

Mechanical Properties and Durability of Concrete made with HVFA Blended Cement Produced in a Cement Plant

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ABSTRACT

This paper presents the results of a study on the mechanical properties and durability of concrete made with High-Volume Fly Ash (HVFA) blended cement produced in a cement plant. The test results obtained were compared with those of a control concrete made with a commercially available ASTM Type I cement; the control concrete had 28-day compressive strength comparable to that of the concrete made with the HFA blended cement.

The results showed that in order to obtain similar slump and air content to those of the control concrete, the use of HVFA blended cement required increased dosages of the superplasticizer and the air-entraining admixture. This resulted in some delay in the initial and final setting times of concrete.

The use of HVFA blended cement resulted in lower compressive and flexural strengths at early ages (before 28 days) and higher mechanical properties after 28 days as compared with those of the control concrete made with ASTM Type I cement. The concrete made the HVFA blended cement developed a 1-day compressive strength of 13 MPa, (compared to 19 MPa for the control concrete) that is considered more than satisfactory for formwork removal.

The use of the HVFA blended cement improved significantly the durability characteristics of the concrete; the only exception was the resistance to the de-icing salt scaling as determined in ASTM C 672 test.

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INTRODUCTION

At present, the production of high-volume fly ash (HVFA) concrete involves the addition of large volumes of fly ash as a separate ingredient at a ready-mixed concrete-batch plant. This necessitates additional storage capacity at the batching plant and quality control at the job site. In order to resolve these issues, CANMET, in partnership with Electric Power Research Institute, Palo Alto, U.S.A., undertook a major research project to develop blended cements incorporating large volumes of ASTM Class F fly ash. The blended cements are made by intergrinding approximately 55% of fly ash and 45% of ASTM Type I cement clinker together with a small amount of gypsum to controlling setting time.

The results of recent laboratory investigations performed at CANMET have shown that the mechanical properties and durability characteristics of concrete made with the laboratory-produced HVFA blended cements are comparable or superior to those of the control concrete using commercially available ASTM Type I cement [1]. Following this, a HVFA blended cement was produced at a grinding facility located in Washington, U.S.A. The cement clinker used was produced at a plant in western Canada, and was the same as that used to produce ASTM Type I cement, and the ASTM Class F fly ash used was from Washington State, U.S.A.

This paper presents the results of a study on the mechanical properties and durability of concrete made with the HVFA blended cement described above. The results were compared with those of a control concrete made with a commercially available ASTM Type I cement. The properties of the fresh concrete determined include the slump loss, stability of air content, bleeding, and setting time; those of the hardened concrete investigated include the compressive strength, flexural- and splitting-tensile strengths, Young's modulus of elasticity, drying shrinkage, air void parameters, and resistance to abrasion, chloride-ion penetration, freezing and thawing cycling, and de-icing salt scaling.

PRODUCTION OF HVFA BLENDED CEMENT

The HVFA blended cement was produced in a grinding facility located in Washington State, U.S.A. using the clinker produced at a plant in western Canada, and the locally available ASTM Class F fly ash from the Centralia plant in Washington State. The plant has the necessary equipment for the production of ASTM Type IP blended fly ash cement. Figure 1 shows a line diagram of the grinding process used in the plant for the production of the blended fly ash cement.

The plant has a grinding mill with a capacity of 20 tonnes, and a fly ash silo with a capacity of 6 tonnes. Thus, the production of a blended fly ash cement that incorporates 55% of fly ash was limited to a grinding capacity of 11 tonnes, i.e. 6 tonnes of fly ash and 5 tonnes of clinker plus gypsum. This was far below the optimum capacity of the mill. The plant was certainly not set up for the production of a HVFA blended cement. In fact, the production of the blended fly ash cement that incorporates more than 30% fly ash (which is the ratio of the maximum capacity of the fly ash silo to that of the grinding mill) would effectively reduce the production capacity of the plant.

The facility used for grinding did not allow 100% of the fly ash to be interground with cement. As shown in Fig. 1, the fly ash, as received, is introduced into a separator. The fine particles of the fly ash are separated and moved to join the final product. The coarse fly ash particles go through the grinding mill with the clinker and gypsum. Therefore, the blended cement produced during the first stage of the process will not, necessarily, incorporate 55% of fly ash. However, it was expected that after 30 to 45 minutes of running the mill, the blended cement **production** would stabilize and include approximately 55% of fly ash.

The grinding lasted for 2 hours; 12 tonnes of HVFA blended cement was produced and stored in three loads of four tonnes each. Two tonnes of blended cement was shipped to the CANMET laboratory, one tonne from the second load designated as BC45, and one tonne from the last load designated as BC65.

The physical properties and the chemical analysis of the two samples of the blended cement produced at the plant are presented in Table 1. The chemical compositions of the two samples indicate that the cement produced was not homogenous. In fact, the blended cement BC45 incorporated 45% of fly ash, and the blended cement BC65 incorporated 65% of fly ash. These numbers were calculated based on the chemical compositions of the ASTM Type I cement and that of the fly ash; the latter results are also presented in Table 1. The physical properties showed that the blended cement BC45 met the requirements of ASTM C 1157 M, whereas, the blended cement BC65 did not (i.e. 7-day compressive strength < 17 MPa).

Since the objective of the project was to evaluate the performance of concrete made with a blended cement that incorporates 55% of fly ash, a third batch of cement was produced at the CANMET laboratory by blending 50% of BC45 and 50% of BC65. The blended cement was designated as BC55.

MATERIALS USED

Portland cement

ASTM Type I portland cement produced at the Tilbury Cement plant, Delta, British Columbia, Canada, was used for the control concrete. Its physical properties and chemical composition are presented in Table 1.

Blended fly ash cements

The blended cements BC45 and BC55 were used to make the test concretes. The physical properties and chemical compositions of the cements are also presented in Table 1.

Admixtures

A sodium salt of naphthalene sulfonate polymer was used as a superplasticizer. A synthetic resin type air-entraining admixture was used in all the concrete mixtures.

Aggregates

Crushed granite with a maximum nominal size of 19 mm was used as coarse aggregate, and a local natural sand was used as fine aggregate. The coarse aggregates were separated into different size fractions and recombined to a specific grading. The coarse and fine aggregates each had a specific gravity of 2.70, and water absorption values of 0.5 and 0.8%, respectively.

MIXTURE PROPORTIONS

Two fly ash concrete and one control portland-cement concrete mixtures were made. One fly ash concrete mixture was made with the blended cement incorporating 45% of fly ash (BC45), and the other mixture was made with the blended cement incorporating 55% of fly ash (BC55). The control portland-cement concrete was made with the control ASTM Type I cement. The proportions of the concrete mixtures are summarized in Table 2.

A water-to-cementitious materials ratio of 0.33 was used for the fly ash concrete mixtures. The water-to-cement ratio of the control concrete made with the ASTM Type I cement was 0.45; this was chosen in order to obtain concrete with a 28-day compressive strength similar to that of the concrete made with the fly ash blended cements. All concrete mixtures were air-entrained with a target air content of $6 \pm 1\%$.

It is, once again, emphasized that the water-to-cement ratio for the control concrete is significantly higher than that of the concrete made with the HVFA blended cement because comparison is based on “equal-strength basis”. If the comparison was based on equal W/C, the 28-day compressive strength for the control concrete would be significantly higher, but for the same slump it would require very high dosage of superplasticizer and the resistance to chloride-ion penetration would not be affected significantly [2].

PREPARATION AND CASTING OF TEST SPECIMENS

For all the mixtures, the coarse and fine aggregates were weighed as received. 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.

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

Batch A

Twenty four 100 x 200-mm and seven 150 x 300-mm cylinders were cast from each concrete mixture. The 100 x 200-mm cylinders were used for the determination of the compressive strength and the resistance to chloride ion-penetration of the concrete. The 150 x 300-mm cylinders were used for determining the splitting-tensile strength, Young's modulus of elasticity, and the autogenous temperature rise in the concrete. One container of approximately 7L

capacity was filled with fresh concrete for determining the bleeding, and one 150 x 150 x 150-mm mould was filled with mortar obtained by sieving the fresh concrete for determining the setting times of the concrete.

Batch B

Three 100 x 200-mm cylinders were cast for the determination of the compressive strength at 28 days. Eight 75 x 100 x 400-mm prisms were cast for determining the drying shrinkage and the resistance of the concrete to freezing and thawing cycling. Four 75 x 100 x 400-mm prisms were cast for the determination of the flexural strength of the concrete, and sawn sections of these prisms were used for the determination of the air-void parameters of the hardened concrete. Six slabs, 300x300x75 mm in size, were cast for the de-icing salt-scaling test, and for the determination of the resistance of concrete to abrasion and to chloride-ion penetration using the AASHTO 259-80 ponding test.

CONSOLIDATION AND CURING OF TEST SPECIMENS

All the cylinder and prism test specimens were cast in two layers, with each layer being consolidated using an internal vibrator for the 150 x 300-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 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 being transferred to a conditioned chamber at $20 \pm 2^\circ\text{C}$ and 50 % relative humidity.

TESTING OF THE SPECIMENS

Mechanical Properties

For each mixture, the compressive strength was determined on three cylinders from batch A at 1, 7, 14, 28 and 91 days. The strength will also be determined at 365 and 730 days. Three cylinders from batch B were tested for the compressive strength at 28 days for control purposes. For each mixture, the flexural strength was determined on two prisms each at 14 and 28 days; the splitting-tensile strength was determined at 28 days using two cylinders. The drying shrinkage was determined on two prisms at 7, 14, 28, 56, and 112 days. The shrinkage measurements will also be taken at 224 and 448 days (two other prisms were stored in the lime-saturated water one day after casting and their length change was measured for control purposes). All the above tests were carried out following the relevant ASTM standards.

Durability

For each mixture, the abrasion resistance of the concrete (ASTM C 779) was determined on one of the slabs after 91 days of moist curing.

The resistance to chloride-ion penetration (ASTM C 1202) was determined at the ages of 28 and 91 days using the top portion of the cylinders. Also, three slabs were used for determining the resistance to chloride-ion penetration (AASHTO T 259-80); the slabs were subjected to continuous ponding with 3% NaCl solution for 90 days, after an initial moist curing of the slabs for 14 days followed by 27 days of drying in laboratory air.

The air-void parameters of the hardened concrete (ASTM C 457) were determined using sawn sections of prisms used for the flexural-strength test. The resistance to the freezing and thawing cycling (ASTM C 666 Procedure A, freezing and thawing in water) was determined on test prisms with changes in length, mass, pulse velocity, and resonant frequency being determined after every 50 cycles. The flexural strength of these prisms was also determined after the completion of the test, and compared with that of the control prisms cured in the moist-curing room. Two slabs were used for the de-icing salt-scaling resistance test (ASTM C 672) and the test started after an initial moist curing of the slabs for 14 days followed by 14 days of drying in laboratory air. The top surface of the slabs was 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 mass of the scaling residue.

RESULTS AND DISCUSSION

Characteristics of the blended cements produced at the plant

The physical properties and chemical composition of the blended cements are presented in Table 1. The blended cement BC45 that incorporates 45% of fly ash meets the general requirements of ASTM C 1157 M. The initial and final setting times of blended cement BC45 were 150 and 270 minutes respectively, that were within the range of 45 to 420 minutes as specified in the above standard. The compressive strengths of the mortar at 3 and 7 days were 16.5, and 21.3 MPa, respectively. These were higher than the minimum strength requirements of 10 and 17 MPa at 3 and 7 days, respectively, as specified in the above standard.

The blended cement BC65 that incorporates 65% of fly ash did not meet the strength requirements of ASTM C 1157 M. In fact, the 7-day compressive strength of the mortar was 13.0 MPa which is below the minimum 7-day strength requirement of 17 MPa as specified in the above standard.

The blended cement BC55, that is a blend of 50% of BC45 and 50% of BC65, meets the general requirements of ASTM C 1157 M. The initial and final setting times of the blended cement were 200 and 265 minutes, respectively, that were within the range of 45 to 420 minutes as specified in the above standard. The compressive strengths of the mortar at 3 and 7 days were 14.0, and 17.6 MPa, respectively. These were higher than the minimum strength requirements of 10 and 17 MPa at 3 and 7 days, respectively, as specified in the above standard.

Properties of Fresh Concrete

The properties of the fresh concrete including the slump, air content, and unit weight are given in Table 3.

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 0.4 to 2.5 L/m³ of concrete (Table 2).

For similar slumps, Mixtures 1 (Batch A), and 2 (Batch A) made with blended cements BC45 and BC55, required similar dosage of the superplasticizer. At these high levels of fly ash content, the 10% increase i.e. 45 to 55% appears not to affect significantly the superplasticizer dosage.

The control concrete required 0.4 L/m³ of superplasticizer to achieve a slump of approximately 100 mm. This was due to the high water content.

Dosage of the air-entraining admixture and air content

The dosage of the air-entraining admixture required for obtaining an air content of 5 to 7 % ranged from 132 to 335 mL/m³.

Mixture 2, made with the blended cement BC55 required more AEA than Mixture 1, made with the blended cement BC45 that incorporated less fly ash. However, it should be noted that the air contents of both batches of Mixture 2 were higher than that of Mixture 1.

The control concrete required an average of 140 mL/m³ of the AEA to obtain the targeted air content, which is about half of that required for the fly ash concretes, and this is in conformity with the published data [3].

Slump loss and stability of air content

The slump loss and the stability of air content were determined by measuring the slump and the air content at 35 and 65 minutes after completion of mixing; during this period the concrete was kept in the mixer and just before the slump and air content measurement at the two said intervals, the concrete was re-mixed for 1 minute. Table 3 shows that there was significant loss in both slump and air content with time for the fly ash concrete mixtures. For example, the slump and air content of concrete Mixture 1 made with blended cement BC45 decreased from 115 to 55 mm and from 5.5 to 3.9%, respectively, after 65 minutes. Those of concrete Mixture 2 made with blended cement BC55 decreased from 120 to 55 mm and from 5.9 to 4.4%, respectively, after 65 minutes. For the control concrete, the slump loss was also significant, but the air content was more stable with time than it was for the fly ash concretes. This might be explained by the fact that the concrete made with the blended cements required significantly higher dosage of the superplasticizer than the control concrete. This is in conformity with published literature [4] that large dosages of a superplasticizer in concrete incorporate some large bubbles that are unstable.

Bleeding of concrete

Table 4 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 0.018 to 0.035 mL/cm². It appears that the increase in the fly ash content from 45% in blended cement BC45 to 55% in blended cement BC55 increased the bleeding of the concrete from 0.018 to 0.027 mL/cm². This was primarily due to the fact that the water content for both concretes was kept constant. This is, once again, in line with the published data that an increase in fly ash content without a corresponding decrease in water content will lead to increased bleeding [3].

Setting Time of Concrete

Table 4 also shows that the initial and final setting times of the concrete mixtures ranged from 4 h: 00 min. to 6 h: 10 min., and from 5 h:25 min. to 7 h:50 min., respectively. The initial and final setting times of the concrete made with the HVFA blended cements were 1 h:50 min to 2 h:30 min longer than those of the control concrete; this was expected, considering the high fly ash content in the blended cements. In hot weather concreting, this can be a decided advantage for the placement of concrete.

Autogenous Temperature Rise

The maximum temperature rise in concrete mixtures 1 (BC45) and 2 (BC55) was 9.7 and 8.9°C, respectively; the corresponding temperature rise in the control mixture 3 made with ASTM Type I cement was 28.9°C (Table 4). The reduced temperature rise of the blended cement concrete as compared with that of the control concrete mixtures is illustrated in Fig. 2.

As in previous investigations [1], the above results demonstrate the potential of HVFA blended cement for reducing the temperature rise in large concrete members due to its low cement content and the slow pozzolanic reaction of the fly ash.

Properties of Hardened Concrete

Compressive strength

The compressive strength test results obtained to date for the three concrete mixtures made in this study are given in Table 5. The results show that the concrete made with the blended cement BC45 and that made with the blended cement BC55 developed a 1-day compressive strength of 17.1 and 13.0 MPa, respectively. These high values are mainly due to the high fineness of the cement used (98.6 % passing 45µm) and are in line with the previous data on HVFA concrete made with ASTM Type III cement [5]. It appears that the 10% increase in the fly ash content in the blended cement decreases the 1-day compressive strength of the concrete by approximately 25%. However, the 1-day compressive strength of the concrete made with the HVFA blended cement (BC55) is still adequate for most of the concrete structures for formwork removal at one-day. This strength development was for concrete cured at 23 ± 2°C in the laboratory. In winter conditions, and when the curing temperature is low, the strength values at one-day will be lower

than those given above; on the contrary, in hot weather, the above strength will be somewhat higher.

The control concrete developed a 1-day compressive strength of only 19.0 MPa, which is approximately similar to that of the concrete made with the blended cement incorporating 45% of fly ash (BC45). This is because the control concrete had a high W/C ($W/C = 0.45$).

At 28 days, the compressive strength of the concrete made with blended cement BC55 (~36.8 MPa) approached that of the control concrete (~39.5 MPa), and at 91 days it surpassed it (44.0 and 41.5 MPa, respectively). Beyond 7 days, the concrete made with blended cement BC45 developed a higher compressive strength than the concrete made with blended cement BC55 and the control concrete. In fact, the 91-day compressive strength of the concrete made with blended cement BC45 was 17, and 24% higher than that of the concrete made with the blended cement BC55 and that of the control concrete, respectively.

Flexural- and splitting-tensile strengths

The flexural- and splitting-tensile strengths of the concrete are given in Table 6. The 28-day flexural- and splitting-tensile strengths of the concrete made with blended cement BC45 were 5.7, and 3.4 MPa, respectively; those of the concrete made with blended cement BC55 were 4.8, and 3.0 MPa; and those of the control concrete were 5.4, and 3.6 MPa, respectively. The results show that the 28-day flexural- and splitting-tensile strengths of the control concrete were similar to those of the concrete made with blended cement BC45, but higher than those of the concrete made with blended cement BC55.

The flexural strength value of the concrete made with the blended cements BC45 and BC55 (> 4 MPa) shows the potential of such HVFA concrete mixture for pavement applications.

Young's Modulus of Elasticity "E"

Table 6 also presents the data on Young's modulus of elasticity of concrete. The "E" values at 28 days for the concrete made with blended cements BC45 and BC55 were 32.8 and 31.0 GPa, respectively; the corresponding values at 91 days were 36.1 and 34.7 GPa. The values at 28 and 91 days for the control concrete were 27.0 and 28.2 GPa, respectively. The results show that the use of the blended cement increased the "E" value of the concrete. This is in line with the previous published data where fly ash was added as a separate ingredient at the batch plant [6]. The probable explanations are the high aggregate contents in the concrete made with the blended cements, the fact that a considerable portion of the unreacted fly ash, consisting of glassy spherical particles, in the blended cements acts as a fine aggregate, and the transition zone in the concrete made with the blended cements is more strong and dense.

Drying Shrinkage

It is reported that the drying shrinkage of small, plain concrete specimens (without reinforcement) ranges from about 400 to 800 $\times 10^{-6}$ when exposed to air at 50% humidity [7]. The drying shrinkage strains for the concretes investigated were low and ranged from 372 $\times 10^{-6}$

to 468×10^{-6} at 112 days (Table 7 and Figure 3). For the concrete made with blended cements, the low values are mainly due to the low unit water content of the concretes.

Air-Void Parameters

The air-void parameters of the concrete are presented in Table 8. The spacing factor and specific surface of the concrete ranged from 0.090 to 0.120 mm, and from 33.9 to 41.5 mm^2/mm^3 , respectively. It is generally agreed that air-entrained concrete should have a spacing factor value not exceeding 0.200 mm for satisfactory resistance to the freezing and thawing cycling. Table 8 shows that all the concretes had a spacing factor well below 0.200 mm, and all the concretes had shown excellent performance in freezing and thawing cycling, as will be discussed later.

Resistance to Abrasion

The abrasion resistance of concrete is a direct function of its compressive strength. Figure 4 presents the results of the abrasion resistance at 91 days of the concretes investigated. The depth of abrasion of the concretes ranged from 1.4 to 2.0 mm after 20 minutes of testing; the highest value was for the control concrete that also had the lowest compressive strength at 91 days.

Resistance to Chloride-Ion Penetration

The resistance to the chloride-ion penetration determined according to ASTM C 1202 was significantly higher for the concrete made with the blended cements than for the control concrete (Table 9). At 91 days, the total charge passed, in coulombs, was < 700 coulombs for the fly ash concretes compared with ~ 4000 coulombs for the control concrete. This is mainly due to the low W/C of the concrete made with the blended cements and also to the fact that the incorporation of the fly ash in the blended cement results in finer pores in the hydrated cement paste. The resistance to chloride-ion penetration of the concrete made with both blended cements was somewhat similar.

Table 9 also presents data on the resistance of concrete to the chloride-ion penetration determined according to AASHTO T 259-80. These results also show that the concretes made with the blended cements were more resistant to the chloride-ion penetration than the control concrete. In fact, the chloride content at 13 to 25 mm from the top of the slab of the control concrete was two to six times higher than that of the concretes made with the blended cements. Table 13 shows that the chloride content at 25 mm from the top of the slabs for the concretes made with blended cements BC45 and BC55, and ASTM Type I cement are 0.005, 0.006, and 0.01% (by mass of the concrete), respectively. These values translate to 0.03, 0.04, and 0.06%, when expressed by mass of the cement; these still remain below the maximum limits recommended by ACI 222, which are 0.08% and 0.20% (by mass of the cement) for prestressed and reinforced concrete, respectively.

Resistance to Freezing and Thawing Cycling

The durability of the concrete to the repeated cycles of freezing and thawing was determined from the 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

10). At the end of 300 cycles, the flexural strength of the control and test prisms was also determined (Table 10). The data indicate an excellent performance of all concretes in the test with durability factors of 100. It should be noted that the performance of concrete in freezing and thawing cycling is a direct function of its entrained-air content and hence the air void parameters, and not the amount of fly ash in concrete.

As seen from Table 10, the percentage of residual flexural strength of the control concrete prisms was 96%, indicating good resistance of this concrete to freezing and thawing cycling. However, the results for the blended cement concrete prisms were found to be lower, ranging from 76 to 78%. The residual strength referred to above is the ratio of the flexural strength of the prisms subjected to 300 cycles of freezing and thawing to the flexural strength of the moist-cured reference prisms made from the same concrete and tested at the same age. The reason for the lower residual strength of the blended cement concrete prisms lies in the fact that the reference prisms from this concrete gained relatively more strength than the companion control concrete prisms, due to the increase in pozzolanic reaction with time. On the other hand, the strength of all the prisms that underwent freezing and thawing cycles, increased only marginally because of the low temperature during the test. Therefore, the larger strength increase in the reference blended cement concrete prisms at the time of testing resulted in the lower residual flexural strengths of the prisms tested after freezing and thawing cycling.

Resistance to De-Icing Salt Scaling

The slabs made with the concrete incorporating the blended cements exhibited severe scaling (Table 11 and Figure 5) with a visual rating of 5 according to ASTM C 672, and a cumulative scaling residue of 2 to 2.8 kg/m². The cumulative scaling residue increased with increasing fly ash content in the blended cement.

The scaling of the slabs cast from the control concrete made with the ASTM Type I cement was low with a visual rating of 1 and a cumulative scaling residue of 0.6 kg/m². The poor de-icing salt scaling resistance of HVFA concrete in laboratory tests has been reported earlier [6]; however, the experimental HVFA concrete sidewalk in Halifax, N.S. Canada, have shown satisfactory performance after four winters during which period the sidewalks have gone through more than 400 cycles of freezing and thawing combined with numerous applications of de-icing salts*. It is, therefore, believed that ASTM C 672 is a very severe test, and is not satisfactory for determining the de-icing salt scaling resistance of HVFA concrete in actual field applications.

CONCLUSIONS

General

An attempt to produce HVFA blended cement in a commercial cement plant was partially successful; the facilities in the plant for this production were certainly not optimum for the industrial production of HVFA blended cement. Consequently, the HVFA blended cement produced was not homogenous, and the fly ash content in the various lots produced ranged from 45 to 65%. These lots had to be blended at CANMET laboratory to produce HVFA blended

cement that incorporated 55% of fly ash. Concrete made with the HVFA blended cements has excellent mechanical properties and durability characteristics and its performance is similar to the HVFA concrete when fly ash is added as a separate ingredient at a concrete batch plant. The relatively high one-day strength of the HVFA concrete investigated is probably due to the high fineness and high C_3S content of the cement.

Specific

For similar slump and air content, the use of HVFA blended cement in concrete resulted in an increase in the dosages of the superplasticizer and the air-entraining admixture, and caused some delay in both the initial and final setting times.

The maximum temperature reached in concrete made with HVFA blended cement was 34°C compared to 52°C for control concrete.

The strength of the concretes made with HVFA blended cements are satisfactory for early-age form removal, even though they are somewhat lower than the strength of the control concrete.

The use of HVFA blended cement in concrete improved significantly the durability characteristics of the concrete as compared with the control concrete. The only exception was the resistance to the de-icing salt scaling, which showed significant decrease.

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Table 1 - Physical properties and chemical analyses of the cements produced

	ASTM Type I Cement	ASTM Class F Fly Ash	Blended Cements		
			BC45	BC55	BC65
<u>Physical tests</u>					
Specific gravity	3.15	2.27	2.73	2.64	2.60
Fineness					
· passing 45µm, %	98.6	82.5	89.3	86.9	86.4
· specific surface, Blaine, cm ² /g	3860	3500	3780	3570	2950
Compressive strength of 51 mm cubes, MPa					
· 3-day	-	-	16.5	14.0	10.4
· 7-day	38.7	-	21.3	17.6	13.0
Time of setting, Vicat test, min					
· initial setting	-	-	150	200	160
· final setting	-	-	270	265	280
Air content of mortar, volume %	-	-	4.6	4.4	2.5
<u>Chemical analyses, %</u>					
Silicon dioxide (SiO ₂)	20.2	46.7	32.8	35.7	37.4
Aluminium oxide (Al ₂ O ₃)	4.7	23.3	12.9	14.6	15.8
Ferric oxide (Fe ₂ O ₃)	3.3	7.7	5.0	5.2	5.6
Calcium oxide (CaO)	64.9	10.1	40.1	35.0	31.2
Magnesium oxide (MgO)	0.8	2.0	1.3	1.5	1.5
Sodium oxide (Na ₂ O)	0.3	2.7	1.8	2.1	2.3
Potassium oxide (K ₂ O)	0.3	0.7	0.5	0.5	0.5
Equivalent alkali (Na ₂ O+0.658K ₂ O)	0.5	3.2	2.1	2.4	2.6
Phosphorous oxide (P ₂ O ₅)	0.1	0.9	0.4	0.5	0.5
Titanium oxide (TiO ₂)	0.3	3.8	-	2.0	-
Sulphur trioxide (SO ₃)	2.6	0.6	-	0.4	1.4
Loss on ignition	1.7	0.6	1.2	0.6	0.7
<u>Bogue potential compound composition</u>					
Tricalcium silicate C ₃ S	67	-	-	-	-
Dicalcium silicate C ₂ S	7	-	-	-	-
Tricalcium aluminate C ₃ A	7	-	-	-	-
Tetracalcium aluminoferrite C ₄ AF	10	-	-	-	-

Table 2 - Proportions of the concrete mixtures

Mix. no.	Batch	Water-to-Cementitious Materials Ratio	Water, kg/m ³	Cement		Fine Aggregate, kg/m ³	Coarse Aggregate, kg/m ³	AEA,* mL/m ³	SP,** L/m ³
				type	kg/m ³				
1	A	0.33	127	BC45	389	755	1131	292	2.4
	B	0.33	126	BC45	385	746	1118	288	2.4
2	A	0.33	126	BC55	384	740	1109	334	2.5
	B	0.33	126	BC55	386	743	1113	335	2.0
3	A	0.45	171	Type I	381	702	1052	150	0.4
	B	0.45	173	Type I	385	710	1065	132	0.4

* Air-entraining admixture

** Superplasticizer.

Table 3 - Properties of the fresh concrete

Mix. No.	Batch	Water-to-Cementitious Materials Ratio	Cement Type	Unit Weight, kg/m ³	Immediately after Mixing		35 min. after Mixing was Completed		65 min. after Mixing was Completed	
					Slump, mm	Air Content, %	Slump, mm	Air Content, %	Slump, mm	Air Content, %
1	A	0.33	BC45	2404	125	5.2	-	-	-	-
	B	0.33	BC45	2375	115	5.5	70	4.3	55	3.9
2	A	0.33	BC55	2360	130	6.1	-	-	-	-
	B	0.33	BC55	2370	120	5.9	65	4.8	55	4.4
3	A	0.45	Type I	2305	90	6.9	-	-	-	-
	B	0.45	Type I	2333	100	6.3	95	5.5	50	5.2

Table 4 - Bleeding and setting time of concrete

Mixture no.	Water-to-Cementitious Materials Ratio	Cement type	Total Bleeding Water, mL/cm ²	Setting Time, h:min		Maximum Autogenous Temperature Rise, °C
				Initial	Final	
1	0.33	BC45	0.018	5:45	7:20	9.7
2	0.33	BC55	0.027	6:10	7:50	8.9
3	0.45	Type I	0.035	4:00	5:25	28.9

Table 5 - Compressive strength of concrete

Mix. no.	Batch	W/C	Cement Type	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	0.33	BC45	2390	17.1	32.6	39.4	44.9	51.6	n.a	n.a
	B	0.33	BC45	-				45.1			
2	A	0.33	BC55	2370	13.0	26.5	32.2	36.6	44.0	n.a	n.a
	B	0.33	BC55	-				36.9			
3	A	0.45	Type I	2290	19.0	32.7	35.7	38.9	41.5	n.a	n.a
	B	0.45	Type I	-				40.1			

n.a.: data not yet available

Table 6 - Young's modulus of elasticity, flexural and splitting-tensile strengths of concrete

Mix. No.	W/(C+FA)	Cement type	28-d compressive strength	Young's modulus of elasticity, GPa		Flexural strength, MPa		Splitting-tensile strength, MPa
				28 d	91 d	14 d	28 d	28 d
1	0.33	BC45	45.0	32.8	36.1	4.6	5.7	3.4
2	0.33	BC55	36.7	31.0	34.7	4.1	4.8	3.0
3	0.45	Type I	39.5	27.0	28.2	5.7	5.4	3.6

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

Mix. no.	W/(C+FA)	Cement type	Drying shrinkage strain, x 10 ⁶						
			7 d	14 d	28 d	56 d	112 d	224 d	448 d
1	0.33	BC45	124	309	387	433	468	n.a	n.a
2	0.33	BC55	181	234	312	351	372	n.a	n.a
3	0.45	Type I	170	-	305	358	415	n.a	n.a

n.a.: data not yet available

Table 8 - Air-void parameters of hardened concrete

Mix. no.	W/(C+FA)	Cement type	Air content, %	Air content, % ASTM C 457	Specific surface, mm ² /mm ³	Spacing factor, mm
1	0.32	BC45	5.5	4.7	38.7	0.120
2	0.32	BC55	5.9	5.9	33.9	0.112
3	0.45	Type I	6.3	7.0	41.5	0.090

Table 9 - Resistance to the chloride-ion penetration

Mix. no.	W/(C+FA)	Cement type	Total charge passed, coulombs (ASTM C 1202)		Chloride content, % (AASHTO T 259-80)			
			28 d	91 d	1.6-7 mm	7-13 mm	13-19 mm	19-25 mm
1	0.33	BC45	1440	480	0.23	0.04	0.007	0.005
2	0.33	BC55	1790	620	0.23	0.08	0.01	0.006
3	0.45	I	-	3940	0.21	0.09	0.04	0.01

Table 10 - Summary of test results after 300 cycles of freezing and thawing

Mix. no.	W/(C+FA)	Cement type	Per cent change at the end of the freezing and thawing cycling				Durability Factor	Residual* flexural strength, %
			Length	Weight	Pulse Velocity	Resonant Frequency		
1	0.33	BC 45	-0.007	+0.076	-0.4	+0.90	100	76.1
2	0.33	BC 55	-0.015	+0.169	0.0	+0.94	100	77.7
3	0.45	Type I	+0.005	+0.192	-1.1	+0.00	100	95.5

* Flexural strength ratio of the prisms that had completed 300 cycles of freezing and thawing to the reference prisms that had been put in the moist-cured room for the same period of time.

Table 11 - Test results of de-icing salt scaling

Mix. no.	W/(C+FA)	Cement type	Visual rating* (ASTM C 672)	Total scaling residue (kg/m ²)
1	0.33	BC 45	5	2.0
2	0.33	BC 55	5	2.8
3	0.45	Type I	1	0.6

* 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)

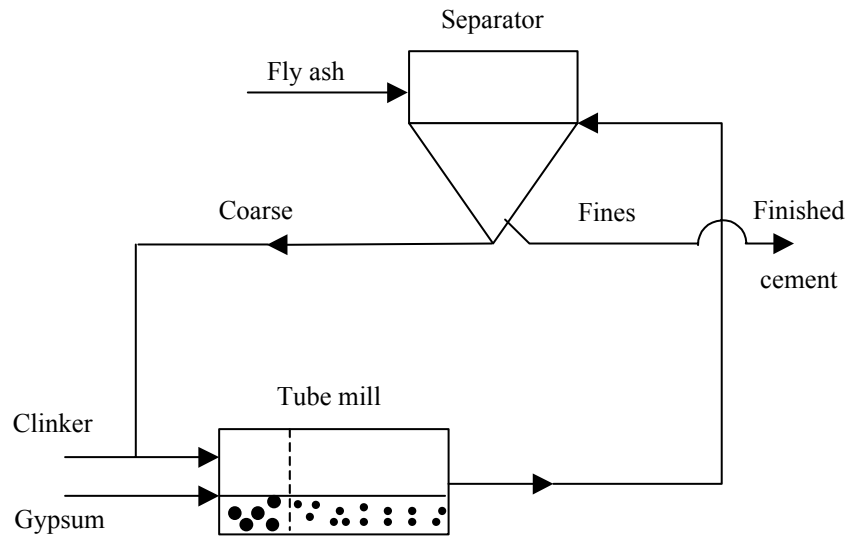


Figure 1 - Grinding method for fly ash cements used at Bellingham cement plant

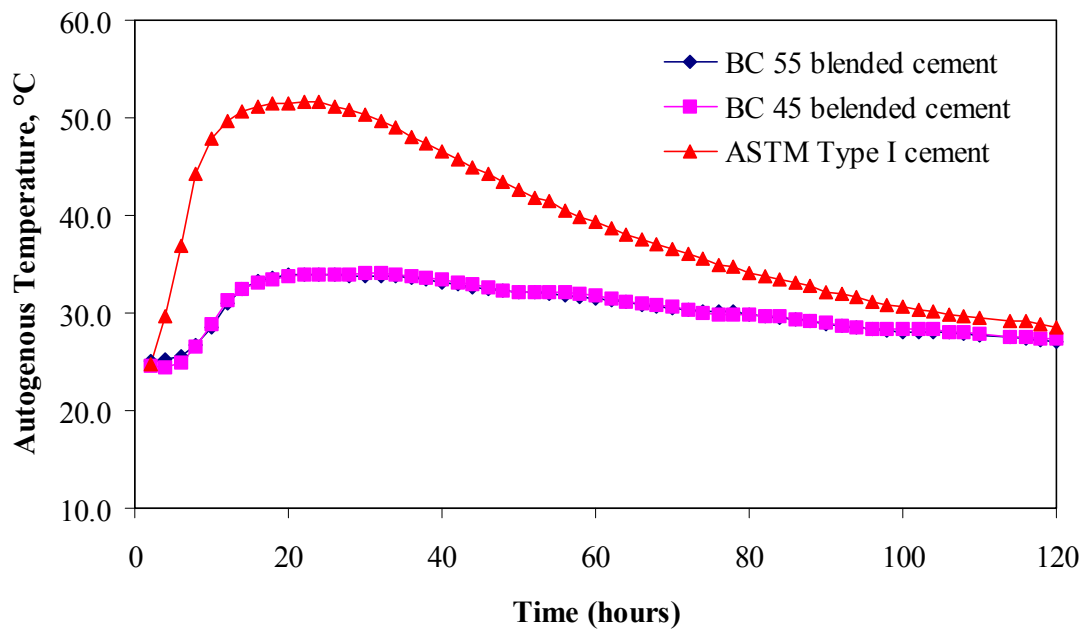


Figure 2 - Autogenous temperature of the concrete

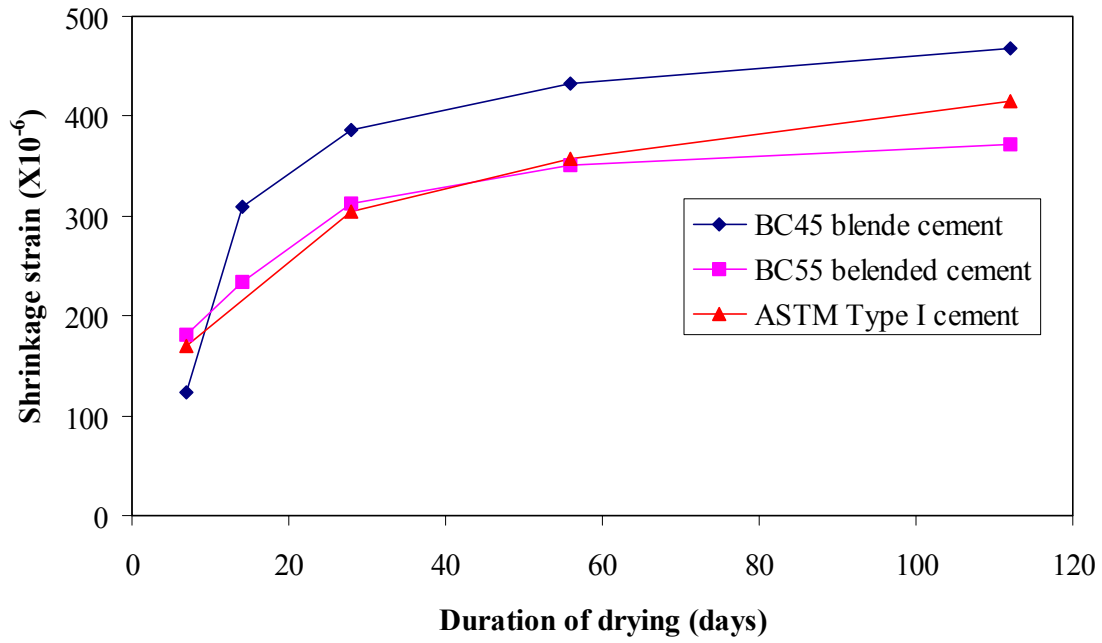


Figure 3 - Drying shrinkage strain versus duration of drying

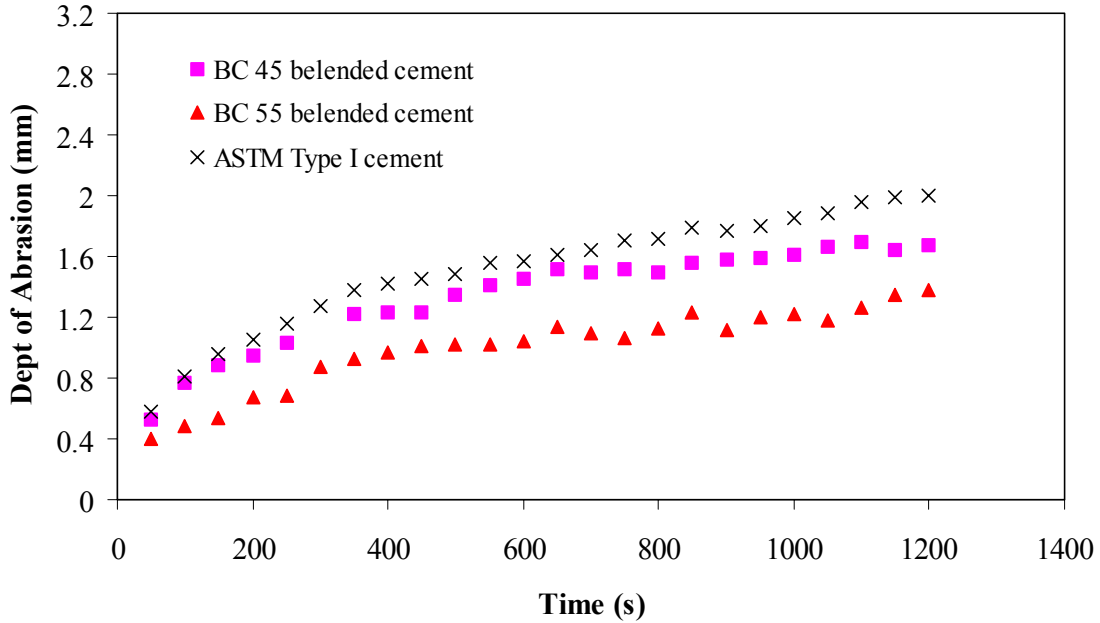


Figure 4 - Depth of abrasion versus duration of wearing of concrete at 91 days

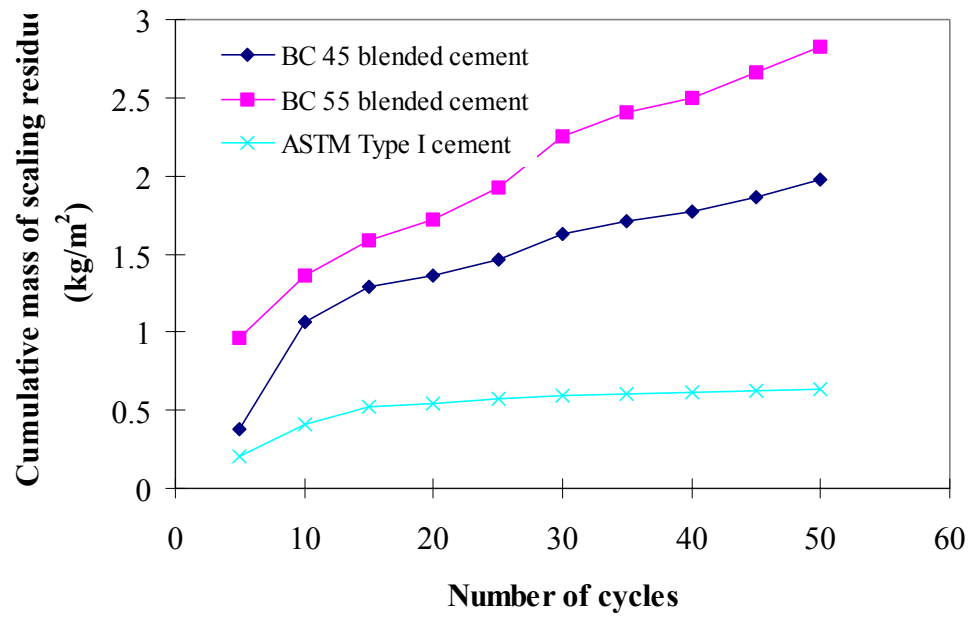


Figure 5 - Variation of the cumulative mass of scaling residue versus the number of cycles

* Unpublished CANMET data