

# **Center for By-Products Utilization**

## **HIGH-STRENGTH CONCRETE CONTAINING LARGE QUANTITIES OF FLY ASH**

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*ABSTRACT*

*Presents research performed to identify and recommend mix designs for high fly ash content 30W and 4000 psi (21 and 28 MPa) structural grade concrete utilizing Class C fly ash. The fly ash was produced at Wisconsin Electric Power Company's Pleasant Prairie Power Plant.*

Keywords: compressive strength; fly ash; foundations; high-strength concretes; mix proportioning<sup>3</sup>; roads; tests.

The fundamental objective of this research project was to develop mix proportioning information for structural grade concrete using high proportions of fly ash. The fly ash used in this project was produced by Wisconsin Electric Power Company at the Pleasant Prairie Power Plant located in Kenosha County, Wisconsin, and is a by-product of western U.S.A. sub bituminous coal combustion. The fly ash is captured by electrostatic precipitators from flue gas prior to discharge by exhaust chimneys and meets the ASTM C 618 Class C designation (see Table 1). The concrete mixes developed were consistent with good quality concrete production and good quality concrete construction needs.

Concrete was produced at two ready-mixed concrete plants utilizing different cement and aggregate sources. Concrete mixes with and without air entrainment was produced in which fly ash was substituted for cement in quantities up to 70 percent of total cement replacement. Compressive strength, air content, density, setting, and workability characteristics were observed. The 28 day design compressive strength was 3000, 4000, and 5000 psi (21, 28, and 35 MPa); slump varied between 3 and 5 in. (75 and 125 mm); and air content varied between 3 and 7 percent. Only non-air-entrained concrete test data are presented in this paper.

Since the 1930s,<sup>1</sup> it has been established that approximately 15 to 20 percent fly ash can be substituted for portland cement in structural grade concrete. For certain applications, concrete containing fly ash enhances the properties of concrete and, therefore, improves the performance of the concrete. Until recently, most of the fly ash available from coal-burning power plants were of the Class F (low calcium) variety.

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Presently, however, Class C (high calcium) fly ash, which is produced by burning low-sulfur western U.S.A. coal, has become more readily available.

Class C fly ash has higher lime content than Class F fly ash. The Class C fly ash can be used in much higher proportions than the 15 to 20 percent range currently used for Class F fly ash for structural quality concrete. The percentage of cement that can be replaced with the Class C and/or Class F fly ash is dependent upon the source of the fly ash. Therefore, for efficient utilization of the fly ash, mix designs for concrete must be developed so that a particular source of fly ash can be utilized in the highest percent replacement possible.

Low-cement content structural grade concrete with 70 percent Class C fly ash substitution for cement also was used for some trial construction projects. Results and recommendations obtained from limited construction experience are also presented.

### OBJECTIVES AND SCOPE

The primary objective of this research project was to develop concrete mix designs for structural grade concrete containing as high a fly ash content as possible, consistent with desirable structural grade concrete properties. The scope of the research phase reported was limited to developing concrete mix designs consistent with specified strength and workability.

### RELEVANT PUBLICATIONS

A literature search was conducted. Rather than compiling an exhaustive annotated bibliography of the available literature, some important publications were reviewed, and they are listed<sup>1-21</sup> in the References at the end of the paper.

### PRELIMINARY MIX PROPORTIONING

Preliminary mix proportions were developed for producing concrete on a 1.25:1 fly ash to cement weight basis in the amounts of 0, 20, 30, 40, 50, and 60 percent. Three strength levels of concrete were developed by varying the water-cement ratio ( $w/c = 0.45, 0.55, \text{ and } 0.65$ ). Test data from two strength levels [3000 and 4000 psi (21 and 28 MPa)] are presented.

Two brands of Type I cement, two sources of rounded aggregate and non-air-entrained and air-entrained mixes with 1/4 in. (19 mm) maximum size aggregates were investigated. Slump was maintained in the range of  $4 \pm 1$  in. ( $100 \pm 25$  mm), and entrained air was maintained in the range of  $5.5 \pm 1$  percent. These variables were chosen judiciously for each mix in consideration of general construction project needs. CONCRETE MIXING Concrete was produced at ready-mixed plants in 2 yd' (1.5 in') test batches. Based upon the preliminary mix proportions developed, the final mix designs were completed in consultations with the ready-mixed concrete producers.

### SPECIMEN PREPARATION AND TESTS

Each batch of concrete produced was tested for acceptability before concrete tests were undertaken. Fresh concrete tests were performed and mix proportions were

recorded (see Tables 2 and 3). Tests for slump, temperature of concrete, air content, and density were performed. Attention was also paid to the workability of the concrete. AU concrete produced was homogeneous and cohesive.

From each concrete mix, 6 in. diameter by 12 in. long (130 x 300 mm) cylindrical specimens was prepared for tests of compressive strength. Typically, three cylinders were tested for strength at each test age. Accelerated strength tests at the age of 1 day and standard moist room-cured compressive strength tests at 3, 7, 28, 56, and 91 days were performed. Accelerated strength tests and compressive strength tests were performed in accordance with standard ASTM test methods.

### TEST RESULTS AND DISCUSSION

Test results are reported in Tables 2 through 5, and Fig. 1 and 2.

**Table 1 — Chemical and physical test data — Pleasant Prairie power plant (P4) fly ash**

Chemical composition	Number of samples	Range, percent	Average, percent	ASTM C 618
Silicon oxide (SiO <sub>2</sub> )	7	38.50 - 42.80	40.89	—
Aluminum oxide (Al <sub>2</sub> O <sub>3</sub> )	7	14.20 - 17.90	16.13	—
Iron oxide (Fe <sub>2</sub> O <sub>3</sub> )	7	5.60 - 6.60	6.01	—
Total (SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub> )	7	61.10 - 66.30	63.03	50.0 Minimum
Sulfur trioxide (SO <sub>3</sub> )	7	2.30 - 3.50	2.98	5.0 Maximum
Calcium oxide (CaO)	7	23.40 - 26.90	25.30	—
Magnesium oxide (MgO)	7	4.10 - 4.80	4.56	5.0 Maximum
Loss on ignition	7	.20 - .64	.45	6.0 Maximum
Available alkalis as Na <sub>2</sub> O	7	.87 - 1.55	1.19	1.5 Maximum
<b>Physical tests</b>				
Fineness percent retained on #325 wet sieve	7	15.31 - 23.73	18.83	34.0 Maximum
Pozzolanic activity index with cement, 28 days, percent	7	86 - 100	92.43	75.0 Minimum
	7	1505 - 2520	1805	800 Minimum
Water requirement, percent of the control	7	89 - 95	91	105 Maximum
Soundness autoclave expansion, percent	7	0.12 - 0.18	0.15	0.8 Maximum
Specific gravity	7	2.42 - 2.64	2.58	—

**Table 2 — Concrete mix and test data — 3000 psi (21 MPa) specified strength (P4 ash structural concrete)**

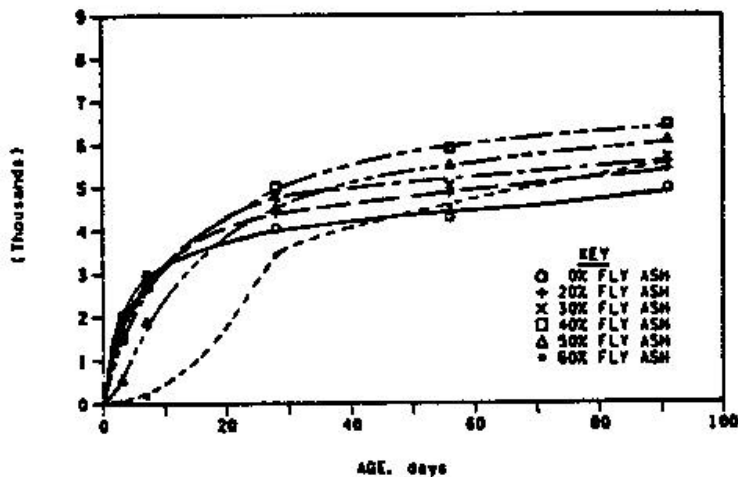
Mix No.	P4 - 1	P4 - 2	P4 - 3	P4 - 4	P4 - 5	P4 - 6
Specified design strength, psi	3000	3000	3000	3000	3000	3000
Cement, lb	425	341	300	255	210	171
Fly ash, lb	0	100	150	208	260	310
Water, lb	281	273	272	262	258	249
Sand, SSD, lb	1610	1610	1610	1610	1610	1610
¼ in. aggregates SSD, lb	1810	1810	1810	1810	1810	1810
Slump, in.	4¼	4¼	4¼	3¾	3¾	4¾
Air content, percent	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, lb/ft <sup>3</sup>	153.4	154.1	154.6	154.8	154.5	154.7
Date cylinders cast	8-21-84	8-21-84	8-21-84	8-21-84	8-21-84	8-21-84

Concrete supplier: Central Ready Mixed Concrete, Milwaukee, WI.

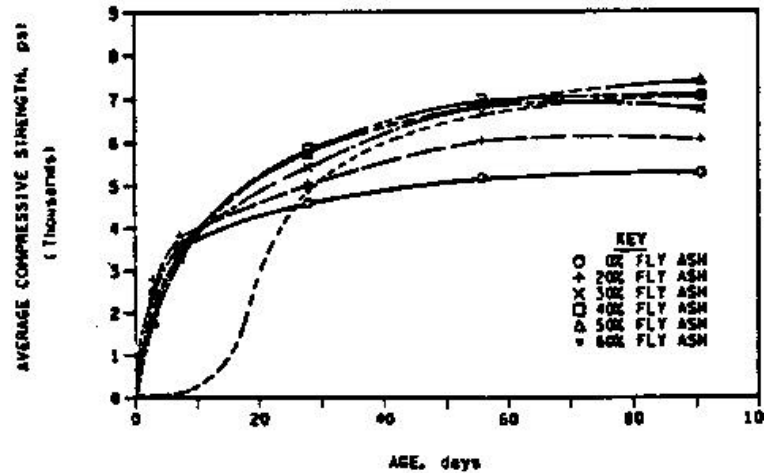
**Table 3 — Concrete mix and test data — 4000 psi (28 MPa) specified strength (P4 ash structural concrete)**

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, lb	517	414	364	310	259	209
Fly ash, lb	0	125	190	251	310	375
Water, lb	297	284	273	274	272	242
Sand, SSD, lb	1530	1530	1530	1530	1530	1530
¼ in. aggregates SSD, lb	1810	1810	1810	1810	1810	1810
Slump, in.	4¾	3¾	4	4¼	4	4
Air content, percent	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, lb/ft <sup>3</sup>	154.2	154.3	154.2	154.4	154.6	153.4
Date cylinders cast	8-28-84	8-28-84	8-28-84	8-28-84	8-28-84	8-28-84

Concrete supplier: Central Ready Mixed Concrete, Milwaukee, WI.



**Fig. 1—Compressive strength versus age comparison for Mixes No. P4-1 through P4-6 (3000 psi at 28 days, 0 through 60 percent fly ash)**



**Fig. 2—Compressive strength versus age comparison for Mixes No. P4-7 through P4-12 (4000 psi at 28 day 0 through 60 percent fly ash)**

### 3000 psi (21 MPa) specified strength

Mixes No. P4-1 through P4-6 were for the specified 28 day compressive strength of 3000 psi (21 MPa) (Table 4). For these mixes, the peak 3 and 7 day compressive strengths were achieved for the no-fly ash concrete (Mix No. P4-1). These test results showed further that the 3 day compressive strength was only 9 percent lower for the 20 percent fly ash replacement (Mix No. P4-2). The 3-day strengths for 30 and 40 percent fly ash replacements were also slightly lower (Mix No. P4-3 and 4). However, this is not considered to be of important consequence as strengths were still satisfactory. The actual 3-day values were 1760 and 1530 psi (12.1 and 10.5 MPa) for the specified 28-day strength of 3000 psi (21 MPa). For fly ash replacements of 50 and 60 percent (Mix No. P4-5 and 6), the 3-day strengths dropped significantly.

The 7-day test results for up to 40 percent cement replacement were very similar, although at 20, 30, and 40 percent replacements (Mix No. P4-2 through P4-4), the compressive strengths were slightly lower - by 5, 7, and 8 percent, respectively, when compared to the no-fly ash concrete (Mix No. P4-1). The 7-day strength for the 50 percent fly ash replacement concrete (Mix No. P4-5) was lower by 35 percent when compared to the no-fly ash concrete. This 7-day compressive strength - 1890 psi (13 MPa), however, can still be considered very satisfactory, because it was 63 percent of the specified 28-day strength of 3000 psi (21 MPa). The 7-day strength level for the mix with fly ash replacement of 60 percent (Mix No. P4-6) was not satisfactory at only 187 psi (1.3 MPa).

**Table 4 — 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
Date cylinder cast	Aug. 21, 1984	Aug. 21, 1984	Aug. 21, 1984	Aug. 21, 1984	Aug. 21, 1984	Aug. 21, 1984

Test age, days	Compressive strength, psi											
	Actual	Average	Actual	Average	Actual	Average	Actual	Average	Actual	Average	Actual	Average
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.

The 28-day peak strength was obtained for the 40 percent fly ash replacement concrete (Mix No. P4-4) with a strength gain 23 percent higher than the no-fly ash concrete (Mix No. P4-1). Even the 50 percent fly ash replacement concrete had a strength gain 12 percent higher than the no-fly ash concrete. The 60 percent fly ash replacement concrete strength at 28 days (Mix No. P4-6) was lower than the no-fly ash concrete (Mix No. P4-1) by 16 percent. However, the 60 percent fly ash replacement concrete still had 3400 psi (23.4 MPa) compressive strength at the age of 28 days, which is 13 percent higher than the specified strength of 3000 psi (21 MPa).

The 56-day peak strength was obtained for the 40 percent fly ash replacement concrete (Mix No. P4-4) with a strength gain 38 percent higher than the no-fly ash concrete (Mix No. P4-7). Even the 50 and 60 percent fly ash replacements provided an increase in the strength of 28 percent and 7 percent, respectively, when compared to the no-fly ash concrete (Mix No. P4-1).

The 91-day peak strength was obtained for the 40 percent fly ash replacement concrete (Mix No. P4-4) with a strength gain 30 percent higher than the no-fly ash concrete (Mix No. P4-1). Even the 50 and 60 percent replacements (Mix No. P4-5 and P4-6) provided an increase in strength of 23 and 12 percent, respectively, when compared to the no-fly ash concrete (Mix No. P4-1).

#### **4000 psi (28 MPa) specified strength**

Mixes No. P4-7 through P4-12 were designed to reach the specified 28-day compressive strength of 4000 psi (28 MPa) (Table 5). For these mixes, the peak 3-day compressive strength was achieved for the 20 percent fly ash concrete (Mix No. P4-8). These test results further show that with a replacement of as high as 40 percent cement with fly ash (Mixes No. P4-9 and 10), there was no significant decrease in the 3-day strength when compared to the no-fly ash concrete (Mix No. P4-7). However, for the 30 percent replacement of cement (Mix No. P4-11), there was a 30 percent decrease in the 3-day strength when compared to the no-fly ash concrete. This is a well-known problem with high-fly ash content concrete;<sup>1,3,5,6,13,16</sup> i.e., the early age strength is lower for the fly ash concrete when compared to the no-fly ash concrete. However, it is important to note that with up to a 40 percent replacement of cement with fly ash, the 3-day strength was not significantly lower than that for the no-fly ash concrete. There was a very significant change in the rate of strength gain for the 60 percent fly ash (Mix No. P4-12). The 3-day compressive strength for this mix was minimal because the concrete specimens were still soft ("green concrete") at the time of the test.

The 7-day peak strength was also achieved for the 20 percent replacement concrete (Mix No. P4-8). The 7-day test results show a clear improvement over the 3-day results. This data show that for up to 50 percent replacement of cement (Mix No. P4-8 through P4-11), there is no significant decrease in strength with increase in fly ash when compared to the no-fly ash concrete (Mix No. P4-7). Once again, similar to the 3-day results, there was a significant change in the rate of strength gain for the 60 percent fly ash concrete (Mix

**Table 5 — 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
Date cylinder cast	Aug. 28, 1984	Aug. 28, 1984	Aug. 28, 1984	Aug. 28, 1984	Aug. 28, 1984	Aug. 28, 1984

Test age, days	Compressive strength, psi											
	Actual	Average	Actual	Average	Actual	Average	Actual	Average	Actual	Average	Actual	Average
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	2589		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.

No. P4-12). The 7-day compressive strength for this mix was minimal because the concrete specimens were still soft ("green concrete") at the time of the test.

The 28-day peak strength was achieved for the 40 percent replacement concrete (Mix No. P4-10) with a strength gain 27 percent higher than the no-fly ash concrete (Mix No. P4-7). Even 50 and 60 percent fly ash replacements provided an increase in strength of 25 and 5 percent, respectively, when compared to the no-fly ash concrete (Mix No. P4-7).

The 56-day peak strength was also achieved for the 40 percent replacement concrete (Mix No. P4-10) with a strength gain 34 percent higher than the no-fly ash concrete (Mix No. P4-7). Similar to the 28-day strength, even the 50 and 60 percent replacements provided an increase in the strength of 32 and 29 percent, respectively, when compared to the no-fly ash concrete (Mix No. P4-7).

The 91-day peak strength was achieved for the 50 percent replacement concrete (Mix No. P4-11) with a strength gain 41 percent higher than the no-fly ash concrete (Mix No. P4-7). Even the 60 percent replacement provided an increase in strength of 34 percent when compared to the no-fly ash concrete mix.

## PROJECT EXPERIENCE WITH HIGH CEMENT REPLACEMENT CLASS C FLY ASH CONCRETE

The use of very high fly ash content concrete by Wisconsin Electric has been limited to two projects as of the spring of 1986. Both projects provided an excellent opportunity to evaluate the practical use of this material.

The first project was constructed in September of 1984 and involved paving 1400 ft (430 in) of a truck access road [24 ft. (7.3 in) wide]. Over 1000 yd<sup>3</sup> (765 m<sup>3</sup>) of high fly ash content concrete were used to pave the 10 in. (254 mm) thick roadway. Class C fly ash replaced 70 percent of the portland cement specified for the project. The mix design utilized was:

Cement, Type I	169 lb (77 kg)
Class C fly ash	395 lb (179 kg)
Fine aggregate	1489 lb (675 kg)
Coarse aggregate	1829 lb (330 kg)

An air-entraining agent was introduced at the rate of 2 oz (59 cm<sup>3</sup>) per hundred weight of cementitious material and produced an air content in the range of 5 to 6 percent for all the concrete of this project. A water-reducing agent was also added at a rate of 11/2 oz (44 cm<sup>3</sup>) per hundred weight of cementitious material to improve workability. The cost of concrete for the project was \$29.75 per yd<sup>3</sup> (\$39.00 per m<sup>3</sup>).

The contractor's opinion of the high-fly ash content concrete was that it was slightly more difficult to handle and place than regular portland cement concrete but the difference was not significant enough to complain about or stop utilization of it again. The approximate in-place cost of the pavement was \$75.00 per yd<sup>3</sup> (\$98.00 per m<sup>3</sup>), including setting of forms, providing concrete and reinforcing steel, finishing, saw cutting joints, and applying the curing compound.

Two problems were encountered with the completed roadway. The rate of gain in compressive strength was slower than anticipated. Seven, twenty-eight, and fifty-six-day strengths averaged 1150, 2200, and 3500 psi (7.9, 15.2, and 24.1 MPa), respectively. This resulted in keeping the road closed to traffic longer than anticipated. The second problem observed was that a crack appeared in each 20 ft (6.1 in) section between saw-cut joints. This indicated that more shrinkage had occurred than anticipated, and saw cuts at 10-ft (3-m) intervals would remedy the problem in the future. The condition of the surface was excellent, as no defects were observed. The truck access road is serving the plant as intended, and the use of high-fly ash concrete is being considered for additional paving projects.

The second project was constructed in November of 1984 and involved placing over 50 yd<sup>3</sup> (38 m<sup>3</sup>) of concrete for each of three 138,000-volt transformer foundations. The foundations were 16 x 18 x 5 ft deep (4.9 x 5.5 x 1.5 m). No problems were reported

during or following their construction. The paving mix described for the first project was specified without the water reducer. Seven, twenty-eight, and eighty-four-day strengths averaged 2100, 4100, and 5500 psi, (14.5, 28.3, and 37.9 MPa), respectively.

## SUMMARY AND CONCLUSIONS

In summary, test results for concrete mixes containing lower amounts of fly ash, in general, followed well-known patterns. The results for high-fly ash concrete mixes were also very encouraging. For example, the 60 percent replacement concretes (Mixes No. P4-6 and P4-12) were very weak at the early age up to 7 days, but at the 28-day age and beyond it was better than the specified strength; and Mix No. P4-12 was even better than the no-fly ash concrete (Mix No. P4-7). However, this high a replacement of cement with fly ash generally will not be made for structural grade concrete for flexural members, such as slabs where rapid form stripping is required, and, therefore, lower early strength will not be a problem.

The test data clearly established that this source of fly ash can be used for structural grade concrete in quantities of up to at least 40 percent replacement of cement. The 7-day results for 50 percent replacement were also quite acceptable. Even with very low cement content, 259 lb/yd<sup>3</sup> (154 kg/m<sup>3</sup>) of concrete, the 28-day strength was 5750 psi (39.6 MPa), and 56-day and 91-day strengths were 6825 and 7390 psi (47.1 and 51.0 MPa), respectively. On the other hand, if early age strength is not an important consideration, then even higher amounts of fly ash such as 60 percent replacement, and lower cement content like 207 lb/yd<sup>3</sup> (123 kg/m<sup>3</sup>) of concrete can be used for high-strength concrete - 4860, 6695, and 7060 psi (33.5, 46.2, and 48.7 MPa) at 28, 56, and 91-day ages, respectively.

The average compressive strength for the two reported construction projects using very high fly ash concrete varied greater than expected. The cause is undetermined because only compressive strength cylinder tests were performed. Even with these variations, the potential usefulness of high Class C fly ash content concrete mixes has been demonstrated.

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