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FIFTEEN-YEAR PERFORMANCE OF HIGH-VOLUME FLY ASH CONCRETE ROADS

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Department of Civil Engineering and Mechanics
College of Engineering and Applied Science
THE UNIVERSITY OF WISCONSIN - MILWAUKEE

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ABSTRACT

This project was conducted to evaluate the long-term performance of pavements constructed with high-volume fly ash concrete. The pavement was designed in accordance with the State of Wisconsin Standard Specification for Road and Bridge Construction with the exception of the experimental high-volume fly ash concrete mixtures used for this project. A total of six different mixtures were tested, three mixtures with Class C fly ash up to 70% replacement of cement and three mixtures with Class F fly ash, up to 60% replacement. Cores were taken from each of the six mixtures and evaluated for compressive strength, resistance to chloride ion penetration, density, and signs of visual deterioration. Chloride ion penetration was determined to be either very low or negligible for all concrete mixtures. Mixtures containing Class F fly ash had somewhat better resistance to chloride ion penetration than comparable mixtures containing Class C fly ash. Compressive strength of cores taken from the pavement achieved strengths of 45 to 57 MPa. The highest compressive strengths were attained by the two mixtures containing the highest percentage of Class F fly ash. Hardened concrete density for all concrete mixtures were approximately the same. The pavement sections containing the highest percentage of Class F fly ash performed well in the field with only minor surface scaling? All other pavement sections had minimal surface scaling. The major surface defect was pop-outs due to "excessive" chert particles in some of the mixtures. The results of this study indicates that concrete mixtures containing high-volumes of Class C and Class F fly ash are suitable for pavement construction. The oldest concrete section (15 years old) had 70 % Class C fly ash. This section as well as all others are currently in use and performing very well.

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* Director and Assistant Director, respectively, UWM Center for By-Products Utilization, Department of Civil Engineering and Mechanics, University of Wisconsin-Milwaukee, College of Engineering and Applied Science, P.O. Box 784, Milwaukee, WI 53201

** Principal Engineer, Manager, Combustion By-Products Utilization, Wisconsin Electric Power Company, P.O. Box 2046, Milwaukee, WI 53201

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Table 1: CHEMICAL COMPOSITION OF CEMENT USED

Item	Cement Type I, Percent
SiO_2	20.0
Al_2O_3	4.7
Fe_2O_3	2.7
SO_3	4.7
MgO	3.7
CaO	63.0
TiO_3	0.3
Na_2O	0.2
K_2O	0.7
Moisture	0.4
L.O.I.	1.3

Table 2: CHEMICAL AND PHYSICAL CHARACTERISTICS OF FLY ASHES

Chemical Composition (%)	Class C Fly Ash	Class F Fly Ash
SiO_2	35.4	46.8
Al_2O_3	17.5	23.7
Fe_2O_3	5.3	13.2
SO_3	2.8	1.2
MgO	4.6	1.0
CaO	26.1	3.1
Moisture	0.1	0.1
L.O.I.	0.4	7.9
Physical (per ASTM C618)		
Fineness		
Retained on #325 sieve, (%)	15.9	25.7
Pozzolanic Activity Index		
With Portland Cement (%)		
Ratio to Control @ 28 days	79	93
With Lime @ 28 days (psi)	1040	1110
Water Requirement, % of Control	89	103
Soundness		
Autoclave Expansion (%)	0.11	0.0
Specific Gravity	2.58	2.34

Note: 145 psi = 1 MPa
1 inch = 25.4 mm

Table 3: CONCRETE MIX AND FRESH CONCRETE TEST DATA

MIX NO.	A-1	B-5	C-4	D-2	E-3	F-6
% Class C Fly Ash	70	50	20	--	--	--
% Class F Fly Ash	--	--	--	60	50	40
Cement, lbs/yd^3	170	295	480	225	305	365
Fly Ash, lbs/yd^3	395	295	110	450	350	245
Water, lbs/yd^3		155	170	310	200	165
SSD Sand, lbs/yd^3	1490	1,250	1,370	1410	1410	1,540
SSD Coarse aggregates, lbs/yd^3	1830	1,830	1,930	1900	1900	1,845
Water Reducing Admixture, liq.oz/yd^3	8	0	0	0	0	0
Superplasticizer (HRWRA), liq.oz/yd^3	0	0	0	144	130	120
Air Entraining Admixture, liq.oz/yd^3	11	12	7	32	32	15
Slump, inches	--	2-3/4	2	1-3/4	2-1/4	2-1/2
Air Content, %	5-6	5	6	5	5.8	5
Air Temp., °F	--	83	76	54	52	95
Concrete Temp., °F	--	88	84	64	64	89
Concrete Density, pcf	--	146.8	143.8	146	146	144.1

Note: 145 psi = 1 MPa

1 inch - 25.4 mm

1°F = 1.8°C + 32

1 cu yd = 0.7646 cu m

1 pound = 0.4536 kg

Table 4: COMPRESSIVE STRENGTH TEST RESULTS

Specified Design Strength 3500 psi at 28-day Age

Test Age	Mix Numbers					
	A-1	B-5	C-4	D-2	E-3	F-6
	70% Class C	50% Class C	20% Class C	60% Class F	50% Class F	40% Class F
	Compressive Strength, psi					
1 day	--	1,023	1,720	--	720	1,233
3 days	--	1,857	2,737	1,290	1,710	2,013
7 days	1,150	2,900	3,590	1,560	2,320	2,453
28 days	2,200	4,185	4,465	2,810	3,590	4,352
56 days	3,500	5,124	5,938	4,210	4,330	5,212
91 days	--	--	--	4,610	4,940	--
182 days	--	--	--	6,480	--	--
365 days	--	--	--	6,770	--	--
7 years	--	--	--	8,250	8,040	--
8 years	--	7,110	7,535	--	--	7,470
14 years	6,595	--	--	--	--	--

Table 5: COMPRESSIVE STRENGTH OF CONCRETE CORES

Mixture No.	Fly Ash Content	Age	Specimen Number	Compressive Strength (MPa)	Average Compressive Strength (MPa)
A-1	70% Class C	14 years	1-1	48.7	45.5
			1-2	43.7	
			1-3	44.1	
B-5	50% Class C	8 years	5-4	50.4	49.0
			5-5	48.1	
			5-6	48.5	
C-4	20% Class C	8 years	4-4	54.3	52.0
			4-5	52.4	
			4-6	49.2	
D-2	60% Class F	7 years	2-1	60.8	56.9
			2-2	52.3	
			2-3	57.7	
E-3	50% Class F	7 years	3-4	54.8	55.5
			3-5	55.6	
			3-6	56.0	
F-6	40% Class F	8 years	6-4	--	51.5
			6-5	48.4	
			6-6	54.7	

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Introduction

LITERATURE REVIEW

High volumes of fly ash have been used in concrete since the late 1940s with a view to reducing costs and controlling temperature rise in mass concrete. Recently, a large number of investigations have been directed toward development of structural as well as high strength concretes incorporating substantial amounts of fly ash and other mineral admixtures [1-17]. Pioneering work for production of structural-grade concrete incorporating large quantities of ASTM Class F fly ash was done by Malhotra, et al. [2-5]. Use of high volumes of Class C fly ash in structural-grade concrete began at the University of Wisconsin-Milwaukee in 1984 [13,14].

Mukerjee et al. [2] manufactured concrete containing a large amount of low-calcium fly ash with the help of three different superplasticizers. Their results revealed that superplasticized concrete incorporating 37% Class F fly ash achieved better mechanical properties compared to the reference mix containing no fly ash. Malhotra and Painter [3] investigated early-age strength and freezing and thawing durability of high-volume fly ash concrete systems. Three different series of tests were carried out. The mixes of Series 1 contained a constant cement of about 145 kg/m^3 of concrete and fly ash content was varied from 110 to 197 kg/m^3. The water-to-cementitious material ratio varied between 0.32 and 0.42, and air content was maintained at 9.5 ± 1 %. The mixes of Series II tests were identical to that of Series I except the air content was reduced to about 5.5 ± 1 %. In Series 3 tests, fly ash content ranged from 183 to 275 kg/m^3. The water-to-cementitious material ratio varied from 0.28 to 0.35 while air content was kept at 4.0 ± 0.5 %. The high-volume concrete attained adequate early-age strength, and its freezing and thawing resistance was excellent except the test prisms suffered moderate to substantial surface scaling. Based on the results obtained, the authors reported an optimum fly ash content of about 200 kg/m^3 of concrete.

Sivasundaram et al. [5] evaluated properties of high-volume fly ash concrete systems using two different sources of fly ash. The reference mix contained about 365 kg/m^3 of cement. The fly ash concrete mixtures contained about 155 kg/m^3 of ASTM Type I cement and 215 kg/m^3 of fly ash. These mixtures were superplasticized and air-entrained. The water-to-cementitious ratio was maintained at 0.31 ± 0.01. Concrete specimens were tested for compressive strength, modulus of elasticity, drying shrinkage, freezing and thawing durability, and permeability to chloride ions. Compressive strength of fly ash concrete increased from 36 MPa at 28 days to 47 MPa at 91 days. Its modulus of elasticity value was 37 GPa at 91 days. Drying shrinkage of fly ash mixes were comparable to no-fly ash concrete. The fly ash concrete exhibited excellent resistance to freezing and thawing; durability factor exceeded 90%. However, test specimens exhibited some scaling. Chloride permeability of the fly ash concrete was lower compared to the reference mix.

Ravina and Mehta [6] studied the effects of replacements of cement with two Class C and two Class F fly ashes on workability, water requirement, bleeding, and setting time, of lean concrete. Fly ash content was varied from 35 to 50% of total cement used. All fly ash concrete mixtures showed higher workability than that for the reference mixture containing no fly ash. The water requirement of the fly ash mixes for a target slump of 5 cm was decreased by 10 to 15% relative to the control mix. The rate of bleed water for fly ash concrete mixes was either higher or comparable to that for the reference concrete mixture. Inclusion of fly ash increased setting time of concrete mixture. The initial setting time was delayed from 20 min. up to 4.3 hours and the final setting time from 1 hour up to 5.25 hours; the delay was longer for the mixtures made with the ASTM Class C fly ashes relative to the ASTM Class F fly ash mixes. Ravina and Mehta [7] also investigated the effects of fly ash addition on compressive strength development of lean concrete mixtures (350 lbs/yd^3; 210 kg/m^3) using the above two types of fly ashes for cement replacement in the range of 35-50%. The no-fly concrete attained 2000 psi (14 MPa) at 28 days, whereas the fly ash mixes achieved this strength level at ages ranging from 35 to 170 days depending upon replacement levels and properties of fly ash.

Naik et al. [8] investigated performance of concrete proportioned to have cement replacement in the 0-60% by Class F fly ash obtained from two different sources. A reference concrete mix having 611 lbs. cement per cu.yd. (362 kg/m^3) was proportioned to achieve 28-day strength of 41 MPa. The water-to-cementitious ratio for the mixes varied from 0.32 to 0.44 and desired workability was achieved through the use of a Melamine-based superplasticizer. In general, addition of these Class F fly ashes in concrete caused reduction in compressive strength, splitting tensile strength, and modulus of elasticity of concrete at early ages. However, all the Class F fly ash mixes showed adequate strength at 28 days for structural applications.

Several investigators [9-17] have shown that concrete incorporating large volumes of Class C fly ash can be proportioned to meet strength and workability requirements for structural applications. Papayianni [11] proportioned concrete mixes to replace cement in the range of 0-100% with a lignite fly ash at water-to-cementitious ratios varying between 0.55 and 0.95. A superplasticizer was utilized to control consistency of concrete mixes. The author reported that the Class C fly ash could be used as cement replacements up to 40% in reinforced concrete and 70% in plain concrete.

Naik and Ramme [15] investigated setting and hardening characteristics of high-volume ASTM Class C fly ash concretes. Both air-entrained and nonair-entrained concrete mixes were proportioned to contain fly ash to replace cement up to 55% by weight at three different nominal strength levels of 3000, 4000, and 5000 psi (21, 28, and 35 MPa). They measured setting time, compressive strength, Poisson's ratio, modulus of elasticity, drying shrinkage, and freezing and thawing durability of concrete. The results of the investigation led to the following major conclusions: (1) initial and final setting times were not significantly affected by inclusion of fly ash for up to 55% cement replacements, (2) the static modulus values were in conformance with the predictions by the ACI 318 Equation, and, (3) as expected, the non air-entrained fly ash concrete had very low resistance to freezing and thawing, and the air entrained showed high resistance to freezing and thawing actions.

Naik and Ramme [13,14] carried out an investigation to develop mix proportions for high-volume fly ash concrete systems incorporating large quantities of an ASTM Class C fly ash. Concrete mixes were proportioned to obtain 28-day strengths of 3000, 4000, and 5000 psi (21, 28, and 35 MPa). The results revealed that concrete containing 40 to 60% cement replacement attained lower compressive strength up to 7 days, but at 28 days and beyond, had substantially higher strength compared to the reference concrete containing no fly ash.

More recently, Naik et al. [16] developed concrete mixes containing an ASTM Class C fly ash obtained from Pleasant Prairie Power Plant of Wisconsin Electric Power Company to have cement replacements up to 70% by weight. The reference concrete was proportioned to attain 28-day strength of 6000 psi (41 MPa). The water-to-cementitious ratio was maintained at 0.31 ± 0.02, and desired workability was achieved by varying the dosage of a Melamine-based superplasticizer. These mixes were evaluated with respect to compressive strength, tensile strength, and modulus of elasticity. Test data indicated that structural grade concrete can be produced at 70% cement replacement with this Class C fly ash.

ROAD DESIGN AND CONSTRUCTION

The existing crushed stone road was used as a base and a 20 ft (6 m) wide, 8 in. (200mm) thick concrete pavement was placed over the base. The crowned concrete surface was sloped one quarter inch per foot from the centerline to the edge of the roadway to provide good drainage, and a 2 ft. (0.6 m) wide crushed reclaimed concrete stone shoulder was placed on each side. Saw cuts were spaced at 20 ft. (6 m) intervals and an expansion joint was placed between each change in concrete mixture (approximately 1320 ft. (402 m) intervals). The pavement was designed to comply with the State of Wisconsin Standard Specification for Road and Bridge Construction with the exception of the two experimental high volume fly ash concrete mixtures utilized on the project. Figure 1 gives the typical cross section used. The minimum 28-day compressive strength was specified at 3500 psi (24 MPa) and the air content was specified to be 5% to 7% by volume.

Concrete was batched at a remote central mix plant and transported to the site in conventional ready mixed concrete trucks. The concrete was discharged in front of a typical highway slip form paver and was placed full width over a two day period in September of 1990. The concrete was sprayed with a curing compound. Sawed joints were filled with a hot application elastic sealer (hot-poured tar) meeting ASTM D3405 requirements. The road was opened to truck traffic within 10 days of paving completion, and has been providing good service with no apparent defects. Air entrainment and slump were more difficult to control with the Class F than with the Class C ash mixtures. The concrete finishers commented that the high volume Class "F" concrete was more "sticky" when troweling and edging but was still readily finished. The Class F concrete took somewhat longer to reach the strength at which saw cuts could easily be made. The wait required for sawing varied between 24 - 48 hours.

There also is a noticeable color difference between the three concrete mixtures with the 20% and 50% Class C mixtures providing two shades of tan earth tone colors while the 40% Class F concrete is a medium gray slate tone color. The latter is now being referred to as "Gray Top". The darker color provided by the Gray Top should prove helpful in melting off snow and ice remnants during sunny winter days in Wisconsin (much like asphaltic concrete).

MATERIALS

Type I Portland cement was used in this project. The chemical composition of the cement used in this work is given in Table 1. Both Class F and Class C fly ash were obtained from electric power plants located in southeastern Wisconsin. Physical and chemical test data for these fly ashes are reported in Table 2. In spite of LOI in excess of 6% for this source of Class F fly ash, it had shown adequate performance for structural applications under laboratory conditions. This research was undertaken to prove that this fly ash is also suitable for paving work. The fine aggregate was natural sand and natural gravel was used as the coarse aggregate. Both fine and coarse aggregates were obtained from local sources and the coarse aggregate had a maximum size of 1-1/2 in (38mm). The coarse as well as fine aggregates met the grading requirements per ASTM C136. A melamine based superplasticizer (ASTM C-494 Type F) was used in the Class F ash concrete and a resin based air entraining admixture manufactured by the Grace Co. was used in all concrete mixtures. Admixture dosages were varied to achieve the desired air entrainment required for the project, see Table 3.

MIX PROPORTIONS

Three mix proportions were selected. The control mix selected was the standard 20% Class C fly ash concrete mixture (mix designation S3) as specified by the State of Wisconsin Department of Transportation. A high volume Class C fly ash concrete mixture (mix designation S2) was selected from previous experience with structural grade and paving quality concrete [13-16]. The cementitious materials in the mix consisted of 50% Class C fly ash and 50% Type I Portland cement. A high volume Class F fly ash concrete mixture was selected from laboratory experience at the Center for By-Products Utilization where these mix proportions were developed for Class F fly ash materials [8]. The mix selected contained 40% Class F fly ash, 60% Type I Portland Cement, aggregates, water, air entraining agent and a superplasticizer (mix designation S1). The slumps for all three mixtures were generally maintained at the site in the 2" ± 1" (51 mm ± 25 mm) range. The addition of the superplasticizer to the Class F mixture allowed the water to cementitious (W/C) ratio to be kept low. The 20% and 50% Class C ash mixtures had W/C ratios of 0.34 - 0.40 and 0.34 -0.37, respectively. The mix details are reported in Table 3.

SPECIMEN TESTING

Standard 6 in. diameter by 12 in. high (150 x 300 mm) cylinders were prepared and tested for compressive strength and splitting tensile strength in accordance with ASTM test procedures. Three cylinders were tested for each experimental condition at various ages.

Standard 6 in. x 6 in. x 30 in. (15 mm x 15 mm x 76 mm) beams were prepared and tested for flexural strength in accordance with ASTM test procedure. Typically three beams were tested for each concrete mixture at various ages.

Durability tests were carried out to determine freezing and thawing resistance of concrete. Prism specimens varied in size from 3" x 3" x 11-1/4" (75 x 75 x 280 mm) to 3" x 4" x 12-1/4" (75 x 100 x 310 mm), were made for measuring of freeze-thaw durability of concrete. The freezing and thawing durability of concrete was evaluated in accordance with ASTM C-666, Produce A. The parameters measured for the durability were durability factor, change in resonance frequency, weight, and pulse velocity.

RESULTS AND DISCUSSION

Compressive Strength

Compressive strength data for the concrete containing Class C fly ash and containing Class F fly ash are shown in Table 4. The data reported in Tables 3 and 4 are from cylinders prepared at the construction site. Table 4 show that all the mixes averaged compressive strengths greater than 3500 psi (24 MPa) at the 28 day age. Compressive strength was found to increase with age for all of the mixtures as shown in Figure 2. Figure 2 also shows that all mixes continued to gain strength between 28 and 56 days.

The site specimen data for the 40% Class F fly ash mixture produced an average compressive strength of 2000 psi (14 MPa) at 3 days, 2500 psi (17 MPa) at 7 days, 4400 psi (30 MPa) at 28 days and 5200 psi (36 MPa) at 56 days. The site specimen data for the 50% Class C fly ash mixture produced an average compressive strength of 1900 psi (13 MPa) at 3 days, 2900 psi (20 MPa) at 7 days, 4200 psi (30 MPa) at 28 days and 5100 psi (35 MPa) at 56 days. Finally the site specimen data for the 20% Class C fly ash produced an average compressive strength of 2700 psi (19 MPa) at 3 days, 3600 psi (25 MPa) at 7 days, 4500 psi (31 MPa) at 28 days and 5900 psi (41 MPa) at 56 days.

Table 4: Chloride Ion Penetration Resistance

Mixture No.	Fly Ash (ASTM Class C) %	Fly Ash (ASTM Class F) %	Age	Specimen No.	Total Charge Passed, Coulombs	Average Charge Passed, Coulombs
				1-4-T	152	
				1-4-B	108	
				1-5-T	102	
				1-5-B	107	
				1-6-T	152	
A-1	70	--	14 years	1-6-B	59	113
				5-1-T	226	
				5-1-B	201	
				5-2-T	191	
				5-2-B	230	
				5-3-T	286	
B-5	50	--	8 years	5-3-B	170	217
				4-1-T	427	
				4-1-B	550	
				4-2-T	537	
				4-2-B	561	
				4-3-T	719	
C-4	20	--	8 years	4-3-B	599	566
				2-4-T	97	
				2-4-B	22	
				2-5-T	49	
				2-5-B	74	
				2-6-T	91	
D-2	--	60	7 years	2-6-B	59	65
				3-1-T	73	
				3-1-B	84	
				3-2-T	74	
				3-2-B	39	
				3-3-T	83	
E-3	--	50	7 years	3-3-B	110	77
				6-1-T	155	
F-6	--	40	8 years	6-1-B	171	155

				6-2-T	205	
				6-2-B	108	
				6-3-T	151	
				6-3-B	142	

*Charge Passed (coulombs)	*Chloride ion Penetrability
>4000	High
2,000-4,000	Moderate
1,000-2,000	Low
100-1,000	Very Low
<100	Negligible

Table 4: Density of Hardened Concrete Cores

Mixture No.	Age	Specimen No.	Density (lb/ft^3)	Average Density (lb/ft^3)
		1-1	143.9	
		1-2	145.8	
		1-3	144.1	
		1-4	144.1	
		1-5	143.7	
1		1-6	142.5	144
		2-1	151.0	
		2-2	146.3	
		2-3	146.1	
		2-4	145.2	
		2-5	145.4	
2		2-6	148.8	147
		3-1	142.9	
		3-2	143.1	
		3-3	143.3	
		3-4	146.2	
		3-5	152.9	
3		3-6	148.3	146
4		4-1	148.7	148

		4-2	148.4	
		4-3	146.5	
		4-4	149.7	
		4-5	148.1	
		4-6	148.6	
		5-1	146.1	
		5-2	147.5	
		5-3	147.1	
		5-4	148.1	
		5-5	145.3	
5		5-6	145.9	147
		6-1	146.3	
		6-2	144.2	
		6-3	143.8	
		6-4	146.0	
		6-5	147.1	
6		6-6	143.6	145

Table 4: Density of Hardened Concrete Cores

Mixture No.	Age	Specimen No.	Density (kg/m^3)	Average Density (kg/m^3)
		1-1	2310	
		1-2	2340	
		1-3	2310	
		1-4	2310	
		1-5	2300	
1		1-6	2280	2310
		2-1	2420	
		2-2	2340	
2		2-3	2340	2360

		2-4	2330	
		2-5	2330	
		2-6	2390	
		3-1	2290	
		3-2	2290	
		3-3	2300	
		3-4	2340	
		3-5	2450	
3		3-6	2380	2340
		4-1	2380	
		4-2	2380	
		4-3	2350	
		4-4	2400	
		4-5	2370	
4		4-6	2380	2380
		5-1	2340	
		5-2	2360	
		5-3	2360	
		5-4	2370	
		5-5	2330	
5		5-6	2340	2350
		6-1	2340	
		6-2	2310	
		6-3	2290	
		6-4	2340	
		6-5	2360	
6		6-6	2300	2320

Table 5: TENSILE STRENGTH TEST RESULTS

Specified Design Strength 3500 psi at 28-day Age

Test Age, Days	Mix Numbers								
	S1-1	S1-2	S1-3	S2-1	S2-2	S2-3	S3-1	S3-2	S3-3
	Tensile Strength, psi								
3	255	230	215	275	230	245	310	345	335
3	235	250	245	225	220	265	305	340	300
3	205	280	245	245	235	255	300	320	385
7	275	310	260	310	315	330	335	415	440
7	295	315	260	340	350	370	325	425	400
7	265	325	260	330	310	370	350	370	385
28	380	370	325	420	395	390	415	475	490
28	410	425	360	410	360	390	420	400	460
28	410	410	340	420	350	410	450	440	520
56	520	515	430	550	375	440	450	525	565
56	480	535	470	520	400	455	460	530	510
56	525	510	430	510	415	420	475	540	545

Mix S1: 40% Class F Fly Ash Note: 145 psi = 1 MPa

Mix S2: 50% Class C Fly Ash

Mix S3: 20% Class C Fly Ash

Table 6: FLEXURAL STRENGTH TEST RESULTS

Specified Design Strength 3500 psi at 28-day Age

Test Age, Days	Mix Number		
	S1-1	S2-3	S3-2
	Flexural Strength, psi		
3	310	350	500
3	360	260	470
3	355	310	500
7	435	340	520
7	410	--	510
7	420	400	530
28	570	640	695
28	570	570	685
28	590	600	635
56	630	685	690
56	675	--	700
56	620	720	725

Note: Mix S1: 40% Class F Fly Ash145 psi = 1 MPa
Mix S2: 50% Class C Fly Ash
Mix S3: 20% Class C Fly Ash