

**MECHANICAL PROPERTIES AND DURABILITY OF CONCRETE MADE WITH
HIGH-VOLUME FLY ASH BLENDED CEMENTS USING A COARSE FLY ASH**

by

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ABSTRACT

This paper presents a study on the mechanical properties and durability of concrete made with a high-volume fly ash blended cement using a coarse fly ash that does not meet the fineness requirement of ASTM C 618. The results were compared with those of the HVFA concrete in which unground fly ash had been added at the concrete mixer. The properties of the fresh concrete determined included the slump, air content, slump loss, stability of air content, bleeding, and setting time; those of the hardened concrete investigated included the compressive strength, flexural- and splitting-tensile strengths, Young's modulus of elasticity, drying shrinkage, resistance to abrasion, chloride-ion penetration, freezing and thawing cycling, and to de-icing salt scaling. The results show that except for the resistance of the concrete to the de-icing salt scaling, the mechanical properties and the durability of concrete made with this blended cement were superior to the concrete in which the unground fly ash and the cement had been added separately at the mixer. The production of HVFA blended cements, therefore, offers an effective way for the utilization of coarse fly ashes that do not otherwise meet the fineness requirements of ASTM C 618.

1. Introduction

In the mid 1990s, CANMET undertook a major research project to develop blended cements incorporating high volumes of ASTM Class F fly ash. The objectives of the project were to reduce CO₂ emissions from the production of cement clinker, to reduce the consumption of raw materials such as limestone and clay, and to contribute to a cleaner environment through the recycling of waste materials such as fly ash. The blended cement developed is made by intergrinding approximately 55% (weight percentage) of ASTM Class F fly ash and 45% of ASTM Type I or Type III cement clinker together with a small amount of gypsum, and in some cases with a small amount of dry superplasticizer [1-6].

The results from previous investigations [6] had shown that, in general, the compressive strength and resistance to chloride-ion penetration of the concrete made with high-volume fly ash (HVFA) blended cements were superior or equal to that of the concrete in which the cement and the unground fly ash had been added as separately batched materials at a concrete mixer. For high-volume fly ash blended cements made with fine fly ashes, the improvement in the mechanical properties and durability characteristics was marginal, while for the HVFA blended cements made using a coarse fly ash, the improvement was significant.

This paper presents a study on the mechanical properties and durability of concrete made with a high-volume fly ash blended cement using a coarse fly ash that does not meet the fineness requirements of ASTM C 618. The results are compared with those of the HVFA concrete where unground fly ash had been added at the concrete mixer, and control portland cement concrete. The control mixtures were made with a commercially available ASTM Type III cement and, a normal-portland cement (LPC) produced in the laboratory that meet the requirements of ASTM Type III cement. The properties of the fresh concrete determined included the slump, air content, slump loss, stability of air content, bleeding, and setting time; those of the hardened concrete investigated included the compressive strength, flexural- and

splitting-tensile strengths, Young's modulus of elasticity, drying shrinkage, resistance to abrasion, chloride-ion penetration, freezing and thawing cycling, and to de-icing salt scaling.

2. Materials

2.1. Portland Cement Clinker

Portland cement clinker was obtained from a cement plant in Montreal area, and this clinker is used by the cement company to produce ASTM Type III cement. Its specific gravity and chemical composition are given in Table 1.

2.2. Portland Cement

A commercially available ASTM Type III portland cement from the same company that provided the clinker was used for the control concrete. Its chemical composition and physical properties are given in Table 2.

2.3. Fly Ash

A fly ash from Genesee, Alberta was used in this study. Its physical properties and chemical composition are given in Table 1. The fly ash has a relatively low Blaine fineness of 2120 cm^2/g , and the amount of the ash retained when wet sieved on a 45 μm sieve was 36.5%. This ash, therefore, fails to meet the fineness requirement of ASTM C 618¹. The ash has a relatively low specific gravity, and this is primarily related to a large numbers of plerospheres that are hollow particles filled with smaller spheres in the sample. The ash has a CaO content of 5.8% and an alkali content (Na_2O equivalent) of 3.6%. This ash meets the chemical requirements of ASTM Class F fly ash.

¹ASTM C 618 requires that the amount retained when wet-sieved on a 45 μm sieve be less than 34%.

2.4. Superplasticizer

A sulphonated, naphthalene-formaldehyde condensate type of superplasticizer in a powder form was used in all the concrete mixtures.

2.5. Air-Entraining Admixture

A synthetic resin type air-entraining admixture (AEA) was used in all the mixtures.

2.6. Aggregates

A crushed granite with a maximum nominal size of 19 mm was used as the coarse aggregate, and a local natural sand was used as the fine aggregate. Both the coarse and fine aggregates were separated into different size fractions and recombined to a specific grading shown in Table 3. The coarse and fine aggregates each had a specific gravity of 2.70, and water absorptions of 0.5 and 0.8%, respectively.

3. Production of the Cements

The production of the HVFA blended cement that meets the requirements of ASTM C 1157 GU involved two stages; these consisted of producing a portland cement with a Blaine fineness of $4000 \text{ cm}^2/\text{g}$ (LPC), and then intergrinding 45% (by mass) of the above cement with 55% of the fly ash for 80 minutes. The cement LPC was produced by grinding 97% clinker together with 3% gypsum. Before the clinker was fed to the grinding mill, it was crushed and sieved so that all the particles were less than 0.6 mm in size. The two cements produced are designated as follows:

Blended cement produced using Genesee fly ash = BCG
Laboratory-produced, normal-portland cement = LPC

A ceramic grinding mill, 420 mm in length and 500 mm in diameter with a grinding capacity of approximately 10 kg material, was used for the production of the cements. A combination of 35 kg of large ceramic cylinders (30-mm thick and 30-mm diameter) and 35 kg of medium ceramic cylinders (20-mm thick and 20-mm diameter) was used for grinding. The weight ratio of the materials to be ground to the grinding media was 1:7.

4. Mixture Proportions

Two high-volume fly ash concrete and two control portland-cement concrete mixtures were made. For the HVFA concrete, one concrete mixture was made in which unground fly ash was added at the concrete mixer, and the other mixture was made with the blended cement. The proportions of the concrete mixtures are summarized in Table 4.

For all the mixtures, the coarse and fine aggregates were weighed in a room dry condition. The coarse aggregate was then immersed in water for 24 hours. The excess water was decanted, and the water retained by the aggregates was determined by the weight difference. A predetermined amount of water was added to the fine aggregate that was then allowed to stand for 24 hours.

A water-to-cementitious materials ratio of 0.32 was used for the fly ash concrete mixtures. The water-to-cement ratios of the control concrete made with the commercially available ASTM Type III cement and the LPC cement were 0.42 and 0.40, respectively; these water-to-cement ratios were chosen to obtain concrete with a 28-day compressive strength similar to that of concrete made with the HVFA blended cement.

5. Preparation and Casting of Test Specimens

All the concrete mixtures were mixed for five minutes in a laboratory counter-current mixer, and for each concrete mixture two batches were made.

5.1. Batch A

Twenty-four 102x203-mm and six 152x305-mm cylinders were cast for each concrete mixture. The 102x203-mm cylinders were used for the determination of the compressive strength and the resistance to the chloride ion-penetration of the concrete, and the 152x305-mm cylinders were used for determining the splitting-tensile strength and the Young's modulus of elasticity. One container of approximately 7 L capacity was filled with the fresh concrete for determining the bleeding, and one 152x152x152-mm mould was filled with mortar obtained by sieving the fresh concrete for determining the setting times of concrete.

5.2. Batch B

Three 102x203-mm cylinders were cast for the determination of the compressive strength at 28 days. For mixture 1, six additional 102x203-mm cylinders were cast for the determination of the compressive strength at 7, 14, 28, and 91 days. Eight 76x102x390-mm prisms were cast for determining the drying shrinkage and the resistance of the concrete to freezing and thawing cycling. Four 76x102x406-mm prisms were cast for the determination of the flexural strength of the concrete, and three slabs, 300x300x75 mm in size, were cast for the de-icing salt-scaling test and for the determination of the abrasion resistance of concrete.

5.3. Consolidation and Curing of Test Specimens

All the cylinders and prisms were cast in two layers, with each layer being consolidated using an internal vibrator for the 152x305-mm cylinders and a vibrating table for the other specimens.

After casting, all the moulded specimens were covered with plastic sheets and water-saturated burlap, and left in the casting room for 24 hours. They were then demolded and transferred to the moist-curing room at $23 \pm 2^\circ\text{C}$ and 100 % relative humidity until required for testing. The only exception was the prisms for the drying shrinkage test that were stored in lime-saturated water for 7 days prior to be transferred to a chamber at $20 \pm 2^\circ\text{C}$ and 50 % relative humidity.

6. Testing of the Specimens

The schedule of testing is shown in Table 5.

6.1. Mechanical Properties

For each mixture, the compressive strength² was determined from batch A at 1, 7, 14, 28, and 91 days, and will be determined at 365 and 730 days; The cylinders from batch B were also tested for the compressive strength³ at 28 days for control purposes. For Mixture 1, two extra cylinders each were also tested for the compressive strength at 7, 14, 28, and 91 days. For each mixture, the flexural strength was determined on two prisms from batch B at 14 and 28 days; the splitting-tensile strength was determined at 28 days using two cylinders from batch A. The drying shrinkage of the two prisms from batch B was measured at 7, 14, 28, 56, 112, and 224 days after an initial curing of 1 day in the mould and 6 days in lime-saturated water, and the measurements will be continued for 448 days; the other two prisms were stored in the lime-saturated water 1 day after casting and their length changes were measured for control purposes. All the above tests were carried out following the relevant ASTM standards.

² Three cylinders were tested at each age.

6.2. Durability

For each mixture, the abrasion resistance of the concrete (ASTM C 779) was determined on one of the slabs cast from batch B after 91 days of moist curing. The other slab was used for the de-icing salt scaling resistance test (ASTM C 672); the test was started after an initial moist curing of the slabs for 14 days, followed by 14 days drying in laboratory air. The top surface of the slabs were exposed to 50 cycles of freezing and thawing in the presence of a 3% NaCl solution. The performance of the concrete was evaluated visually and by determining the cumulative scaling residue. The resistance to the chloride-ion penetration (ASTM C 1202) was measured at the ages of 28 and 91 days, and will be determined at the age of 365 days using the top portion of the cylinders. The resistance to freezing and thawing cycling (ASTM C 666 Procedure A, freezing and thawing in water) was determined on test prisms; the changes in length, mass, pulse velocity, and resonant frequency of the two prisms were determined after every 50 cycles. The flexural strength of the test prisms was also determined after the completion of the test, and compared with that of the control prisms cured in the moisture room.

7. Results and Discussion

7.1. Characteristics of Laboratory-Produced Cements

The physical properties and chemical compositions of the laboratory-produced cements are presented in Table 2. The laboratory-produced normal-portland cement (LPC) meets the general requirements of ASTM C 150 Type III cement. Its initial- and final- setting times were 130 and 240 minutes, respectively, that were within the range of 45 to 375 minutes as specified in ASTM C 150. The air content of the mortar made with the LPC was less than 12%, and the compressive strength of the mortar at 1 and 3 days was 15.3 and 24.2 MPa, respectively. This was higher

than the minimum strength of 12.4 and 24.1 MPa at 1 and 3 days, respectively, as specified in ASTM C 150.

The HVFA blended cement BCG meets all the requirements of ASTM C 1157M. The initial- and final-setting times of the HVFA blended cement were 275 and 380 minutes, respectively, and these were within the range of 45 to 420 minutes as specified in ASTM C 1157M. The 3- and 7-day compressive strength of the mortar made with the BCG cement was 13.1 and 18.0 MPa; this was higher than the minimum strength of 10 and 17 MPa at 3 and 7 days, respectively, as specified in ASTM C 1157M.

Table 2 shows that the air content of the mortar made with the HVFA blended cement BCG was 3.9% and that of the mortar made with the commercially available ASTM Type III cement and the LPC was 6.9 and 6.6%, respectively. This indicates that the use of the fly ash increased the packing density, and decreased the air content of the mortar made with the blended cement.

7.2. Properties of Fresh Concrete

The properties of the fresh concrete including the slump, air content, and unit weight are given in Table 6.

7.2.1. Dosage of the superplasticizer and slump

The dosage of the superplasticizer in all the concrete mixtures was adjusted to give a slump of approximately 100 to 150 mm, and ranged from 0.9 to 3.6 L/m³ of concrete (Table 4). The parameters that affected the dosage included the composition and the fineness of the cement used, and whether the fly ash was used as is, or after being interground with the cement LPC.

In order to obtain similar slumps, Mixture 2 made with blended cement BCG required more superplasticizer than Mixture 1 that was made with the laboratory-produced normal-portland

cement LPC and unground fly ash. The increase of the superplasticizer was from 2.5 L/m³ for Mixture 1 to 3.6 L/m³ for Mixture 2. This was due primarily to the intergrinding of the fly ash with the LPC that resulted in the increase in the fineness of the fly ash and the LPC in the blended cement.

To obtain similar slumps, the control concrete made with the commercially available ASTM Type III cement required an average of 0.8 L/m³ more superplasticizer than that made with the laboratory-produced portland cement LPC, even though the water-to-cement ratio of the former was higher than that of the latter. This was probably due to the fact that the fineness and the C₃A content of ASTM Type III cement were higher than those of the LPC.

7.2.2. Dosage of the air-entraining admixture and air content

The dosage of the air-entraining admixture (AEA) required for obtaining an air content of 5 to 7 % was influenced primarily by the composition and fineness of the cement used, and whether the fly ash was used as received, or after being interground with the cement LPC.

Mixture 2 made with the blended cement BCG required more AEA than that for Mixture 1 in which unground fly ash had been added at the concrete mixer. This increase in the dosage of the AEA was due to the intergrinding of the fly ash with the LPC cement that resulted in an increase in the fineness of the fly ash and the LPC in the blended cement.

For similar air content for the control concrete, the concrete made with the commercially available ASTM Type III cement required higher dosage of the AEA than that made with the LPC cement; this was probably due to higher fineness of the former.

The air content of concrete Mixture 1, Batch A, was 8.5% and this was outside the targeted range of 5 to 7%. The dosage of the AEA was, therefore, adjusted for Batch B of the mixture to obtain an air content of approximately 7%.

7.2.3. Slump loss and stability of air content

The results on the slump loss and the stability of the entrained air in the fresh concrete are summarized in Table 7. There was significant loss in both slump and air content with time for all the concrete mixtures. For example, the air content of the concrete Mixture 2 (Batch B) made with the blended cement BCG decreased from 5.7 to 3.2% after 65 minutes.

7.2.4. Bleeding of concrete

Table 8 gives the results of the bleeding of fresh concrete. The total amount of the bleed water was very low for all the concrete mixtures, and ranged from 0.004 to 0.032 mL/cm². It appears that the use of the blended cement decreased the bleeding of the concrete compared to that of the concrete in which unground fly ash had been added at the concrete mixer. This is probably due to the increase in the fineness of the fly ash and the LPC in the blended cement by the intergrinding of the two components. The bleed water of the control concrete made with the commercially available ASTM Type III cement was lower than that of the control concrete made with the LPC cement, and this was due to the higher fineness of the former cement.

7.2.5. Setting Time of Concrete

Table 8 shows that the initial- and final-setting times of the concrete ranged from 3 h:55 min. to 8 h:00 min., and from 5 h:15 min. to 10 h:30 min., respectively (Table 8). The setting times of the high-volume fly ash concrete were 3 to 5 hours longer than those for the control concrete; this was expected considering the high fly ash content in the former concrete mixtures. The use of the blended cement reduced both the initial- and final-setting times of the high-volume fly ash concrete by 30 to 40 minutes; this was probably due to the higher fineness of the ground fly ash.

7.3. Compressive Strength

The compressive strength test results for the concrete are given in Table 9. As mentioned above, the air content of concrete Batch A of Mixture 1 was 8.5%; this was outside the targeted range of 5 to 7%. Additional cylinders were, therefore, cast from Batch B of the concrete (air content = 7.1%) to determine the compressive strength at 7, 14, 28, and 91 days, and to compare these results with that of the other concrete mixtures. The results showed that the use of the blended cement resulted in a significant increase in the compressive strength of the high-volume fly ash concrete ranging from 30% at 91 days to 45% at 7 days.

At one day, the compressive strength of the HVFA concrete was lower than that of the control portland cement concrete. After the first day, the strength development of the control concrete was slower than that of the fly ash concrete. At 7 days, the compressive strength of the concrete made with the blended cement (Mixture 2) approached that of the control concrete made with the LPC. At 28 days, all concrete mixtures had somewhat similar strengths except for the high-volume fly ash concrete made with unground fly ash (Mixture 1). The control concrete made with ASTM Type III cement developed higher compressive strength at early age than the control concrete made with the LPC cement due to the higher fineness of the former cement.

7.4. Flexural- and Splitting-Tensile Strengths

The flexural- and splitting-tensile strengths of the concrete are given in Table 10. The 28-day flexural strengths of the control concrete made with the LPC and the commercially available ASTM Type III cement were 6.3 and 6.7 MPa, respectively; the corresponding strengths of the concrete made with the LPC in which fly ash had been batched separately, and that of the blended cement BCG were 4.0 and 5.1 MPa, respectively. The 28-day splitting-tensile strength for all the concretes were approximately 3 MPa except for concrete Mixture 1 (2.2 MPa). The above results show that the use of HVFA blended cement improves the flexural- and splitting-

tensile strength of concrete, and this increase was due to an increase in the fineness of the fly ash and the LPC in the blended cement resulting from the intergrinding of the two components.

7.5. Young's Modulus of Elasticity "E"

Table 10 presents the data on Young's modulus of elasticity of concrete. The "E" values at 28 days for the concrete made with blended cement BCG (Mixture 2), and the concrete in which the laboratory-produced portland cement LPC and the fly ash had been batched separately (Mixture 1) were 34.4 and 22.4 GPa, respectively; the corresponding values at 91 days were 38.7 and 30.6 GPa, respectively. The values at 28 days for the control concrete made with the LPC and the commercially available ASTM Type III cements were 30.3 and 33.0 GPa, respectively; the corresponding values at 91 days were 31.6 and 32.5 GPa, respectively. Previous published data [7,8] show that the "E" values for the high-volume fly ash concrete are generally higher than those of the normal-portland cement concrete with similar 28-day compressive strength. The lower "E" values of Mixture 1 (Batch A) was due mainly to its high air content and low strength.

7.6. Drying Shrinkage

The drying shrinkage strains for the concretes investigated were low, and did not exceed 450×10^{-6} at 112 days (Table 11). The highest value of 450×10^{-6} was for the concrete made with blended cement BCG, and the lowest value of 312×10^{-6} was for the control concrete made with the LPC cement.

7.7. Resistance to Abrasion

Figure 1 presents the results of the abrasion resistance of the concrete. The depth of abrasion of the concrete ranged from 1.3 to 1.6 mm after 20 minutes of testing. The lowest value was for the concrete made with HVFA blended cement, and the highest value was for the concrete in which

the unground fly ash and the LPC had been added separately to the concrete mixer. These results are a function of the compressive strength of the concrete.

7.8. Resistance to Chloride-Ion Penetration

The resistance to the chloride-ion penetration determined according to ASTM C 1202 was significantly higher for the concrete incorporating fly ash than for the control concrete (Table 12). At 91 days, the total charge passed, in coulombs, was less than 400 coulombs for the HVFA concretes compared with > 2000 coulombs for the control concrete. The concrete made with the blended cement BCG (Mixture 2) showed higher resistance to the chloride-ion penetration at 28 days than the mixture in which fly ash had been added as a separate ingredient at the concrete mixer. However, at 91 days, the resistance of these two HVFA concrete mixtures was similar.

7.9. Resistance to Freezing and Thawing Cycling

The durability of the concrete to the repeated cycles of freezing and thawing was determined from changes in length, mass, resonant frequency, and pulse velocity of the test specimens before and after the freezing and thawing cycling, and by calculating the durability factors (Table 13). At the end of the 300 freezing and thawing cycling, the flexural strength of the control and test prisms were also determined (Table 14). The test data indicated that all the test prisms had excellent performance in freezing and thawing cycling with durability factors ranging from 95 to 102. The residual flexural strength of the prisms also demonstrated good resistance of the concrete to the freezing and thawing cycling with values ranging from 72.6 to 93.0 % of the control prisms (Table 14).

7.10. Resistance to De-Icing Salt Scaling

The slabs made with the HVFA concrete exhibited severe scaling (Table 15 and figure 2), and with a visual rating of 5 according to ASTM C 672, and cumulative scaling residues of 4.1 ± 0.4 kg/m².

The scaling of the slabs cast from the control concrete made with the LPC cement was negligible with a visual rating of 1, and with the cumulative scaling residue of 0.1 kg/m². The concrete slabs made with the commercially available ASTM Type III cement showed moderate scaling with a visual rating of 3, and with the cumulative scaling residue of 1.5 kg/m² that was above 0.8 kg/m², a value specified by Ontario Ministry of Transportation for satisfactory performance in the de-icing salt scaling test [9].

8. Conclusions

The coarse Genesee fly ash that fails to meet the fineness requirement of ASTM C 618 was successfully used to produce a HVFA blended cement. Except for the resistance of the concrete to the de-icing salt scaling, the mechanical properties and durability of the concrete made with this blended cement were superior to the concrete in which the unground fly ash and the cement had been added separately at the mixer. The production of HVFA blended cements, therefore, offers an effective way for the utilization of coarse fly ashes that otherwise do not meet ASTM C 618 requirements for fineness.

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Table 1 - Physical properties and chemical analyses of the materials used

	Clinker**	Fly ash	
		Genesee	
<u>Physical properties</u>			
Specific gravity	3.23		2.01
Fineness			
-passing 45 Φ m, %	-		64.1
-specific surface, Blaine, cm ² /g	-		2120
-median particle size (:m)	-		21.2
Water requirement, %	-		95.8
Pozzolanic Activity Index,* %			
-7-day	-		76.0
-28-day	-		90.5
<u>Chemical analyses, %</u>			
Silicon dioxide (SiO ₂)	22.3		62.6
Aluminum oxide (Al ₂ O ₃)	4.5		20.9
Ferric oxide (Fe ₂ O ₃)	3.4		4.5
Calcium oxide (CaO)	65.5		5.8
Magnesium oxide (MgO)	2.9		1.5
Sodium oxide (Na ₂ O)	0.4		2.5
Potassium oxide (K ₂ O)	0.8		1.7
Equivalent alkali (Na ₂ O+0.658K ₂ O)	0.9		3.6
Phosphorous oxide (P ₂ O ₅)	0.2		0.1
Titanium oxide (TiO ₂)	0.2		0.7
Sulphur trioxide (SO ₃)	<0.01		0.1
Loss on ignition	0.01		0.3

* using ASTM Type I cement

** obtained from a cement producer, and used for the production of cements in the laboratory

Table 2 - Physical properties and chemical composition of the cements used

	ASTM Type III cement	LPC	BCG	ASTM requirements	
				C 150 Type III	C 1157 GU
<u>Physical properties</u>					
Specific gravity	3.15	3.15	2.70	-	-
Fineness					
-passing 45 μ m, %	93	88.5	99.4	-	-
-specific surface, Blaine, cm ² /g	5070	4000	-	-	-
Compressive strength of 51 mm cubes, MPa					
-1-day	30.7	15.3	-	12.4 (min)*	-
-3-day	38.8	24.2	13.1	24.1 (min)	10 (min)
-7-day	-	31.0	18.0	-	17 (min)
Time of setting, Vicat test, min					
-initial setting	115	130	275	45 (min)	45 (min)
-final setting	210	240	380	375 (max) ⁺	420 (max)
Air content of mortar, volume %	6.9	6.6	3.9	12 (max)	-
<u>Chemical analyses, %</u>					
Silicon dioxide (SiO ₂)	21.2	20.9	39.6	-	-
Aluminium oxide (Al ₂ O ₃)	5.0	4.8	11.8	-	-
Ferric oxide (Fe ₂ O ₃)	1.8	3.3	3.3	-	-
Calcium oxide (CaO)	63.6	62.4	36.9	-	-
Magnesium oxide (MgO)	3.0	2.8	2.1	6.0 (max)	-
Sodium oxide (Na ₂ O)	0.1	0.3	1.3	-	-
Potassium oxide (K ₂ O)	0.6	0.9	1.4	-	-
Equivalent alkali (Na ₂ O+0.658K ₂ O)	0.5	0.9	2.2	-	-
Phosphorous oxide (P ₂ O ₅)	0.1	0.2	0.2	-	-
Titanium oxide (TiO ₂)	0.3	0.2	0.5	-	-
Sulphur trioxide (SO ₃)	2.0	3.4	1.9	3.5 (max)	-
Loss on ignition	2.1	0.7	0.9	3.0 (max)	-
<u>Bogue potential compound composition</u>					
Tricalcium silicate C ₃ S	55.5	48.5	-	-	-
Dicalcium silicate C ₂ S	19.0	23.3	-	-	-
Tricalcium aluminate C ₃ A	10.3	7.1	-	15 (max)	-
Tetracalcium aluminoferrite C ₄ AF	5.5	10	-	-	-

* minimum + maximum

Table 3 - Grading of coarse and fine aggregate

Coarse aggregate		Fine aggregate	
Sieve size, mm	Passing, %	Sieve size, mm	Passing, %
19.0	100	4.75	100
12.7	70	2.36	90.0
9.5	32	1.18	67.5
4.75	0	0.600	42.5
		0.300	20.0
		0.150	6.0

Table 4 - Proportions of the concrete mixtures

Mix. no.	Batch	$\frac{W}{(C+FA)^*}$	Water, kg/m ³	Cement		Fly ash added in the mixer		Fine aggregate, kg/m ³	Coarse aggregate, kg/m ³	AEA,** mL/m ³	SP,*** L/m ³
				type	kg/m ³	source	kg/m ³				
1	A	0.32	120	LPC	168	Genesee	206	701	1052	486	2.5
	B	0.32	122	LPC	170	Genesee	209	710	1066	305	2.5
2	A	0.32	125	BCG	391	-	-	740	1111	509	3.6
	B	0.32	125	BCG	391	-	-	740	1111	509	3.6
3	A	0.40	154	LPC	385	-	0	729	1094	116	1.0
	B	0.40	154	LPC	385	-	0	729	1094	106	0.9
4	A	0.42	164	III	389	-	0	729	1093	174	2.2
	B	0.42	162	III	384	-	0	720	1081	172	1.4

* Water-to-(cement+fly ash) ratio

** Air-entraining admixture

*** Superplasticizer. The superplasticizer was used in a dry form. The values reported in this Table is the corresponding volume of liquid superplasticizer that was calculated assuming its density of 1.21 kg/cm³ and solid content of 40% by mass

Table 5 - Testing schedule of concrete

Mix. no.	Batch	Type of testing	Age of testing, days							
			0	1	7	14	28	91	365	730
		Compressive strength (ASTM C 39)		3 cyl.	3 cyl.	3 cyl.	3 cyl.	3 cyl.	3 cyl.	3 cyl.
		Resistance to the chloride-ion penetration (ASTM C 1202)					2 disks	2 disks		
		Splitting tensile strength (ASTM C 496)					2 cyl.			
1-4	A	Young's modulus of elasticity (ASTM C 469)					2 cyl.	2 cyl.		
		Bleeding (ASTM C 232)	Fresh Concrete							
		Setting times (ASTM C 403)	Fresh Concrete							
		Slump loss	Fresh Concrete							
		Air content stability	Fresh Concrete							
		Compressive strength (ASTM C 39)			2 cyl.*	2 cyl.*	3 cyl.	2 cyl.*		
1-4	B	Flexural strength (ASTM C 78)				2 prisms	2 prisms			
		De-icing salt-scaling (ASTM C 672)					2 slabs			
		Abrasion						1 slab		
		Resistance to the freezing and thawing cycling (ASTM C 666, Procedure A)	After 14 days of moist curing, two prisms were exposed to freezing and thawing cycling. Two prisms were kept in the moist-curing room until the end of the freezing and thawing cycling.							
		Drying shrinkage (ASTM C 157)	Two prisms were exposed to air at 50% relative humidity and 23°C after 7 days in lime-saturated water curing. Two prisms were kept in water for control purpose.							

*tested for mixture 1 only.

Table 6 - Properties of the fresh concrete

Mixture no.	Batch	W/(C+FA)	Cement type	Source of fly ash added in the mixer	Unit weight, kg/m ³	Slump, mm	Air content, %
1	A	0.32	LPC	Genesee	2250	190	8.5
	B	0.32	LPC	Genesee	2280	160	7.2
2	A	0.32	BCG	-	2370	200	6.2
	B	0.32	BCG	-	2370	215	5.7
3	A	0.40	LPC	-	2362	70	6.9
	B	0.40	LPC	-	2362	90	7.1
4	A	0.42	III	-	2376	70	5.9
	B	0.42	III	-	2348	75	6.2

Table 7 - Slump loss and stability of the air content of the fresh concrete

Mixture no.	$\frac{W}{(C+FA)}$	Cement type	Source of fly ash added in the mixer	Immediately after mixing		35 min. after the mixing was completed		65 min. after the mixing was completed	
				Slump, m	Air content, %	Slump, m	Air content, %	Slump, mm	Air content, %
1 (Batch B)	0.32	LPC	Genesee	160	7.2	80	6.0	70	4.4
2 (Batch B)	0.32	BCG	-	215	5.7	140	4.1	105	3.2
3 (Batch B)	0.40	LPC	-	90	7.1	65	6.2	50	5.4
4 (Batch B)	0.42	III	-	75	6.2	40	5.6	30	4.2

Table 8 - Bleeding and setting time of concrete

Mixture no.	W/(C+FA)	Cement type	Source of fly ash added in the mixer	Total Bleeding Water, mL/cm ²	Setting Time, h:min	
					Initial	Final
1	0.32	LPC	Genesee	0.032	8:00	10:30
2	0.32	BCG	-	0.004	7:25	9:50
3	0.40	LPC	-	0.023	4:15	5:35
4	0.42	III	-	0.006	3:55	5:15

Table 9 - Compressive strength of concrete

Mix. no.	Batch	W/(C+FA)	Cement type	Source of fly ash added in the mixer	Density of hardened concrete (1-d) kg/m ³	Compressive strength, MPa						
						1 d	7 d	14 d	28 d	91 d	365 d	730 d
1	A	0.32	LPC	Genesee	2248	7.7	15.9	19.6	24.0	32.7	40.3	n.a
	B	0.32	LPC	Genesee	-	-	20.9	27.1	30.5	41.6	-	-
2	A	0.32	BCG	-	2385	13.1	30.5	37.5	43.8	53.7	61.9	n.a
	B	0.32	BCG	-	-	-	-	-	43.3	-	-	-
3	A	0.40	LPC	-	2381	21.4	32.5	34.4	38.6	43.4	n.a	n.a
	B	0.40	LPC	-	-	-	-	-	38.8	-	-	-
4	A	0.42	III	-	2376	30.5	39.1	41.0	46.3	50.4	n.a	n.a
	B	0.42	III	-	-	-	-	-	42.1	-	-	-

n.a.: data not yet available

Table 10 - Flexural, splitting-tensile strengths and Young's modulus of elasticity of concrete

Mixture no.	W/(C+FA)	Cement type	Source of fly ash added in the mixer	Flexural strength, MPa			Splitting-tensile strength, MPa		Young's modulus of elasticity, GPa	
				14 d	28 d				28 d	14 d
1	0.32	LPC	Genesee	3.2	4.0		2.2		22.4	30.6
2	0.32	BCG	-	3.9	5.1		3.2		34.4	38.7
3	0.40	LPC	-	5.6	6.3		3.3		30.3	31.6
4	0.42	III	-	6.5	6.7		3.4		33.0	32.5

Table 11 - Drying shrinkage test results after 7 days of curing in lime-saturated water

Mixture no.	W/(C+FA)	Cement type	Source of fly ash added in the mixer	Drying shrinkage strain, x 10 ⁻⁶						
				7 d	14 d	28 d	56 d	112 d	224 d	448 d
1	0.32	LPC	Genesee	142	258	272	341	414	403	n.a
2	0.32	BCG	-	254	330	385	435	450	428	n.a
3	0.40	LPC	-	109	178	283	290	312	n.a	n.a
4	0.42	III	-	196	287	388	396	388	n.a	n.a

n.a.: data not yet available

Table 12 - Resistance to the chloride-ion penetration

Mixture no.	W/(C+FA)	Cement type	Source of fly ash added in the mixer	Total charge passed, coulombs		
				28 d	91 d	365 d
1	0.32	LPC	Genesee	1170	320	110
2	0.32	BCG	-	333	290	105
3	0.40	LPC	-	2580	2140	n.a
4	0.42	III	-	2432	2100	n.a

n.a.: data not yet available

Table 13 - Summary of test results after 300 cycles of freezing and thawing

Mixture no.	W/(C+FA)	Cement type	Source of fly ash added in the mixer	% change at the end of the freezing and thawing cycling				Durability Factor
				Length	Weight	Pulse Velocity	Resonant Frequency	
1	0.32	LPC	Genesee	0.004	-0.587	+0.20	-2.36	95
2	0.32	BCG	-	0.002	+0.007	-1.30	+0.92	102
3	0.40	LPC	-	-0.002	-0.126	-0.24	-2.35	95
4	0.42	III	-	-0.030	-0.055	+0.54	-0.22	95

Table 14 - Flexural strength of control prisms and test prisms after the freezing and thawing cycling

Mixture no.	W/(C+FA)	Cement type	Source of fly ash added in the mixer	Flexural strength, MPa			Residual Flexural Strength, %
				14 days	Control prisms*	After 300 cycles of freezing and thawing	
1	0.32	LPC	Genesee	3.2	6.2	4.5	72.6
2	0.32	BCG	-	3.9	6.5	5.7	87.7
3	0.40	LPC	-	5.6	7.2	5.4	75.0
4	0.42	III	-	6.5	7.1	6.6	93.0

* Control prisms had been put in the moist-cured room and were tested at the same age as the prisms which had completed 300 cycles of freezing and thawing

Table 15 - Test results of de-icing salt-scaling

Mixture No.	W/(C+FA)	Cement type	Source of fly ash added in the mixer	Visual rating* (ASTM C672)	Total scaling residue (kg/m ²)
1	0.32	LPC	Genesee	5	4.5
2	0.32	BCG	-	5	3.7
3	0.40	LPC	-	1	0.1
4	0.42	III	-	3	1.5

* Rating (ASTM C 672)

0 No scaling

1 Very slight scaling (3.2 mm depth max, no coarse aggregate visible)

2 Slight to moderate scaling

3 Moderate scaling, (some coarse aggregate visible)

4 Moderate to severe

5 Severe scaling, (coarse aggregate visible over the entire surface)

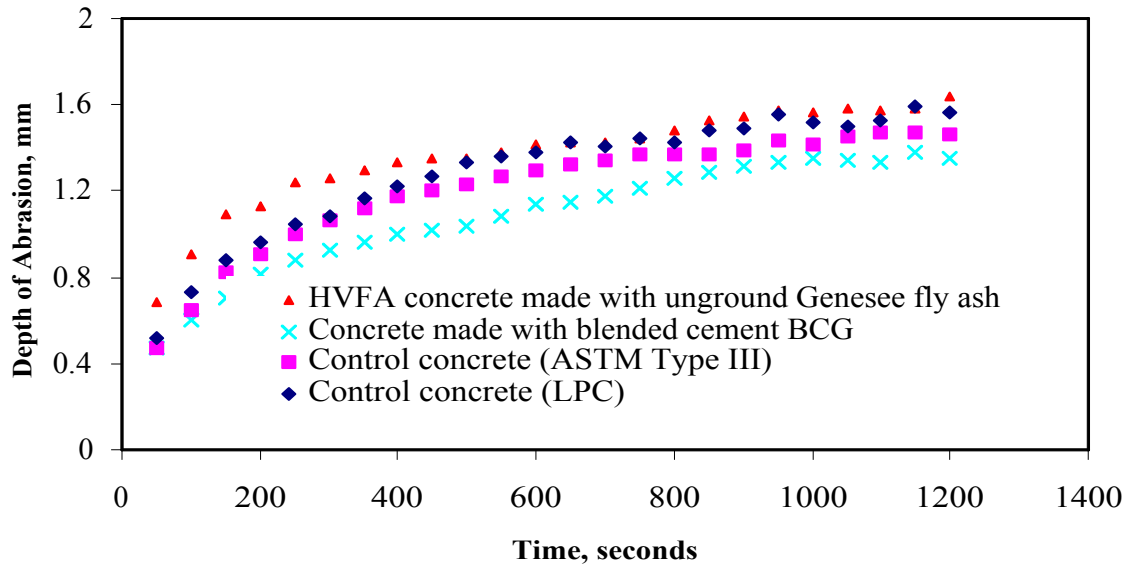


Fig. 1 - Depth of abrasion vs. duration of wearing of concrete

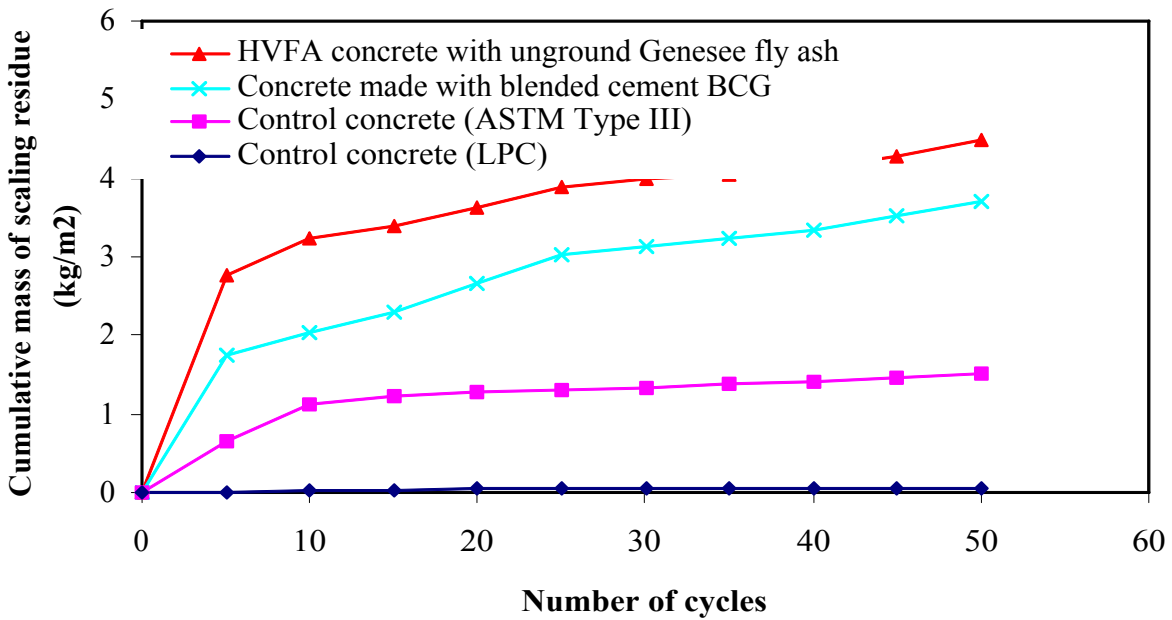


Fig. 2 - Variation of the cumulative mass of scaling residue vs. the number of cycles