Center for By-Products Utilization

MECHANICAL AND DURABILITY PROPERTIES OF CONCRETE MADE WITH BLENDED FLY ASH

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Synopsis: This study focused on evaluating the effects of blended fly ash on mechanical properties and durability of concrete. In this investigation two reference mixtures were used. One was a mixture without fly ash, and the other contained 35% ASTM Class C fly ash. Additional mixtures were composed of three blends of ASTM Class C and Class F fly ash while maintaining a total fly ash content of 40% of the total cementitious materials. Mechanical properties such as compressive strength, tensile strength, flexural strength, and modulus of elasticity were determined. Durability related properties determined were: drying shrinkage, abrasion resistance, salt scaling resistance, and electrical prediction of chloride ion penetration. The results showed that blending of Class C fly ash with Class F fly ash showed either comparable or better results than either the reference mixture without fly ash or the unblended Class C fly ash. Blending of fly ash, therefore, leads to comparable or better quality and reduced cost, due to the use of Class F versus Class C fly ash in concrete.

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INTRODUCTION

Concrete strength and durability-related properties are heavily dependent upon its microstructure. The microstructure of concrete is dependent upon a number of parameters such as type, amount, and structure of constituent materials; curing environment; etc.(1-3). Constituent materials for concrete include fine as well as coarse aggregates, and hydrated cement paste (HCP) as a binder resulting from hydration or pozzolanic reaction of cementitious materials with water. The structure of concrete is greatly influenced by the rate of hydration or reaction, type of hydration or reaction products formed, and their distribution in the HCP. It is well established that rate of hydration or reaction and the resulting hydration or reaction products can be substantially modified by use of chemical admixtures (1,2).

In high cement content concrete mixtures, the rate of hydration reaction may be high enough to cause plastic shrinkage cracks are due to drying - i.e. poor curing and non-homogeneity in the microstructure of concrete. The accelerated hydration for such concretes results from evolution of heat of hydration in the mixtures. This results in creation of long and thin cementing crystals during the hydration process. These crystals occupy less space relative to those formed during normal hydration process. Consequently, concrete strength and durability-related properties are adversely affected. With a view to eliminate such effects in rich mixtures, low-heat cement as well as mineral and chemical admixtures are used (1,2). Fly ash is added to concrete to control rate of hydration reaction and to improve its microstructure. The improvement in microstructure occurs due to grain as well as pore refinements, especially in the interface region between the aggregates and HCP(2). The rate of chemical reactions is lower when portland cement is replaced with a Class F fly ash. Use of a Class C fly ash generally results in a rate of reaction similar (through lower heat of hydration) to that of plain portland cement concrete. Therefore, a hypothesis that a blend of Class C and Class F ashes should produce the rate of hydration reaction in between the one with Class F fly ash mixture and the plain portland cement mixture with a favorable microstructure compared to plain portland cement mixture. Keeping this in perspective, it was postulated that a blend of Class F and Class C fly ashes will result in improved concrete microstructure because of favorable rate of hydration reaction as well as other benefits that are derived when fly ash is incorporated in concrete. The improved microstructure is expected to cause improvement in mechanical and durability-related properties of concrete. This research was undertaken primarily to verify this hypothesis through experimental investigation.

MATERIALS

Cement

A cement meeting ASTM C 150 requirements for Type I was used in this work. The chemical and physical properties of the cement used are given in Table 1.

Fly Ash

Two fly ashes, a Class C and a Class F, were used for preparing blended ash products. Both fly ashes conformed to the ASTM C 618 requirements (Table 2). Three different blends of these fly ashes were prepared and used in this investigation.

Aggregate

The coarse aggregate was crushed limestone, nominal maximum size 19 mm. The fine aggregate was natural sand (6.3 mm max. size). Both the aggregates met the requirements of ASTM C 33 (Table 3 and 4).

Admixture

A commercially available melamine-based high-range water-reducing admixture (HRWRA) and a synthetic-resin air-entraining agent were used in all mixtures.

MIXTURE PROPORTIONS

In this work, two reference mixtures designated as C1 and C2 were proportioned for a 28-day design strength of 35 MPa (Table 5). Mix C1 contained no fly ash and Mix C2 contained 35% Class C fly ash of the total cementitious materials. The blended fly ash mixtures, designated as B1, B2, and B3, were prepared using variable amounts of Class C and F fly ashes. The proportions of the fly ash blends used were 75% Class C : 25% Class F for Mix B1, 50% Class C : 50% Class F for Mix B2, and 25% Class C : 75% Class F for Mix B3. In all blended ash mixtures, a total fly ash content of 40% of total cementitious materials was used. The water to cementitious materials ratio was kept at 0.30 ± 0.02 for all the mixtures. The amount of HRWRA was varied to obtain desired level of workability (190 ± 25 mm). Air content was kept at 5.5 ± 0.3% for all the mixtures by adjusting the dosage of the air-entraining admixture. Each mixture was mixed in accordance with ASTM C 192 using a batch size of 0.15 m^3. Soon after mixing, fresh concrete properties such as slump, unit weight, temperature, and air content were measured for each mixture using applicable ASTM standards, Table 5.

PREPARATION AND CASTING OF TEST SPECIMENS

Cylinders (150 x 300 mm) were cast for compressive strength, splitting tensile strength, and modulus of elasticity for all the test mixtures. Prism specimens (75 x 100 x 300 mm) were cast for flexural strength determinations. Prism specimens (75 x 100 x 400 mm) were cast for drying shrinkage measurements. Slab specimens (100 x 300 x 300 mm) were made for abrasion resistance and salt scaling resistance evaluations. All the specimens were prepared in accordance with ASTM C 192. After casting, test specimens were covered with plastic sheets, and left in the casting room for 24 hours at a temperature of about 23°C. They were then demolded and put into a 100% RH moist curing room at about 23°C until the time of test.

TESTING OF SPECIMENS

The compressive strength was determined in accordance with ASTM C 39. The tensile strength was measured according to ASTM C 469. The flexural strength was measured in accordance with ASTM C 78. The drying shrinkage was measured according to the ASTM C 157. A modified ASTM C 944 test method, appropriate for high-strength concrete, was used for measurement of abrasion resistance of concrete. In this method a rotating cutter was equipped with a washer having a smaller diameter relative to the dressing wheels. An equal amount of silica sand (Ottawa Sand) was added to the concrete surface during exposure to abrasion at one minute intervals. One level teaspoon of sand was added at each intervals. At each wear location (circle of wear), for each wear time, depth of wear readings were taken at two points. At each of these points, three readings were recorded. The average of these six readings were recorded as one reading for each experimental condition. The salt scaling resistance was measured according to ASTM C 672. Potential Chloride penetration was measured in accordance with ASTM C 1202.

TEST RESULTS AND DISCUSSIONS

Compressive Strength

The compressive strength data are shown in Table 6 and in Fig. 1. At one-day age, blend B1 (75% Class C and 25% Class F) concrete exhibited the highest value of the mixtures tested. One reference mixture without fly ash (Mix C1) showed better results than the other reference mixture (Mix C2) with unblended Class C 35% fly ash. The blend B3 (25% Class C and 75% Class F) concrete attained the lowest value of compressive strength. The worst performance of this mixture (Mix B3) was due to its high Class F content which did not contribute adequately to the one-day strength because of its relatively low reactivity. At the age of 7 days, a dramatic improvement in the performance of the fly ash mixtures was noticed. All the fly ash concrete mixtures, except Mix B3, outperformed significantly compared to the reference mixture without fly ash. The highest compressive strength (46.4 MPa) at the 7-day age was observed for blended fly ash (Mix B1) concrete. Even Mix B3 was equivalent to no-fly ash Mix C1 (27.3 vs. 28.4 MPa) at the 7-day age.

At 28 days, the test results exhibited continued excellent compressive strength values for all fly ash mixtures compared to the no-fly ash Mix C1. The observed compressive strength values at 28 days were 34, 47, 59, 51, and 39 MPa for Mix C1, C2, B1, B2, and B3, respectively. The test data at 91 days exhibited the same trend as that recorded at 28 days (Fig. 1); i.e., all fly ash concrete mixtures outperformed the no-fly ash Mix C1. The improvement that occurs in properties of concrete due to pozzolanic contributions is well established. The grain and pore refinements that occur due to inclusion of blending fly ash are not yet fully understood. It is postulated that structure of concrete is improved by modifying the rate of hydration reaction up to a certain level of cement or Class C fly ash replacement with Class F fly ash. In this work, however, beyond 50% of the Class C fly ash replacement with the Class F fly ash, a decrease in compressive strength was observed at the early age of one day. The best results obtained for the blend had 25 percent Class C fly ash replacement with Class F fly ash. At the age of 7-day and beyond, the blended ash mixtures outperformed the no-fly ash and Class C fly ash only concretes.

Tensile Strength

The tensile strength test results, as a function of age, are depicted in Table 6 and Fig. 2. At the one-day age, the reference mixture without fly ash (Mix C1) exhibited the best results amongst all the mixtures tested. This may be attributed to the fact that at this age both types of fly ash did not contribute to pozzolanic reaction for forming pozzolanic C-S-H. In fact, the ash particles present in the mixtures may have behaved like flaws or notches at this very early age due to a poor bond between the matrix and the fly ash particles. This, in turn, can affect the splitting tensile strength more adversely than it can compressive strength. A similar trend was observed at the age of 7 days, though difference between the no-fly ash concrete mixture (Mix C1) and all other fly ash mixtures (Mix C2, B1, B2, and B3) were significantly smaller than that at the one day age.

At 28 days, the same general trend, as that at the 7-day age, was noticed. But differences between the reference mixture without fly ash (Mix C1) and the fly ash mixtures decreased to a much greater extent. This was attributed to substantial increase in formation of pozzolanic C-S-H at this later age of 28 days.

A dramatic improvement in performance of the fly ash mixtures occurred at the age of 91 days. This is believed to be due to large pozzolanic contributions of the fly ash mixtures. All the fly ash mixtures except Mix B3 exhibited tensile strength values equivalent to that of the no-fly ash reference mixture (Mix C1).

Flexural Strength

The flexural strength data are presented in Table 7 and Fig. 3. At the 7-day age, the blended ash concrete mixtures (Mix B1 and B2) performed better than the reference concrete mixture (Mix C2) with Class C fly ash only. At 28 days, all the concrete mixtures containing the blended ash mixtures and the unblended Class C fly ash (Mix C2) produced higher flexural strengths than the control mixture without fly ash (Mix C1). Blended fly ash mixture (Mix B2) showed the best result followed by blended fly ash mixture (Mix B1) and unblended fly ash mixture (Mix C2). At the age of 91 days, the results followed a similar trend as that observed at 28 days. Blended mixture (Mix B2) exhibited the highest flexural strength value, and the result was comparable to that obtained for blended fly ash mixture Mix B1. The unblended mixture (Mix C2) and blended Mix B3 were equivalent. All fly ash mixtures were superior to the no-fly ash mixture (Mix C1).

Modulus of Elasticity

The modulus of elasticity test data are shown in Table 7 and Fig. 4. At the age of one day, the control mixture without fly ash (Mix C1) showed the best result. The difference between the fly ash mixtures and the mixture without fly ash decreased to a significant extent with increasing age at 7 days and beyond. This is due to the increased contributions of fly ash in the formation of cementing material in the mixtures incorporating fly ash. At the 7-day age, the performance of the control mixture was equivalent to that shown by blended fly ash mixture Mix B1. Other mixtures showed slightly lower modulus values compare to the control mixture without fly ash (Mix C1). At 28 days, the blended ash mixtures (Mix B1 and B2) had equivalent values as the no-fly ash mixture (Mix C1) but better than the fly ash only mixture (Mix C2). At 91 days, the best result was observed for Mix B1. At this age, essentially, all mixtures exhibited equivalent results.

Drying Shrinkage

The drying shrinkage data on the blended fly ash mixtures (Mix B1, B2 and B3) are shown in Table 8. The drying shrinkage strains of the blended ash mixtures varied between 417 $\times 10^{-6}$ to 1487 $\times 10^{-6}$ after 224 days of drying. The performance of blends Mix B1 and B2 was equivalent. The worst performance was observed for blend Mix B3.

Abrasion Resistance

Abrasion resistance data for all concrete mixtures are given in Table 9 and 10. All mixtures with or without fly ash exhibited excellent (and equivalent) abrasion resistance at the 28-day age, Table 9. However, the fly ash alone mixtures (Mix C2) showed a lower resistance compared to all other mixtures, including the non-fly ash mixture (Mix C1). At 91 days, the blended ash mixtures, especially Mix B2 and B3, showed better results than either unblended fly ash mixture (Mix C2) or the non-fly ash mixture (Mix C1). Blend Mix B1 showed equivalent resistance to abrasion as the no-fly ash concrete (Mix C1) and the Class C only fly ash concrete (Mix C2).

Salt Scaling Resistance

The deicing salt scaling data are presented in Table 11. The 35% Class C alone mixture (Mix C2) had excellent performance (no scaling). Mix C2 performed the best, even better than Mix C1 without fly ash. Blends Mix B1 and B2 showed results comparable to the reference mixture without fly ash (Mix C1). Their scaling resistance was rated slight to moderate scaling, according to ASTM C 672. Blend Mix B3 showed the worst result among all the mixtures tested. However, its salt scaling resistance may be acceptable for roadways.

Resistance to Chloride Penetration

All the fly ash mixtures exhibited equivalent or better results than the non-fly ash concrete (Mix C1) at the 28-day age (Table 12). At 91 days and beyond, blends Mix B1 and B2 showed excellent performance. Their resistance to chloride ion penetration was equivalent to that observed for comparable silica fume concrete. The no-fly ash concrete (Mix C1) and Class C fly ash only (Mix C2) performed equivalently and the blended mixtures (Mix B1, B2, and B3) performed the best at the 91-day and 365-day ages.

CONCLUSIONS

1. The effect of blending of Class C and Class F was significant on mechanical and durability-related properties of concrete mixtures tested. In general, up to 50 percent replacement of the Class C fly ash with a Class F showed favorable strength and durability-related properties.

2. The highest compressive strength was observed for blended fly ash Mix B1 at all ages, followed by blended fly ash Mix B2 at the ages of 7 days and up to 91 days.

3. At ages up to 28 days, the no-fly concrete showed better tensile strength test results than the mixtures containing either blended fly ash mixtures or unblended ash. All the fly ash mixtures, except blended ash Mix B3, exhibited tensile strength equivalent to that shown by the reference mixture without fly ash at the age of 91 days.

4. The concretes incorporating either unblended ash or blended ash mixture showed higher flexural strength than the non-fly ash reference mixture beyond the age of 7 days.

5. The no-fly ash mixture attained higher modulus compared to the fly ash mixtures up to 28 days. At the age of 91 days, blended fly ash Mix B1 showed the best result, but all the other mixtures attained equivalent results.

6. The drying shrinkage strains of concrete having blended ash B1 and B2 were essentially the same. However, blend B3 showed the worst results amongst the three blends tested.

7. All the concretes with or without fly ash exhibited excellent resistance to abrasion at the 28-day and 91-day ages. At the 28-day age, the depth of abrasion was slightly higher for the fly ash concretes than the non-fly ash mixture. At 91 days, blends B2 and B3 showed excellent resistance to abrasion compared to the reference mixtures (Mix C1 and C2) and blend B1.

8. The salt scaling resistance of the blended ash concretes was equivalent to the non-fly ash reference concrete (Mix C1) up to 50% Class C fly ash replacement with Class F fly ash replacement. The 35% Class C fly ash concrete (Mix C2) had better performance than all mixtures including the no-fly ash concrete (Mix C1).

9. The blended ash mixtures showed significantly better resistance to chloride ion penetration than the no-fly ash reference concrete (Mix C1).

10. Overall the results show that for obtaining equivalent or better strength properties and durability of concrete, up to 50% Class C fly ash can be substituted by Class F fly ash in blended ash concretes.

LIST OF REFERENCES

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Table 1: Chemical and Physical Properties of Cement

Results of Chemical Analysis	Cement, %	Requirements ASTM C 150 Type I, %
Silicon Dioxide, SiO_2	21.1	-
Aluminum Oxide, Al_2O_3	3.9	-
Ferric Oxide, Fe_2O_3	2.9	-
Sulfur Trioxide, SO_3	3.7	3.0 max.
Calcium Oxide, CaO	64.7	-
Magnesium Oxide, MgO	2.0	6.0 max.
Titanium Dioxide, TiO_2	0.0	-
Potassium Oxide, K_2O	0.6	-
Sodium Oxide, Na_2O	1.2	-
Loss on Ignition	1.0	3.0 max.
Physical Tests		
Air Content (%)	8.0	12 max.
Fineness (m^2/kg)	385	280 max.
Autoclave Expansion (%)	-0.02	0.8 max.
Specific Gravity	3.11	-
Compressive Strength, MPa		
1-day	9.6	-
3-day	23.8	12.6 min
7-day	30.7	19.3 min
28-day	36.6	-
Vicat Time of Initial Set (min)	230	45 min. 3-5 max.

Table 2: Chemical and Physical Properties of Fly Ash

Results of Chemical Analysis	Class C Fly Ash, %	Class F Fly Ash, %	Requirements ASTM C 618, %	
			Class C	Class F
Silicon Dioxide, SiO_2	34.2	48.4	-	-
Aluminum Oxide, Al_2O_3	19.3	27.0	-	-
Ferric Oxide, Fe_2O_3	5.8	6.6	-	-
Total, SiO_2 + Al_2O_3 + Fe_2O_3	59.4	82.0	50.0 min.	70.0 min.
Sulfur Trioxide, SO_3	3.1	0.6	5.0 max.	5.0 max.
Calcium Oxide, CaO	29.2	8.5	-	-
Magnesium Oxide, MgO	5.0	2.0	5.0 max.	5.0 max.
Titanium Dioxide, TiO_2	1.5	1.3	-	-
Potassium Oxide, Ka_2O	0.5	1.0	-	-
Sodium Oxide, Na_2O	0.8	0.5	1.5 max.	1.5 max.
Moisture Content	0.1	0.2	3.0 max.	3.0 max.
Loss on Ignition	0.5	2.8	6.0 max.	6.0 max.

Physical Properties				
Fineness Retained on No. 325 Sieve (%)		24.4	34 max.	34 max.
Strength Activity Index with Lime, 7-days, psi	1805	-	800 min.	-
Strength Activity Index with Cement, 28-days (% of control)	107.0	81.8	75 min.	75 min.
Water Requirement (% of control)	96.0	104.2	105 max.	105 max.
Autoclave Expansion(%)	+0.02		±0.8 max.	±0.8 max.
Specific Gravity	2.59	2.24	-	-

Table 3: Grading of Aggregates

Fine aggregates			Coarse aggregates		
Sieve Number	% Passing	Requirements ASTM C 33 % Passing	Sieve Size	% Passing	Requirements ASTM C 33 % Passing
4 (4.75 mm)	100	95-100	25 mm (1")	100	100
8 (2.36 mm)	87	80-100	19 mm (3/4")	83	90-100
16 (1.18 mm)	73	50-85	12.5 mm (1/2")	38	-
30 (600 ìm)	54	25-60	9.5 mm (3/8")	10	20-55
50 (300 ìm)	11	10-30	(4.75 mm) #4	1	0-10
100 (150 ìm)	5	2-10	(2.36 mm) #8	0	0-5

Table 4: Physical Properties of Aggregates

Aggregates	Bulk Specific Gravity	Bulk Specific Gravity (SSD)	Apparent Specific Gravity	SSD Absorption (%)	Dry Rodded Unit Weight (kg/m^3)	Voids (%)
Fine	2.66	2.70	2.76	1.4	1762	34
Coarse	2.62	2.63	2.65	0.5	1506	43

Table 5: Mixture Proportions and Fresh Concrete Test Results

Mixture No.	C1	C2	B1	B2	B3
Cement (kg/m^3)	356	259	227	227	225
Blended Ash (kg/m^3)	0	0	154	153	150
Class C Fly Ash (kg/m^3)	0	139	0	0	0
Water (kg/m^3)	107	133	119	120	107
[W/(C + FA)]	0.30	0.34	0.31	0.32	0.29
Sand SSD (kg/m^3)	836	677	827	830	810
19-mm Aggregates, SSD (kg/m^3)	1044	1172	1032	1035	1020
HRWRA (L/m^3)	5.4	2.8	3.6	3.7	4.3
Air Entraining Admixture (ml/m^3)	460	350	385	425	500
Slump (mm)	165	160	185	210	215
Air Content (%)	5.8	5.2	5.7	5.2	5.7
Air Temperature (°C)	23	21	21	21	27
Concrete Temperature (°C)	25	23	23	22	26
Fresh Concrete Density (kg/m^3)	2345	2380	2360	2360	2320
Hardened Concrete Density, SSD (kg/m^3)	2440	2470	2395	2385	2365

1 kg/m^3 = 1.685 lb/yd^3; 1 mm = 0.0394 in.; 1 L/m^3 = 25.9 fl. oz/yd^3;
1 ml/m^3 = 0.026 fl. oz/yd^3; $t_C = (t_F - 32)/1.8$;

Table 6: Compressive and Tensile Strength Test Results

Mixture No.	Fly ash,* %	Compressive Strength, MPa					Tensile Strength, MPa				
		1-day	7-day	28-day	91-day	365-day	1-day	7-day	28-day	91-day	365-day
C1	0	18.3	28.4	33.7	33.8	----	3.3	3.9	4.4	4.6	------
C2	35	12.3	36.5	47.4	55.7	70.6	1.3	3.0	3.9	4.8	5.3
B1	40	19.4	46.4	58.9	69.4	76.1	1.5	2.9	3.8	4.5	4.0
B2	40	15.3	38.1	51.2	61.1	63.8	1.7	3.3	3.4	4.7	5.1
B3	40	9.5	27.3	38.9	45.3	52.0	0.5	2.5	3.1	3.4	3.9

* Fly ash as a percentage of total cementitious materials, FA/(cement + FA)

Table 7: Flexural Strength and Modulus of Elasticity Test Results

Mixture No.	Fly ash,* %	Flexural Strength, MPa			Modulus of Elasticity, GPa				
		7-day	28-day	91-day	1-day	7-day	28-day	91-day	365-day
C1	0	-	4.4	4.6	24.5	29.1	30.3	31.7	-
C2	35	4.3	4.8	5.6	13.4	22.8	25.4	34.1	46.2
B1	40	4.6	4.8	6.3	11.8	27.8	29.3	34.8	34.5
B2	40	5.1	6.3	6.4	13.9	24.6	29.8	29.3	33.1
B3	40	3.4	4.7	5.2	7.9	17.0	21.4	29.0	29.6

* Fly ash as a percentage of total cementitious materials, FA/(cement + FA)

Table 8: Drying Shrinkage Test Data

Mixture No.	Fly* ash, %	Drying Shrinkage Strain x 10^{-6}													
		4-day		7-day		14-day		28-day		56-day		112-day		224-day	
		Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.
B1	40	-	-	-		414	362	472	408	543	426	650	574	557	417
		-	-	-		364		*		350		614		286	
		-		-		307		343		386		457		407	
B2	40	-	221	171	186	307	286	364	321	471	445	421	454	386	497
		-		257		357		379		478		428		571	
		-		129		193		221		385		514		535	
B3	40	300		*	290	400	371	-	-	428	516	1478	1383	1162	1487
		86		279		314		-		557		1557		1992	
		279		300		400		-		564		1114		1307	

* Fly ash as a percentage of total cementitious materials.

Table 9 : Abrasion Resistance Test Results at the 28-Day Age

Mixture No.	C1	C2	B1	B2	B3
Fly ash,* %	0	35	40	40	40
Time (min.)	Average Depth of Wear, mm				
5	0.04	0.14	0.18	0.16	0.12
10	0.09	0.34	0.37	0.41	0.27
15	0.12	0.50	0.61	0.57	0.38
20	0.23	0.66	0.70	0.65	0.55
25	0.25	0.85	0.84	0.75	0.66
30	0.28	1.02	1.02	0.84	0.79
35	0.44	1.18	1.17	1.02	0.89
40	0.64	1.33	1.28	1.12	1.06
45	-	1.50	1.38	1.19	1.30
50	-	1.74	1.53	1.31	1.44
55	1.20	1.88	1.67	1.37	1.49
60	1.22	2.05	1.74	1.41	1.61

* Fly ash as a percentage of total cementitious materials, FA/(cement + FA)

Table 10: Abrasion Resistance Test Results at the 91-Day Age

Mixture No.	C1	C2	B1	B2	B3
Fly ash,* %	0	35	40	40	40
Time (min.)	Average Depth of Wear, mm				
5	0.14	0.05	0.17	0.032	0.12
10	0.21	0.17	0.35	0.09	0.20
15	0.35	0.35	0.55	0.26	0.33
20	0.52	0.53	0.76	0.39	0.50
25	0.65	0.76	0.95	0.47	0.58
30	1.00	0.90	1.09	0.53	0.71
35	1.05	1.04	1.25	0.66	0.81
40	1.15	1.18	1.39	0.83	0.94
45	1.27	1.31	1.52	0.94	1.00
50	1.47	1.48	1.59	1.02	1.03
55	1.51	1.64	1.64	1.08	1.06
60	1.57	1.70	1.69	1.12	1.08

* Fly ash as a percentage of total cementitious materials, FA/(cement + FA)

Table 11: Deicing Salt Scaling Test Results

Mixture No.	Fly Ash,* %	Specimen No.	Visual Rating**, Cycles									
			5	10	15	20	25	30	35	40	45	50
C1	0	1	0	0	1	1	1	1	1	1	2	2
		2	0	0	0	0	0	0	1	1	1	1
		3	0	0	0	0	0	0	0	1	1	1
C2	35	1	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0
B1	40	1	0	0	0	1	1	1	2	2	2	2
		2	0	0	0	0	0	0	0	1	1	1
		3	0	0	0	0	0	0	0	0	0	0
B2	40	1	0	1	1	1	1	1	1	2	2	2
		2	0	0	0	0	0	0	0	1	1	1
		3	0	0	1	1	1	1	1	1	1	1
B3	40	1	2	2	3	3	3	3	3	3	3	3
		2	2	2	3	3	3	3	3	3	3	3
		3	2	2	3	3	3	3	3	3	3	3

* Fly ash as a percentage of total cementitious materials, FA/(cement + FA)

<u>**Rating Condition of Surface</u>

0 No scaling
1 very slight scaling (1/8 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)

** Per ASTM C 672.

Table 12: Electrical Prediction of Chloride Penetration Test Results

Mixture No.	Fly ash,* %	Specimens No.	Charge, Coulombs					
			28-day		91-day		365-day	
			Act.	Ave.	Act.	Ave.	Act.	Ave.
C1	0	1 2 3	1734 3995 3725	3150	1705 1740 1725	1725	-	-
C2	35	1 2 3	2120 2400 1710	2075	1540 1515 1640	1565	611 604 601	605
B1	40	1 2 3	1719 1890 1776	1795	532 614 599	580	216 214 212	214
B2	40	1 2 3	1377 1339 1267	1330	622 598 590	600	209 249 223	225
B3	40	1 2 3	2790 3132 2990	2970	1207 1362 1262	1275	228 353 513	365

* Fly ash as percentage of total cementitious materials, FA/(C + FA)

Charge passed, Chloride Permeability,
Coulombs**
>4000 High
2000-4000 Moderate
1000-2000 Low
100-1000 Very Low
<100 Negligible

** Per ASTM C 1202

Keywords: Blended Fly Ash, Compressive Strength, Flexural Strength, Tensile Strength, Modulus of Elasticity, Durability, Salt Scaling Resistance, Abrasion Resistance, Chloride Ion Penetration, Shrinkage.

Rep-268B