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# Mechanical properties and durability of concrete made with high-volume fly ash blended cements using a coarse fly ash

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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 (HVFA) 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 deicing salt scaling. The results show that except for the resistance of the concrete to the deicing 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. 

*Keywords:* Blended cement; Compressive strength; Concrete; Durability; Fly ash

## 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 $CO_2$ 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 HVFA 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 an HVFA 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-

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and splitting-tensile strengths, Young's modulus of elasticity, drying shrinkage, resistance to abrasion, chloride-ion penetration, freezing and thawing cycling, and to deicing 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 35.9%. This ash, therefore, fails to meet the fineness requirement of ASTM C 618.[1] The ash has a relatively low specific gravity, and this is primarily related to a large number 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.

Table 1
Physical properties and chemical analyses of the materials used

| | Clinker[a] | Fly ash, Genesee |
|---|---|---|
| *Physical properties* | | |
| Specific gravity | 3.23 | 2.01 |
| Fineness | | |
| passing 45 μm, % | – | 64.1 |
| specific surface, Blaine, $cm^2/g$ | – | 2120 |
| median particle size (μm) | – | 21.2 |
| Water requirement, % | – | 95.8 |
| Pozzolanic Activity Index,[b] % | | |
| 7-day | – | 76.0 |
| 28-day | – | 90.5 |
| *Chemical analyses, %* | | |
| Silicon dioxide ($SiO_2$) | 22.3 | 62.6 |
| Aluminum oxide ($Al_2O_3$) | 4.5 | 20.9 |
| Ferric oxide ($Fe_2O_3$) | 3.4 | 4.5 |
| Calcium oxide (CaO) | 65.5 | 5.8 |
| Magnesium oxide (MgO) | 2.9 | 1.5 |
| Sodium oxide ($Na_2O$) | 0.4 | 2.5 |
| Potassium oxide ($K_2O$) | 0.8 | 1.7 |
| Equivalent alkali ($Na_2O+0.658K_2O$) | 0.9 | 3.6 |
| Phosphorous oxide ($P_2O_5$) | 0.2 | 0.1 |
| Titanium oxide ($TiO_2$) | 0.2 | 0.7 |
| Sulfur trioxide ($SO_3$) | < 0.01 | 0.1 |
| Loss on ignition | 0.01 | 0.3 |

[a] Obtained from a cement producer, and used for the production of cements in the laboratory.
[b] Using ASTM Type I cement.

### *2.4. Superplasticizer*

A sulfonated naphthalene–formaldehyde condensate type of superplasticizer in a powder form was used in all the concrete mixtures.

### *2.5. Air-entraining admixture (AEA)*

A synthetic resin type 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 $cm^2/g$ (LPC), and then intergrinding 45% (by mass) of the above cement with 55% of the fly ash for 80 min. 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 approxi-

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

Table 2
Physical properties and chemical composition of the cements used

| | ASTM Type III cement | LPC | BCG | ASTM requirements C 150 Type III | ASTM requirements C 1157 GU |
|---|---|---|---|---|---|
| *Physical properties* | | | | | |
| Specific gravity | 3.15 | 3.15 | 2.70 | – | – |
| Fineness | | | | | |
| passing 45 μm, % | 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)[a] | – |
| 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)[b] | 420 (max) |
| Air content of mortar, volume % | 6.9 | 6.6 | 3.9 | 12 (max) | – |
| *Chemical analyses, %* | | | | | |
| Silicon dioxide ($SiO_2$) | 21.2 | 20.9 | 39.6 | – | – |
| Aluminum oxide ($Al_2O_3$) | 5.0 | 4.8 | 11.8 | – | – |
| Ferric oxide ($Fe_2O_3$) | 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 ($Na_2O$) | 0.1 | 0.3 | 1.3 | – | – |
| Potassium oxide ($K_2O$) | 0.6 | 0.9 | 1.4 | – | – |
| Equivalent alkali ($Na_2O + 0.658K_2O$) | 0.5 | 0.9 | 2.2 | – | – |
| Phosphorous oxide ($P_2O_5$) | 0.1 | 0.2 | 0.2 | – | – |
| Titanium oxide ($TiO_2$) | 0.3 | 0.2 | 0.5 | – | – |
| Sulfur trioxide ($SO_3$) | 2.0 | 3.4 | 1.9 | 3.5 (max) | – |
| Loss on ignition | 2.1 | 0.7 | 0.9 | 3.0 (max) | – |
| *Bogue potential compound composition* | | | | | |
| Tricalcium silicate ($C_3S$) | 55.5 | 48.5 | – | – | – |
| Dicalcium silicate ($C_2S$) | 19.0 | 23.3 | – | – | – |
| Tricalcium aluminate ($C_3A$) | 10.3 | 7.1 | – | 15 (max) | – |
| Tetracalcium aluminoferrite ($C_4AF$) | 5.5 | 10 | – | – | – |

[a] Minimum.
[b] Maximum.

mately 10 kg material was used for the production of the cements. A combination of 35 kg of large ceramic cylinders (30 mm thickness and 30 mm diameter) and 35 kg of medium ceramic cylinders (20 mm thickness and 20 mm diameter) was used for grinding. The weight ratio of the materials to be ground to the grinding media was 1:7.

Table 3
Grading of coarse and fine aggregate

| Coarse aggregate Sieve size, mm | Coarse aggregate Passing, % | Fine aggregate Sieve size, mm | Fine aggregate 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 |

## 4. Mixture proportions

Two HVFA 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 h. 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 h.

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

Table 4
Proportions of the concrete mixtures

| Mix no. | Batch | W/(C + FA)[a] | Water, kg/m$^3$ | Cement type | Cement kg/m$^3$ | Fly ash added in the mixer source | Fly ash added in the mixer kg/m$^3$ | Fine aggregate, kg/m$^3$ | Coarse aggregate, kg/m$^3$ | AEA,[b] ml/m$^3$ | SP,[c] l/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 |

[a] Water-to-(cement + fly ash) ratio.
[b] Air-entraining admixture.
[c] 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/cm$^3$ and solid content of 40% by mass.

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 5 min in a laboratory counter-current mixer, and for each concrete mixture two batches were made.

### 5.1. Batch A

Twenty-four 102 × 203-mm and six 152 × 305-mm cylinders were cast for each concrete mixture. The 102 × 203-mm cylinders were used for the determination of the compressive strength and the resistance to the chloride ion-penetration of the concrete, and the 152 × 305-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

Table 5
Testing schedule of concrete

| Mixture no. | Batch | Type of testing | Age of testing, days 0 | 1 | 7 | 14 | 28 | 91 | 365 | 730 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1–4 | A | Compressive strength (ASTM C 39) | | 3 cylinders | 3 cylinders | 3 cylinders | 3 cylinders | 3 cylinders | 3 cylinders | 3 cylinders |
| | | Resistance to the chloride-ion penetration (ASTM C 1202) | | | | | 2 disks | 2 disks | | |
| | | Splitting tensile strength (ASTM C 496) | | | | | 2 cylinders | | | |
| | | Young's modulus of elasticity (ASTM C 469) | | | | | 2 cylinders | 2 cylinders | | |
| | | Bleeding (ASTM C 232) | Fresh concrete | | | | | | | |
| | | Setting times (ASTM C 403) | Fresh concrete | | | | | | | |
| 1–4 | B | Slump loss | Fresh concrete | | | | | | | |
| | | Air content stability | Fresh concrete | | | | | | | |
| | | Compressive strength (ASTM C 39) | | | 2 cylinders[a] | 2 cylinders[a] | 3 cylinders | 2 cylinders[a] | | |
| | | Flexural strength (ASTM C 78) | | | | 2 prisms | 2 prisms | | | |
| | | Deicing 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 purposes. | | | | | | | |

[a] 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. | 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, mm | Air content, % | Slump, mm | 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 |

fresh concrete for determining the bleeding, and one 152 × 15 × 152-mm mould was filled with mortar obtained by sieving the fresh concrete for determining the setting times of concrete.

### 5.2. Batch B

Three 102 × 203-mm cylinders were cast for the determination of the compressive strength at 28 days. For Mixture 1, six additional 102 × 203-mm cylinders were cast for the determination of the compressive strength at 7, 14, 28, and 91 days. Eight 76 × 102 × 390-mm prisms were cast for determining the drying shrinkage and the resistance of the concrete to freezing and thawing cycling. Four 76 × 102 × 406-mm prisms were cast for the determination of the flexural strength of the concrete, and three slabs, 300 × 300 × 75 mm in size, were cast for the deicing 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 152 × 305-mm cylinders and a vibrating table for the other specimens. After casting, all the molded specimens were covered with plastic sheets and water-saturated burlap, and left in the casting room for 24 h. They were then demolded and transferred to the moist-curing room at 23 ± 2 °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 ± 2 °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 strength[2] 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 strength[2] 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 mold 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.

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 |

### *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 deicing 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 LPC meets the general requirements of ASTM C 150 Type III cement. Its initial- and final-setting times were 130 and 240 min, respectively, that were within the range of 45–375 min 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 min, respectively, and these were within the range of 45–420 min 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

Table 9
Compressive strength of concrete

| Mixture no. | Batch | W/(C + FA) | Cement type | Source of fly ash added in the mixer | Density of hardened concrete (1 day) kg/m$^3$ | Compressive strength, MPa | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1 day | 7 days | 14 days | 28 days | 91 days | 365 days | 730 days |
| 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 days | 28 days | 28 days | 28 days | 91 days |
| 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 |

to 150 mm, and ranged from 0.9 to 3.6 l/m$^3$ 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 LPC and unground fly ash. The increase of the superplasticizer was from 2.5 l/m$^3$ for Mixture 1 to 3.6 l/m$^3$ 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/m$^3$ 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 $C_3A$ content of ASTM Type III cement were higher than those of the LPC.

#### *7.2.2. Dosage of the AEA and air content*

The dosage of the 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 5–7%. 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 min.

#### *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/cm$^2$. 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

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, $\times 10^{-6}$ | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 7 days | 14 days | 28 days | 56 days | 112 days | 224 days | 448 days |
| 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.

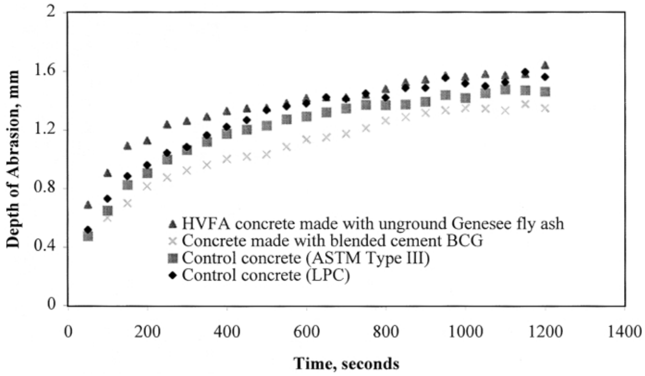


Fig. 1. Depth of abrasion vs. duration of wearing of concrete.

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 and 55 min to 8 h, and from 5 h and 15 min to 10 h and 30 min, respectively (Table 8). The setting times of the HVFA concrete were 3 to 5 h 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 HVFA concrete by 30 to 40 min; 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 5–7%. 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 HVFA concrete ranging from 30% at 91 days to 45% at 7 days.

At 1 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 HVFA 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 HVFA 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 $450 \times 10^{-6}$ at 112 days (Table 11). The highest value of $450 \times 10^{-6}$ was for the concrete made with blended cement BCG, and the lowest value of $312 \times 10^{-6}$ was for the control concrete made with the LPC cement.

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 days | 91 days | 365 days |
| 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: Length | Weight | Pulse velocity | Resonant frequency | Durability factor |
|---|---|---|---|---|---|---|---|---|
| 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: 14 days | Control prisms[a] | After 300 cycles of freezing and thawing | Residual flexural strength, % |
|---|---|---|---|---|---|---|---|
| 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 |

[a] 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.

### 7.7. Resistance to abrasion

Fig. 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 min 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 (C), was less than 400 C for the HVFA concretes compared with > 2000 C 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 deicing salt scaling

The slabs made with the HVFA concrete exhibited severe scaling (Table 15 and Fig. 2), and with a visual rating of 5 according to ASTM C 672, and cumulative scaling residues of $4.1 \pm 0.4$ kg/m$^2$.

Table 15
Test results of deicing salt-scaling

| Mixture no. | W/(C + FA) | Cement type | Source of fly ash added in the mixer | Visual rating[a] (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 |

[a] 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).

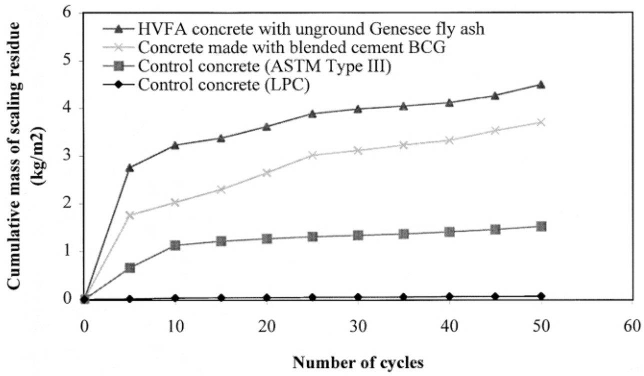


Fig. 2. Variation of the cumulative mass of scaling residue versus the number of cycles.

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/m$^2$. 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/m$^2$ that was above 0.8 kg/m$^2$, a value specified by Ontario Ministry of Transportation for satisfactory performance in the deicing 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 deicing 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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