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HIGH-VOLUME FLY ASH SYSTEM: THE CONCRETE SOLUTION FOR SUSTAINABLE DEVELOPMENT

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**HIGH-VOLUME FLY ASH SYSTEM:
THE CONCRETE SOLUTION FOR
SUSTAINABLE DEVELOPMENT**

by

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ABSTRACT

The challenge for the civil engineering community in the near future will be to realize projects in harmony with the concept of sustainable development, and this involves the use of high-performance materials produced at reasonable cost with the lowest possible environmental impact.

Portland cement concrete is a major construction material worldwide. Unfortunately, the production of portland cement releases large amounts of CO₂ into the atmosphere, and because this gas is a major contributor to the greenhouse effect and the global warming of the planet, the developed countries are considering very severe regulations and limitations on the CO₂ emissions.

In view of the global sustainable development, it is imperative that supplementary cementing materials be used to replace large proportions of cement in the concrete industry, and the most available supplementary cementing material worldwide is fly ash, a by-product of thermal power stations. In order to increase considerably the utilization of fly ash that otherwise is being wasted, and to have a significant impact on the production of cement, it is necessary to advocate the use of concrete that will incorporate large amounts of fly ash as replacement for cement. However, such concrete will have to demonstrate performance comparable to that of conventional portland cement concrete, and must be cost effective.

In 1985, CANMET developed a concrete incorporating large volumes of fly ash that has all the attributes of high-performance concrete i.e. excellent mechanical properties, low permeability, superior durability, and that is environmentally friendly. This paper gives an overview of the properties of this type of concrete that is believed to be a very promising alternative for the industry seeking to meet the sustainable development objectives.

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INTRODUCTION

All human activity results in some degree of environmental degradation. The challenge is to minimize this degradation to a level consistent with sustainable development. The sustainable development is the integration of environmental, economic and social considerations when deciding whether and how development should proceed. For the civil engineering community, the concept of sustainable development involves the use of high-performance materials produced at a reasonable cost and with the lowest possible environmental impact. The ways to reduce environmental impact include the reduction in the production of waste and of the emission of the harmful greenhouse gases into the atmosphere, a more efficient use of mineral and metal resources, and an increased use of recycled materials such as aggregates, gypsum and plastics.

Portland cement concrete is a major construction material worldwide. Unfortunately, the production of portland cement releases large amounts of CO₂ into the atmosphere; for example, the production of one tonne of cement contributes approximately one tonne of CO₂ into the atmosphere. Because this gas is a major contributor to the greenhouse effect and the global warming of the planet, the developed countries are considering very severe regulations and limitations on the CO₂ emissions. Due to the infrastructure needs of the developing countries, the demand for concrete and consequently cement, is expected to increase significantly in the near future. The net cement production in the world is expected to increase from about 1.4 billion tonnes in 1995 to almost two billion tonnes in the year 2010. This would translate to the emission of about two billion tonnes of CO₂ into the atmosphere every year (1). Most of the increase in the cement production is expected to be in the developing countries such as China and India.

In view of the global sustainable development, it is imperative that supplementary cementing materials be used to replace large proportions of cement in the concrete industry. The most available supplementary cementing material worldwide is fly ash, a by-product of the thermal power stations. It is estimated that approximately 600 million tonnes of fly ash will be available worldwide by the year 2000 but at present the current worldwide utilization rate of fly ash in concrete is about 10 per cent indicating that there is a potential for the use of much larger amounts of fly ash in concrete, and therefore for significant reductions in cement production resulting in considerable environmental benefits (1).

In order to increase considerably the utilization of fly ash, that otherwise is being wasted, and to have a significant impact on the production of cement, it is necessary to advocate the use of concrete that will incorporate large amounts of fly ash as replacement for cement. However, such concrete will have to demonstrate performance comparable to that of conventional portland cement concrete, and must be cost effective.

In 1986, CANMET developed a concrete incorporating large volumes of fly ash which meets and often exceeds the above requirements (2,3). The so-called high-volume fly ash concrete has all the attributes of high-performance concrete i.e. excellent mechanical properties, low permeability and superior durability. Over the years, CANMET, in partnership with the Electric Power Research Institute, U.S.A., and the Canadian Electrical Association, has developed vast data on the properties of the high-volume fly ash concrete (4-19). This concrete has also been investigated and used by other agencies. This paper, partly based on a CANMET publication issued in 1993,¹ gives an overview of the properties of this type of concrete that is believed to be a very promising alternative for the industry seeking to meet the sustainable development objectives.

APPLICATIONS OF THE HIGH-VOLUME FLY ASH CONCRETE SYSTEM

The high-volume fly ash concrete was first developed for mass concrete applications where low-heat generation and adequate early strength were required (2). Subsequent work has demonstrated that this type of concrete, given its excellent mechanical and durability properties can also be used for structural applications and for pavement construction (3,6,20,21). Some investigations have also shown the potential use of the high-volume fly ash system for shotcreting (22,23), lightweight concrete (19) and roller-compacted concrete (21). CANMET is currently working on the development of a blended cement incorporating high volumes of fly ash (24,25). The use of this type of cement may overcome the problems of additional quality control and storage facilities related to the addition of fly ash as a separate ingredient at the ready-mixed concrete batching plants. The preliminary results with this new type of cement are promising, especially for the use of coarse fly ashes (25).

PROPERTIES OF MATERIALS USED

Most investigations on high-volume fly ash concrete at CANMET were carried out using several ASTM Type I cements covering a wide range of chemical compositions, and having different physical properties and strength development characteristics. Some investigations were also made using ASTM Type III cements. A large number of ASTM Class F and Class C fly ashes from various sources in Canada and the U.S.A. having very different chemical compositions and physical properties, were used.

Due to the very low water content of the high-volume fly ash concrete, the use of a superplasticizer is necessary for obtaining workable concrete. In CANMET studies, naphthalene-

¹ Chapter by V.M. Malhotra entitled "High-Volume Fly Ash Concrete", and published in "Advances in Concrete Technology", issued in 1993 by CANMET.

based superplasticizers were used successfully. Most investigations on the high-volume fly ash concrete involved the making of air-entrained concrete, and several commercially available air-entraining admixtures were used without any problems. In most of the CANMET investigations dealing with this type of concrete, natural sand and minus 19-mm crushed limestone were used as fine and coarse aggregates, respectively. Other types of coarse aggregates used in some instances included lightweight aggregates.

Several investigators from other organizations have successfully produced high-volume fly ash concrete using their local materials and admixtures (21,26,27).

MIXTURE PROPORTIONS

The mixture proportions were optimized at CANMET to produce a high-performance, air-entrained concrete both for mass and structural concrete applications. Typical mixture proportions used in CANMET investigations are shown below.

Typical Mixture Proportions			
	Low-Strength	Medium-Strength	High-Strength
Water	115 kg/m ³	120 kg/m ³	110 kg/m ³
ASTM Type I Cement	125 kg/m ³	155 kg/m ³	180 kg/m ³
ASTM Class F Fly Ash	165 kg/m ³	215 kg/m ³	220 kg/m ³
Coarse Aggregate	1170 kg/m ³	1195 kg/m ³	1110 kg/m ³
Fine Aggregate	800 kg/m ³	645 kg/m ³	760 kg/m ³
Air-Entraining Admixture	200 mL/m ³	200 mL/m ³	280 mL/m ³
Superplasticizer	3.0 L/m ³	4.5 L/m ³	5.5 L/m ³

Some investigations involved concrete mixtures made with ASTM Type III cement using the above mixture proportions (4,17). ASTM Class C fly ashes have also been used successfully in some studies (13,14,15,19).

The mixture proportions may be modified depending on the type of application or for any specific properties required for the concrete. The main principle for this type of concrete is that the amount of fly ash be as high as possible, and the water content and water-to-cementitious materials ratio as low as possible to insure high performance; the use of a superplasticizer is mandatory to provide adequate workability.

PROPERTIES OF FRESH CONCRETE

Slump, Air Content and Dosage of Admixtures

In this type of concrete, the slumps are adjusted by varying the dosages of the superplasticizer. Most of the investigations at CANMET have been performed with "flow" slumps i.e. slumps between 180 and 220 mm. The dosage of a superplasticizer may vary considerably depending on the characteristics of the cement and fly ash used. This type of concrete has also been used without superplasticizers at very low, and even zero slump for roller-compacted concrete applications.

In CANMET investigations, the air content was usually kept between 5 and 7 per cent, and satisfactory bubble-spacing factors, \bar{L} , were obtained in the hardened concrete. As for the superplasticizer, the dosage of the air-entraining admixture is strongly influenced by the characteristics of the fly ash and cement used. In spite of the high fly ash content in this type of concrete, no problems were encountered in entraining air in the concrete, except with fly ashes having very high carbon content; in the latter case much higher dosages of air-entraining admixture were needed.

Bleeding and Setting Time

The bleeding of high-volume fly ash concrete ranges from being very low to negligible due to the very low water content. Proper care, therefore should be taken to prevent plastic shrinkage at the concrete surface immediately after placing.

The setting time for this concrete is, in general, somewhat longer than that of conventional concrete made using portland cement alone. This is expected considering the low cement content, the slow reaction process of the fly ash, and the large amounts of the superplasticizer used. In general, the high-volume fly ash concrete does not show unacceptable retardation in setting time, and demonstrates adequate strength at one day (13). However, special care and measures are needed in cold-weather concreting as the combination of low cement content, superplasticizer, and low temperature will result in significant retardation in setting and low early-age strength.

The setting time of high-volume fly ash concrete can potentially be reduced by using ASTM Type III cement instead of Type I. However, this can be partly offset by higher dosages of superplasticizers in the mixtures incorporating Type III cement (17).

Autogenous Temperature Rise

Because of the low cement content, the autogenous temperature rise in high-volume fly ash concrete is rather low. Several investigations have shown that the autogenous temperature rise of high-volume fly ash concrete was about 15 to 25°C less than that of a reference concrete without fly ash (17,19,21,27). For example, in a large high-volume fly ash concrete block, 3.05x3.05x3.05 meters in size, the maximum temperature reached was 54°C (rise of 35°C), noticeably less than the

83°C (rise of 65°C) reached in a block of the same size made of concrete incorporating ASTM Type I portland cement only (9). In this investigation, the total amount of cementitious materials by weight was the same for the two types of concrete.

In another study, the maximum temperature rise measured in large monoliths, 2.5x4.0x5.0 meters in size, was 33°C for high-volume fly ash concrete and 36°C for a reference concrete (without fly ash) made with a modified version of ASTM Type II (moderate heat of hydration) cement (10). In this study, both types of concrete were proportioned to have similar 28 and 91-day strengths. The low temperature rise of the high-volume fly ash concrete is a desirable property that has been successfully exploited in some field applications (21).

CURING OF HIGH-VOLUME FLY ASH CONCRETE

The need for adequate curing cannot be over-emphasized for high-volume fly ash concrete. To ensure satisfactory early- and later-age strength development, low permeability, and long-term resistance to aggressive media, it is most essential that the above concrete be protected from premature drying by curing for adequate length of time. The duration of curing will depend on the nature of exposure conditions. In general, a curing period of seven days should be adequate.

MECHANICAL PROPERTIES OF HIGH-VOLUME FLY ASH CONCRETE

The properties of high-volume fly ash concrete are strongly dependent on the characteristics of the cement and fly ash used. However, in general, the mechanical properties of high-volume fly ash concrete are excellent, due to its low water content and low water-to-cementitious materials ratio, and the dense microstructure. Typical mechanical properties of high-volume fly ash concrete determined in CANMET investigations are given in Table 1.

Due to the slow pozzolanic reaction, the high-volume fly ash concrete achieves significant improvements in its mechanical properties at later ages compared to conventional portland cement concrete. Nevertheless, its early-age mechanical properties are adequate, and these can be significantly improved, if needed, by using ASTM Type I cement with rapid strength development or ASTM Type III cement.

Compressive Strength

In the studies performed at CANMET, compressive strengths of the order of 8 MPa at one day, 35 Mpa at 28 days, and 43 Mpa at 91 days were obtained with medium strength high-volume fly ash normal-weight concrete made with Type I cement (Table 1). As mentioned above, the early-age strength of the high-volume fly ash concrete can be increased significantly by selecting the proper cement. This is illustrated in Fig. 1 that shows the strength development of high-volume fly ash

concrete made with two different ASTM Type I cements and a Type III cement (13,17). Each curve represents the average strength of concrete made with three different fly ashes. In this particular case, the long-term strength was not affected by the use of ASTM Type III cement.

In some field applications, the high-volume fly ash concrete strengths ranged from 35 to 50 MPa at 28 days, and from 50 to 70 MPa at 90 days (21). Concrete cores taken from large experimental blocks made from ready-mixed high-volume fly ash concrete have shown a compressive strength of 110 MPa after 10 years in an outdoor exposure; the blocks had 7 days of moist-curing before being exposed (28,29). This demonstrates potential for long-term strength gain in this type of concrete.

Some attempts were made to increase the early-age strength of the high-volume fly ash concrete by incorporating small percentages (3 and 8.5%) of silica fume to the system (4,18); however, these studies showed that the use of silica fume did not affect significantly the strength development of the high-volume fly ash concrete.

Flexural and Splitting-Tensile Strengths

Flexural strengths of the order of 4.5 and 6.0 MPa were obtained at 14 and 91 days, respectively, and the 28-day splitting tensile strength was of the order of 3.5 MPa, for the medium strength high-volume fly ash concrete produced at CANMET. The ratios of the flexural and splitting-tensile strengths to compressive strength are comparable to those for conventional portland cement concrete.

Young's Modulus of Elasticity

The Young's modulus of elasticity "E" of high-volume fly ash concrete was of the order of 35 and 38 GPa at 28 and 91 days, respectively. The high modulus achieved is probably due to the fact that a considerable portion of the unreacted fly ash, consisting of glassy spherical particles, acts as a fine aggregate.

Drying Shrinkage and Creep

The drying shrinkage strains of high-volume fly ash concrete were comparable to, or lower than that of conventional portland cement concrete, with measured values of the order of 500×10^{-6} after 64 weeks of air drying.

The creep strain of high-volume fly ash concrete can be considered low, with specific creep values ranging, in general, from 24 to 32×10^{-6} per MPa of stress for normal-weight concrete after one year under loading. A study with lightweight aggregates has confirmed those results with specific creep values ranging from 27.5 to 44.3×10^{-6} per MPa of stress for the high-volume fly ash concrete compared to 65.6×10^{-6} for a reference concrete of similar strength as illustrated in Fig. 2 (19). The somewhat low creep strains of high-volume fly ash concrete are, once again, probably due

to the unreacted fly ash particles in concrete acting as fine aggregate, and thus providing increased restraint against creep. Also, the very low water content of the concrete makes some contribution to these low creep strains.

DURABILITY OF HIGH-VOLUME FLY ASH CONCRETE

Several laboratory and field investigations involving cements and fly ashes from various sources in Canada and the U.S.A. have demonstrated the excellent durability of high-volume fly ash concrete, the only exception being deicing salt scaling resistance. Some typical durability test results are given in Table 2.

Water Permeability

The water permeability of the high-performance, high-volume fly ash concrete is very low. Tests performed on 50-mm thick concrete discs under uniaxial flow conditions with a uniaxial pressure of 2.7 MPa indicate that the permeability of high-volume fly ash concrete is less than or equal to 10^{-13} m/s. The detailed test procedure for the above test is described elsewhere (30).

Resistance to Freezing and Thawing Cycling

The air-entrained, high-performance, high-volume fly ash concrete shows excellent resistance to repeated cycles of freezing and thawing. Even after 1000 cycles in ASTM C 666 Procedure A test (freezing and thawing in water), the durability factors are in excess of 90 (14); conventional air-entrained portland cement concrete is considered satisfactory if it can withstand 300 cycles in the above test. As in conventional concrete, the durability to freezing and thawing cycling of high-volume fly ash concrete is linked to the quality of its air-void parameters. It is emphasized that no difficulty was encountered in obtaining adequate air-void parameters in high-volume fly ash concrete.

Resistance to Deicing Salt Scaling

Although high-volume fly ash concrete performs excellently when subjected to repeated cycles of freezing and thawing, its performance in deicing salt scaling tests performed at CANMET in accordance with ASTM C 672 leaves something to be desired. During this test, both visual examination and weight loss of the test specimens indicated severe scaling of the surfaces of the test specimens with coarse aggregate visible over the entire surface. According to the ASTM scale of visual rating of 0 to 5, the test specimens were rated at 5 (11,14,31). Control plain portland cement concrete, made with the same water-to-cementitious materials ratio and the same total cementitious materials content has shown good scaling resistance with a visual rating of 1. However, other investigators have shown that high-volume fly ash concrete can perform adequately in the de-icing salt scaling test (32). Also, sidewalk sections made with the high-volume fly ash concrete in 1994,

and subjected to deicing salts in a metropolitan city in eastern Canada have shown good performance since construction (21).

At this stage, the authors do not recommend the use of high-volume fly ash concrete for applications where the concrete will be exposed severely to de-icing chemicals, although it is believed that the problem is less serious than that found in the laboratory investigations. Further research is needed in this area.

Resistance to the Penetration of Chloride Ions

The high-performance, high-volume fly ash concrete shows very high resistance to the penetration of chloride ions in tests performed according to ASTM C 1202. Its resistance is considerably higher than that of conventional portland cement concrete of similar strength. The charge measured on high-volume fly ash concrete usually ranges from 500 to 2000 coulombs at 28 days, and from 200 to 700 coulombs at 91 days. A value of less than 600 coulombs is indicative of very high resistance, and hence, very low permeability.

The "coulomb" values at 28 and 91 days are influenced by the properties of the cement and fly ash used. For instance, somewhat lower test values at early ages can be obtained with high-volume fly ash concrete using ASTM Type III cement. At later ages the resistance of high-volume fly ash concrete to chloride-ion penetration is very high, with values of the order of only 150 coulombs at one year. These values are similar to the chloride-ion penetration results obtained on high-strength silica fume concretes.

The addition of small amounts of silica fume to the high-volume fly ash concrete can increase further its resistance to the chloride-ion penetration and make it extremely high as illustrated in Fig. 3 (18).

Corrosion of Steel Reinforcement

Laboratory tests have demonstrated that high-volume fly ash concrete can provide an excellent protection to the reinforcing steel against corrosion (33). It was found that after six months of ponding with a 3.4% sodium chloride solution, there was no significant corrosion taking place on the reinforcing steel embedded in the high-volume fly ash concrete with only 13 mm of concrete cover (Table 3). This performance of the high-volume fly ash concrete was equivalent to that of a conventional portland cement concrete with a water-to-cement ratio of 0.32 and a portland cement content of 376 kg/m³.

Resistance to Sulphate Attack

A comparative study performed at CANMET on the sulphate resistance of concrete specimens immersed in a 5% Na₂SO₄ solution demonstrated that the high-volume fly ash concrete performed better than the reference concrete made with the ASTM Type V cement, and the concrete

incorporating 25 and 50% slag as partial replacement for cement (Fig. 4). It should be noted that the water-to-cementitious materials ratios are different for the different systems being compared. Nevertheless, the data shows that the performance of the high-volume fly ash system with a water-to-cementitious material ratio of 0.31 is superior to that of other systems with much higher cement content.

The primary reasons for the low expansion in the high-volume fly ash concrete appear to be the very low permeability of the high-volume fly ash concrete system, and the dilution effect i.e. the reduction in the C_3A and the $Ca(OH)_2$ contents; in addition, most of the available $Ca(OH)_2$ is consumed in pozzolanic reactions, thus inhibiting the sulphate reactions.

Controlling Expansion Due to Alkali Aggregate Reactions

The undesirable expansion of concrete due to the reaction between the cement alkalis and certain types of reactive silica in aggregates is a serious problem in Canada, the U.S.A., and a number of other countries. Extensive tests performed at CANMET have shown that the use of high-performance, high-volume fly ash concrete can effectively reduce the expansion due to alkali-silica reaction (ASR) (7,16). This has been demonstrated by several accelerated test methods performed on concrete made with known reactive aggregates. The reduction in expansion due to ASR in the high-volume fly ash concrete results from the dilution effect due to the reduced cement content, the low permeability of this type of concrete, the reduction in the pH of the pore solution by consumption of the portlandite, and from changes in C/S of the CSH that allows more alkalis to be trapped in the CSH.

The effectiveness of fly ashes in reducing expansion due to ASR in the high-volume fly ash system is a function of the chemical composition of the fly ashes, in particular their calcium and alkali contents (16). CANMET results have shown that fly ashes with high alkali contents (≈ 7 to 9% Na_2O equivalent) could possibly be used in the high-volume fly ash system to control ASR in concrete providing the CaO content of the fly ash is less than a threshold value of about 15%. The expansion values from the same study obtained for the high-volume fly ash concrete incorporating a high-calcium fly ash ($CaO > 25\%$) confirmed that for specifying preventive actions against ASR, the limit on the alkali content of high-calcium fly ashes should be much lower than the 4.5% Na_2O equivalent value proposed in the Appendix B of the Canadian standard CSA A23.1-94, Concrete Materials and Methods of Concrete Construction.

Carbonation

Results of carbonation tests performed using the phenolphthalein indicator on broken portions of 100x200-mm cores drilled at frequent intervals from a block of high-volume fly ash concrete over a 13 year period are shown in Table 2. The block, cast at CANMET in December 1985, was moist cured for 28 days, and following this the block was left in a room with limited ventilation and at a

temperature of about 23°C and a relative humidity of 40 to 50 per cent. The average carbonation depth was 11.5 mm after 13 years

Other data on carbonation of the high-volume fly ash concrete exposed to outdoor conditions in Ontario, Canada, for ten years have shown negligible carbonation depths of only 3 to 5 mm (29).

Durability in Marine Environment

High-volume fly ash concrete prisms, 305x305x915-mm in size, have been exposed to marine environment at Treat Island, Maine, since 1987 (34). The prisms are positioned at mid-tide level so that they are exposed alternatively to a marine atmosphere and then to the immersion in sea water. Twice daily, the alternating conditions of immersion and exposure result in two cycles of wetting and drying per day and over 100 cycles of freezing and thawing of the concrete during the winter. After 8 years of exposure, the high-volume fly ash concrete prisms with a water-to-cementitious materials of 0.31 are in excellent condition but the concrete prisms with a water-to-cementitious materials ratio of 0.35 show some surface scaling. Based on the laboratory experience, it is recommended that for this type of very severe exposure at Treat Island, the water-to-cementitious materials ratio of the high-volume fly ash concrete should not exceed 0.32.

CONCLUDING REMARKS

The need for reducing CO₂ emissions and other environmental considerations demand that the use of large amounts of fly ash and other supplementary cementing materials in concrete should be made mandatory in a near future for the concrete industry. The high-volume fly ash concrete system is environmentally friendly, and the concrete so-produced also demonstrates the attributes of high-performance concrete.

The high-volume fly ash concrete is one example of a construction material fully in harmony with the concept of sustainable development: lower environmental impact (reduced CO₂ emission), judicious use of resources (energy conservation, use of by-products) and a high-performance product.

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Table 1 - Typical Mechanical Properties of Hardened High-Volume Fly Ash Concrete
(Medium Strength) Made at CANMET with ASTM Type I Cement.

Compressive Strength	
1 day	8 ± 2 MPa
7 days	20 ± 4 MPa
28 days	35 ± 5 MPa
91 days	43 ± 5 MPa
365 days	55 ± 5 MPa
Flexural Strength	
14 days	4.5 ± 0.5 MPa
91 days	6.0 ± 0.5 MPa
Splitting-Tensile Strength	
28 days	3.5 ± 0.5 MPa
Young's Modulus of Elasticity	
28 days	35 ± 2 GPa
91 days	38 ± 2 GPa
Drying Shrinkage Strain at 448 days	
	$500 \pm 50 \times 10^{-6}$
Specific Creep Strain at 365 days (per MPa of stress)	
	$28 \pm 4 \times 10^{-6}$

Table 2 - Typical Durability Test Results from CANMET Studies on High-Volume Fly Ash Concretes Made with ASTM Type I Cement

Test	Duration of moist curing	Exposure Conditions	Results
Water Permeability (CANMET Developed Test)	~ 120 days	> 100 days under a pressure of 2.7 MPa	$\leq 10^{-13}$ m/s
Freezing and Thawing Cycling (ASTM C 666, Procedure A)	14 days	1000 cycles	Durability Factors ≥ 90
Deicing Salt Scaling Resistance (ASTM C 672)	14 days moist cured followed by 14 days of air drying	50 cycles of freezing and thawing	Visual rating = 5 (severe scaling)
Resistance to Chloride-Ion Penetration (ASTM C 1202)	28 days 91 days 365 days	6 hours at 60 volts 6 hours at 60 volts 6 hours at 60 volts	500 - 2000 coulombs 200 - 700 coulombs ≈ 150 coulombs
Corrosion	7 days moist cured followed by 28 days of air drying	Ponding of concrete slabs with 3.4% NaCl solution for 6 months	No indication of corrosion of steel bars with 13-mm cover
Sulphate Resistance	28 days moist cured	Immersed in 5% Na ₂ SO ₄ solution for 7 years	Negligible expansion of test prisms
Alkali-Silica Reaction	24 hours in moulds	Different Accelerated Test Conditions	Considerable reduction in expansion
Carbonation (Phenolphthalein test on cores drilled from a 1.6x1.6x1.6-m block)	28 days	31 months 50 months 90 months 156 months	4 mm 7 mm 8 mm 11.5 mm
Marine Exposure (At Treat Island, Maine)	> 91 days	8 years of wetting and drying cycling, 100 freezing and thawing cycles per year, sea-water attack	No significant deterioration

Table 3 - Probability of Corrosion after Six Months of Ponding with a 3.4% NaCl Solution Evaluated by Half-Cell Potential Method Using Hg/HgCl₂ Electrodes.

Type of Concrete	13 mm*	25 mm*	51 mm*	76 mm*
High-Volume Fly Ash Concrete ASTM Class F Fly Ash W/(C+FA) = 0.32	Low	Low	Low	Low
High-Volume Fly Ash Concrete ASTM Class C Fly Ash W/(C+FA) = 0.32	Low	Low	Low	Low
Reference Portland Cement Concrete W/C = 0.32	Low	Low	Low	Low
Reference Portland Cement Concrete W/C = 0.43	High	Low	Low	Low
Reference Portland Cement Concrete W/C = 0.55	High	High	Low	Low
Reference Portland Cement Concrete W/C = 0.76	High	High	Med.	Low

* Thickness of concrete cover

Low: half-cell potential less negative than -128 mV indicating a 90% probability of no corrosion;

Med.: half-cell potential between -128 mV and -278 mV indicating an increasing probability of corrosion;

High: half-cell potential more negative than -278 mV indicating a 90% probability of corrosion.

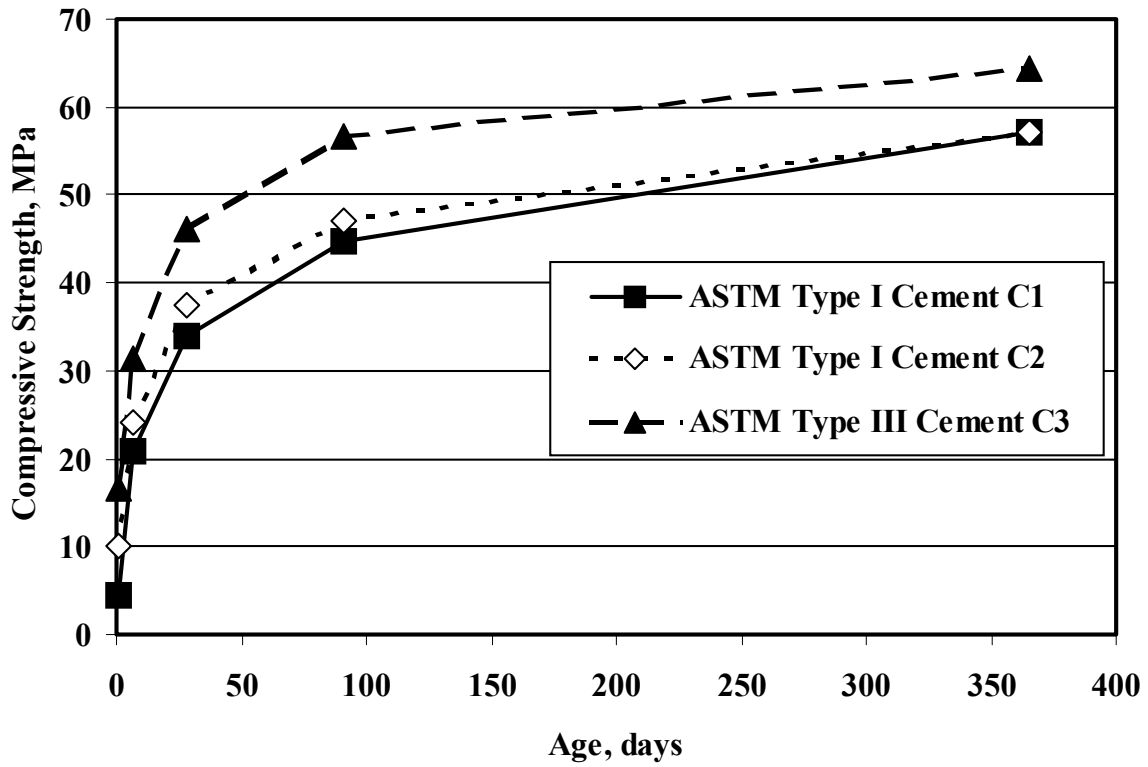


Fig. 1 - Strength development of high-volume fly ash concrete made with two different ASTM Type I and one ASTM Type III cements. (Data from reference 13 and 17)

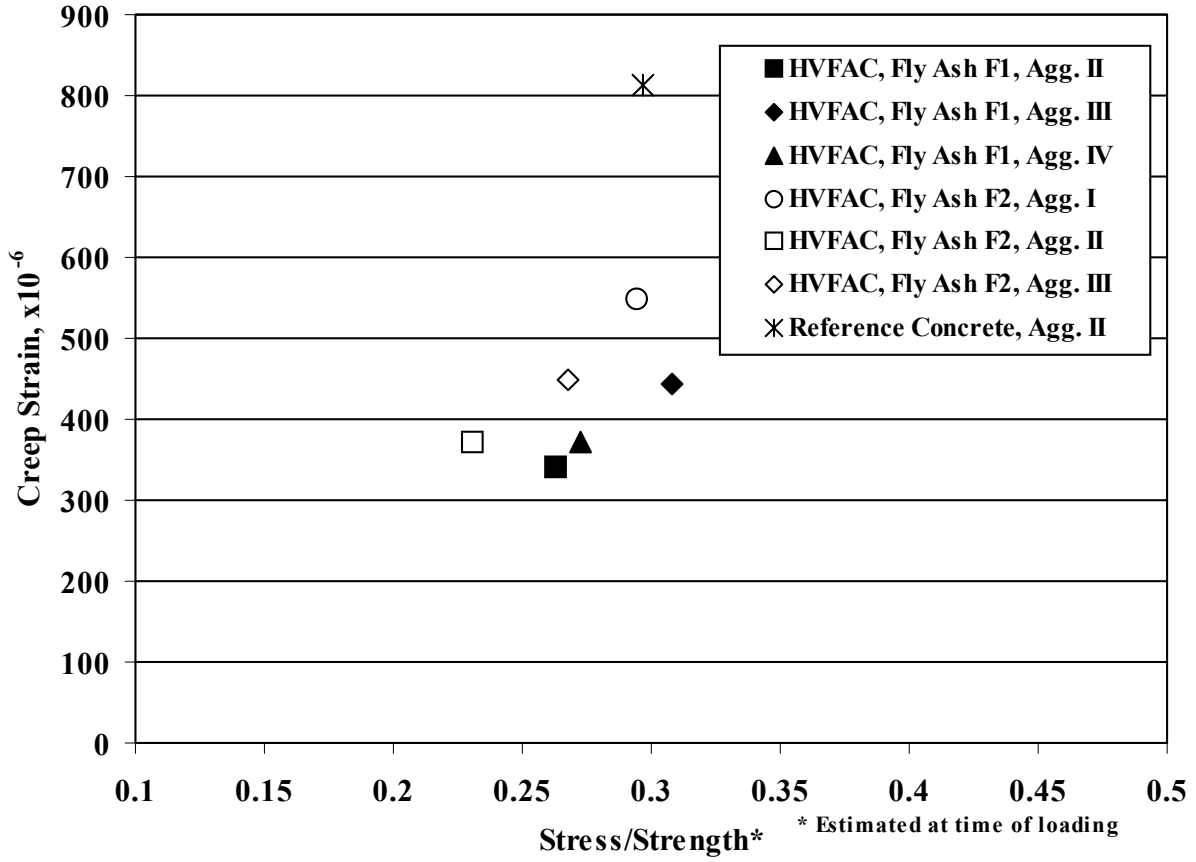


Fig. 2 - Creep strain versus stress-strength ratio of high-volume fly ash concrete (HVFAC) and reference concrete made with coarse lightweight aggregates from different sources. (19)

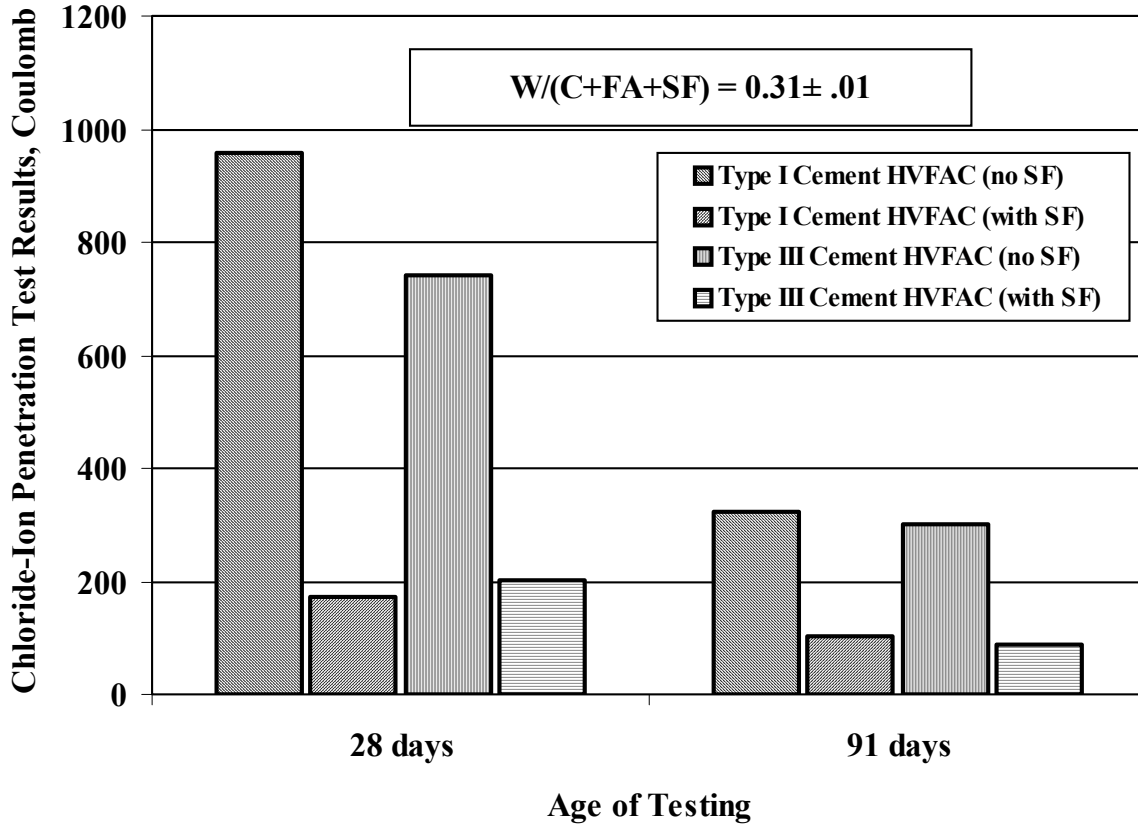


Fig. 3 - Resistance to chloride-ion penetration of high-volume fly ash concrete made with ASTM Type I and III cements, with and without silica fume. (18)

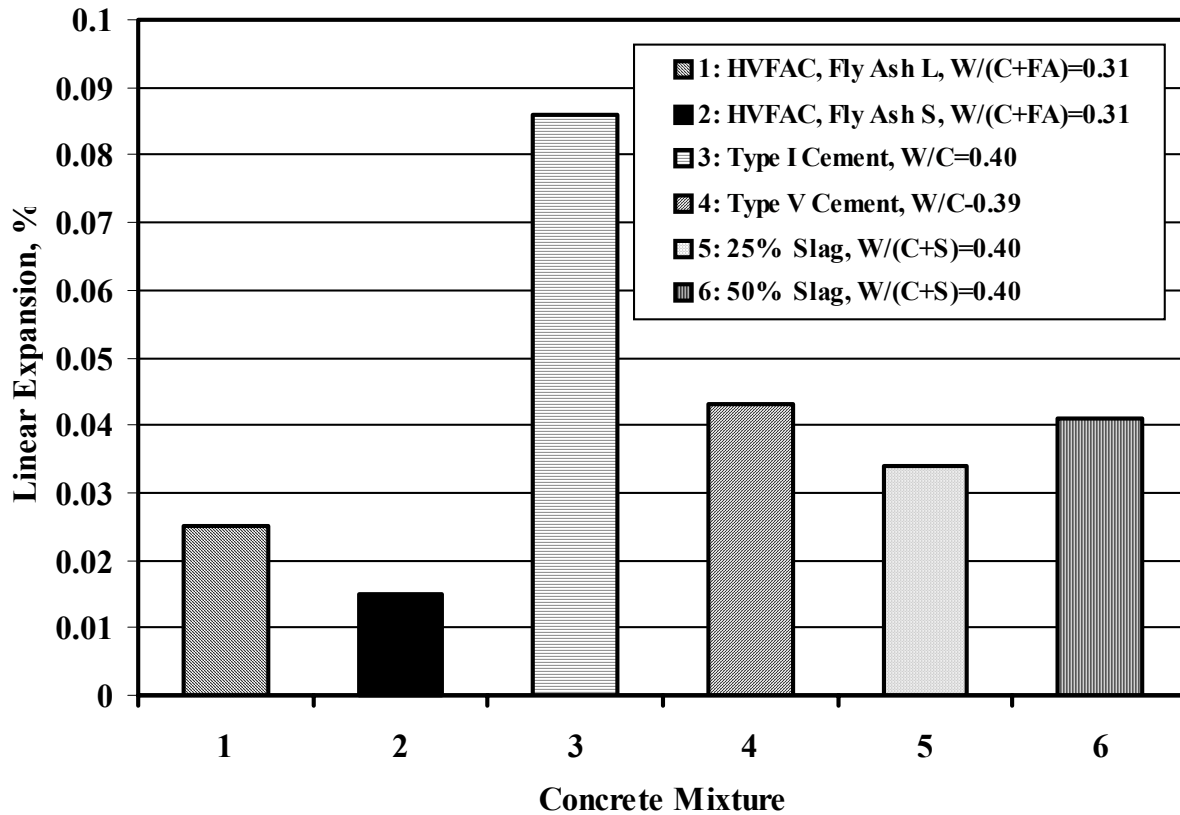


Fig. 4 - Expansion of concrete prisms after 7 years of immersion in 5% Na_2SO_4 solution. Comparison between high-volume fly ash concrete made with two different fly ashes, reference concretes made with ASTM Type I and Type V cement, and concrete incorporating 25 and 50% slag as replacement for cement. (From CANMET unpublished data)