PERMEABILITY OF HIGH-STRENGTH CONCRETE CONTAINING LOW CEMENT FACTOR

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Abstract: Coal burning power plants generate about 80 million tons of combustion by-products per year in the United States. Each ton of by-products used in lieu of portland cement in concrete saves about 6.5 million BTU of energy, and prevents one ton of CO_2 released in the air due to avoided cement manufacture. This specific project was directed toward studying the influence of ASTM Class C fly ash on concrete permeability. A plain portland cement concrete mixture was proportioned to have a 28-day compressive strength of 40 MPa. Concrete mixtures were also proportioned to have cement replacement with Class C fly ash in the range of 0-70% by weight. Each concrete mixture was tested for compressive strength, air permeability, water permeability, and chloride ion permeability. Air and water permeabilities were evaluated by using the Figg method. Chloride ion permeability was measured in accordance with ASTM C 1202. Air permeability of plain portland cement concrete was lower than that for concrete containing fly ash at the age of 14 and 28 days. At the age of 91 days, the 55% fly ash mixture exhibited the highest resistance to air permeability. All the concrete mixtures showed "fair" resistance to water permeability at ages up to about 40 days. The maximum resistance to water permeability was observed for the 35% fly ash mixture at ages of 28 and 91 days. At the two-month age, chloride ion permeability of all mixtures except the 74% fly ash mixture were rated as "moderate" to "very low" in accordance with ASTM C 1202 criteria. When duration of curing was increased to three months, the fly ash concrete mixtures with FA to cementitious materials in the range of 18 - 55% showed lower chloride ion permeability than the concrete without fly ash. The same trend was observed at the age of one year.

INTRODUCTION

Portland cement is the primary ingredient of concrete. Cement manufacturing consumes large amounts of energy: about 6.5 million BTU per ton of cement. Therefore, a reduction in the amount of cement used will provide substantial energy savings in production of concrete and other cement-based materials. At the present time, nearly 80 million tons per year of coal combustion by-products are generated in the United States of which about 60 million tons/year are landfilled. This results in high disposal costs to the producer and in deterioration of the environment. Therefore, the use of these by-products in construction material, especially as a cement replacement, will minimize these problems, and will provide energy savings in production of cement-based materials. Each ton of cement manufactured also produces one ton of CO_2 gas. This investigation was undertaken for determining the maximum level of fly ash that can be used as a cement replacement for high-strength concrete without adversely affecting its properties. Efficient use of fly ash will lead to energy savings and cleaner air and improved solid waste disposal options and recycling opportunities.

Permeability is an important property with regard to the durability of concrete (Young 1988; Mehta 1986). The movement of water or other fluids through concrete generally also carries aggressive agents which create various types of durability problems for concrete construction. In fact, permeability dictates the rate at which aggressive agents such as gases (CO_2, SO_3, etc.), liquids (acid rain, sea water, sulfate rich water, salt-bearing snow/water, ground water, etc.), penetrate into the concrete. This leads to various types of chemical reactions. Corrosion damage to a reinforced concrete would occur if chloride salts penetrate the concrete cover and reach the reinforcing steel. This type of problem often occurs in highway bridge decks, parking structures, and structures in marine environment. Low permeability concrete is needed to protect such concrete structures from penetration of aggressive chemicals into concrete. Recently there has been a significant increase in interest in the measurement of the permeability of concrete because of the impact of the permeability on the durability of concrete structure (Whiting 1988).

RESEARCH SIGNIFICANCE

The major objective of this research project was to investigate the permeability of fly ash concrete systems. The data obtained in this investigation would be of use in determining the appropriate mixture proportions for ASTM Class C (high-lime) fly ash concrete for obtaining low permeability concrete. A decrease in permeability of concrete translates into an increased resistance to the ingress of aggressive agents, which in turn, would lead to improved concrete durability.

LITERATURE REVIEW

Several recent studies have been directed toward the evaluation of the effects of inclusion of fly ash on concrete permeability (Martin 1991; Naik et al. 1993). Davis (1954) indicated that ASTM Class F (low-lime) fly ash concretes at ages up to 28 days was more permeable than no-fly ash concretes. However, at 6 months, fly ash concretes became more impermeable than no-fly ash concretes. Similar trends were also reported by Kanitakis (1981).

Hansen et al. (1986) evaluated diffusion behavior of chloride ions in concrete using water-to-cementitious materials ratio varying from 0.45 to 2.50, and fly ash content varied from 0 to 400% of total cement used. Their results revealed that the fly ash activation factor with respect to chloride diffusion was almost twice as large as the activation factor with respect to compressive strength of concretes.

Rodway and Fedirko (1989) reported coefficient of permeability of a Class C fly ash concrete, having 68% cement replacement, of the order of 3.65×10^{-12} m/s at the age of 91 days. Krell (1989) evaluated oxygen permeability of concrete having 37% cement replacement with a Class F fly ash. His results showed that oxygen permeability of the fly ash concrete decreased with increasing concrete strength.

Ellis et al. (1991) reported that addition of Class F fly ash was more effective than Class C fly ash in reducing concrete chloride permeability for a fixed amount of cement content. They further reported that the chloride permeability values of Class F fly ash concrete were either comparable or superior to those achieved by using either silica fume or ground granulated blast furnace slag.

Malhotra (1989) studied the chloride ion permeability of superplasticized high-volume Class F fly ash concretes. Fly ash content was varied from 54 to 58% of the total cementitious material at a water-to-cementitious materials ratio of 0.30. In accordance with ASTM C 1202, the test results indicated "very low" to "negligible" chloride ion permeability of high-volume fly ash concretes at 91 days, ranging from 197 to 973 coulombs.

Al-Amoudi et al. (1989) indicated that 28-day permeability values for fly ash concretes were higher than no-fly ash concrete. However, fly ash concretes exhibited lower permeability than plain portland cement concrete when duration of curing was increased to 91 days.

Ozyildirim and Halstead (1988) studied the influence of inclusion of fly ash, slag, and silica fume, on the chloride ion intrusion into concretes. The results indicated that good resistance to the penetration of chloride ions can be achieved at relatively early ages by addition of slag or silica fume as a supplemental cementitious material with a low water-to-cementitious materials ratio.

Armaghani et al. (1991) determined the water and chloride permeability of concrete containing a Class F fly ash at water-to-cementitious materials ratios of 0.33, 0.38, and 0.45. Fly ash content ranged between 10 and 50% of the total weight of cement used. They reported that the water permeability at 91 days was reduced by as much as 50% in some concrete mixtures.

Bilodeau and Malhotra (1992) investigated performance characteristics of concretes having 58% cement replacement by different sources of Class F fly ash. Concrete made with a fly ash having 12% CaO showed lower permeability compared to concrete made with fly ash having lower CaO contents (2 or 3% CaO). The total charge in coulombs at the age of 91 days ranged from 278 to 1078 for fly ash concretes, while it ranged from 1003 to 2313 for concrete without fly ash.

Torri and Kawamura (1992) determined permeability of concretes with cement replacements of 3% by fly ash, 5% by blast-furnace slag, and 10% by silica fume. The authors reported extremely low chloride permeability values for the mixtures containing mineral admixtures at one year age.

Thomas and Mathews (1992) measured oxygen permeability of fly ash concretes. The concrete permeability values with 15, 30, and 50% fly ash were on average reduced by 50, 60, and 86%, respectively, compared to the no-fly ash concrete.

Bilodeau et al. (1994) determined water and chloride ion permeability of high-volume fly ash concretes using eight fly ashes obtained from different sources at a water-to-cementitious materials ratio of about 0.33. The coefficient of permeability for all air entrained concrete mixtures were low, ranging from 1.6×10^{-14} to 5.7×10^{-13} m/s. The total charge passed through concrete specimens when tested in accordance with ASTM C 1202, ranged from 494 to 2175 coulombs at 28 days and from 221 to 635 coulombs at 91 days.

Naik et al. (1992) carried out three different series of tests to determine the effects of addition of mineral admixtures on concrete chloride permeability. The first series of mixtures contained Class C and Class F fly ash to replace cement in the range of 20-50%. In the second series of mixtures Class C fly ash was added to replace cement in the range of 10-25% by weight. The third series of mixtures were made with cement replacements by a Class C fly ash (11 - 30%) and/or silica fume (8 - 11%) at a water-to-cementitious materials ratio of 0.30. According to the ASTM C 1202 criteria, their observed permeability values were "very low" for the first and third series of mixtures at one year of age. For the second series of the concrete mixtures, the permeability varied from a "low" at 28 days to "very low" at 90 days.

MATERIALS AND TEST PROCEDURES

Materials

Portland Cement: A Type I portland cement conforming to ASTM C 150 requirements was obtained from one source. This cement was used in all test mixtures. The chemical and physical properties of the cement are shown in Table 1.

Fly Ash: An ASTM Class C fly ash, which was obtained from one source was used in this study. The chemical and physical properties of the fly ash were determined according to applicable ASTM standards (Table 2).

Aggregates: A natural sand with 6 mm maximum size meeting ASTM C 33 requirements was used as a fine aggregate for this work. A coarse aggregate with 25 mm nominal maximum size of crushed limestone conforming to ASTM C 33 requirements was used. The grading and physical properties of the aggregates are given in Table 3.

Chemical Admixtures: A commercially available resin-type air entraining agent and a melamine-based superplasticizer, were used in all the mixtures.

MIXTURE PROPORTIONS

A total of eleven different concrete mixtures were proportioned using one source of Class C fly ash. The mixture proportions for this investigation are presented in Table 4. The proportions of fly ash in concrete were based upon 1.25 lbs. of fly ash for each pound of cement replaced. For this study, water-to-cementitious materials ratio (W/(C+FA)) and air content of the primary mixtures were maintained at about 0.35 ± 0.02 and 6 ± 1%, respectively. The mixtures which did not meet these target parameters, were categorized as secondary mixtures. The primary mixtures were used to derive the major conclusions of this investigation. The secondary mixtures were used to study the effects of air content on concrete strength and permeability. The mixing procedure was conducted according to ASTM C 192. Concrete batches (0.76 m^3 each) were mixed in a power-driven revolving-paddle fixed drum mixer.

CASTING AND CURING OF TEST SPECIMENS

Cylinders (150 x 300 mm) for compressive strength measurements were cast in plastic cylindrical molds. Specimens (300 x 300 x 100 mm) for air permeability and water permeability were cast using reusable wooden molds. Chloride ion permeability specimens (100 x 200 mm) were cast in cylindrical steel molds. All specimens were cast according to ASTM C 192. Air and water permeability test specimens were compacted using an internal and external vibrator. After casting, test specimens were finished with a steel trowel, and covered with plastic. All the test specimens were stored at a temperature of about 20°C for 24 hours. They were then put into a curing room maintained at about 23°C ±1.7°C temperature and 100% relative humidity until the time of test.

FRESH CONCRETE PROPERTIES

Slump, unit weight, temperature, and air content were determined according to appropriate ASTM test methods. One sample was used for measurement of each of these parameters. The results are presented in Table 4.

HARDENED CONCRETE PROPERTIES

Compressive strength tests were performed according to ASTM C 39. Air and water permeabilities of concrete were measured in accordance with the Figg Method (Figg 1973; Cather et al. 1984). The Figg test method involved drilling a hole, 40 mm deep by 10 mm diameter, from the top of the concrete surface by using a slow speed hammer drill. A disc of 11 mm diameter cut from 3 mm thick polyethylene foam sheet was then pressed into the hole so that its innermost surface was 20 mm from the top of the concrete surface. A silicon rubber caulk was then carefully placed into the hole up to the top of the concrete surface. A hypodermic needle was then inserted into the plug and bore of the needle was checked for freedom from obstruction by rodding with a brass wire. This arrangement provided an air and water tight connection to the cavity in the concrete. A detailed description of the test method is presented elsewhere (Figg 1973; Cather et al. 1984; Arup Research and Development 1987). For air and water permeability measurements, five test holes were selected randomly at each test age. The chloride ion permeability of concrete was determined in accordance with ASTM C 1202. Three cylinders (100 x 200 mm) were cast for each test condition. From each cylinder, 100 mm diameter x 50 mm thick slice was cut from the middle portion using a diamond-tipped saw for chloride permeability measurement.

TEST RESULTS AND DISCUSSIONS

It is well understood, from this and other prior investigations, that strength and durability properties of concrete may be negatively affected by inclusion of fly ash above certain very high levels of cement replacement. This happens due to net reduction in amount of reactive cementitious components of the mixture which are responsible for formation of hydration products, especially calcium silicate hydrates (C-S-H).

These hydration products affect concrete microstructure which, in turn, affect concrete strength and durability properties. However, from resource and energy conservation, economics, and environmental impact viewpoint, it is desirable to have maximum amount of cement replacement with fly ash. Therefore, in this work, the optimum fly ash range was based upon acceptable concrete mixtures for various applications, depending upon strength and permeability values. Concrete permeability is an indirect measure of its durability properties, as discussed previously. In the following sections, effects of fly ash inclusion on concrete strength and permeability are discussed.

COMPRESSIVE STRENGTH

Compressive strength test results for all concrete mixtures are presented in Table 5 and Fig. 1 and 2. In general, early compressive strengths for fly ash mixture were lower than the control mixture without fly ash. Fly ash concrete mixtures up to 30% cement replacement (i.e. up to 35% FA to cementitious materials ratio) showed results similar to the reference concrete at the 3-day age. Beyond 35% fly ash content, the mixtures exhibited much lower strengths compared to the reference mixture at the 3-day age. The same trend was also noticed at 7 days. The 35% fly ash content mixture showed the maximum compressive strength of all the mixtures tested at 28 days. However, the fly ash concretes having 45 and 55% fly ash contents exhibited compressive strength greater than 21 MPa at 28 days. The 35% fly ash concrete also showed best compressive strength at 91 days of age with compared to all other mixtures. The 45% fly ash mixtures produced a little lower compressive strength compared to the reference concrete at the age of 91 days. The compressive strength data at the 365-day age followed the same general trend as that observed at the 91-day age (Table 5 and Fig. 1). These compressive strength test results are in general agreement with previously published results (Naik and Singh 1991).

In general, compressive strength of concrete decreased as air content increased, especially beyond 7 days of curing (Table 5 and Fig. 2). However, the effect of air content on compressive strength of the 74% fly ash mixture was not noticeable in the tested range. This is to be expected for lower cement factor concrete (Naik et al. 1993).

PERMEABILITY

The concrete air and water permeabilities were measured at the ages of 14, 28, and 91 days. The chloride ion permeability was determined at 2-month, 3-month and 1-year ages. In general, a high coefficient of variation in both the air and water permeability values were observed. This is believed to be primarily due to the test method itself. The method used (Figg 1973; Cather et al.1984; Arup Research and Development 1987) is not an ASTM method but a relatively new method in use in England in the last ten years or so. The values of coefficient of variation decreased substantially when duration of curing was increased to 91 days. As expected, air, water, and chloride permeability values decreased (i.e., the concrete became more impervious) with increasing age due to the improvement in concrete microstructure, resulting from the increased amount of the C-S-H phase.

Air permeability

The air permeability test results are given in Table 6. The concrete mixtures without fly ash and 18% fly ash were rated "good" at 14 days, whereas other fly ash mixtures were rated "fair" at this age, in accordance with the rating system proposed by Cather et al. (1984). At 28 days, the reference concrete (Mix No. C-3 (P)) as well as concretes with fly ash to cementitious materials ratio of up to 45% showed "good" resistance to air permeability (Fig. 3). The fly ash mixtures above 45% fly ash were rated as "fair". At 91 days, all the concrete mixtures up to 55% fly ash were rated as "good". The high-volume fly ash mixtures (45 and 55% fly ash) showed very rapid increase in resistance to air permeability compared to that at the 28-day age. This occurred probably due to improved structure of fly ash concretes that resulted from substantial pozzolanic reactions of fly ash beyond 28 days of curing (Gillot et al. 1993). The 55% fly ash mixture showed the maximum resistance to air permeability at 91 days. At 74% fly ash content, the air permeability increased due to a large reduction in cementitious content of the mixture, which resulted in reduced amount of the C-S-H phase compared to the reference mixture.

The effect of air content on concrete resistance to air permeability is illustrated in Fig. 4. The results did not show any distinct relation between air permeability and air content of these concretes with or without fly ash.

The above results revealed that optimum range of fly ash content should be in the range of 35-55% with respect to air permeability.

Water permeability

The water permeability test results are prgsented in Table 7. As anticipated, concrete permeability decreased with age (Fig. 5). At 14 days, concrete resistance to water permeability improved with increases in fly ash content up to 35% fly ash to cementitious materials ratio. The 18 to 45% fly ash mixtures were rated as "good", whereas other mixtures were rated as "fair" at 14 days.

When the concretes were cured for 28 to 40 days, the 35% fly ash mixture showed the best result (Table 7), but the general trend was the same as that obtained at 14 days. The 74% mixture showed the lowest resistance to water permeability.

At 91 days, the fly ash concretes having cement replacements in the range of 30 - 50%(i.e. FA to cementitious materials ratio of 35 to 55%) were rated as "excellent", while the other mixtures were rated as "good". Again, the 35% fly ash mixture exhibited the best result at this age. Probably, the improved performance of the high-volume fly ash concrete up to 55% fly ash were mainly due to improved pore and grain refinement resulting from substantial pozzolanic reactions of the fly ash used (Gillot et al. 1993). When fly ash content was increased to 74%, the air permeability increased sharply. This occured primarily because of the poor concrete microstructure that resulted from a large reduction in the amount of hydration products due to the lower amount of reactive cementitious materials content of the mixture.

The effect of air content on water permeability is presented in Fig. 6. The water permeability was relatively unaffected by the levels of air content for all concretes with or without fly ash.

Chloride permeability

The chloride permeability of concrete mixtures are presented in Table 8. At the two-month age, the high-volume fly ash mixtures exhibited lower permeability compared to the reference mixture, except the 74% fly ash to cementitious materials ratio concrete. However, in accordance with ASTM C 1202 criteria, all the concrete mixtures except the 74% fly ash mixture, showed "moderate" permeability in the range of 2000 to 4000 coulombs at this age (Fig. 7).

After three months of curing, the performance of high-volume fly ash concrete mixtures was substantially improved compared to their results at the 2-month age. The mixtures incorporating the fly ash with cement replacements in the range of 15 to 50% (i.e. fly ash to cementitious materials ratio in the range of 18 to 55%) attained better resistance to chloride permeability (approximately "low") than the reference mixture ("moderate"). The 74% mixture showed result similar to the no-fly ash mixture at the three- month age. Again, improved resistance to chloride permeability of the fly ash mixture was probably due to the pozzolanic contributions of the fly ash which improved the concrete microstructure (Gillot et al. 1993). At the age of one year, all the fly ash concrete mixtures attained a "very low" level of chloride permeability in accordance with ASTM C 1202 criteria, except the reference mixture which exhibited a "low" level of chloride permeability.

Fig. 8 shows the chloride permeability of fly ash concretes as a function of air content. The results indicated insignificant effect of air content on chloride permeability of fly ash concrete within the experimental range.

SUMMARY AND CONCLUSIONS

This work was directed toward developing low-permeability concrete mixtures with low amounts of cement and large amounts of fly ash without compromising their performance. Amount of energy needed for production of cement is estimated to be 6.5 million BTU/ton of cement. Total cement production in the USA is about 90 million tons each year. If, at a minimum, 30% of cement is replaced with fly ash, there will be a reduction in cement demand of about 27 million tons each year. This will translate in energy saving of 1.74 x 10^{14} BTU/year. However, the present research indicates that for low permeability concretes up to 50% cement can be replaced with fly ash. Therefore, higher energy savings in production of cement-based materials can be realized by increasing the fly ash content.

The major conclusions of this work are as presented below.

1. In general concrete mixtures having various cement replacements for up to 55% fly ash content exhibited acceptable performance for a number of construction applications. The optimum fly ash content was found to be in the range of 35 to 55% with respect to compressive strength, air permeability, water permeability, and chloride permeability.
2. In this work, air entrained high-strength concretes were produced with fly ash inclusion up to 35% fly ash to cementitious materials ratio. These concretes showed strength in excess of about 50 MPa at 28 days, 55 MPa at 91 days, and 70 MPa at 365 days of age. The high-volume fly ash mixtures (45 and 55% fly ash) exhibited adequate performance for normal structural applications.
3. The resistance to air permeability of concrete up to 18% fly ash at 14 days was rated to be good in accordance with the Cather et al. criteria. At 28 days, the mixtures up to 45% fly ash showed good resistance to air permeability. When the curing period was increased to 91 days, all the concrete mixtures, except the 74% fly ash mixture, showed good resistance to permeability. However, the peak resistance to air permeability was obtained for the 55% fly ash mixture at the 91-day age.
4. The water permeability resistance of the fly ash mixtures except at the 74% fly ash mixture was

either superior or equivalent to the no fly ash concrete even at the age of 14 days. At 28 days, all the fly ash mixtures up to 45% fly ash showed better results than the no-fly ash concrete. At 91 days, the concretes with 35 to 55% fly ash exhibited excellent resistance to water permeability and all the remaining mixtures, with or without fly ash, showed good resistance to water permeability in accordance with the Cather et al. criteria.

5. The fly ash concrete mixtures up to 55% fly ash content showed lower permeability to chloride ions compared to the no fly ash concrete, up to the 2-month age. At the 3-month age, all the fly ash mixture up to 55% fly ash content showed low permeability, while the no fly ash reference mixture and the 74% fly ash mixture showed moderate permeability. At the one year age, all the mixtures except the no fly ash reference mixture attained very low permeabilities, ranging from 230 to 605 coulombs. The reference no fly ash mixture showed a chloride permeability of 1340 coulombs at this age.
6. Test results showed that air content had little effect on air, water, and chloride permeabilities of concrete within the tested range.

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Table 1: Chemical and physical properties of cement

Chemical composition	Cement, %	ASTM C 150 Type I, %
Silicon dioxide, SiO_2	20.2	-
Aluminum oxide, Al_2O_3	4.7	-
Ferric oxide, Fe_2O_3	0.3	-
Sulfur trioxide, SO_3	+	3.0 max.
Calcium oxide, CaO	64.1	-
Magnesium oxide, MgO	0.9	6.0 max.
Titanium dioxide, TiO_2	0.3	-
Potassium oxide, K_2O	0.1	-
Sodium oxide, Na_2O	0.1	-
Loss on ignition	+	3.0 max.
Physical properties		

Air content (%)	7.1	12 max.
Fineness (m^2/kg)	396	280 min.
Autoclave expansion (%)	-0.03	0.8 max.
Specific gravity	3.16	-
Compressive strength, MPa		
1-day	16.2	-
3-day	25.7	12.4 min.
7-day	31.5	19.3 min.
28-day	37.9	-
Vicat time of initial set (min)	145	45 min. 375 max

1 MPa = 145 psi

\+ Data not available.

Table 2: Chemical and physical properties of fly ash

Chemical composition	Fly ash, %	ASTM C 618 Class C, %
Silicon dioxide, SiO_2	30.5	-
Aluminum oxide, Al_2O_3	17.2	-
Ferric oxide, Fe_2O_3	5.5	-
Total, $SiO_2+Al_2O_3+Fe_2O_3$	53.2	50 min.
Sulfur trioxide, SO_3	+	5.0 max.
Calcium oxide, CaO	28.6	-
Magnesium oxide, MgO	4.7	5.0 max.
Titanium dioxide, TiO_2	1.6	-
Potassium oxide, Ka_2O	0.4	-
Sodium oxide, Na_2O	2.0	1.5 max.
Moisture content	0.1	3.0 max.
Loss on ignition	0.3	6.0 max.
Physical properties		
Fineness retained on No. 325 Sieve (%)	18.6	34 max.
Pozzolanic activity index with cement at 28-day (% of Control)	105	75 min.
Water requirement (% of Control)	90.4	105 max.
Autoclave expansion (%)	+0.02	0.8 max.
Specific gravity	2.78	-

\+ Data not available.

Table 3: Gradation and physical properties of aggregates

Fine aggregate			Coarse aggregate		
Sieve number	% Passing	ASTM C 33 % Passing	Sieve size, mm	% Passing	ASTM C 33 % Passing
4	100	95-100	25.0	99.2	95-100
8	91.2	80-100	19.0	95.7	-
16	73.5	50-85	12.5	44.3	25-60
30	48.6	25-60	9.5	15.4	-
50	16.5	10-30	4.75	2.6	0-10
100	4.3	2-10	2.36	2.4	0-5

Physical properties							
Aggregates	Bulk specific gravity	Bulk specific gravity (SSD)	Apparent specific gravity	SSD absorption (%)	Dry rodded unit weight (kg/m^3)	Voids (%)	Fineness modulus
Fine	2.54	2.57	2.62	1.3	1764	30.5	2.66
Coarse	2.76	2.78	2.84	1.1	1756	36.4	3.40

Table 4: Mixture proportions using ASTM Class C fly ash - 40 MPa specified strength

Mixture No.*	C-1(S)	C-2(S)	C-3(P)	P4-1(S)	P4-2(P)	P4-3 (P)	P4-4(S)	P4-5(S)	P4-6(P)	P4-7(P)	P4-8(P)
Cement (kg/m^3)	398	397	375	328	259	220	174	107	320	179	110
Fly ash (kg/m^3)	0	0	0	72	139	182	216	310	71	226	316
Water (kg/m^3)	123	125	135	139	133	150	141	153	129	136	155
[W/(C+FA)]	0.31	0.32	0.36	0.35	0.34	0.37	0.36	0.37	0.33	0.33	0.36
Sand, SSD (kg/m^3)	715	712	682	695	677	659	624	637	693	655	607
25 mm aggregates, SSD (kg/m^3)	1259	1264	1182	1207	1172	1153	1099	1128	1180	1139	1145
Slump (mm)	25	45	120	65	160	120	55	75	145	115	120
Air content (%)	2.6	2.4	6.3	4.1	5.2	6.4	8.5	3.7	6.7	7.0	6.4
Superplasticizer (L/m^3)	2.7	2.7	2.9	2.9	2.8	2.7	2.6	2.6	2.8	2.7	2.6
Air entraining agent (ml/m^3)	280	330	270	300	350	515	810	905	420	885	1380
Air temperature (°C)	20	20	21	21	21	21	26	26	-	-	-
Concrete temperature (°C)	20	20	23	23	23	26	26	26	21	26	25
Fresh concrete density (kg/m^3)	2500	2500	2380	2445	2395	2360	2250	2335	2400	2335	2365
Hardened concrete density, SSD (kg/m^3)	2515	2510	2470	2510	2430	2415	2280	2300	2440	2340	2325

* Sub-designation (P) indicates primary mixtures and (S) indicates secondary (duplicate) mixtures. Main conclusions are drawn based on the data obtained from primary mixtures. Secondary mixtures are used for analysis of effect of air content variations.

1 kg/m^3 = 1.6855 lb/yd^3; 1 mm = 0.0394 in.; 1 ml/m^3 = 0.026 U.S. fl oz./yd^3
L/m^3 = 25.9 U.S. fl oz./yd^3; $t_c = (t_f - 32)/1.8$.

Table 5: Compressive strength test results*

Mixture No.**	C-1(S)	C-2(S)	C-3(P)	P4-1(S)	P4-6(P)	P4-2(P)	P4-3(P)	P4-4(S)	P4-7(P)	P4-5(S)	P4-8(P)
Fly ash, % +	0	0	0	18	18	35	45	55	55	74	74
Test age, days	Compressive strength, MPa										
1	35.9	36.1	27.3	27.7	16.7	12.3	7.8	2.8	-	-	-
3	44.4	41.1	31.6	35.2	29.2	27.9	18.2	10.3	11.4	0.4	-
7	47.5	46.1	35.6	42.8	35.8	36.5	24.3	15.4	17.0	0.4	0.7
28	53.2	54.3	43.3	49.8	46.5	47.4	35.9	21.9	31.8	16.3	17.5
91	63.6	60.7	47.6	56.7	54.3	55.7	41.7	29.2	39.8	29.3	32.8
365	79.2	78.2	58.5	70.3	62.7	70.7	49.9	33.4	39.0	36.5	40.8

* The data presented are average of three test observations.
** P and S refer to primary and secondary mixture, respectively.
\+ Fly ash as a percentage of total cementitious materials, FA/(Cement + FA).
1 MPa = 145 psi

Table 6: 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

* Test data are average of five test observations.
** P and S refer to primary and secondary mixture, respectively.

Classification of air permeability of concrete (23)

Time in sec. for pressure change	Interpretation
< 30	Poor
30 - 100	Moderate
100 - 300	Fair
300 - 1000	Good
> 1000	Excellent

+ Fly ash as a percentage of total cementitious materials, FA/(Cement + FA).

Table 7: 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	358***	902
P4-2(P)	35	330	418	1713
P4-3(P)	45	201	241	1365
P4-4(S)	55	156	173	1477
P4-7(P)	55	155	163***	1457
P4-5(S)	74	-	120	613
P4-8(P)	74	-	127***	673

* Test results are average of five test observations.
** P and S refer to primary and secondary mixture, respectively.
*** Tests were performed at 40 days.

Typical water permeability qualitative classification (24)

Time is sec. for absorption	Protective quality
< 40	Poor
40 - 100	Moderate
100 - 200	Fair
200 - 1000	Good
> 1000	Excellent

+ Fly ash as a percentage of total cementitious materials, FA/(Cement + FA).

Table 8: Chloride permeability test results*

Mixture No.**	Fly ash, % +	Average charge passed, coulombs		
		2-month	3-month	1-year
C-1(S)	0	-	2128	1170
C-2(S)	0	-	1729	1085
C-3(P)	0	2792	2488	1340
P4-1(S)	18	2782	1907	985
P4-6(P)	18	2084	1873	590
P4-2(P)	36	2077	1576	605
P4-3(P)	45	2026	1638	650
P4-4(S)	55	2041	1620	650
P4-7(P)	55	2200	2075	430
P4-5(S)	74	2561	2750	405
P4-8(P)	74	6370	2482	230

* Test data are average of three test observations.
** P and S refer to primary and secondary mixture, respectively.

Charge passed (coulombs)	Chloride permeability ***
> 4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very low
< 100	Negligible

+ Fly ash as a percentage of total cementitious materials, FA/(Cement + FA).

*** Per ASTM C 1202