Properties of Concrete Incorporating Low Quantity of Cement and High Volumes of Low-Calcium Fly Ash

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Synopsis: This report presents the results of investigations forming part of a long-term study of concrete incorporating low quantities of cement and high-volumes of low-calcium (ASTM Class F) fly ash. Two types of low-calcium fly ashes from sources in Nova Scotia and Alberta were studied. For comparison purposes, a control concrete containing only ASTM Type I cement was also investigated. Each fly ash concrete contained 155 ± 5 kg/m^3 of ASTM Type I cement and 215 ± 5 kg/m^3 of fly ash, whereas, the control concrete contained 365 ± 5 kg/m^3 of cement, equivalent by mass to the total cementitious materials in the fly ash concretes. The water-to-cementitious materials ratio was kept at 0.31 ± .01, and the concrete mixtures were air-entrained and superplasticized.

A large number of concrete test cylinders and prisms were subjected to the determination of strength, modulus of elasticity, drying shrinkage, freezing and thawing durability, carbonation, and permeability to chloride ions. The test results up to 1 year corroborate the results of previous investigations on concrete incorporating high volumes of low-calcium fly ash. At 7 and 28 days, the compressive strengths were of the order of 22 MPa and 36 MPa. At 91 days, the compressive strength and the modulus of elasticity were about 47 MPa and 37 GPa, respectively.

Air-curing of test specimens did not seem to affect the compressive strength development significantly up to the testing period of 91 days. However, under long-term air-curing conditions, both fly ash L concrete and the control concrete showed a marked reduction in strength, when compared to the moist-cured specimen strengths. Resistance of all the concretes to repeated cycles of freezing and thawing was found to be excellent with durability factors > 99, when tested after 14 days of initial-moist curing. The drying shrinkage strains of the fly ash concretes were comparable to or lower than that of the control concrete, and were of the order of 400x10^{-6} at 224 days of drying preceded by 91 days of storage in lime-saturated water. Further, permeability tests carried out on one of the fly ash concretes indicated exceedingly low permeability to chloride ions at 1 year.

Keywords: carbonation; chlorides; compressive strength; concretes; drying shrinkage; flexural strength; fly ash; freeze-thaw durability; modulus of elasticity; permeability; pozzolan cements; tests

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INTRODUCTION

Research work on structural concrete incorporating high volumes of low-calcium (ASTM Class F) fly ash has been in progress since its development at CANMET in 1985(1). The cement content is kept at a relatively low value, typically of the order of 155 kg/m^3 in this concrete, and the proportion of low-calcium fly ash in the total cementitious materials is about 58 per cent. The water content of these concretes is also kept at a minimum value, at about 115 kg/m^3, and high workability of the concrete is achieved through the use of large dosages of a superplasticizer (high-range water reducing admixture). Preliminary investigations have indicated that the above type of concrete has high unit weight, satisfactory early-age strength, high modulus of elasticity, and high later-age strength (1-6).

This report presents the results of investigations at ages up to 1 year on two concretes, each incorporating a different low-calcium fly ash, and a control concrete with ASTM type I portland cement. The cement content of the control concrete was equivalent by mass to the total cementitious materials content of the fly ash concretes. Fly ash L, of bituminous coal origin, was obtained from a source in Nova Scotia, and fly ash S, of subbituminous coal origin, was obtained from a source in Alberta. Though the CaO content of fly ash S is about 12%, it is considered as a low-calcium fly ash when compared with those fly ashes which have a CaO content >20%.

SCOPE OF INVESTIGATION

Three concrete mixtures, namely, one control concrete and two concretes incorporating high volumes of fly ashes L and S were made. Four batches from the control concrete, 9 batches from fly ash L concrete, and 7 batches from fly ash S concrete were prepared. The size of each batch was 0.07 m^3. The water-to-cementitious materials ratio was kept constant at0.31 ± .01. All concrete mixtures were air-entrained and superplasticized and the properties of fresh concrete were determined. From all three concretes, specimens were subjected to the determination of compressive and flexural strengths, modulus of elasticity, drying shrinkage, and carbonation. Further, tests for 28-day splitting-tensile strength, resistance to repeated cycles of freezing and thawing, and air-void parameter measurements were performed on both fly ash concretes. In addition, specimens from fly ash L concrete were tested for permeability to chloride ion penetration.

CONCRETE MIXTURES

Materials

The concrete mixtures were made in the CANMET laboratory in the summer of 1987 using the following materials.

Cement--Normal portland cement, ASTM Type I, was used. Its physical properties and chemical analysis are given in Table I.

Fly ash--Both fly ashes were of low-calcium variety (ASTM Type F), and were obtained from sources in Nova Scotia (fly ash L) and Alberta (fly ash S). Their physical properties and chemical analyses are given in Table 1, and the particle size distributions are given in Fig. 1.

Aggregates--The fine and coarse aggregates were local natural sand and minus 19-mm crushed limestone, respectively. To keep the grading uniform for each mixture, both the fine and coarse aggregates were separated into different size fractions that were then recombined to a specific grading. The grading and the physical properties of both aggregates are given in Tables 2 and 3.

Superplasticizer (High-Range Water-Reducing Admixture)--A sulphonated naphthalene formaldehyde condensate of Japanese origin was used. This superplasticizer is available as a dark brown 42% solids aqueous solution, having a density of 1200 kg/m^3.

Air-entraining admixture--Two types of air-entraining admixtures, a sulphonated hydrocarbon type and a synthetic resin type were used. The former was used in fly ash L concrete, and the latter was used in control concrete and fly ash S concrete.

Mixture Proportioning

Concrete mixture proportions are given in Table 4. For all mixtures, the graded coarse and fine aggregates were weighed in room-dry condition. The coarse aggregate was then immersed in water for 24h, the excess water was decanted and the water retained by the aggregate was determined by the weight difference. A predetermined amount of water was added to the fine aggregate which was then allowed to stand for 24h. The 0.07 m^3 concrete mixtures were made in a laboratory counter-current mixer with fly ash added as a separate ingredient. The sulphonated hydrocarbon type admixture was used in fly ash L concrete. The synthetic resin type admixture was used in both the control and fly ash S concretes, as the former admixture did not function effectively in these concretes.

PROPERTIES OF FRESH CONCRETE

The properties of freshly-mixed concrete, i.e. temperature, slump, unit weight, and air-content are given in Table 5. The results of bleeding and time of setting measurements are given in Table 5 as well.

PREPARATION AND CASTING OF TEST SPECIMENS

In general, ten 152x305-mm cylinders, or sixteen 76x102x406-mm prisms and two 152x305-mm cylinders were made from one typical batch of concrete. The cylinders were cast for testing in compression, splitting-tension, and modulus of elasticity, and the prisms were made for testing in flexure, freezing and thawing cycling, drying shrinkage, and carbonation. Two extra batches were made from fly ash L concrete for freezing and thawing tests following 14, 21, and 28 days of initial moist-curing and for testing of permeability to chloride ions. Eight 152x305-mm cylinders and eight 102x203-mm cylinders were cast from one of the above batches for strength and chloride permeability testing, and sixteen 76x102x406-mm prisms and two 152x305-mm cylinders were cast from the other batch for freezing and thawing cycling.

After casting, all the moulded specimens were covered with water-saturated burlaps and left in the casting room at 23 ± 1.7°C and 50% relative humidity. After 24h, the specimens were demoulded, weighed, and transferred to the moist-curing room until required for testing. The only exceptions were the shrinkage test prisms, which were stored in lime-saturated water at 23 ± 1.7°C until required for the drying shrinkage tests.

Seven days after casting, the specimens to be tested under air-curing conditions were removed from the moist room and left under air-curing conditions at 23 ± 1.7°C and 50 ± 4% relative humidity.

TESTING OF SPECIMENS

The testing schedules for the control and fly ash concretes are given in Tables 6 and 7 respectively.

The cylinders and prisms cast from batches 1,2,5,6, and 7 of the high-volume fly ash concretes and batches 1,2, and 3 of the control concrete were used to determine the compressive and flexural strength development of these concretes, under both moist-cured and air-cured conditions, at ages up to 3 years. The air-cured specimens were tested in the air dried conditions, without any presoaking. Portions of air-cured prisms tested in flexure at different ages were to be used in carbonation testing. Cylinders cast from batch 3 of both fly ash concretes and batch 4 of the control were used for modulus of elasticity determination at 28 and 91 days. Prisms cast from batch 4 of all three concretes were subjected to drying shrinkage measurements after initial storage in lime-saturated water for periods of 7 and 91 days. Shrinkage strains and moisture losses under air-drying conditions at 23 ± 1.7°C and 50± 4% relative humidity are being monitored for up to 448 days.

Cylinders and prisms cast from batch 4 of the fly ash concretes were used in the determination of 28 day splitting-tension and resistance to repeated cycles of freezing and thawing. The freezing and thawing testing according to procedure A of ASTM C 666 was carried out on prisms from both fly ash concretes. Test prisms from batch 4 of the fly ash S concrete were subjected to freezing and thawing cycling after 14 days of initial moist-curing. Test prisms cast from batch 8 of fly ash L concrete were subjected to freezing and thawing cycling following initial moist-curing periods of 14, 21 and 28 days. Permeability of concrete to chloride ion penetration was measured by the rapid chloride permeability test. The test specimens were cut from the 102x203-mm cylinders cast from batch 9 of fly ash L concrete and tested at the ages of 7, 28, 91, and 365 days.

For reference purposes, 152x305-mm cylinders were tested in compression at 28 days from all batches of concrete, with the exception of batch 4 of the control concrete. As far as possible, all tests were conducted according to the relevant ASTM test procedures.

TEST RESULTS

The compressive, flexural, and splitting-tensile strengths, and the modulus of elasticity test results from all batches of concrete are given in Table 8 for ages up to 1 year. The averaged values of compressive strength versus age are plotted in Fig. 2. The data on air-void parameters of the hardened concrete and the flexural strengths of the reference prisms and test prisms after 300 cycles of freezing and thawing are shown in Tables 9 and 10. The changes in weight, length, pulse velocity, and resonant frequency of the prisms subjected to freezing and thawing cycling are shown in Table 11, together with the values of the relative dynamic modulus and durability factor. Photographs of test prisms after exposure to freezing and thawing cycling are shown in Fig. 3 and 4. The drying shrinkage/expansion test results are summarized in Table 12, and illustrated in Fig. 5. The chloride permeability test results are shown in Table 13.

DISCUSSION OF TEST RESULTS

Density of Test Specimens

The one-day density of test specimens is shown in Table 8. The densities of the control concrete and both the high-volume fly ash concretes are comparable, and are in the order of 2400 kg/m^3. Considering that the specific gravities of the fly ashes are lower than that of portland cement, these density values for the concretes incorporating high volumes of fly ash are unusually high. As noted in previous investigations (1-5), these high values are probably due to the filler effect of the fly ash particles, filling the voids in the mortar matrix.

Time of Setting

The initial and final setting times of concretes, determined in accordance with ASTM C 403, at 23 ± 1.7°C and 50% relative humidity are given in Table 5. The initial times of setting of control and fly ash L concrete were comparable, at 7h: 20 min and 7h: 30 min, while that of fly ash S concrete was slightly retarded at 8h: 40 min. But the times of final setting of both fly ash concretes, which were about the same, were retarded by about 3h, when compared to that of the control. This is to be expected, due to the low cement content and high volume of fly ash in the former concretes. This set retardation, though significant, is not expected to be a problem in field applications since the concretes were observed to set within 12 h of casting.

Bleeding

Bleeding tests were performed in accordance with ASTM C 232. No accumulation of bleeding water was found at the surface of test specimens. This has been observed in the earlier investigations as well (4). This effect is undoubtedly due to the extremely low water content and the high density of the concrete mixtures.

Dosage of Superplasticizer

The dosage of superplasticizer incorporated in the fly ash concretes was about 1.5 per cent of the total cementitious material. This resulted in concretes with good workability, having slumps in the range of 150-200 mm. In order to obtain slumps of about 100 mm for the control concrete, however, a superplasticizer dosage of about 2.5 per cent of the cement content was required. Hence, it is clear that the large volumes of fly ash used impart significant workability to the concretes.

Compressive Strength

The data on the development of compressive strength of each batch of concrete are given in Table 8, and the averaged strength values of each type of concrete are shown in Figure 2. The control concrete, incorporating 365 ± 5 kg/m^3 of cement, exhibits higher strengths at all ages than the fly ash concretes, with 155 ± 5 kg/m^3 of cement. The one-year strengths under moist-curing conditions for the control, fly ash L, and fly ash S concretes are 66.0, 56.5, and 49.1 MPa, respectively. Under moist-curing conditions, fly ash S concrete appears to develop strength at a higher rate than fly ash L concrete up to the age of 28 days. However, at later ages, the strength development of fly ash L concrete is higher, yielding a strength 7 MPa higher than that of fly ash S concrete at one year. The rapid early-age strength development of fly ash S concrete could be due to the high calcium content of fly ash S compared to that of fly ash L. But the pozzolanic activity of fly ash L appears to be greater than that of fly ash S, resulting in higher long-term strengths for fly ash L concrete.

Air-curing of test specimens, preceded by 7 days of initial moist curing, does not appear to have severe effects on the strength development up to the age of 91 days. Rather up to 28 days, the strength development of all three concretes under air-curing conditions is comparable to that under moist-curing conditions. However, under long-term air-curing conditions, both fly ash L concrete and the control concrete show a marked reduction in strength, when compared to the moist-cured specimen strengths. Fly ash L concrete shows the highest strength loss of about 19% at one year. On the other hand, air-curing up to one year does not appear to affect the strength development of fly ash S concrete. Curing conditions, thus seem to be more critical for fly ash L concrete than for fly ash S concrete.

Flexural Strength

The flexural strength results for each batch of concrete are shown in Table 8. Under moist-curing conditions, the average flexural strength of control concrete increased from 7.5 MPa at 14 days to 8.4 MPa at 91 days, whereas this increase was 4.2 to 5.6 MPa and 4.7 to 6.0 MPa for fly ash L and fly ash S concretes, respectively. These values are comparable with other published data for concrete of comparable strength (7). From 91 days to one year of age, the flexural strengths of all three concretes appear to level off; in two instances, there is a slight unexplained reduction in strength. Among the two fly ash concretes, again fly ash S concrete shows a rapid strength development only at early ages.

The flexural strengths under air-curing were lower than those under moist-curing. Here again, this trend of levelling off of flexural strengths were noted after one-year testing.

Splitting-Tensile Strength

The splitting-tensile strength results of fly ash L and S concretes are shown in Table 8. The test was not performed on control concrete. The 28 day strength values are 3.3 MPa and 3.5 MPa for fly ash L and fly ash S concretes respectively. These values are about 10 per cent of the 28 day compressive strengths, and are comparable with other published data for normal portland cement concrete of similar strength (7).

Modulus of Elasticity

The 28- and 91-day modulus of elasticity results of all three concretes are shown in Table 8. The high modulus values exhibited by the control concrete are due to its high strength, and these modulus results are in agreement with the modulus values calculated according to ACI Building Code 318. But, the modulus values of both the fly ash concretes are 15 to 20 per cent higher than that of a conventional limestone concrete of comparable strength. As discussed in a previous report (4), the higher modulus is probably due to the densifying effect caused by the unhydrated fly ash particles acting as fine filler in the concrete. Of the two fly ash concretes, fly ash S concrete exhibits slightly higher modulus at both 28 and 91 days.

Air-Void Parameters of Hardened concrete

Air-void parameters of the hardened concrete were determined according to 'ASTM C 457 - Modified Point Count Method' on both fly ash concretes. The results are given in Table 9. The air voids, specific surface, and spacing factor values were determined as 3.5%, 25.2 mm^2/mm^3, and 0.203 mm for fly ash L concrete, and 4.0%, 36.1 mm^2/mm^3, and 0.141 mm for fly ash S concrete, respectively. While the air voids appear to be slightly low for both concretes, the specific surface and spacing factor values comply with the recommended minimum specific surface of 25 mm^2/mm^3 and the spacing factor of 0.20 mm for satisfactory resistance to repeated cycles of freezing and thawing.

Resistance to Repeated Cycles of Freezing and Thawing

Durability of concrete prisms exposed to repeated cycles of freezing and thawing (ASTM C 666 Procedure A: freezing and thawing in water) was determined from the measurements of weight, length, resonant frequency, and pulse-velocity of test specimens before and after freezing and thawing cycling, and by calculating the durability factors. Following the freezing and thawing cycling, the reference and test prisms were broken in flexure.

The freezing and thawing durability tests were done on both fly ash concretes following varying periods of initial moist-curing. The strength and the freezing and thawing data are shown in Tables 10 and 11. The test prisms from mixture 4 of the fly ash S concrete were subjected to freezing and thawing after 14 days of initial moist-curing. They showed no significant distress in freezing and thawing cycling, and had a durability factor of 99 after 300 cycles. The prisms did, however, exhibit considerable surface scaling (Fig. 3).

Prisms from mixture 8 of fly ash L concrete were subjected to freezing and thawing cycling following initial moist-curing periods of 14, 21, and 28 days. All three sets of prisms performed satisfactorily in the freezing and thawing cycling, with durability factors of 99 and over after 300 cycles. Again, considerable surface scaling was observed on the test prisms (Fig. 4).

Drying Shrinkage

The drying shrinkage tests were performed in accordance with ASTM C 157. The test prisms were stored in lime-saturated water at 23 ± 1.7°C for 7 and 91 days. Following this conditioning, the prisms were transferred to the drying room at 23 ± 1.7°C and 50 ± 4 per cent relative humidity. Shrinkage data up to 224 days are presented in Table 12 and Fig. 5. The drying shrinkage strains of control concrete and fly ash concretes following 7 days of water storage are comparable. This is so, in spite of the fact that the recorded moisture loss of the fly ash concretes is much higher than that of the control concrete at all ages. The drying shrinkage of the control concrete following 91 days of water storage is low at early ages of drying; however, the shrinkage strains appear to increase rapidly with time approaching the shrinkage strain values of 7 day water-cured prisms. On the other hand, the fly ash concretes stored in water for 91 days exhibit lower drying shrinkage as well as significantly lower moisture loss at all ages compared to the 7 day values. Under both curing conditions and at all ages of drying, the fly ash S concrete exhibits the lowest drying shrinkage. This effect is more pronounced following the 91 day initial water storage.

The moisture losses of control concrete following the two initial curing regimes does not appear to be significantly different as in the case of fly ash concretes. This may be due to the fact that the bulk of the cement hydration takes place at early ages, whereas pozzolanic reaction proceeds at later ages.

Expansion/shrinkage strains were also determined simultaneously on test prisms stored continuously in lime-saturated water. The data are shown in Table 12 as well. These results did not show any significant shrinkage/expansion or moisture change of the concretes with time.

Carbonation

The extent of carbonation in the concretes was determined by the phenophthalein test on portions of prisms under air-curing tested in flexure. At 91 days, all three concretes showed either negligible or no detectable carbonation. However, when tested at one year, both fly ash concretes showed an average carbonation depth of about 3 mm. The control concrete showed very little carbonation, 0-1mm depth on average. Further long-term data are required to make an evaluation of carbonation tendency of these concretes.

Chloride Permeability

The permeability of concrete to chloride ions was determined according to 'AASHTO T277-831 : Rapid Determination of the Chloride Permeability of Concrete'. Chloride permeability tests were performed only on specimens of mixture 9 of fly ash L concrete. The testing was carried out at 7-, 28- and 91 days, and 1 year, and the results are shown in Table 13, along with some previous CANMET test results on granulated blast-furnace slag and silica fume concretes. The 7-day permeability was substantial, at 8247 coulombs, but this decreased to 1322 coulombs at 28 days, 478 coulombs at 91 days, and 132 coulombs at 1 year. These permeability values are comparable with the slag and silica fume concrete results. As expected, the chloride permeability of the fly ash concrete decreases substantially with time.

CONCLUSIONS

The investigations reported above demonstrate the excellent properties of concretes made with very low cement factors and high volumes of low-calcium (ASTM Class F) fly ashes, and supports the previously published CANMET data on the subject.

The fly ash concretes developed substantial compressive and flexural strengths at both early and later ages, together with high densities and high values of modulus of elasticity.

The drying shrinkage strains of control and fly ash concretes following 7 days of initial storage in lime-saturated water are comparable; however after 91 days of initial storage in lime-saturated water, the shrinkage strains of fly ash concretes are significantly lower than that of the control concrete.

The resistance of the fly ash concretes to repeated cycles of freezing and thawing (ASTM C 666: Procedure A) was satisfactory with durability factors exceeding 99, though some scaling was observed.

Limited data on the permeability of fly ash L concrete to chloride ions show that very low total charge passed across the specimens over the test period at 1 year, thereby implying very low permeability of the concrete to chloride ions.

REFERENCES

1. Sivasundaram, V. "Thermal Crack Control of Mass Concrete", MSL Division Report MSL 86-93 (IR), Energy, Mines and Resources Canada, Ottawa, Canada, 32 pp., 1986.

2. Malhotra, V.M. "Superplasticized Fly Ash Concrete for Structural Applications", ACI Concrete International, Vol. 8, No. 12, December 1986, pp. 28-31.

3. Sivasundaram, V., Carette, G.G., and Malhotra, V.M. "Superplasticized High-Volume Fly Ash System to Reduce Temperature Rise in Mass Concrete", Proceedings, Eighth International Coal Ash Utilization Symposium, Washington, October 1987, Paper No. 34.

4. Giaccio, G.M. and Malhotra, V.M. "Mechanical Properties, and Freezing and Thawing Resistance of High-Volume Fly Ash Concrete made with ASTM Types I and III cements", MSL Division Report MSL 87-112 (OP&J), Energy, Mines and Resources Canada, Ottawa, Canada, 21 pp., 1987.

5. Malhotra, V.M. and Painter, K.E. "Early-Age Strength Properties and Freezing and Thawing Resistance of High-Volume Fly Ash Concrete", MSL Division Report MSL 87-113 (OP&J), 1987.

6. Langley, W.S., Carette, G.G. and Malhotra, V.M. "Structural Concrete Incorporating High Volumes of ASTM Class F Fly Ash", MSL Division Report MSL 88-43 (OP&J), January 88.

7. Neville, A.M. "Properties of Concrete", Third Edition, Pitman Publishing Limited, London, 1981.

TABLE 1--PHYSICAL PROPERTIES AND CHEMICAL ANALYSES OF CEMENT AND FLY ASHES

	Portland Cement* (ASTM Type I)	Fly Ash L**	Fly Ash S**
Physical Tests			
Fineness - passing 75 µm %	-		
- passing 45 µm %	92.8	82.7	80.6
- Blaine, m^2/kg	-	289	326
Setting time, min.			
- Initial	130		
- Final	-		
Autoclave expansion %	0.16		
Compressive strength of 51-mm			
Cubes, MPa: 3-day	25.1		
7-day	31.5		
28-day	39.3		
Chemical Analysis			
Insoluble residue	0.20		
Silicon dioxide (SiO_2)	21.24	47.1	55.6
Aluminum oxide (Al_2O_3)	4.09	23.0	23.1
Ferric oxide (Fe_2O_3)	2.81	20.4	3.48
Calcium oxide (CaO), total	62.21	1.21	12.3
Calcium oxide (CaO), free	0.59	-	-
Magnesium oxide (MgO)	3.75	1.17	1.21
Sulphur trioxide (SO_3)	3.03	0.67	0.30
Sodium oxide (Na_2O)	-	0.54	1.67
Potassium oxide (K_2O)	-	3.16	0.50
Loss on ignition	1.64	2.88	0.29
Bogue Potential Compounds			
C_3S	51.63		
C_2S	22.03		
C_3A	6.09		
C_4AF	8.54		
Pozzolanic Activity with Portland Cement			
Water requirement, %		92	92
Activity index at 28 days, %		98.2	94.6
Accelerated activity index at 7 days, %		90.1	85.5
Pozzolanic Activity Index with Lime at 7 days, MPa		6.8	6.3

* Manufacturers' data
** CANMET data

TABLE 2--GRADING OF AGGREGATES

Coarse aggregate		Fine aggregate	
Sieve size	Cumulative percentage retained	Sieve size	Cumulative percentage retained
19.0 mm	0.0	4.75 mm (No. 4)	0.0
12.7 mm	33.4	2.36 mm (No. 8)	10.0
9.5 mm	66.6	1.18 mm (No. 16)	32.5
4.75 mm	100.0	600 µm (No. 30)	57.5
		300 µm (No. 50)	80.0
		150 µm (No. 100)	94.0
		pan	100.0

TABLE 3--PHYSICAL PROPERTIES OF AGGREGATES

	Coarse Aggregate*	Fine Aggregate**
Specific Gravity	2.69	2.70
Absorption, %	0.82	1.1

*Crushed limestone
**Natural sand

TABLE 4--MIXTURE PROPORTIONS

Mixture Series	Batch No.	$\frac{W}{C+F}$	$\frac{F}{C+F}$	Quantities, kg/m³						
				Water	Cement	Fly Ash	C.A.	F.A.	S.P.	AEA, mL/m³
A (Control)	1	0.31	-	113	362	-	1277	620	8.6	582*
	2	0.32	-	116	366	-	1294	628	10.6	590*
	3	0.32	-	115	365	-	1291	627	9.3	808*
	4	0.31	-	115	367	-	1295	629	8.7	517*
B(Fly Ash L)	1	0.31	0.58	116	159	218	1299	634	5.3	836**
	2	0.31	0.58	116	158	217	1288	629	5.6	829**
	3	0.31	0.58	116	159	218	1295	632	5.6	833**
	4	0.31	0.58	115	157	215	1282	625	5.6	824**
	5	0.31	0.58	114	155	214	1271	620	5.5	817**
	6	0.31	0.58	116	158	217	1291	631	5.6	830**
	7	0.31	0.58	115	157	216	1284	627	5.6	827**
	8	0.31	0.58	114	155	212	1264	616	6.2	1921**
	9	0.31	0.58	115	158	217	1289	629	5.6	2711**
C(Fly Ash S)	1	0.31	0.58	114	157	215	1246	605	4.7	523*
	2	0.31	0.58	115	157	216	1253	608	4.7	526*
	3	0.31	0.58	115	157	215	1249	606	5.1	599*
	4	0.31	0.58	115	158	217	1260	611	4.8	528*
	5	0.31	0.58	118	162	222	1290	626	6.0	1006*
	6	0.31	0.58	113	156	214	1243	603	4.7	522*
	7	0.31	0.58	114	157	215	1247	605	4.7	523*

NOTE: C.A. - Coarse Aggregate, F.A. - Fine Aggregate, S.P. - Superplasticizer, AEA - Air-Entraining Admixture

* - Synthetic resin type admixture
** - Sulphonated hydrocarbon type admixture

TABLE 5--PROPERTIES OF FRESH CONCRETE

Mixture Series	Batch No.	Temperature °C	Slump mm	Unit Weight kg/m³	Air Content %	Setting Time h:min.		Bleeding cm³/cm²
						Initial	Final	
A (Control)	1	22	90	2375	5.9	7:20	8:40	*
	2	22	125	2410	4.9			
	3	23	90	2400	5.6			
	4	23	90	2410	5.0			
B(Fly Ash L)	1	24	175	2430	4.8	7:30	11:30	*
	2	21	200	2410	5.0			
	3	21	200	2420	4.7			
	4	21	200	2395	5.2			
	5	22	225	2375	5.2			
	6	23	200	2415	4.0			
	7	24	200	2400	4.6			
	8	25	175	2365	5.6			
	9	22	175	2410	3.8			
C(Fly Ash S)	1	25	175	2340	4.9	8:40	11:40	*
	2	25	150	2350	4.9			
	3	26	200	2345	4.6			
	4	24	190	2365	4.4			
	5	25	130	2420	3.7			
	6	23	200	2330	4.9			
	7	23	150	2340	4.5			

* No water accumulated on the surface when tested according to ASTM C 232

TABLE 6--TESTING SCHEDULE FOR CONTROL CONCRETE

Mixture No.	Batch No.	Type of Testing	Age of Testing							
			1d	7d	14d	28d	91d	365d	2yr	3yr
A	1	Compression (ASTM C 39)		2 cylinders		2 cylinders	2 cylinders	2 cylinders		2 cylinders
		Modulus of Elasticity (ASTM C 469)					2 cylinders			
A	2	Compression, Air-Curing (ASTM C39)				2 cylinders	2 cylinders	2 cylinders		2 cylinders
		Compression (ASTM C39)				2 cylinders				
A	3	Flexure (ASTM C 78)			2 prisms		2 prisms	2 prisms	2 prisms	
		Flexure, Air-Curing (ASTM C 78)			2 prisms		2 prisms	2 prisms	2 prisms	
		Carbonation (RILEM CPC-18)					2 specimens	2 specimens	2 specimens	
		Compression (ASTM C 39)				2 cylinders				
		Modulus of Elasticity (ASTM C 469)				2 cylinders				
A	4	Modulus of Elasticity (ASTM C 469)					1 cylinder			
		Compression (ASTM C 39)					1 cylinder			
		Drying Shrinkage (ASTM C 157)	Two prisms each were exposed to air-drying at 23° C and 50% R.H. after 7 and 91 days of water-curing.							

TABLE 7--TESTING SCHEDULE FOR THE CONCRETES INCORPORATING HIGH VOLUMES OF LOW-CALCIUM FLY ASHES

Mixture No.	Batch No.	Type of Testing	Age of Testing								
			1d	7d	14d	28d	56d	91d	365d	2yr	3yr
B,C	1	Compression (ASTM C 39)	2 cylinders	2 cylinders		2 cylinders			2 cylinders		
		Flexure (ASTM C 78)			2 prisms	2 prisms					
B,C	2	Compression, (ASTM C 39)				2 cylinders		2 cylinders		2 cylinders	2 cylinders
		Flexure (ASTM C 78)						2 prisms	2 prisms		
B,C	3	Modulus of Elasticity (ASTM C 469)				2 cylinders		1 cylinder			
		Compression (ASTM C 39)				2 cylinders		1 cylinder			
B,C	4	Splitting Tension (ASTM C 496)				2 cylinders					
		Drying Shrinkage (ASTM C 157)	Two prisms each were exposed to air-drying at 23°C and 50% R.H. after 7 and 91 days of water-curing.								
		Compression (ASTM C 39)				2 cylinders					
C	4	Freezing and Thawing (ASTM C 666)	Two prisms were subjected to repeated cycles of freezing and thawing at the end of 14 days of moist-curing.								
B,C	5	Compression, Air-Curing (ASTM C 39)				2 cylinders		2 cylinders	2 cylinders		
		Compression (ASTM C 39)		2 cylinders		2 cylinders					
B,C	6	Compression, Air-Curing (ASTM C 39)					2 cylinders			2 cylinders	2 cylinders
		Compression (ASTM C 39)		2 cylinders		2 cylinders					
B,C	7	Flexure (ASTM C 78)			2 prisms			2 prisms		2 prisms	
		Flexure, Air-Curing (ASTM C 78)			2 prisms	2 prisms		2 prisms	2 prisms	2 prisms	
		Compression (ASTM C 39)				2 cylinders					
		Carbonation (RILEM CPC-18)						2 specimens	2 specimens	2 specimens	2 specimens
B	8	Freezing and Thawing (ASTM C 666)	Two prisms each were subjected to repeated cycles of freezing and thawing at the end of 14, 21, and 28 days of moist-curing.								
		Compression (ASTM C 39)				2 cylinders					
B	9	Chloride Permeability (AASHTO T277-831)		2 specimens		2 specimens		2 specimens	2 specimens		
		Compression (ASTM C 39)		2 cylinders		2 cylinders		2 cylinders	2 cylinders		

TABLE 8--SUMMARY OF STRENGTH AND MODULUS OF ELASTICITY TEST RESULTS

Mixture Series	Batch No.	Density at 1-day	Compressive Strength, MPa 152x305 -mm cylinders													Flexural Strength, MPa 76x102x406 -mm prisms										Splitting Tension, MPa 152x305 -mm cyl.	Modulus of Elasticity 152x305 -mm cyl. Moist Cured	
			Moist Cured							Air Cured						Moist Cured					Air Cured							
		kg/m^3	1-d	7-d	28-d	91-d	1 yr	2 yrs	3 yrs	28-d	56-d	91-d	1 yr	2 yrs	3 yrs	14-d	28-d	91 -d	1 yr	2 yrs	14-d	28-d	91 -d	1 yr	2 yrs	28d-moist cured	28-d	91-d
A (Control)	1	2415		39.3	47.2	56.7	66.0		*																			39.2
	2	2450			49.6					49.5		53.5	56.7		*													
	3	2445			46.9											7.5		8.4	7.3	*	5.4		7.2	7.1	*		37.2	
	4	2455				57.7+																						41.0+
B (Fly Ash L)	1	2445	8.8	21.5	37.0		59.0									4.7	4.9											
	2	2445			34.8	48.2		*	*									6.0	6.0									36.5+
	3	2445			36.7	48.5+																					35.1	36.6+
	4	2440			35.4											4.0										3.3		
	5	2445		22.5	37.7					38.1		42.6	46.0															
	6	2455		23.0	36.8						42.4			*	*													
	7	2455			36.4											4.1		5.1		*	3.4	4.4	5.1	5.0	*			
	8	2440			39.7											4.1	5.1++											
	9	2445		21.1	35.7	46.0	54.0																					
C (Fly Ash S)	1	2390	9.4	24.7	38.8		49.1									4.7	5.4											
	2	2390			39.3	47.0		*	*									6.4	5.6									38.9+
	3	2405			38.2	47.0+																					37.9	40.0+
	4	2395			41.2											4.6										3.5		
	5	2410		26.3	42.4					41.7		45.4	48.1															
	6	2385		24.2	40.0						41.6			*	*													
	7	2395			40.6											4.8		5.6		*	3.3	4.6	4.6+	4.5	*			

* Data not yet available.

\+ Only one specimen tested, each value is an average of two tests elsewhere.

++ From this batch, the 21-day flexural strength under moist-cured conditions is 5.0 MPa.

TABLE 9--AIR-VOID PARAMETERS OF HARDENED CONCRETE

Mixture No.	Air content of fresh concrete %	Air-void parameters of hardened concrete			
		Voids in hardened concrete %	Voids per mm	Specific surface, mm^2/mm^3	Spacing factor, mm
B8 (Fly ash L)	5.6	3.5	0.22	25.2	0.203
C4 (Fly Ash S)	4.4	4.0	0.36	36.1	0.141

TABLE 10--FLEXURAL STRENGTH OF REFERENCE PRISMS AND TEST PRISMS SUBJECTED TO REPEATED CYCLES OF FREEZING AND THAWING

Mixture No.	$\frac{W}{C+F}$	Flexural Strength of 76x102x406 -mm Prism, MPa				Residual Flexural Strength, %
		Reference prisms, moist cured			Test prisms	
		At the beginning of testing		At the end of Testing	At the end of Testing	
		Initial moist-curing	Strength, MPa			
B8	0.31	14-d	4.1	5.8	5.5	94.8
B8	0.31	21-d	5.0	5.7	5.0	87.7
B8	0.31	28-d	5.1	5.7	4.7	82.5
C4	0.31	14-d	4.6	5.7	5.0	87.7

TABLE 11--SUMMARY OF TEST RESULTS ON CONCRETE PRISMS AFTER 300 CYCLES OF FREEZING AND THAWING

Mixture No	$\frac{W}{C+F}$	Air Content %	Initial Moist-Curing Period	76 x 102 x 390 -mm Test Prisms													
				Weight, kg			Length, mm			Pulse Velocity, m/sec			Resonant Frequency, Hz			Relative Dynamic Modulus of Elasticity %	Durability Factor
				W_0	W_{300}	Change %	L_0	L_{300}	Change %	V_0	V_{300}	Change %	N_0	N_{300}	Change %		
B8	0.31	3.5	14-d	7.282	7.193	-1.22	361.08	361.15	+0.019	4782	4872	+1.88	5420	5430	+0.18	100	100
B8	0.31	3.5	21-d	7.316	7.193	-1.68	361.47	361.51	+0.011	4788	4695	-1.94	5370	5460	+1.68	100	100
B8	0.31	3.5	28-d	7.375	7.097	-3.77	361.05	361.22	+0.047	4947	4735	-4.29	5540	5510	-0.54	99	99
C4	0.31	4.0	14-d	7.370	7.173	-2.67	361.63	361.72	+0.025	4701	4800	+2.11	5390	5350	-0.74	99	99

TABLE 12--SHRINKAGE/EXPANSION AND MOISTURE CHANGE UP TO 224 DAYS FOR DRYING SHRINKAGE PRISMS AND COMPANION PRISMS STORED IN WATER

Curing Conditions	Mixture No.	Shrinkage/Expansion Strain, x10-6 (Prism size 76 x 102 x 390 mm)						Moisture Loss*, %					
		7d	14d	28d	56d	112d	224d	7d	14d	28d	56d	112d	224d
Air dried at 23°C and 50% RH, after 7 days of water-curing.	A4	252	305	348	390	500	610	12.1	13.7	14.2	15.2	19.8	28.8
	B4	259	340	422	411	496	574	35.7	39.4	41.3	42.3	43.4	49.3
	C4	188	284	326	369	454	543	26.0	30.5	31.1	31.8	35.5	41.8
Air-dried at 23°C and 50% RH, after 91 days of water-curing.	A4**	135	184	355	383	447	489	7.8	9.8	12.9	16.4	19.8	25.3
	B4	128	174	262	305	383	418	7.5	9.3	16.7	21.4	29.5	34.8
	C4	64	121	149	223	294	344	11.6	14.2	18.3	23.4	28.9	34.1
Continuous water-storage.	A4	28	+7	+25	11	+50	+78	+2.3	+1.2	+3.2	+2.0	+3.7	+5.9
	B4	+4	+25	+25	+50	25	7	+1.3	+1.9	+1.6	+2.9	+3.5	+3.2
	C4	+21	+25	+39	+21	+4	+11	1.3	2.3	+0.6	+1.9	+1.7	+2.9

* As a percentage of total original water
** Strain values for A4 are from measurement on one prism only. All other values shown are average of measurements on two prisms.

Note I: The positive (+) values denote either expansion or moisture gain.
Note II: The testing is to continue up to 448 days.

TABLE 13--RESULTS OF CHLORIDE PERMEABILITY TESTS ON CONCRETES

Concrete Type	Chloride Permeability, Coulombs				
	1-day	7-day	28-day	91-day	1 year
Fly Ash L concrete W/(C+F) = 0.31	-	8247	1322	478	132
Silica fume concrete* W/(C+SF)=0.33	4404	1705	373	-	-
Silica fume concrete* W/(C+SF)=0.47	6942	3721	1037	-	-
Slag concrete (Algoma)* W/(C+S)=0.55	15477	4931	1650	-	-
Slag concrete (Standard)* W/(C+S)=0.55	15924	3751	1355	-	-

* From previous CANMET investigations.

NOTE: Each result is an average of tests on two specimens, discs of 100 -mm diameter by 50 -mm length.

The water-to-cementitious material ratios of the concretes should be taken into consideration, when comparing the above data.

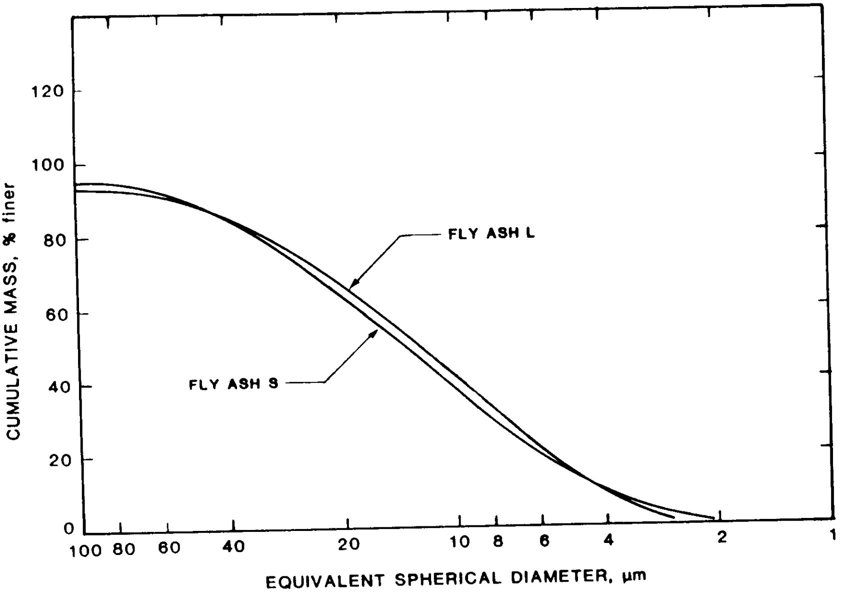

Fig. 1--Particle size distribution of the fly ashes (obtained by Sedigraph Particle Size Analyser)

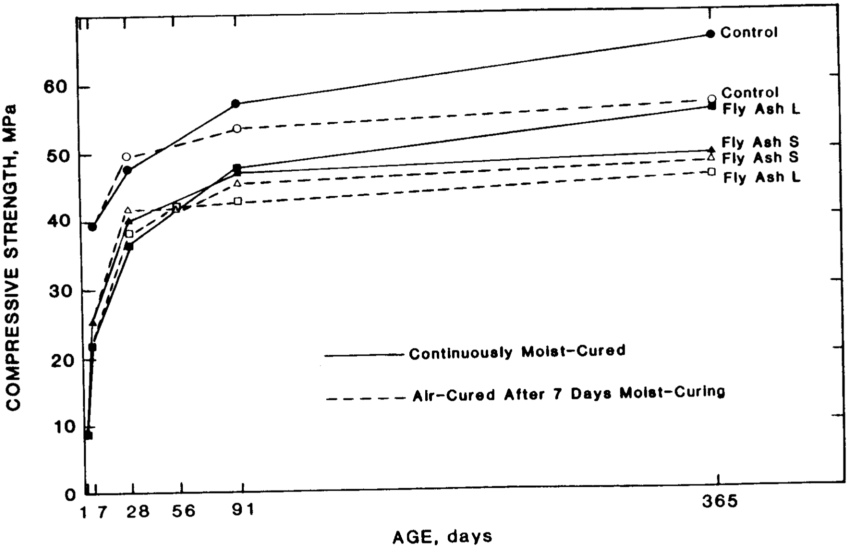

Fig. 2--Compressive strength development under moist-cured and air-cured conditions

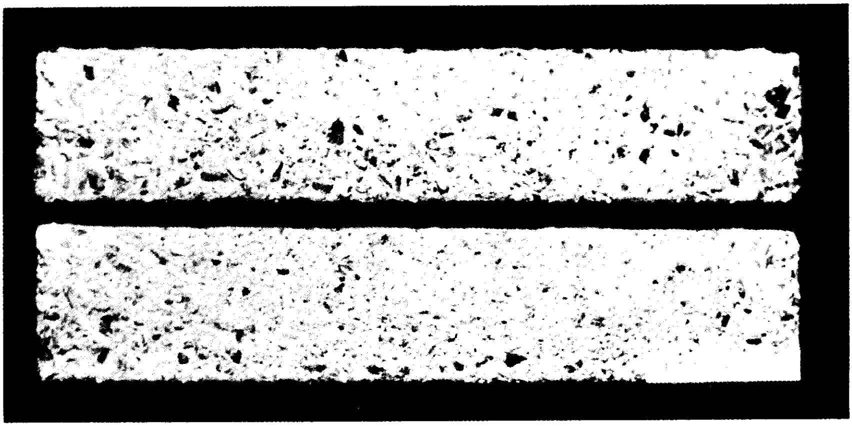

Fig. 3--Test prisms from Batch 4 of Fly Ash S concrete after 300 cycles of freezing and thawing -- initial moist-curing period of 14 days

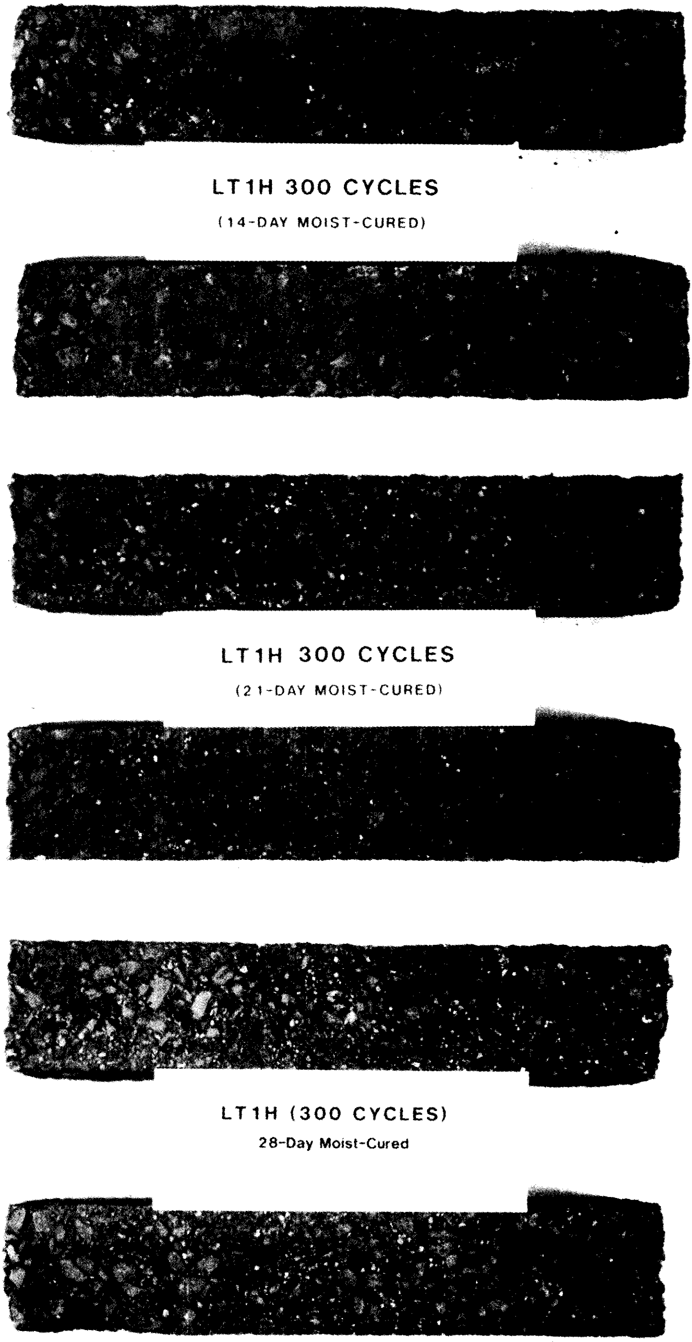

Fig. 4--Test prisms from Batch 8 of Fly Ash L concrete after 300 cycles of freezing and thawing -- initial moist-curing periods of 14, 21, and 28 days

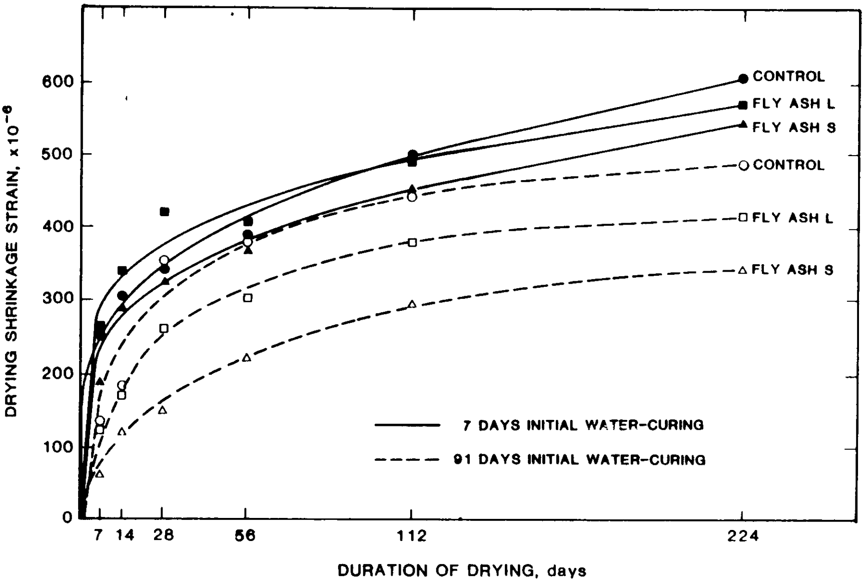

Fig. 5--Drying shrinkage versus age of drying of concretes after 7 and 91 days of initial moist-curing