MATERIALS TECHNOLOGY LABORATORY

USE OF HIGH-VOLUME FLY ASH CONCRETE AT THE LIU CENTRE

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by

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ABSTRACT

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. The Liu Centre for the Study of Global Issues was designed using sustainable principles in order to reduce its demand on the environment and existing infrastructure. In accordance with those principles it was decided to use the high-volume fly ash concrete in some elements of the building because of the beneficial impact that the use of this type of concrete has on the environment. The use of the high-volume fly ash concrete in the Liu Building will serve to demonstrate the potential of this type of concrete for other future applications, especially in the Vancouver area.

This paper gives an overview of the properties of the high-volume fly ash concrete, and present the results of the work associated with the use of this type of concrete for the construction of the Liu Centre.

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INTRODUCTION

In view of the global sustainable development, it is imperative that supplementary cementing materials (SCMs) be used to replace large proportions of portland cement in the concrete industry. The production of portland cement releases large amounts of CO_2 into the atmosphere, approximately 0.9 tonne of CO_2 per tonne of cement produced, consequently, each tonne of cement displaced by using SCMs translates into 0.9 tonne less of CO_2 emitted. The annual production of cement is expected to increase from about 1.4 billion tonnes in 1995 to almost 2 billion tonnes in 2010. The most available SCM worldwide is fly ash, a by-product of the thermal power stations. It is estimated that approximately 600 million tonnes of fly ash is available worldwide, 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 (1). This demonstrates that the large increase in the demand for cement could be compensated in significant part by using larger amounts of SCMs, mainly fly ash in the concrete.

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 proportions 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 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 other agencies, has developed vast data on the properties of the high-volume fly ash concrete (4-19).

The Liu Centre for the Study of Global Issues was designed using sustainable principles in order to reduce its demand on the environment and existing infrastructure. In accordance with those principles it was decided to use the high-volume fly ash concrete in some elements of the building because of the beneficial impact that the use of this type of concrete has on the environment.

The use of the high-volume fly ash concrete in the Liu Building will serve to demonstrate the potential of this type of concrete for other future applications, especially in the Vancouver area.

THE HIGH-VOLUME FLY ASH CONCRETE

The following describes the concept of high-volume fly ash concrete and gives an overview of its properties.

Applications of the High-Volume Fly Ash Concrete

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). More recently, CANMET has worked 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 results obtained with this new type of cement are promising, especially for the use of coarse fly ashes (25).

Properties and Materials Used for Producing High-Volume Fly Ash Concrete

Most investigations on high-volume fly ash concrete at CANMET were carried out using several CSA Type 10 (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 CSA Type 20 and Type 30 (ASTM Type II and 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.

In most studies performed at CANMET the high-volume fly ash concrete was made using very low water contents, and the use of superplasticizer was necessary to obtain workable concrete; naphthalene-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).

Mixtures Proportioning

In CANMET studies, the mixture proportions were optimized to produce a high-performance (highly durable), air-entrained concrete, both for mass and structural concrete applications. Typical mixture proportions used in CANMET investigations are shown in Table 1 below.

Table 1 - Typical Mixture Proportions of High-Volume Fly Ash Concrete Used in CANMET Studies

Water	120 kg/m^3
ASTM Type I Cement	155 kg/m^3
ASTM Class F Fly Ash	215 kg/m^3
Coarse Aggregate	1195 kg/m^3
Fine Aggregate	645 kg/m^3
Air-Entraining Admixture	200 mL/m^3
Superplasticizer	4.5 L/m^3

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 proportion of fly ash be as high as possible, and the water content and water-to-cementitious materials ratio (W/CM) as low as possible to provide adequate early-age strength and insure durability. It is not recommended to produce high-volume fly ash concrete with W/CM higher than about 0.35 unless it is for an application where durability is not at all an issue. In many cases, the use of a superplasticizer is mandatory to provide adequate workability.

Properties of the Fresh Concrete

Slump, Air Content and Dosage of Admixtures

Most of the investigations at CANMET involved the use of a superplasticizer and 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. The use of higher water contents than that shown in Table 1 will result in lower dosage of superplasticizer. High-volume fly ash concrete can also be produced without superplasticizer by increasing, sometimes noticeably, the water content of the mixture. However, in this case, the total amount of cementitious materials of the mixtures will have to be increased significantly to keep the W/CM low which is necessary to produce the required strengths, especially at early ages, and to insure long-term durability. This type of concrete has also been used without superplasticizers at very low, and even zero slump for roller-compacted concrete applications.

A water-reducing admixture can be used in high-volume fly ash concrete to help reducing the water content of the concrete but care should be taken to use the correct dosage in order to avoid set retardation.

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. 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.

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). This is a very important advantage of the high-volume fly ash concrete for applications where thermal gradient and stress are an issue.

Curing of High-Volume Fly Ash Concrete

As for any type of 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.

Mechanical Properties

Most studies performed at CANMET on high-volume fly ash concrete were done with the intent of producing high-performance concrete using the mixture proportions given in Table 1, and the mechanical properties given below refers to this type of concrete. However, the relative performance of high-volume fly ash concrete versus conventional portland cement concrete of similar design strength will, in general, also apply to different grades of concrete.

As mentioned before, in order to obtain adequate early-age mechanical properties, the W/CM of high-volume fly ash concrete must be kept as low as possible. This is made easier by the fact that, in general, the replacement of large proportions of cement by fly ash reduces significantly the water demand of the concrete. The use of superplasticizer may be necessary, and is in fact recommended, to achieve very low W/CM when needed.

Due to the slow pozzolanic reaction, the mechanical properties at later ages of high-volume fly ash concrete will be, in general, superior to those of conventional portland cement concrete of similar design strength.

The properties of high-volume fly ash concrete are strongly dependent on the characteristics of the cement and fly ash used.

Compressive Strength

Figure 1 illustrates the typical strength development of high-performance high-volume fly ash concrete from studies performed in CANMET laboratory. It shows that one-day strength of the order of 8 Mpa, 28-day strength of about 35 Mpa, and 91-day strength close to 45 Mpa are normally achieved with this type of concrete. Again, the levels of strength may be significantly different, depending on the characteristics of the materials used. For instance, the early-age compressive strength can be increased significantly by using a Type 10 cement with rapid strength development, or even a Type 30 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). This illustrates the potential of this type of concrete for high-strength concrete applications.

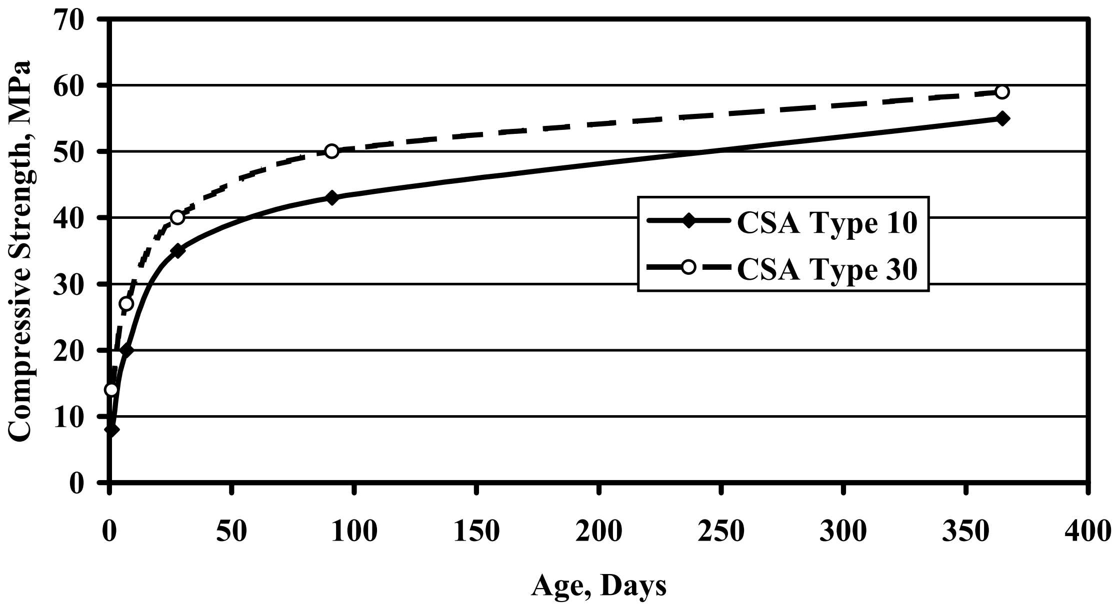

Fig. 1 – Typical Compressive Strength Development of High-Volume Fly Ash Concrete Made with CSA Type 10 and CSA Type 30 Cements

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 obtained for conventional portland cement concrete.

Young's Modulus of Elasticity

In CANMET investigations, Young's modulus of elasticity "E" values of the order of 35 and 38 GPa at 28 and 91 days, respectively, were achieved with the high-performance high-volume fly ash concrete. These values are considered high for the level of compressive strength of the concrete. The high modulus values are probably due to unreacted fly ash, consisting of glassy spherical particles, acting as a fine aggregate.

Drying Shrinkage and Creep

The drying shrinkage strains of the high-volume fly ash concrete is comparable to, or lower than that of conventional portland cement concrete, with measured values of the order of $500x10^{-6}$ 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 $32x10^{-6}$ per MPa of stress for normal-weight concrete after one year under loading. 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

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.

Once again, most durability tests performed at CANMET on high-volume fly ash concrete were done on the very low W/CM concrete mixtures. In general, the W/CM of high-volume fly ash concrete will be significantly lower than that of a conventional portland cement concrete of similar strength, resulting in a superior durability performance for the former type of concrete. To achieve highly-durable concrete for severe exposure conditions, low W/CM and adequate curing are of paramount importance.

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

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, and it performed very well when submitted to the ASTM C 666 freezing and thawing test, Procedure A.

Resistance to Deicing Salt Scaling

The high-volume fly ash concrete showed poor performance in the deicing salt scaling test done at CANMET using ASTM C 672 standard test procedure. However, other investigators using other materials and mixture proportions, 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, from 200 to 700 coulombs at 91 days, and can be as low as about 150 coulombs at one year. A value of less than 600 coulombs is indicative of very high resistance, and hence, very low permeability.

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. This performance of the high-volume fly ash concrete was superior to that of a conventional portland cement concrete of similar 28-day compressive strength, and equivalent to that of a high-performance portland cement concrete with a water-to-cement ratio of 0.32 and a portland cement content of 376 kg/m^3.

Resistance to Sulphate Attack

A comparative study performed at CANMET on concrete specimens immersed in a 5% Na_2SO_4 solution demonstrated the excellent performance in sulphate resistance of the high-volume fly ash concrete made with ASTM Class F fly ashes. This type of concrete appears to be an excellent alternative to the use of CSA Type 50 (ASTM Type V) cement for concrete exposed to sulphate. On the other hand, the combined use of high-volume fly ash concrete using Type 50 cement and superplasticizer is not recommended since this may result in significant set retardation and very slow strength development, especially in cold weather conditions.

Controlling Expansion Due to Alkali Aggregate Reactions

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 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, provided 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 from a block of high-volume fly ash concrete, have shown a carbonation depth of 11.5 mm after 13 years. The block, cast at CANMET, was moist cured for 28 days, and following this, was left in a room with limited ventilation and at a temperature of about 23EC and a relative humidity of 40 to 50 per cent. Since the depth of carbonation is roughly proportional to the square root of the time, the depth of carbonation for this concrete under this condition, would be of the order of only 35 mm after 100 years of exposure.

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-performance, 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. Therefore, the prisms are exposed to a combination of wetting and drying cycles, chemical attack, and over 100 cycles of freezing and thawing in the presence of salts during the winter. After 9 years of exposure to this very severe conditions, 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 in marine environment, the water-to-cementitious materials ratio of the high-volume fly ash concrete should not exceed 0.32.

USE OF HIGH-VOLUME FLY ASH CONCRETE AT THE LIU CENTRE

Laboratory Study

At the time of the field application at the Liu Centre, CANMET/ICON awarded a contract to Levelton Engineering Ltd., Richmond, British Columbia to perform a laboratory study to determine the basic properties of different high-volume fly ash concrete mixtures, using the same materials that were used for the concrete at the Liu Centre. The results of this study can be used for optimizing mixtures for future applications in the Vancouver area.

The laboratory study included two series of mixtures; one non-air entrained, and one air-entrained. Five different water-to-cementitious materials ratios, and two fly ash/cement proportions were used, to cover a range of high-volume fly ash concrete mixtures having different compressive strengths for different applications. In particular, two high-volume fly ash concrete mixtures were made with lower cementitious contents and significantly higher W/CM in order to develop data on this type of concrete for potential applications where the strength requirements would be low and durability not an issue. A superplasticizer was used in some mixtures, but was not needed for others. All mixtures were made using a water-reducing admixture. Four different water contents were used in order to make high-volume fly ash concrete with and without superplasticizer. In addition to the high-volume fly ash concrete mixtures, one reference concrete incorporating 20 per cent fly ash was made for comparison purpose.

The compressive strength of the concrete at different ages was determined for all the mixtures. The resistance to chloride-ion penetration, absorption, and the volume of permeable voids were determined on selected mixtures.

Materials

An ASTM Type I (CSA Type 10) normal portland cement, produced in British Columbia, was used for all the mixtures. The fly ash used was an ASTM Class F (CSA Type CI) fly ash from Washington State, but commonly distributed in the Vancouver area. The fine and coarse aggregates were from the same sources as those used by the concrete producer for the Liu Centre. Commercially available water-reducing admixture, superplasticizer, and air-entraining admixture were used.

Mixture Proportions

The proportions of the concrete mixtures are given in Table 2. A total of 14 high-volume fly ash concrete mixtures; nine non-air entrained and five air-entrained, were made. One reference non-air entrained mixture was also made. The water-to-cementitious materials ratio (W/CM) of the "high-performance" high-volume fly ash concrete mixtures ranged from 0.33 to 0.36 and two proportions of cement replacement by fly ash, 50 and 60 % were used. Two different water contents, 125 and 135 kg/m^3 of concrete were used for the "high-performance" high-volume fly ash concrete. The purpose of the higher water content was to make high-volume fly ash concrete with lower, or even without superplasticizer for practical or cost considerations.

Two "lower-grade" high-volume fly ash concrete mixtures were made with lower cementitious materials contents, significantly higher W/CM (0.48 and 0.41), and without superplasticizer. The reference concrete incorporated 20% fly ash, had a water content of 169 kg/m^3 of concrete, and a water-to-cementitious materials ratio of 0.47.

Table 2 - Mixtures Proportions for The Laboratory Study at Levelton Engineering Ltd.

Mix No.	W/CM	Water, kg/m^3	Cement, kg/m^3	Fly Ash,		Coarse Agg., kg/m^3	Fine Agg., kg/m^3	WRA,* mL/m^3	AEA,** ML/m^3	SP,*** mL/m^3
				%	kg/m^3					
1	0.33	125	190	50	190	1123	780	950	0	500
2	0.33	125	152	60	228	1115	775	950	0	1000
3	0.35	125	179	50	179	1136	789	895	0	1670
4	0.35	135	193	50	193	1103	767	965	0	0
5	0.35	125	143	60	215	1129	784	895	0	0
6	0.36	125	173	50	173	1143	795	865	0	0
7	0.36	135	188	50	188	1109	771	940	0	0
8	0.36	125	150	60	226	1117	777	940	0	1330
9	0.48	144	150	50	150	1151	873	750	0	0
10	0.47	169	288	20	72	1126	781	900	0	0
11	0.33	125	190	50	190	1060	736	950	115	830
12	0.35	125	179	50	179	1073	745	895	110	500
13	0.35	125	143	60	215	1066	740	895	110	330
14	0.36	125	173	50	173	1080	750	865	105	730
15	0.41	131	160	50	160	1085	820	800	95	0

Note: Mixtures 1 to 10 are non-air entrained, and mixtures 11 to 15 are air entrained.
* WRA: Water-Reducing Admixture
**AEA: Air-Entraining Admixture
*** SP: Superplasticizer

Properties of the Fresh Concrete.

The properties of the fresh concrete are given in Table 3. The superplasticizer was required to achieve the target slump of 100 to 120 mm in four of the non-air entrained high-volume fly ash concrete mixtures, and in four of the air-entrained mixtures. The mixtures that were made with 135 kg of water per cubic meter of concrete did not require any superplasticizer. This shows the capacity of the fly ash to reduce significantly the water demand of the concrete when used in high proportions of 50 to 60%.

The differences in the dosage of the superplasticizer for the mixtures made with 125 kg of water per cubic meter of concrete, and the fact that some of them did not require superplasticizer, indicate that there was probably some differences in the actual moisture content of the aggregates used, mainly the sand, although this value was determined a few time throughout the mixing program. Therefore, there is probably some uncertainty on the actual W/CM of the mixtures, and this was reflected by the compressive strength test results.

In principle, the dosages of the superplasticizer in the air-entrained mixtures should be lower than those of the corresponding non-air entrained mixtures due to the contribution of the entrained air bubbles to the workability of the concrete, but this was not always the case here. Again, this is another indication of the variability of the moisture content in the aggregates.

The target air content of the air-entrained mixtures was obtained easily, and the dosages of air-entraining admixture were not high.

Table 3 - Properties of the Fresh Concrete of the Laboratory Study

Mix. No.	W/CM	Water, kg/m^3	Cement, %	Fly Ash, %	Slump, mm	Unit Mass, kg/m^3	Air Content, %
1	0.33	125	50	50	130	2480	2.4
2	0.33	125	40	60	130	2463	2.3
3	0.35	125	50	50	100	2484	2.3
4	0.35	135	50	50	100	2471	2.4
5	0.35	125	40	60	130	2448	2.6
6	0.36	125	50	50	120	2451	2.3
7	0.36	135	50	50	130	2463	1.8
8	0.36	125	40	60	110	2491	2.4
9	0.48	144	50	50	120	2474	1.8
10	0.47	169	80	20	110	2468	1.8
11	0.33	125	50	50	120	2363	5.6
12	0.35	125	50	50	120	2378	5.8
13	0.35	125	40	60	130	2334	6.0
14	0.36	125	50	50	110	2363	5.4
15	0.41	161	50	50	100	2353	6.4

Compressive Strength Development

The compressive strength test results are given in Table 4. The results do not always follow a logical trend, with for example, concrete with lower W/CM showing lower strength than concrete with higher W/CM. As observed from the data on the dosage of superplasticizer, the variations in the actual moisture content of the aggregates could have resulted in some uncertainty in the actual W/CM of the mixtures. Nevertheless, the results show that, in general, for the non-air entrained high-volume fly ash concrete, with the exception of the low-cementitious content mixture (mixture 9), compressive strength in the range of 5 to 8 MPa can be achieved at one day, 40 to 45 MPa at 28 days, 45 to 55 MPa at 56 days, and 55 to 65 Mpa at 91 days. Mixture No.8 was an exception, showing a significantly lower one-day strength of 1.7 MPa. This low strength is possibly due to some set retarding effect of the admixtures, which however was not noticed for any other mixture in the program. Mixtures 5 and 6 also showed lower strengths at all ages. Again, the actual W/CM of those mixtures was possibly slightly higher than the theoretical value.

Table 4 - Compressive Strength of the Concrete from the Laboratory Study

Mix. No.	W/CM	Cement, %	Fly Ash, %	Compressive Strength, MPa					
				1 day	3 days	7 days	28 days	56 days	91 days
1	0.33	50	50	7.6	23.6	32.2	46.6	51.8	55.3
2	0.33	40	60	5.9	22.4	33.0	41.3	49.3	55.6
3	0.35	50	50	7.6	27.0	36.5	49.6	56.8	65.2
4	0.35	50	50	8.6	26.1	35.8	45.3	57.8	63.2
5	0.35	40	60	3.8	14.6	21.9	30.3	37.0	43.9
6	0.36	50	50	4.8	17.4	24.4	35.7	41.7	49.5
7	0.36	50	50	4.8	20.5	30.7	41.6	50.0	58.0
8	0.36	40	60	1.7	19.6	28.6	41.4	46.9	50.7
9	0.48	50	50	5.4	14.2	20.1	30.0	34.4	38.1
10	0.47	80	20	9.3	26.2	34.7	46.2	53.6	54.2
11	0.33	50	50	7.8	21.6	28.6	42.1	48.1	48.7
12	0.35	50	50	7.5	19.3	25.9	36.9	43.3	46.8
13	0.35	40	60	4.5	14.0	18.1	27.1	31.7	36.7
14	0.36	50	50	6.9	19.3	25.9	36.7	42.0	47.0
15	0.41	50	50	5.7	14.1	18.2	27.1	31.7	35.2

The air-entrained concrete showed a more logical trend, and the strength values ranged from 4.5 to 7.8 MPa at one day, 27.1 to 42.1 MPa at 28 days, 31.7 to 48.1 at 56 days, and 36.7 to 48.7 at 91 days. The compressive strength of the air-entrained concrete is about 10 to 20% lower than that of the corresponding non-air entrained concrete mixture.

The low-cementitious high-volume fly ash concrete mixtures (mixtures 9 and 15) showed similar strengths. The reduction in strength due to the presence of 6.4% of air in the air-entrained concrete was somewhat compensated by the lower W/CM (0.41) as compared to that of the non-air-entrained concrete (0.48). Both types of concrete showed acceptable strengths of about 5.5 Mpa at one day, and reached strengths in the range of 27.1 to 30.0 MPa at 28 days. This demonstrates that high-volume fly ash concrete can be used for lower-grade concrete in a cost effective manner by using lower cement contents and not requiring a superplasticizer. However, this type of lower-grade concrete should never be used for applications potentially subjected to any kind of aggressive environment.

Resistance to Chloride-Ion Penetration, Absorption, and Volume of Voids in Concrete

The data on the resistance to chloride-ion penetration, absorption, and the volume of permeable voids in concrete of selected mixtures at the age of 56 days are given in Table 5. The resistance to chloride-ion penetration of the high-volume fly ash concrete mixtures ranged from 803 coulombs (rated very low penetrability) to 1364 coulombs (low penetrability), and was significantly better than that of the reference concrete, at 2224 coulombs (moderate penetrability). These results demonstrate that although the high-volume fly ash concrete and the reference concrete have similar strengths, the former concrete offers a significant advantage over the latter on an important durability aspect. The excellent resistance of the high-volume fly ash concrete to the chloride-ion penetration has been demonstrated by several other investigations (6, 8, 10, 11).

The high-volume fly ash concrete with a W/CM of 0.35 showed a better resistance to chloride-ion penetration than the concrete with a W/CM of 0.33. A similar trend was noticed in the compressive strength and, again, this probably reflects some uncertainty about the actual W/CM of the concretes.

The data on the absorption and volume of voids in concrete also demonstrate the superior quality of the high-volume fly ash concrete as compared to the reference concrete.

Table 5 - Resistance to Chloride-Ion Penetration, Absorption and Volume of Permeable Voids of the Concrete from the Laboratory Study

Mix. No.	W/CM	Cement, %	Fly Ash, %	Chloride-Ion Penetrability		Absorption Soaked, %	Absorption Boiled, %	Volume of Permeable Voids, %
				Charge Passed, Coulombs	Rating*			
1	0.33	50	50	1107	low	2.41	2.43	5.9
3	0.35	50	50	803	very low	2.23	2.29	5.6
6	0.36	50	50	1364	low	3.00	3.10	7.4
10	0.47	80	20	2224	moderate	3.44	3.49	8.3

* According to ASTM C 1202 Standard Test Procedure

Field Application

The plan was to use the high-volume fly ash concrete for the foundation and for the cast-in-place structural elements of the building. Other types of concrete, also incorporating some amounts of fly ash would be used for other elements of the building such as exterior slabs and topping of precast concrete slabs. The specified strength of the foundation and the structural elements were 25 MPa, and 30 Mpa, respectively. At the time of pouring the concrete in the field, there was no data available on high-volume fly ash concrete mixtures made with the given materials (cement, fly ash, aggregates) used in the concrete for the Liu Centre. Given this, a somewhat conservative concrete mixture was designed to fulfill the requirements for the structural elements.

It was decided to try this high-volume fly ash concrete mixture firstly in the foundation elements of the building, and depending on its performance, to assess whether or not the same proportions could be used for the structural parts of the building. Modification to the proportions would have been needed if the concrete was found to be unsuitable for structural elements. This, of course, resulted in using a concrete of significantly higher quality than what was required for the foundation elements of the building.

The mixture proportions used are given in Table 6. They differ from those commonly used in CANMET studies, mainly by their slightly higher water content, and the proportion of fly ash used, 50 percent instead of 55 percent.

Table 6 - Proportions and Properties of the Fresh Concrete of the Mixture Poured in the Foundation of the Liu Centre

Mixture Proportions	W/CM	0.33
	Water, kg/m^3	130
	Cement, kg/m^3	195
	Fly Ash, kg/m^3	195
	Fine Aggregate, kg/m^3	770
	Coarse Aggregate, kg/m^3	
	- 14-5 mm	360
	- 20-10 mm	720
	Air-Entraining Admixture, mL/m^3	30
	Water-Reducing Admixture, mL/m^3	600
	Superplasticizer, mL/m^3	0
Properties of the Fresh Concrete	Slump, mm	90
	Unit mass, kg/m^3	2395
	Air Content, %	2.2
	Temperature, °C	18

Since the efficiency of the fly ash in reducing the water demand of the concrete mixture, and its compatibility with the superplasticizer were not known, it was decided to use a slightly higher water content than that commonly used in the CANMET laboratory studies (Table 1). The objective was to avoid a situation, where very high dosages of superplasticizer would have been needed to provide workability. Experience has shown that when this is the case, the concrete becomes very sticky, hard to place, and could be very difficult to pump.

The proportion of the fly ash was reduced from 55% to 50% in order to provide slightly higher strength at early-ages, especially for form removal, again due to the insufficient knowledge about the materials used for this specific project.

Surprisingly, superplasticizer was not needed to obtain the target slump with this concrete; the water content was high enough, with the help of the water-reducing admixture, to provide adequate workability. This indicates that the fly ash used contributed significantly to reduce the water demand of the concrete. The concrete was pumped and placed into the formwork without any difficulties.

Concrete cylinders were cast in the field for compressive strength determination at different ages. The strength data for the concrete poured in the foundation are given in Table 7. The one-day strength was 9.7 MPa which was adequate for the removal of the forms. The strength at 28 days was 32.2 Mpa, which exceeds slightly the specified strength for the structural elements (30 Mpa). It is, of course, significantly higher than that specified for the foundation (25 MPa). The concrete reached a strength of 37.0 MPa at 56 days.

Table 7 - Compressive Strength of the Concrete Placed in the Foundation of the Liu Centre

Age, days	Compressive Strength of 100x200- mm Cylinders, MPa	
	Foundation	Above Ground Structural Element
1	9.7	10.1
3	n.a.	19.5
4	18.7	n.a.
7	19.8	24.4
14	27.4	29.7
28	32.2	34.7
56	37.0	39.8

It was decided, considering the general performance of the concrete, workability, pumpability, strength, visual aspects, to use the same mixture for above-ground structural elements of the building. Table 7 also gives data on the compressive strength of one mixture used for this part of the building, and these are very similar to those obtained with the mixture used in the foundation.

CONCLUSION

Given the large increase forecast in the demand for concrete, and consequently cement, the need for reducing CO_2 emissions and other environmental considerations, all efforts should be made to achieve that much larger proportions of fly ash and other supplementary cementing materials available be used in the concrete industry in the near future. The high-volume fly ash concrete system provides an excellent alternative to conventional concrete, it is environmentally friendly, and 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 CO_2 emission), judicious use of resources (energy conservation, use of by-products) and a high-performance product.

To support this concept, high-volume fly ash concrete was used successfully both in the foundation and the structural elements of the Liu Centre using conventional concreting practices. Field and laboratory data produced with materials from the Vancouver area demonstrated the potential of this type of concrete for different types of applications.

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