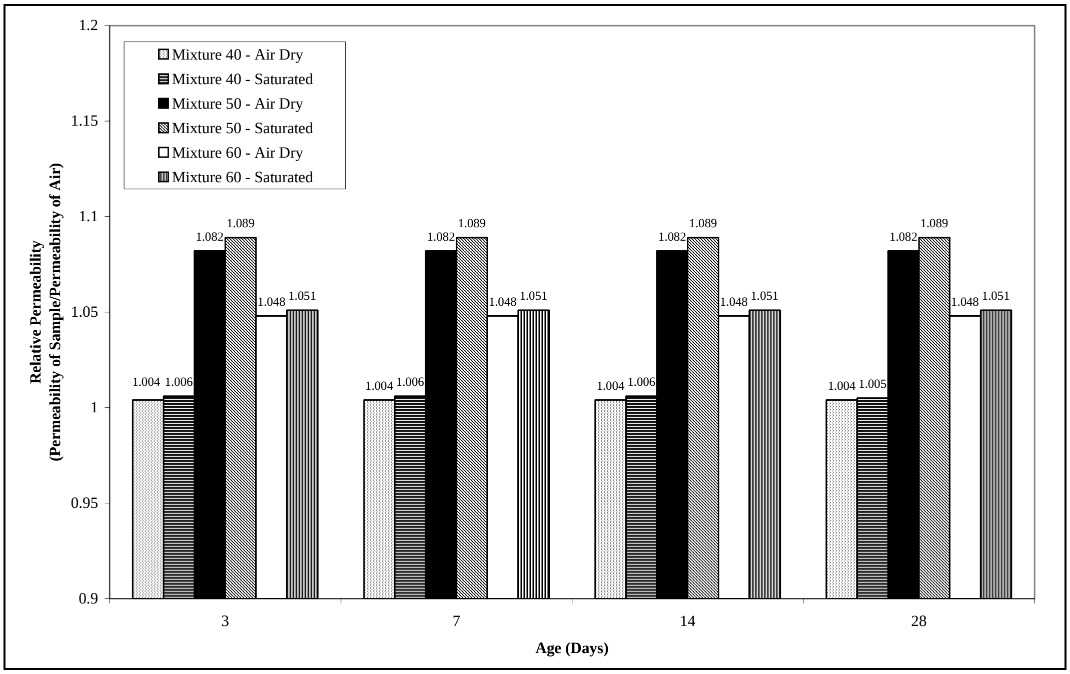

Figure 4–28: Relative Electrical Permeability of Concrete Mixtures

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	

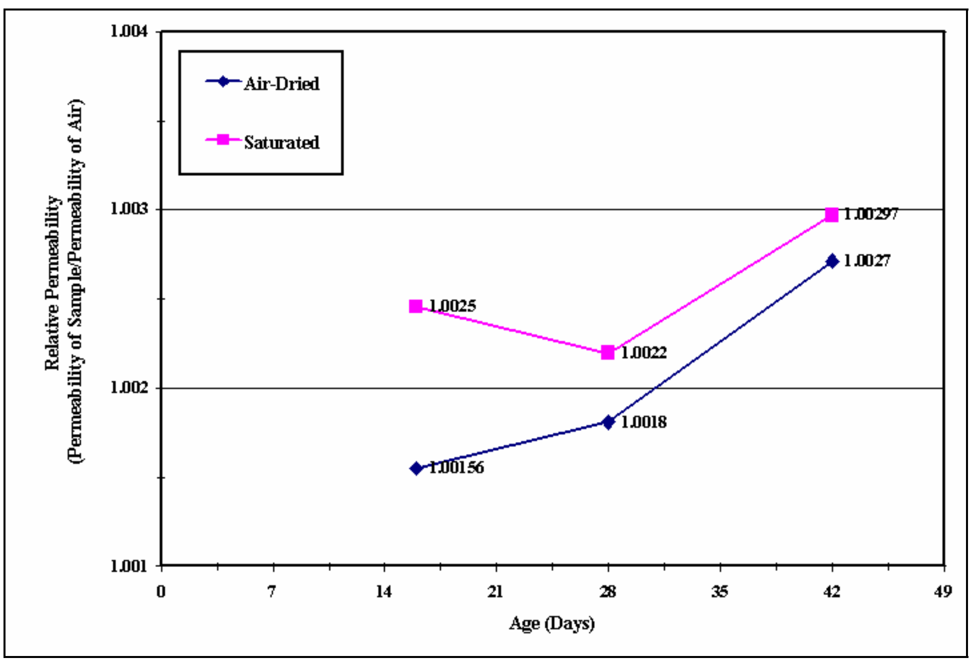

Figure 4–29: Electrical Permeability of High Carbon Fly Ash Concrete Contained Carbon Fibers, Mixture CON-C