Properties of High-Volume Fly Ash Concrete Made with High Early-Strength ASTM Type III Cement

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Synopsis: Canada Centre for Mineral and Energy Technology (CANMET) has an ongoing project dealing with the role of supplementary cementing materials in concrete technology. As a part of this program, a new type of concrete known as high-volume fly ash concrete has been developed. In this type of concrete, the water and cement (ASTM Type I) contents are kept very low, i.e. about 115 and 155 kg/m^3, respectively, and the proportion of low-calcium fly ash in the total cementitious materials content is about 56 per cent. This type of concrete has excellent mechanical properties and durability characteristics.

In spite of very good properties shown by the high-volume fly ash concrete, one concern about the use of this type of concrete is its performance at early ages due to its low cement content and the slow reaction process of the fly ash. This can be an obstacle for the use of this type of concrete when compressive strengths over 10 MPa at one day are needed or when proper curing cannot be provided for a long period of time. One way to improve the early-age properties of this type of concrete is to use ASTM Type III portland cement. Therefore a study was undertaken to develop engineering data base on the high-volume fly ash concrete using ASTM Type III cement. Concrete mixtures were made using ASTM Type III portland cement from a source in the U.S.A., and three low-calcium fly ashes also from sources in the U.S.A. A reference mixture (without fly ash) was also made for comparison purposes.

The use of ASTM Type III cement instead of Type I cement noticeably improved the early-age strength properties of the high-volume fly ash concrete incorporating the fly ashes investigated in this study, and this without having any detrimental effect on the long-term properties of the concrete. The one-day compressive strengths were about 5 to 8 MPa higher than those of the high-volume fly ash concrete made with the same fly ash and Type I cement. The use of Type III cement also shortened slightly the setting time of the high-volume fly ash concrete. The durability characteristics and the drying shrinkage of high-volume fly ash concrete made with ASTM Type III cement were no different than those for the concrete made with Type I cement.

Keywords: Chloride ions; compressive strength; drying shrinkage; flexural strength; fly ash; freeze thaw durability; high early-strength cements; modulus of elasticity; splitting tensile strength; superplasticizer

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INTRODUCTION

In 1990, CANMET undertook a project to develop data base on high-volume fly ash concrete incorporating selected fly ashes and cements from the U.S.A. This investigation was performed for the Electric Power Research Institute (EPRI), Palo Alto, California, under a subcontract with Radian Canada Inc., Mississauga, Ontario. Eight fly ashes, covering a wide range of chemical compositions, and two ASTM Type I portland cements from two different sources were used in the study. Regardless of the type of fly ash and irrespective of the brand of cement used, all air-entrained high-volume fly ash concretes performed well as regard to workability, bleeding, setting time, temperature rise, and mechanical properties. They also exhibited excellent durability characteristics in freezing and thawing cycling, resistance to chloride-ion penetration, resistance to sulphate attack, and water permeability tests (1, 2).

In spite of the excellent properties shown by the high-volume fly ash concrete in the above mentioned study, one concern about the use of this type of concrete is its performance at early ages due to its low cement content and the slow reaction process of the fly ash. This can be a disadvantage for the use of this type of concrete when high-early strengths at one day are needed or when proper curing cannot be provided for a long period of time. For example, in the field, a certain level of strength at early age is needed to remove the formwork. In the above mentioned investigation, one-day compressive strengths ranging from 3.1 to 13.9 MPa were obtained, depending on the cement-fly ash combination. The one-day compressive strength of 3.1 MPa could be considered unacceptable for some applications (1).

One way to improve the early-age strength of the concrete is to use ASTM Type III portland cement. A previous investigation at CANMET has shown that the use of Type III cement in high-volume fly ash concrete increased significantly the early-age strengths (3). Therefore the above EPRI/Radian study was extended to develop engineering data base on the high-volume fly ash concrete using ASTM Type III cement. In this new phase, concrete mixtures were made using one ASTM Type III portland cement from a source in the U.S.A. and three of the low-calcium fly ashes used in the previous study with Type I cement (1, 2). A reference mixture without fly ash was also made for comparison purposes. Some mechanical properties and durability characteristics were determined, and the results are presented in this paper.

SCOPE

Four air-entrained concrete mixtures involving eight 0.11 m^3 batches were made. The water-to-(cement+fly ash) ratio [W/(C+FA)] was kept at 0.32 for all the high-volume fly ash concrete mixtures. The water-to-cement ratio of the reference concrete was kept at 0.45 to obtain concrete with strength comparable to that of the fly ash concrete at 28 days. The proportion of fly ash in the concrete mixtures was 58 per cent by weight of the cementitious materials.

The properties of the freshly mixed concrete were determined. These included, unit weight, slump, air content, setting time, and bleeding. The adiabatic temperature rise was monitored on 152x305-mm cylinders. A number of specimens were cast, moist-cured, and tested for the determination of the mechanical properties of concrete. These included compressive, flexural, and splitting-tensile strengths at various ages, Young's modulus of elasticity, and drying shrinkage.

A number of specimens were also cast to determine the air-void parameters, the resistance to freezing and thawing cycling, and the resistance to chloride-ion penetration.

MATERIALS

ASTM Class F fly ashes from three sources in the U.S.A., and one ASTM Type III portland cement also from the U.S.A. were used in the concrete mixtures. The materials used in this program are described below.

Portland Cement

ASTM Type III portland cement was from the same source as one of the Type I cements used in the original study (1, 2). The chemical analysis and physical properties of the cement are given in Table 1.

Fly Ash

Three fly ashes from sources in the U.S.A. were used. These fly ashes were the same as used in the original study with Type I cement (1, 2). Fly ashes FA1 and FA2 had low CaO contents of 2.88 and 4.49 per cent, respectively, whereas fly ash FA3 had a CaO content of 9.51 per cent[1]. The chemical analysis and physical properties of the three fly ashes are also given in Table 1.

Aggregates

The coarse aggregate was a crushed limestone (19-mm maximum size), and the fine aggregate was a natural sand. To keep the grading uniform for each mixture, both the fine and coarse aggregates were separated into different size fractions that were then recombined to a specific grading. The grading and physical properties of the aggregates are given in Tables 2 and 3.

Superplasticizer

A commercially available sulphonated naphthalene formaldehyde condensate superplasticizer was used. This superplasticizer is available as a dark brown aqueous solution with 40 per cent solids.

Air-Entraining Admixture

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

MIXTURE PROPORTIONS

Three high-volume fly ash concrete mixtures and one reference mixture without fly ash were made in February and March 1993. Two 0.11 m^3

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[1]Fly ashes FA1, FA2 and FA3 correspond to the fly ashes F2, F4 and F8 in the original investigation.

batches were made for each mixture in order to cast a sufficient number of specimens for testing. The concrete mixtures were made in a laboratory counter-current mixer with the fly ash added as a separate ingredient.

The proportioning of the concrete mixtures is summarized in Table 4. For all the mixtures, the graded coarse and fine aggregates were weighed in a room dry condition. The coarse aggregate was then immersed in water for 24 h, the excess water was decanted, and the water retained by the aggregates was determined by the weight difference. A predetermined amount of water was added to the fine aggregate which was then allowed to stand for 24 h.

The water-to-cementitious materials ratio, as well as the water, cement and fly ash contents were kept constant for the three high-volume fly ash mixtures, and these were very similar to those used in the original study with ASTM Type I cement (1, 2). The water-to-cement ratio of the reference concrete was 0.45, which was chosen to obtain concrete with 28-day compressive strength similar to that of the high-volume fly ash concrete. All mixtures were air-entrained, with the target air content of 5.5 $\pm$ 0.5 per cent. The dosage of the superplasticizer was adjusted to give a slump of 150 $\pm$ 25 mm.

PROPERTIES OF FRESH CONCRETE

The properties of the freshly mixed concrete, i.e., temperature, slump, unit weight and air content, are given in Table 5.

PREPARATION AND CASTING OF TEST SPECIMENS

Two batches were made for each mixture in order to obtain sufficient test specimens.

Batch A

Twelve 152x305-mm cylinders and three 75x102x406-mm prisms were cast from Batch A of each mixture. The 152x305-mm cylinders were used for the determination of compressive strength at various ages, and the prisms were used for determining the flexural strength at 14 days.

Batch B

Eight 152x305-mm cylinders, ten 76x102x390-mm prisms and three 102x203-mm cylinders were cast from Batch B of each mixture. The

152x305-mm cylinders were used for determining the compressive strength, the Young's modulus of elasticity, the splitting-tensile strength at 28 days, and the autogenous temperature rise of concrete. The prisms were used for determining the freezing and thawing resistance and the drying shrinkage of concrete. The 102x203-mm cylinders were used for the determination of the resistance of concrete to chloride-ion penetration. One container of approximately 7 L capacity was filled with fresh concrete for determining the bleeding of concrete.

Compaction and Curing of Test Specimens

For all batches, the cylinders and prisms were cast in two layers, with each layer being compacted using an internal vibrator for the 152x305-mm cylinders and a vibrating table for the prisms and the 102x203-mm cylinders. After casting, all the moulded specimens were covered with plastic sheets and water-saturated burlap, and left in the casting room for 24 h. They were then demoulded and transferred to the moist-curing room at 100 per cent relative humidity until required for testing. The only exception was the prisms for the drying shrinkage tests which were stored in lime-saturated water.

TESTING OF SPECIMENS

The schedule of testing is shown in Table 6. The adiabatic temperature rise of the concretes was measured by means of thermocouples embedded in the centres of two 152x305-mm cylinders of fresh concrete placed in an autogenous curing chamber. This curing chamber was somewhat similar to that described in Procedure C of ASTM C 684: Making, Accelerated Curing and Testing Concrete Compression Test Specimens. The temperature of the concrete was recorded at 30-minute intervals for about 48 h.

Two cylinders from Batch A were tested at various ages up to one year. For control purposes, two 152x305-mm cylinders from Batch B were also tested in compression at 28 days. Two 152x305-mm cylinders from Batch B were used for the determination of the Young's modulus of elasticity at 28 days; also two 152x305-mm cylinders from the above batch were used for determining the splitting-tensile strength at 28 days. Three prisms, 75x102x406 mm in size, from Batch A were tested in flexure at the age of 14 days. Four 76x102x390-mm prisms, cast from batch B of all the mixtures were used for determining the drying shrinkage of concrete; two of these prisms were subjected to the drying shrinkage after 7 days of initial storage in lime-saturated water whereas the two remaining prisms were kept in the lime-saturated water for reference purposes.

Following 14 days of initial moist-curing, six prisms, 75x102x390 mm in size, from Batch B were used for determining the freezing and thawing resistance of concrete using ASTM C 666, Procedure A, freezing and thawing in water. Two of these prisms were broken in flexure to determine the initial flexural strength before freezing and thawing cycling. Sawn sections of these prisms were used for determining the air-void parameters of the hardened concrete. Prior to the freezing and thawing testing, the temperature of the four remaining prisms was reduced to 4.4 ± 1.7°C by placing them in a cold water tank. The initial and all subsequent measurements of the freezing and thawing specimens and the reference specimens were made at this temperature. After the initial measurements, two test specimens were subjected to freezing and thawing cycling and the two companion prisms were placed in the moist-curing room for reference purposes. After the completion of the freezing and thawing test, the reference and the freezing and thawing prisms were tested in flexure.

The resistance of the concretes to the chloride-ion penetration was determined at the ages of 7, 28 and 91 days on disks cut from 102x203-mm cylinders from Batch B, using the method outlined in ASTM C 1202.

TEST RESULTS

The data on the bleeding, the setting time, and the maximum temperature rise of the concrete are given in Table 7. The autogenous temperature rise of the concrete is illustrated in Fig. 1. Densities of the test cylinders at one day and the compressive strength test results at different ages are given in Table 8. The compressive strength development of the concrete is illustrated in Fig. 2. The Young's modulus of elasticity test results determined at 28 days are given in Table 9. The flexural strength at the ages of 14 and 91 days, and the 28-day splitting-tensile strength are shown in Table 10. The drying shrinkage test results are summarized in Table 11 and 12, and illustrated in Fig. 5. The air-void parameters of the hardened concrete are given in Table 13. A summary of the test results after 300 cycles of freezing and thawing, including the durability factors, is given in Table 14. The flexural strengths of the reference prisms and the test prisms after 300 cycles of freezing and thawing are shown in Table 15. The data on the resistance of concrete to the chloride-ion penetration are summarized in Table 16.

DISCUSSION OF TEST RESULTS

Dosage of the Superplasticizer and Slump

The dosage of the superplasticizer varied noticeably depending on the kind of fly ash used, and ranged from 3.6 to 6.8 L/m^3 of concrete (Table 4). This is somewhat higher than the dosage used in the corresponding mixtures made with the fly ashes from the same sources and the Type I cement (1). This is probably due to the higher fineness of the Type III cement.

Some superplasticizer was needed in the reference concrete to obtain the target slump, and this is due to the higher fineness of the cement, and the relatively low water content of the mixture at water-to-cement ratio of 0.45.

Air Content and Dosage of the Air-Entraining Admixture

The dosages of the air-entraining admixture (AEA) of the high-volume fly ash concretes made with ASTM Type III cement were slightly higher than those used in the corresponding mixtures made with the ASTM Type I cement; and this is, once again, due to the higher fineness of the Type III cement (Table 4) (2).

Concrete mixtures made with fly ashes FA2 and FA3 required similar dosages of AEA; however, the dosages of AEA for the concrete mixture incorporating fly ash FA1 was significantly higher than for FA2 and FA3 fly ashes, and this was probably due to the higher carbon content of the FA1 fly ash.

As expected, the dosage of the AEA for the reference concrete was noticeably lower than those for the high-volume fly ash concrete mixtures.

Bleeding of Concrete

The total amount of the bleeding water was negligible for all the high-volume fly ash concretes, and was very low at 0.8 x 10^{-2} mL/cm^2 for the reference concrete (Table 7). These results were in line with those obtained with the corresponding high-volume fly ash concrete mixtures made with the ASTM Type I cement (1).

Setting Time of Concrete

The initial and final setting times of high-volume fly ash concretes ranged from 6:34 to 7:33 h:min., and from 8:23 to 9:08 h:min., respectively (Table 7). As expected, the reference concrete set much faster, with initial and final setting times of 4:51 and 5:25 h:min., respectively. The slower setting of the high-volume fly ash concrete was due to the low cement content of this type of concrete. However, the setting times for the high-volume fly ash concretes in this investigation probably may not cause any practical problems in field applications.

For fly ashes FA1 and FA2, both the initial and final setting times of the concretes made with ASTM Type III cement were of the same order or slightly shorter than those of the corresponding concretes made using the Type I cement; for fly ash FA3, both the initial and final setting times were significantly shorter when Type III cement was used (1).

The potential reduction in the setting time of the high-volume fly ash concrete made using ASTM Type III cement instead of Type I cement might have been partly offset by the higher dosages of the superplasticizer in the mixtures incorporating the finer Type III cement, especially for concrete made with fly ashes FA1 and FA2.

Autogenous Temperature Rise

The data in Table 7 show that the maximum temperature rise of about 17.5°C was very similar for the three high-volume fly ash concretes investigated. The maximum temperature rise for the reference concrete was considerably higher at 35.9°C.

The maximum temperature rise of the fly ash concretes made with ASTM Type III cement was higher (from 3.6 to 4.8°C) than those of the corresponding concretes made with the Type I cement, and this was due to the faster hydration of the Type III cement (1).

Figure 1 shows that all the high-volume fly ash concretes had very similar heat evolutions. It also illustrates the much higher temperature in the reference concrete, and that the peak temperature was attained much sooner in the reference concrete than in the fly ash concrete.

As in previous investigations (4, 5), the above results demonstrate the potential of high-volume fly ash concrete system for reducing the temperature rise in large concrete members due to its low cement content and slow reaction process of the fly ashes.

Compressive Strength

The data on the compressive strength of the concrete are given in Table 8 and illustrated in Fig. 2. The one-day compressive strength of the reference concrete (28.3 MPa) was noticeably higher than that of the high-volume fly ash concrete which ranged from 16.5 to 17.1 MPa. Following this, the strength development of the reference concrete was slower than that of the fly ash concrete, especially between 7 and 91 days. The compressive strength of the reference concrete was slightly lower at 28 days, and significantly lower at 91 days and one year than that of the fly ash concretes.

Figures 3 and 4 illustrate the compressive strength development at early ages, and up to one year, respectively, of high-volume fly ash concrete made with ASTM Type I and Type III cements. The data are the average values of the test results obtained with the same fly ashes used in this investigation, and the previous study with Type I cement (1). The average one-day compressive strength of the high-volume fly ash concretes made with Type III cement is about 6.5 MPa higher than that obtained for the corresponding concretes made with ASTM Type I cement (Fig. 3). The average strength development of the concrete made with the Type III cement was slightly faster up to 28 days than that of the concrete made with the Type I cement. The objective of increasing significantly the early-age strength of the high-volume fly ash concrete by using ASTM Type III cement appears to have been achieved. However, the data illustrated are based on the averaged values, and this trend is not representative for all the fly ashes. For example, the fly ash FA3 showed slower strength development with the Type III cement than with Type I cement after one day.

The compressive strength of the high-volume fly ash concretes at 28 and 91 days ranged from 45.0 to 47.5 MPa (Batch A), and from 54.8 to 59.6 MPa, respectively (Table 8). These values are noticeably higher than the corresponding strengths of the concretes made with ASTM Type I cement, as illustrated in Fig. 4. The 91-day compressive strength of concrete made with Type III cement is of the same order as the one-year compressive strength of concrete made with Type I cement. The increase in the compressive strength between 91 days and one year was less for the concrete made with ASTM Type III cement than for concrete made with Type I cement. However, the former concrete produced significantly higher compressive strength at one year than the latter.

Young's Modulus of Elasticity

The Young's modulus of elasticity at 28 days ranged from 35.9 to 38.0 GPa for the high-volume fly ash concrete, and was 33.1 GPa for the reference