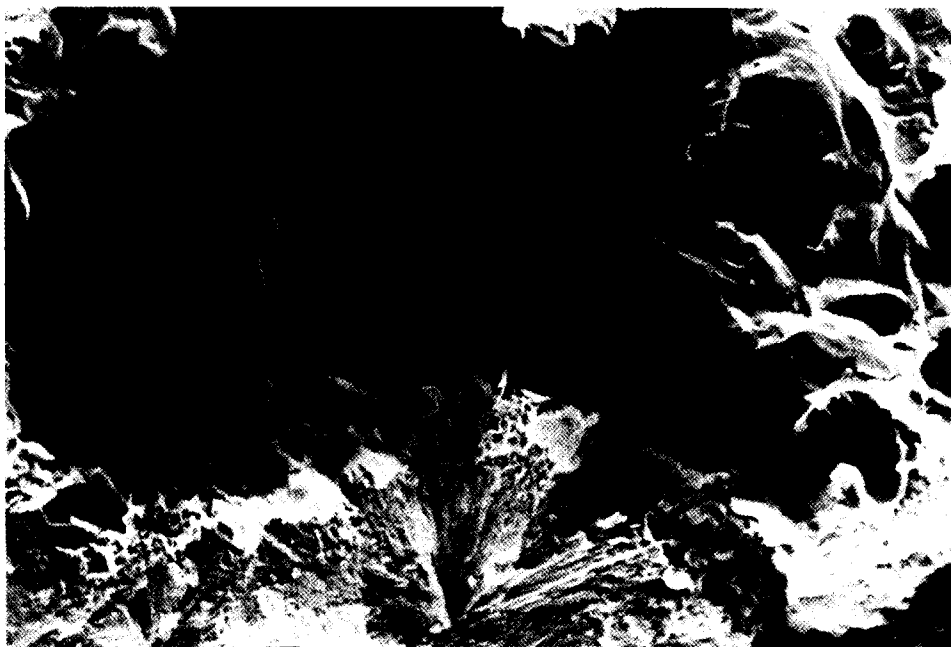


Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete

Proceedings
Fifth International Conference
Milwaukee, Wisconsin, USA, 1995



Editor

V.M. Malhotra

Volume 1


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PREFACE

The Canadian Centre for Mineral and Energy Technology (CANMET) of Natural Resources Canada, Ottawa, has played a significant role in Canada for over twenty-eight years in research on fly ashes, ferrous and nonferrous slags, and silica fumes, in order to conserve both resources and energy. In July-August 1983, CANMET, in association with the American Concrete Institute and the U.S. Corps of Engineers, sponsored a five day international conference at Montebello, Quebec, Canada, on the Use of Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete. The main purpose of the conference was to bring together representatives from industries, universities, and government agencies to present the latest information on these materials and to explore new areas of needed research. The two volume proceedings of the conference containing 62 papers from 15 countries were published as ACI Special Publication SP-79.

In 1986, CANMET, in association with the American Concrete Institute, the Canadian Society for Civil Engineering, and a number of organizations in Spain, sponsored the Second International Conference on the subject of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete. The conference was held April 21-25, 1986, in Madrid, Spain. The two volume proceedings of the conference containing 72 papers from more than 20 countries were published as ACI Special Publication SP-91.

In 1989, CANMET, in association with the American Concrete Institute, Norwegian Institute of Technology, and several other organizations in Canada and Norway, sponsored the Third International Conference on the above subject. The conference was held June 18-23, 1989, in Trondheim, Norway. The two volume proceedings of the conference containing 83 papers from more than 25 countries were published as ACI Special Publication SP-114.

In 1992, CANMET, in association with the American Concrete Institute, Electric Power Research Institute, U.S.A., and several other organizations in Canada and Turkey, sponsored the Fourth International Conference on the subject. The conference was held May 3-8, 1992, in Istanbul, Turkey. More than 130 papers from 32 countries were received and reviewed in accordance with the policies of the American Concrete Institute; 89 papers were accepted for publication as ACI Special Publication SP-132.

In 1995, CANMET, in association with the American Concrete Institute, Electric Power Research Institute, U.S.A., Canadian Electrical

Association, Montreal, and several other organizations in Canada and the United States, sponsored the Fifth International Conference on the subject. The conference was held June 4-9, 1995, in Milwaukee, U.S.A. The two volume proceedings of the conference containing 62 papers from 23 countries were published as ACI Special Publication SP-153.

To all those whose submissions could not be included in the conference volumes, the Institute and the Conference Organizing Committee extend their appreciation for their interest and hard work. The accepted papers have been published in two volumes. The first volume contains papers dealing with fly ash and natural pozzolans, and the second volume consists of papers dealing with silica fume, slag, and other materials. Some papers could have been published in either volume because the material covered more than one subject.

In addition to the papers which have been published in these volumes, more than 20 other papers were presented. Most of these papers were published as supplementary papers, and the authors have been encouraged to publish them in technical journals of their choice.

Thanks are extended to the members of the "Paper Review Panel" which met at Cascais, Portugal, June 5-9, 1994, to review the papers. Without their dedicated effort it would not have been possible to publish these volumes before the conference. The cooperation of the authors in accepting reviewers' suggestions and revising their manuscripts accordingly is greatly appreciated.

The help and assistance of Mr. H. S. Wilson, Consultant, Ottawa, Gordon D. Brearly and Maria Venturino of CANMET are gratefully acknowledged in the administrative work associated with the conference, and in processing of the manuscripts both for ACI proceedings and the supplementary volume. Thanks are also extended to A. Bilodeau (Chairman) and Messrs. B. Fournier and R. Chevrier (Members) of the Slide Review Panel for their services to ensure that the slides meet the CANMET/ACI criterion.

As an integral part of the conference, a special symposium to honor Dr. Narayan Swamy, Prof. Dept of Civil Engineering, University of Sheffield, U.K., was held during the conference. The papers presented at this symposium have been published in a separate volume.

V. M. Malhotra, Editor
Chairman, CANMET/ACI Fifth International
Conference on Fly Ash, Silica Fume, Slag
and Natural Pozzolans in Concrete
June 1995

**Organizing Committee
Fifth International Conference
on
Fly Ash, Silica Fume, Slag
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**Milwaukee, Wisconsin
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Dedicated to Members of the "Paper Review Panel" who assisted in the review of the manuscripts.

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SP 153-1

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

by A. Bilodeau and V. M. Malhotra

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/m³, 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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ACI honorary member V. Mohan Malhotra is Program Principal, Advanced Concrete Technology Program, CANMET. He is a former member of the ACI Board of Direction and has served on numerous ACI and ASTM committees. He is a prolific author, editor, and researcher, and has received many awards and honors from ACI and other institutions throughout the world.

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 m³ 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 cent¹. 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 m³

¹Fly 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 ± 0.5 per cent. The dosage of the superplasticizer was adjusted to give a slump of 150 ± 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 $4.4 \pm 1.7^\circ\text{C}$ 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/m³ 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 0.8×10^2 mL/cm² 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

concrete (Table 9). These results are in accordance with those of the previous investigations, and demonstrate the high values of the modulus of elasticity of the high-volume fly ash concrete (1, 3, 5, 6, 7, 9, 10). As mentioned in earlier studies, this could be due to the unhydrated fly ash particles acting as fine aggregate, and thus contributing to an increase in the restraint against deformation.

Flexural Strength

The flexural strengths of the high-volume fly ash concrete ranged from 5.3 to 5.6 MPa at 14 days, and from 6.2 to 6.9 MPa at 91 days (Table 10). The flexural strength of the reference concrete was 6.2 and 5.9 MPa at 14 and 91 days, respectively.

For each fly ash, the flexural strength of the concrete made with ASTM Type III cement was slightly higher than that of the corresponding concrete made with Type I cement (1).

Splitting-Tensile Strength

The 28-day splitting-tensile strength of the high-volume fly ash concrete ranged from 3.2 to 4.1 MPa, and was 3.6 MPa for the reference concrete (Table 10). These values are about 7 to 9 per cent of the 28-day compressive strength, and are comparable with other published data for conventional portland cement concrete of similar compressive strength (8).

The ratios of the splitting-tensile to compressive strengths of the concrete made with ASTM Type III cement are slightly lower than those of the concrete made with ASTM Type I cement in the previous investigation (1). This is probably due to the higher level of the compressive strength of the concrete made with Type III cement, because the ratio of splitting-tensile to compressive strengths tends to decrease with an increase in the level of compressive strength (8).

Drying Shrinkage

The drying shrinkage strains of the high-volume fly ash concrete after 448 days of drying ranged from 497 to 678×10^{-6} (Table 11). These values are similar to those of the corresponding concretes made with ASTM Type I cement in the previous investigation (1).

The shrinkage of the reference concrete (688×10^{-6}) is of the same order as the highest shrinkage strain obtained for the high-volume fly ash concretes (Fig. 5).

Air-Void Parameters of the Hardened Concrete

All the concretes exhibited good air-void parameters with spacing factors ranging from 0.074 to 0.174 mm which are less than the recommended value of about 0.230 mm for freezing and thawing durability (Table 13).

Resistance to Freezing and Thawing Cycling

The durability of concrete prisms to repeated cycles of freezing and thawing was determined from weight, length, resonant frequency, and pulse velocity measurements of test specimens before and after freezing and thawing cycling, and by calculating the durability factors (Tables 14). At the end of the freezing and thawing cycling, the reference and test prisms were broken in flexure (Table 15). The test data after 300 cycles indicate that all the test prisms performed excellently in freezing and thawing with durability factors equal to or greater than 100.

All the high-volume fly ash concrete test prisms have shown some weight loss due to surface scaling, (Table 14). The reference concrete did not show any weight loss nor surface scaling. However, the weight loss of the high-volume fly ash concrete made with the Type III cement is noticeably lower than that of the corresponding concrete made with the Type I cement in the previous investigation (2). This improvement is probably due to the greater maturity of the concrete made with ASTM Type III cement at the time of testing.

Resistance to Chloride-Ion Penetration

The data in Table 16 show that all the high-volume fly ash concretes investigated exhibited high resistance to the chloride-ion penetration, especially at 28 and 91 days. These results are in accordance with those of previous investigations (2, 7, 9, 10).

The use of ASTM Type III cement instead of Type I cement did not improve the resistance to chloride-ion penetration at 28 and 91 days of concrete incorporating fly ashes FA2 and FA3, but slightly increased that of the concrete made with the fly ash FA1 (2). There are no data on the resistance to chloride-ion penetration at 7 days of concretes incorporating the above fly ashes and Type I cement. It is possible that the effect of the Type III cement would have been visible at that early age.

CONCLUSIONS

The use of ASTM Type III cement instead of Type I cement improved significantly the early-age compressive strengths of high-volume fly ash concrete incorporating the fly ashes investigated in this study. The one-day compressive strength ranged from 16.5 to 17.1 MPa, these values being about 5 to 8 MPa higher than those of the high-volume fly ash concrete made with the same fly ashes but using Type I cement. The use of the Type III cement had no detrimental effect on the long-term strength development of the high-volume fly ash concrete; on the contrary, the concrete made with this cement resulted in higher compressive strengths at one year than those made with ASTM Type I cement.

The use of ASTM Type III cement shortened the setting time of the high-volume fly ash concrete slightly, and this could be an advantage in some applications.

The durability characteristics and the drying shrinkage of the high-volume fly ash concrete made using ASTM Type III cement were no different from the concrete made with Type I cement.

The use of Type III cement increased the autogenous temperature rise of the high-volume fly ash concrete slightly as compared with that of Type I cement; however, the rise was still much lower than that of the reference concrete.

In general, the properties of the high-volume fly ash concrete investigated were as good as or better than those of the reference concrete of equivalent 28-day compressive strength.

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TABLE 1 — PHYSICAL PROPERTIES AND CHEMICAL ANALYSIS OF CEMENT AND FLY ASH

	ASTM Type III Cement	ASTM Class F Fly Ash		
		FA1	FA2	FA3
<u>Physical Properties</u>				
Fineness - passing 45 μm, %	95.6	79.5	84.5	82.7
- Blaine, m ² /kg	495	224	285	320
Specific Gravity	3.06	2.26	2.42	2.39
Compressive Strength of 51-mm cubes, MPa: - 3 d	35.7	-	-	-
- 7 d	39.7	-	-	-
- 28 d	45.9	-	-	-
<u>Chemical Analysis</u>				
Silicon dioxide (SiO ₂), %	19.76	53.64	48.87	55.39
Aluminum oxide (Al ₂ O ₃), %	5.65	27.42	21.12	18.54
Ferric oxide (Fe ₂ O ₃), %	2.02	7.74	16.57	6.38
Calcium oxide (CaO), %	63.07	2.88	4.49	9.51
Magnesium oxide (MgO), %	2.39	0.99	1.09	2.16
Sulphur trioxide (SO ₃), %	3.91	0.37	1.85	0.92
Sodium oxide (Na ₂ O), %	0.34	0.38	1.43	3.08
Potassium oxide (K ₂ O), %	0.98	2.42	2.40	1.22
Loss on ignition, %	1.41	1.49	0.95	0.30
<u>Bogue Potential Compound Composition</u>				
C ₃ S	54.6	-	-	-
C ₂ S	15.4	-	-	-
C ₃ A	11.6	-	-	-
C ₄ AF	6.1	-	-	-
<u>Strength Activity Index with Portland Cement*</u>				
7 days	-	83.1	89.7	89.2
28 days	-	90.5	99.0	95.8

* These values were obtained with an ASTM Type I cement

TABLE 2 — GRADING OF AGGREGATES

Coarse Aggregate		Fine Aggregate	
Sieve Size	Cumulative Percentage Retained	Sieve Size	Cumulative Percentage Retained
19.0 mm	0.0	4.75 mm	0.0
12.7 mm	40.0	2.36 mm	10.0
9.5 mm	65.0	1.18 mm	32.5
4.75 mm	100.0	600 μm	57.5
		300 μm	80.0
		150 μm	94.0
		pan	100.0

TABLE 3 — PHYSICAL PROPERTIES OF AGGREGATES

	Coarse Aggregate	Fine Aggregate
Specific Gravity	2.69	2.7
Absorption, %	0.7	0.8

TABLE 4 — CONCRETE MIXTURE PROPORTIONS

Mixture No.	Batch	W/(C+FA)*	Water, kg/m ³	Cement, kg/m ³	Fly Ash,		Coarse Agg., kg/m ³	Fine Agg., kg/m ³	AEA,** mL/m ³	SP,*** L/m ³
					Source	kg/m ³				
1	A	0.32	119	155	FA1	214	1192	642	640	6.8
	B	0.32	119	155	FA1	214	1192	642	575	6.3
2	A	0.32	118	154	FA2	214	1202	647	185	4.1
	B	0.32	117	154	FA2	213	1195	643	185	4.1
3	A	0.32	117	153	FA3	212	1189	639	185	3.6
	B	0.32	119	155	FA3	214	1202	647	180	3.7
4	A	0.45	170	380	-	0	1041	694	90	2.5
	B	0.45	171	384	-	0	1054	702	85	2.5

* Water-to-(Cement+Fly Ash) Ratio

** Air-Entraining Admixture

*** Superplasticizer

TABLE 5 — PROPERTIES OF FRESH CONCRETE

Mixture No.	Batch	W/(C+FA)	Water, kg/m ³	Cement, kg/m ³	Fly Ash,		Slump, mm	Unit Weight, kg/m ³	Air Content, %	Temp., °C
					Source	kg/m ³				
1	A	0.32	119	155	FA1	214	205	2325	5.8	21
	B	0.32	119	155	FA1	214	195	2325	6.1	21
2	A	0.32	118	154	FA2	214	160	2335	5.9	21
	B	0.32	117	154	FA2	213	125	2325	6.0	21
3	A	0.32	117	153	FA3	212	165	2310	6.2	21
	B	0.32	119	155	FA3	214	165	2335	5.7	21
4	A	0.45	170	380	-	0	150	2285	6.6	22
	B	0.45	171	384	-	0	125	2310	6.2	22

TABLE 6 — TESTING SCHEDULE OF CONCRETE

Batch	Test	Age of testing, days							
		0	1	3	7	14	28	91	365
A	Setting Time (ASTM C 403)	Fresh Concrete							
	Compression (ASTM C 39)	2 cyl.	2 cyl.	2 cyl.			2 cyl.	2 cyl.	2 cyl.
	Flexure (ASTM C 78)						3 prisms		
	Bleeding (ASTM C232)	Fresh Concrete							
	Adiabatic Temperature Rise	Fresh Concrete							
	Compression (ASTM C 39)						2 cyl.		
	Young's Modulus of Elasticity (ASTM C 469)						2 cyl.		
	Splitting-Tensile (ASTM C 496)						2 cyl.		
	Drying Shrinkage (ASTM C 157)	Two prisms were exposed to air drying after 7 days of water curing. Two prisms were kept in water for reference purpose.							
	Flexure (ASTM C 78)						2 prisms		
B	Freezing and Thawing (ASTM C 666, Procedure A)	After 14 days of moist curing, two prisms were exposed to freezing and thawing cycling. Two prisms were kept in the moist-curing room until the end of the freezing and thawing cycling.							
	Resistance to Chloride-Ion Penetration (ASTM C 1202)						2 disks	2 disks	2 disks
	Air-Void Parameters (ASTM C 457)						2 samples		

TABLE 7 — BLEEDING, SETTING TIME, AND MAXIMUM TEMPERATURE RISE OF CONCRETE

Mixture No.	W/(C+FA)	Fly Ash Source	Total Bleeding Water mL/cm ² x 10 ⁻²	Setting Time, h:min		Maximum Temperature Rise, °C
				Initial	Final	
1	0.32	FA1	negligible	7:33	8:55	17.2
2	0.32	FA2	negligible	6:34	8:23	17.6
3	0.32	FA3	negligible	7:27	9:08	17.5
4	0.45	-	0.8	4:51	5:26	35.9

TABLE 8 — DENSITY OF CYLINDERS AND COMPRESSIVE STRENGTH OF CONCRETE

Mixture No.	Batch	W/(C+FA)	Water, kg/m ³	Cement, kg/m ³	Fly Ash,		Density of Cylinders* kg/m ³	Compressive Strength, MPa					
					Source	kg/m ³		1 d	3 d	7 d	28 d	91 d	365 d
1	A	0.32	119	155	FA1	214	2365	16.5	25.5	31.1	45.9	59.6	68.1
	B	0.32	119	155	FA1	214	2365	-	-	-	45.5	-	-
2	A	0.32	118	154	FA2	214	2380	17.1	25.2	31.0	45.0	54.8	61.9
	B	0.32	117	154	FA2	213	2385	-	-	-	47.7	-	-
3	A	0.32	117	153	FA3	212	2365	16.6	24.7	32.2	47.5	55.3	63.2
	B	0.32	119	155	FA3	214	2365	-	-	-	48.4	-	-
4	A	0.45	170	380	-	0	2330	28.3	31.5	35.2	41.5	44.4	50.2
	B	0.45	171	384	-	0	2330	-	-	-	41.7	-	-

• 152 x 305-mm cylinders

TABLE 9 — YOUNG'S MODULUS OF ELASTICITY OF CONCRETE

Mixture No.	W/(C+FA)	Fly Ash Source	Young's Modulus of Elasticity at 28 days, GPa
1	0.32	FA1	35.9
2	0.32	FA2	38.0
3	0.32	FA3	37.5
4	0.45	-	33.1

TABLE 10 — FLEXURAL AND SPLITTING-TENSILE STRENGTHS OF CONCRETE

Mixture No.	W/(C+FA)	Fly Ash Source	Flexural Strength, MPa		Splitting-Tensile Strength at 28 days, MPa
			14 d	91 d	
1	0.32	FA1	5.6	6.9	3.2
2	0.32	FA2	5.3	6.2	4.1
3	0.32	FA3	5.6	6.7	3.5
4	0.45	-	6.2	5.9	3.6

TABLE 11 — DRYING SHRINKAGE OF CONCRETE PRISMS*

Mixture No.	W/(C+FA)	Fly Ash Source	Drying Shrinkage Strain, $\times 10^{-4}$						
			7 d	14 d	28 d	56 d	112 d	224 d	448 d
1	0.32	FA1	347	464	535	603	610	621	678
2	0.32	FA2	316	429	510	522	525	543	600
3	0.32	FA3	288	376	390	480	493	489	497
4	0.45	-	213	359	497	539	553	617	688

* The prisms were cured for seven days in lime-saturated water before being subjected to drying

TABLE 12 — LENGTH CHANGE OF PRISMS STORED IN WATER*

Mixture No.	W/(C+FA)	Fly Ash Source	Shrinkage/Expansion Strain, $\times 10^{-4}$						
			7 d	14 d	28 d	56 d	112 d	224 d	448 d
1	0.32	FA1	+22	+6	-14	-21	+7	+36	-4
2	0.32	FA2	-14	-7	+24	+14	+32	+53	+32
3	0.32	FA3	+39	+35	+67	+63	+89	+89	+74
4	0.45	-	+60	+64	+71	+113	+195	+160	+138

* The prisms were continuously stored in lime-saturated water

"+" means expansion

"-" means shrinkage

TABLE 13 — AIR-VOID PARAMETERS OF HARDENED CONCRETE

Mixture No.	W/(C+FA)	Fly Ash Source	Air Content, %	Specific Surface, mm^2/mm^3	Spacing Factor,* mm
1	0.32	FA1	3.4	35.7	0.156
2	0.32	FA2	4.0	32.3	0.155
3	0.32	FA3	4.2	35.0	0.074
4	0.45	-	4.7	28.5	0.174

* The Canadian Standard Association (CSA) requirement for freezing and thawing durability is 0.230 mm

TABLE 14 — SUMMARY OF TEST RESULTS OF CONCRETE PRISMS AFTER 300 CYCLES OF FREEZING AND THAWING

Mixture No.	W/(C+FA)	Fly Ash Source	Per Cent Change at the End of Freezing and Thawing Cycling				Durability Factor
			Weight	Length	Pulse Velocity	Resonant Frequency	
1	0.32	FA1	-0.27	0.011	1.18	0.62	101
2	0.32	FA2	-0.12	0.017	1.26	0.15	100
3	0.32	FA3	-0.25	0.036	1.14	0.01	100
4	0.45	-	0.19	0.012	1.28	1.87	104

TABLE 15 — FLEXURAL STRENGTH OF REFERENCE PRISMS AND TEST PRISMS AFTER FREEZING AND THAWING CYCLING

Mixture No.	W/(C+FA)	Fly Ash Source	Flexural Strength of 76x102x390-mm Prisms, MPa			Residual Flexural Strength, %
			Reference, Moist-Cured		Test Prisms after 300 Cycles of Freezing and Thawing	
			After 14 Days of Moist Curing	At the End of Freezing and Thawing Cycling		
1	0.32	FA1	5.6	6.8	5.7	84
2	0.32	FA2	5.3	6.9	5.8	84
3	0.32	FA3	5.6	7.2	6.1	85
4	0.45	-	6.2	7.2	6.6	92

TABLE 16 — RESISTANCE OF CONCRETE TO CHLORIDE-ION PENETRATION

Mixture No.	W/(C+FA)	Fly Ash Source	Total Charge Passed, Coulombs		
			7 d	28 d	91 d
1	0.32	FA1	4247	1031	321
2	0.32	FA2	2738	632	240
3	0.32	FA3	2184	668	247
4	0.45	-	6008	4863	2783

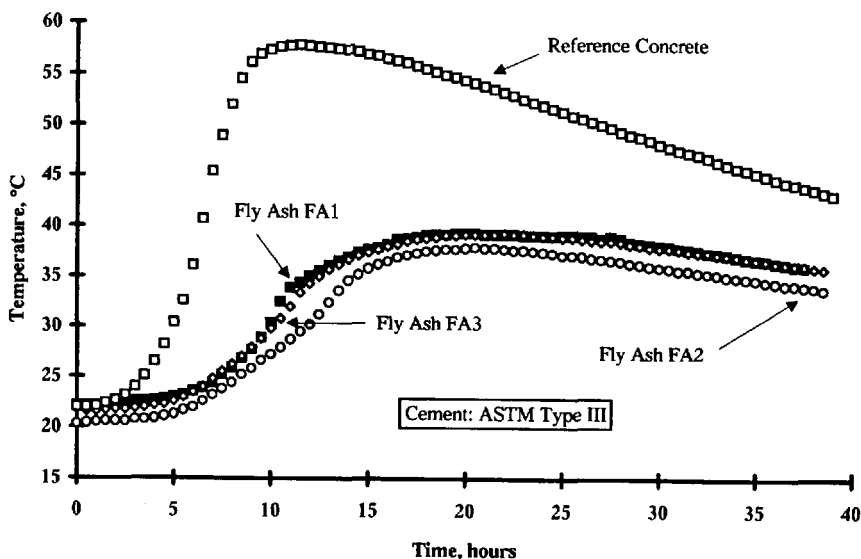


Fig. 1—Autogenous temperature rise of concrete

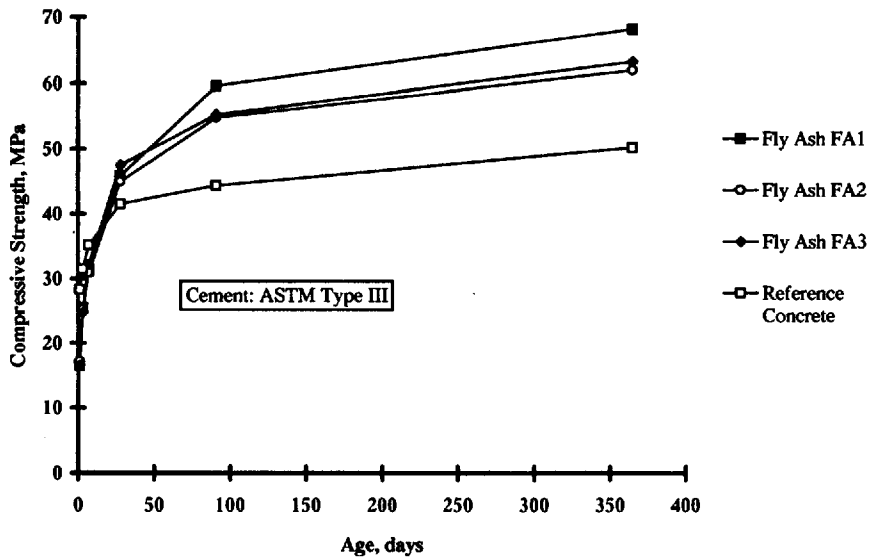


Fig. 2—Compressive strength development of high-volume fly ash concrete and reference concrete made with ASTM Type III cement

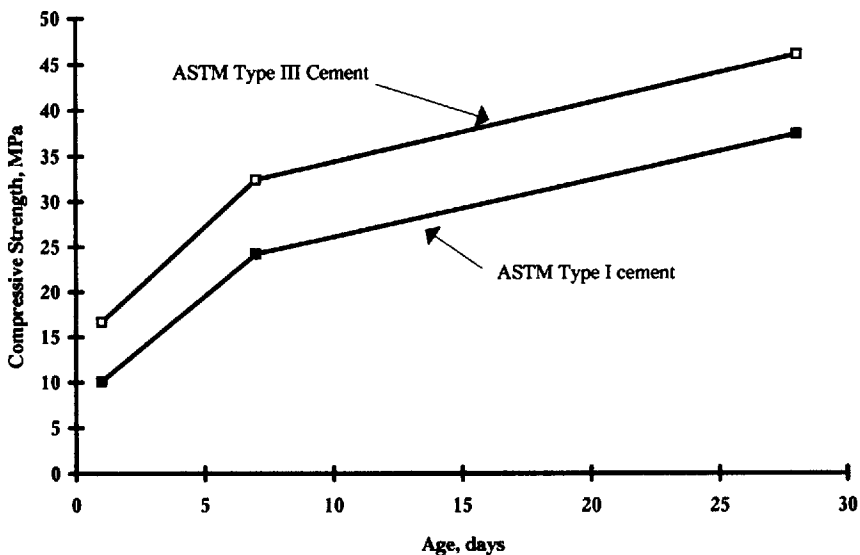


Fig. 3—Early-age compressive strength development of high-volume fly ash concrete made with ASTM Type I and Type III cements based on averaged values of test results obtained with the same three fly ashes

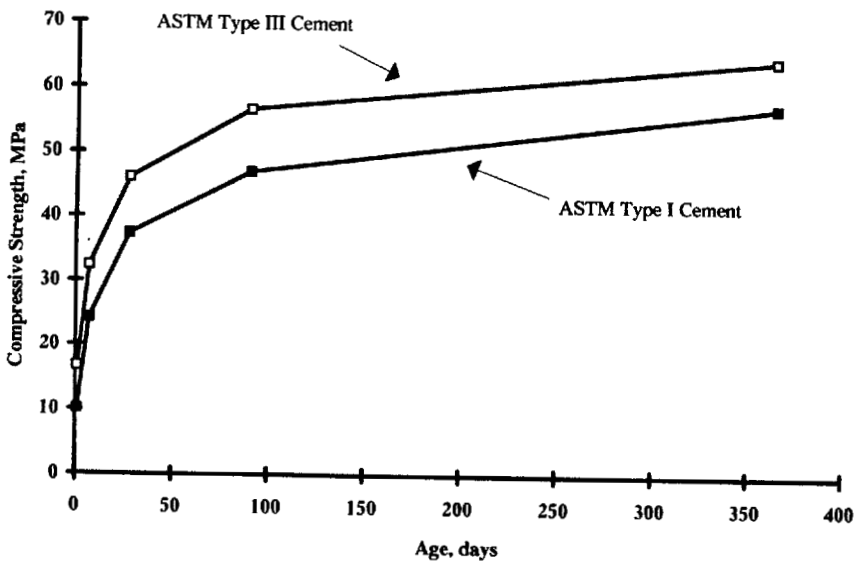


Fig. 4—Long-term compressive strength development of high-volume fly ash concrete made with ASTM Type I and Type III cements based on averaged values of test results obtained with the same three fly ashes

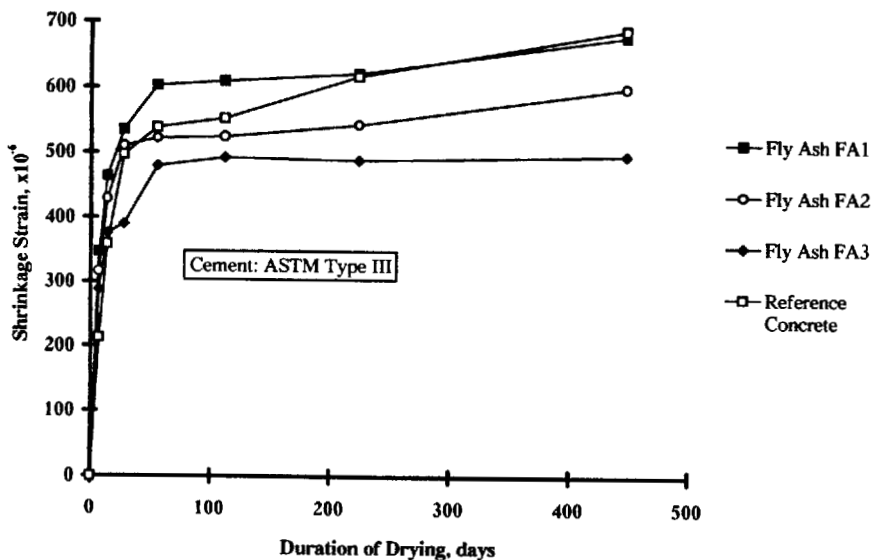


Fig. 5—Drying shrinkage strain versus duration of drying of concrete after 7 days of initial water curing

SP 153-2

Structural Concrete Incorporating High Volume of Fly Ash

by D. Galeota, M. M. Giammatteo, and R. Marino

Synopsis: The purpose of this study was to examine the mechanical and durability properties of high-volume fly ash concretes for structural applications.

Four concrete mixtures were prepared with the amount of fly ash, from Italian source, varying from 0 to 50 percent by weight of total cementitious materials.

A large number of concrete specimens were cast and tested in order to determine the compressive, flexural and splitting-tensile strength, modulus of elasticity, fracture parameters, concrete-steel bond properties, drying shrinkage and durability properties.

The results of this study showed that high-volume fly ash concrete has considerable potential in a wide variety of structural applications.

Keywords: Bonding; compressive strength; drying shrinkage; durability; flexural strength; fly ash; fracture properties; freeze thaw durability; modulus of elasticity; splitting tensile strength; strength

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INTRODUCTION

In recent years research in Canada, United States and other countries has led to a better understanding of the chemical-physical characteristics of concrete incorporating fly ash (1, 5, 8). In particular, extensive testing has shown that mechanical and durability characteristics of high-volume fly ash concrete are generally comparable and sometimes better than normal portland cement concrete (2, 6, 7).

Currently coal fired electric power plants in Italy produce about 750,000 tons of fly ash per year. In absence of specific national code recommendations, approximately 92 percent of all the fly ash produced is utilized in cement, concrete and in other minor applications. In spite of the extensive use of fly ash, until recently in Italy very few studies have been carried out on the use of fly ash in concrete.

This study focused on the ways in which high-volume of low-lime fly ash influences the main mechanical and durability properties of concrete and the economic benefits obtained from the reduction of the amount of cement used.

A large number of concrete specimens incorporating fly ash were cast and tested in order to determine their behavior under compression, modulus of elasticity, behavior in tension, fracture parameters, concrete-steel bond characteristics, drying shrinkage, durability properties, including freezing-thawing resistance, permeability, and sulphate and chloride resistance. The test results were analyzed and the influence of fly ash on the above characteristics of concrete was studied.

EXPERIMENTAL PROGRAM

A comprehensive experimental program was designed to investigate the mechanical properties at various ages of concretes incorporating high volumes of low-lime fly ash. Four concrete mixtures (A, B, C, D) were prepared in order to obtain the same workability (given slump=180mm) and the same water/(cement+fly ash) ratio ($W/(C+FA)=0.42$).

The dosage of the superplasticizer was adjusted by exploratory tests. Concrete mixture A was designed in order to obtain a specific compressive strength of about 45MPa at the age of 28 days.

Ordinary portland cement (comparable to ASTM Type III), river sand, crushed limestone and fly ash (comparable to Class F) from Italian sources were used. The amount of fly ash incorporated varied from 0 to 50 percent by weight of total cementitious materials. Tables I, II and III show the concrete mixture proportions and the physical-chemical characteristics of the cement and fly ash.

From each concrete mixture (A, B, C, D) the following specimens were cast:

- a) behavior under compression (compressive tests, according to UNI 6132 Italian Standard, comparable to ISO 4012/1, and according to UNI 9771 Italian Standard, comparable to ASTM C215, for determination of dynamic modulus of elasticity): twentyone 150×150×150mm cubic specimens, twelve 150×300mm cylindrical specimens;
- b) behavior under tension (flexural and split-cylinder tests, according to UNI 6133 Italian Standard, comparable to ASTM C293 and according to UNI 6135 Italian Standard, comparable to ASTM C496): twelve 100×100×400mm prismatic specimens and twelve 150×300mm cylindrical specimens;
- c) bond properties (pull-out tests, according to RILEM/CEB-FIP, RC6): twelve 200×200×200mm cubic specimens; only a short length (5 times the bar diameter d_b) of a $d_b=16$ mm deformed reinforcing bar (Type Feb44k, $f_y=435$ MPa) was embedded in each specimen;
- d) fracture energy (notched-beam tests, according to RILEM TC50-FMC and RILEM TC89-FMT): twelve 100×100×840mm notched-beam specimens;
- e) drying shrinkage (test according to UNI 6555 Italian Standard, comparable to ASTM C157): twelve 100×100×400mm prismatic specimens;
- f) freezing and thawing resistance (test according to UNI 7087 Italian Standard, comparable to ASTM C666, procedure B): three 100×100×400mm prismatic specimens;
- g) autogenous temperature rise: four 150×150×150mm cubic specimens;
- h) water permeability (test according to ISO/DIS 7031): two 150×150×150mm cubic specimens;
- i) resistance to chloride-ion penetration (test according to UNI 7928 Italian Standard): two 150×300mm cylindrical specimens;

- j) resistance to sulphate-ion penetration (test according to UNI 8019 Italian Standard): two 150×300mm cylindrical specimens;
- k) air voids parameters (test according to ASTM C457): one 150×300mm cylindrical specimen.

ANALYSIS OF RESULTS

Compressive Strength

Table IV and Fig.1 show the average (3 specimens) compressive strength (R_c) development of cubic specimens (continuously moist cured) after 1, 3, 7, 28, 60, 90, 365 days of curing. It can be seen that all concretes containing fly ash (B, C, D) developed adequate early age strength (at 3 days) for structural applications. After 90 days concrete C reached the same compressive strength as that for the reference concrete without fly ash (A). Strength gap between concretes A, B, C and D became relatively small at one year (Fig.2) in percentage terms with respect to concrete A. In particular concrete C showed the highest compressive strength at one year age.

A similar trend can be seen in Table V and Fig.3 and 4, showing the average (3 specimens) compressive strength (f_c) and the peak strain (ϵ_0) development of cylindrical specimens after 28, 60, 90, 365 days of curing.

Typical compressive stress-strain curves (σ - ϵ) for the tested cylindrical specimens are shown in Fig.5. Fly ash substantially influenced both the ascending and the descending branch of the stress-strain curves. The ascending branch for the concretes B, C, D at 28 days of age were less linear compared with that of concrete A (2), and they began to deviate from linearity at a stress (indicated in Fig.6 as σ_1) about 55-60 percent of respective compressive strength (Fig.6). At later ages substantial increase in the ratio σ_1/f_c occurred. From 28 to 365 days there was a significant increase in the steepness of the descending branch (indicated in Fig.7 as S) of the stress-strain curves for concretes B, C, D (more brittleness, Fig.7). Nevertheless, concrete containing fly ash showed a more ductile failure than concrete A at 90 and 365 day ages.

Dynamic Modulus of Elasticity

The dynamic modulus of elasticity (E_d) was evaluated from cylindrical specimens after 28, 60, 90, 365 days. Table VI and Fig.8 show that fly ash concretes exhibited, at all ages, suitable high average values (3 specimens) of modulus of elasticity for structural applications, even if they were slightly lower than those of the reference concrete A. On the basis of analysis of the test results, the relation [Eq.2.1-15] of MC90 (3), with equation power 0.3 instead of 0.33 and coefficient $\alpha_E=2.54\text{GPa}$ instead of 2.15GPa , is more suitable for predicting the dynamic modulus at 28 days (Fig.9):

$$E_d = \alpha_E 10(f_{cm}/f_{cmo})^{0.3},$$

where:

f_{cm} = average compressive strength [MPa],

$f_{cmo} = 10$ MPa,

$\alpha_E = 2.54$ GPa.

Flexural Strength

Table VII shows the average (3 specimens) flexural strength development ($f_{ct,fl}$) after 28, 60, 90, 365 days. The average values of $f_{ct,fl}$ at different ages were found to range from 11 to 13 percent of the corresponding compressive strength f_c for concrete A, from 11 to 19 percent for concrete B, from 12 to 14 percent for concrete C and from 10 to 16 percent for concrete D (4). From 90 to 365 days there was a remarkable increase (up to 70 percent) in $f_{ct,fl}$ for concretes B, C, D. The values of $f_{ct,fl}$ at 28 days can be estimated using the following approximate relation, based on test results:

$$f_{ct,fl} = 0.72\sqrt{f_{cm}}$$

Splitting-Tensile Strength

The average (3 specimens) splitting-tensile strength ($f_{ct,sp}$) at different ages is shown in Table VII. After 28 days of age, the ratio $f_{ct,fl}/f_{ct,sp}$ was often higher for concretes B, C, D than for reference concrete A, particularly at 365 days. However fly ash did not seem to substantially influence the values of $f_{ct,sp}$.

Bond of Concrete to Steel

The average values (3 specimens) of bond stress of concrete to steel at different slip values (0.01, 0.1, 0.3mm) and of bond strength (τ_1) together with peak slip (s_1) are shown in Table VIII. In most cases, bond failure occurred due to the crushing and shearing of the concrete between the bar ribs, while steel stress was above yielding stress ($f_y=435$ MPa). In a few cases splitting failure of concrete specimens was dominant. From 28 to 365 days there was a remarkable increase (up to 60 percent) in τ_1 for concretes B, C, D (Fig. 10).

Fracture Energy

The average values (3 specimens) of f_c , fracture energy (G_F), characteristic length (ℓ_{ch}), fracture toughness (K_{IC}) and critical crack tip opening displacement (CTOD_c) are listed in Table IX. Fig. 11 show typical load-displacement and load-crack mouth opening displacement (CMOD) curves. It can be seen from Table IX that G_F generally increased as f_c increased. The brittleness of concretes was evaluated by the characteristic length (9):

$$\ell_{ch} = G_F E_d / f_{ct,sp}^2$$

All tested concretes tend to be slightly less tough than normal strength concrete (Table IX, for normal strength concrete $\ell_{ch}=200$ to 500mm). The fracture parameters K_{IC} , CTOD_c showed a similar trend.

Drying Shrinkage

The drying shrinkage test results after 1 day of initial moist-curing are given in Fig.12. The shrinkage strain values after 365 days (50 RH and 20±1°C) for all concretes are comparable or lower than other published data (8) for portland concrete of similar strength. Concrete A, B and C had similar shrinkage values beyond 90-day age. Concrete D showed more shrinkage than concretes A, B and C at all ages.

Freezing and Thawing Resistance

After 60 days of water-curing, freezing and thawing resistance of all concretes was determined by measuring the relative dynamic modulus (durability factor) at every 25 freezing-thawing cycles (Fig.13) up to failure.

In a single 12 hour cycle the specimens were cooled from 5°C±2°C to -25°C±2°C in air and then warmed to 5°C±2°C in water. Concretes A and B failed after the first 25 cycles. Concretes C and D failed the freezing-thawing testing after 230 cycles. These findings are in line with other published data on non-air entrained concretes containing fly ash (8).

Autogenous Temperature Rise

All concretes containing fly ash showed a reduced rate of heat generation. It can be seen (Fig.14) that the larger the quantity of cement replaced by fly ash, the lower the contribution to early-age heat generation.

Water Permeability

Fig.15 shows the average values (2 specimens) of the test results at 365 days of age obtained at water pressure varying between 100 and 700kPa. In order to determine the water depth penetration the specimens were broken after the test. Except for concrete D (50% fly ash), the other concretes A, B, C showed low water permeability, with equivalent permeability as the no fly ash concrete (mix A).

Resistance to Chloride-Ion Penetration

In this test, one face of each test specimen at 365 days of age was exposed to a CaCl_2 solution (0.27 mol/l) for 30 days. Concretes B, C, D showed excellent resistance to chloride-ion penetration (Table X).

Resistance to Sulphate-Ion Penetration

In this test, one face of each test specimen at 365 days of age was exposed to a Na_2SO_4 solution (0.50 mol/l) for 30 days. Concretes B, C, D showed no measurable ion penetration as shown in Table X.

Air Voids Parameters of Hardened Concretes

At 365 days of age the air voids parameters for all concretes were determined following a microscopic technique. It can be seen from Table XI that fly ash improved the specific surface, the spacing factor and the average diameter of the bubbles. In particular concrete C showed the most favorable parameter with low spacing factor of 0.515mm.

ECONOMIC ANALYSIS

The constituent costs of concrete A, B, C, D (average costs in Italy) are shown in Table XII. It can be seen that if the concrete cost per m^3 is plotted against fly ash percentage, an almost linear concrete cost reduction can be observed.

CONCLUSIONS

The following conclusions can be drawn from this study:

- All concretes incorporating fly ash (B, C, D) showed adequate early age compressive strength (at 3 days) for structural applications.
- Beyond 28 days of age the gap in compressive strength for fly ash concretes became smaller compared to plain concrete, in particular after one year the compressive strength of concrete C exceeded the compressive strength of no-fly ash concrete A.
- Fly ash substantially influenced the shape of the compressive stress-strain curves. From 28 to 365 days of age there was a significant increase in the steepness of both the ascending and the descending branch of the compressive stress-strain curves, indicating brittleness.
- The dynamic modulus of elasticity measured at 28, 60, 90, 365 days was lower for concretes B, C, D than that for concrete A, however it was quite good for structural applications.
- The flexural strength at 365 days was higher for fly ash concretes B, C, D. The splitting tensile strength was similar at all ages to that observed for no-fly ash concrete.

- From 28 to 365 days of age there was a high bond strength gain (up to 60 percent) between concrete and steel for concretes incorporating fly ash.
- Calculation of the fracture parameters showed that all tested concretes tended to be slightly less tough than normal strength concrete.
- Fly ash did not cause notable change in shrinkage behavior except for concrete D (50% fly ash).
- At 365 days of age, concretes incorporating fly ash exhibited in general good characteristics in water permeability (except 50% of fly ash mix), in resistance to chloride-ion and sulphate-ion penetration tests.
- Freezing and thawing durability of all concretes was poor because air was not entrained in all concretes.

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TABLE 1 — MIXTURE PROPORTIONS AND PROPERTIES OF FRESHLY MIXED CONCRETE

Mixture		A	B	C	D
Portland Cement 42.5R ⁽¹⁾	(kg/m ³)	380	266	230	190
Sand (0-4mm)	(kg/m ³)	860	846	841	837
Coarse aggr. (4-22mm)	(kg/m ³)	1050	1034	1029	1023
Fly Ash (Class F, low-lime)	(kg/m ³)	0	114	150	190
Water	(kg/m ³)	160	160	160	160
Superplasticizer ⁽²⁾	% ⁽³⁾	1.00	1.68	1.90	2.00
W/C		0.42	0.60	0.70	0.84
W/(C+FA)		0.42	0.42	0.42	0.42
Air Content	%	2.20	1.60	1.40	1.20
Slump	(mm)	180	180	180	180
Unit Weight	(kg/m ³)	2454	2426	2417	2408

(1) Portland Cement ENV197-1 CEM I 42.5R (European Prestandard), comparable to ASTM Type III.

(2) Sulphonated Naphthalene Formaldehyde Condensate.

(3) By weight of cement + fly ash.

TABLE 2 — PHYSICAL PROPERTIES AND CHEMICAL ANALYSIS OF CEMENT

Physical Properties			Chemical Analysis			Bogue Potential Compounds Composition	
Fineness-passing 9µm	%	98.2	SiO ₂	%	20.54	C ₃ S	% 67.5
-Blaine	(m ² /kg)	410	Al ₂ O ₃	%	5.88	C ₂ S	% 12.5
Specific Gravity	(g/cm ³)	3.02	Fe ₂ O ₃	%	2.59	C ₃ A	% 9.0
Compressive Strength			CaO	%	62.55	C ₄ AF	% 7.0
-3 days	(MPa)	30.2	MgO	%	2.23		
-7 days	(MPa)	44.8	Na ₂ O	%	0.34		
-28 days	(MPa)	52.0	K ₂ O	%	0.40		
Setting Time			SO ₃	%	2.42		
-Initial	(min)	175	Loss on Ignition	%	2.40		
-Final	(min)	235	Insoluble Residue	%	1.50		

TABLE 3 — PHYSICAL PROPERTIES AND CHEMICAL ANALYSIS OF FLY ASH

Physical Properties			Chemical Analysis		
Fineness-passing 45 μ m	%	79	SiO ₂	%	45.71
-Blaine	(m ² /kg)	450	Al ₂ O ₃	%	29.73
Specific Gravity	(g/cm ³)	2.20	Fe ₂ O ₃	%	4.21
			CaO	%	4.75
			MgO	%	1.13
			Na ₂ O	%	0.31
			K ₂ O	%	1.14
			TiO ₂	%	1.34
			P ₂ O ₅	%	0.96
			MnO	%	0.04
			Loss on Ignition	%	7.0
			Activity with Cement	%	89.5

TABLE 4 — COMPRESSIVE STRENGTH DEVELOPMENT OF CUBIC SPECIMENS

Concrete	Fly Ash (%)	Compressive Strength R_c (Average Values/Std Deviations) (MPa)						
		1 d	3 d	7 d	28 d	60 d	90 d	365 d
A	0	14.7	39.3	50.7	63.5	69.2	69.1	77.7
		0.1	1.6	0.6	0.7	2.0	2.3	4.1
B	30	12.3	27.1	36.8	55.1	63.5	64.6	73.7
		0.5	0.6	0.1	2.2	1.5	1.0	3.0
C	40	7.0	24.9	35.4	54.1	66.8	68.9	81.4
		0.4	0.6	0.6	1.2	2.5	1.7	2.6
D	50	2.9	12.5	24.0	44.5	56.2	59.9	68.7
		0.2	0.4	0.7	0.3	1.1	1.4	4.3

TABLE 5 — COMPRESSIVE STRENGTH DEVELOPMENT AND PEAK STRAIN OF CYLINDRICAL SPECIMENS

Concrete	Fly Ash (%)	Compressive Strength f_c (MPa), Peak Strain ϵ_o (‰) (Average Values/Std Deviations)							
		28 d		60 d		90 d		365 d	
		f_c	ϵ_o	f_c	ϵ_o	f_c	ϵ_o	f_c	ϵ_o
A	0	47.9	2.97	52.7	2.68	54.6	2.43	67.3	3.02
		2.9	0.18	1.7	0.03	2.9	0.12	4.2	0.17
B	30	40.1	2.60	47.6	2.27	50.6	2.38	58.9	2.82
		1.6	0.31	2.2	0.11	2.2	0.14	0.8	0.12
C	40	43.7	2.64	54.3	2.47	57.4	2.49	71.6	3.09
		2.0	0.02	3.1	0.09	4.3	0.10	2.3	0.03
D	50	40.2	2.55	46.0	2.24	51.6	2.41	59.0	2.71
		1.1	0.11	0.6	0.05	1.5	0.09	2.0	0.03

TABLE 6 — DEVELOPMENT OF DYNAMIC MODULUS OF ELASTICITY

Concrete	Fly Ash (%)	Dynamic Modulus of Elasticity E_d (Average Values/Std Deviations) (GPa)			
		28 d	60 d	90 d	365 d
A	0	40.5	43.1	44.7	49.3
		0.9	0.9	0.6	0.7
B	30	37.9	40.5	41.9	43.9
		1.3	0.3	1.4	0.5
C	40	39.9	42.2	43.9	45.8
		0.2	0.6	0.5	0.5
D	50	39.0	40.6	40.1	43.3
		0.5	0.3	1.3	0.1

TABLE 7 — FLEXURAL AND SPLITTING-TENSILE STRENGTH DEVELOPMENT

Concrete	Fly Ash (%)	Flexural Strength $f_{ct,f}$ (Av. Val./Std Dev.) (MPa)				Splitting-Tens. Str. $f_{ct,sp}$ (Av. Val./Std Dev.) (MPa)			
		28 d	60 d	90 d	365 d	28 d	60 d	90 d	365 d
A	0	5.1	6.0	6.6	8.6	4.3	5.5	5.4	5.8
		0.7	0.7	0.6	0.3	0.3	0.5	0.0	0.5
B	30	4.4	6.4	7.9	11.1	4.6	4.5	5.0	5.3
		0.2	0.4	0.2	0.1	0.1	0.5	0.2	0.3
C	40	5.2	5.2	5.8	9.9	4.6	4.1	5.1	6.0
		0.4	0.6	0.4	1.1	0.2	0.1	0.3	0.3
D	50	4.2	5.3	5.6	9.7	4.0	5.4	5.2	5.5
		0.1	0.5	0.5	0.5	0.1	0.4	0.4	0.7

TABLE 8 — BOND PROPERTIES

Conc.	Fly Ash (%)	Age (days)	Bond Stresses $\tau_{0.01}$, $\tau_{0.1}$, $\tau_{0.3}$ (MPa), Bond Strength τ_1 (MPa), Peak Slip s_1 (mm) (Average Values and Std Deviations)				
			$\tau_{0.01}$	$\tau_{0.1}$	$\tau_{0.3}$	τ_1	s_1
A	0	28	8.9 (1.7)	20.6 (3.9)	24.9 (3.9)	27.6 (3.0)	1.02 (0.24)
		60	13.3 (3.3)	22.1 (3.5)	26.2 (3.5)	27.7 (3.2)	0.98 (0.22)
		90	12.2 (4.5)	22.7 (2.0)	26.7 (1.8)	29.1 (0.6)	1.16 (0.38)
		365	9.5 (4.5)	20.7 (3.0)	26.2 (1.7)	28.2 (1.0)	1.14 (0.74)
B	30	28	8.1 (1.3)	15.8 (2.3)	19.4 (2.7)	21.1 (3.1)	1.01 (0.07)
		60	7.5 (2.9)	18.7 (1.9)	23.2 (1.8)	25.9 (1.6)	1.32 (0.31)
		90	14.2 (1.6)	22.5 (1.7)	25.8 (0.9)	26.6 (0.3)	0.67 (0.07)
		365	8.5 (11.6)	21.8 (0.1)	25.8 (0.1)	27.6 (0.1)	0.78 (0.09)
C	40	28	11.2 (2.5)	18.3 (1.4)	20.9 (1.4)	21.7 (1.5)	0.74 (0.11)
		60	12.6 (2.0)	21.7 (1.6)	24.8 (1.5)	25.8 (1.1)	0.88 (0.27)
		90	13.9 (2.7)	22.6 (0.6)	25.1 (0.4)	26.1 (0.1)	0.96 (0.04)
		365	10.1 (2.2)	24.2 (0.1)	28.4 (0.4)	28.7 (0.3)	0.32 (0.02)
D	50	28	7.8 (1.2)	13.5 (2.2)	16.3 (2.8)	17.6 (2.9)	0.75 (0.18)
		60	10.1 (1.0)	18.5 (1.0)	21.6 (1.6)	22.8 (2.1)	0.86 (0.08)
		90	12.4 (2.0)	18.6 (1.4)	21.5 (1.1)	22.3 (1.7)	0.62 (0.21)
		365	16.5 (1.2)	23.2 (0.9)	26.2 (1.6)	28.2 (1.8)	1.10 (0.08)

TABLE 9 — FRACTURE PROPERTIES

Concrete	Fly Ash (%)	Age (days)	Compressive Strength f_c (MPa) Fracture Energy G_F (N/m) Characteristic Length ℓ_{ch} (mm) (Average Values and Std Deviations)		
			f_c	G_F	ℓ_{ch}
A	0	28	47.9	94.0 (16.0)	205.7 (35.1)
		60	52.7	101.0 (16.4)	143.9 (23.3)
		90	54.6	113.6 (32.8)	174.0 (50.1)
		365	67.3	112.0 (3.0)	162.6 (4.3)
B	30	28	40.1	98.0 (3.6)	175.6 (6.5)
		60	47.6	101.4 (19.3)	203.1 (38.6)
		90	50.6	98.7 (23.4)	165.4 (39.2)
		365	58.9	94.8 (18.7)	146.4 (28.9)
C	40	28	43.7	89.6 (5.8)	169.0 (11.0)
		60	54.3	70.6 (7.5)	177.2 (18.7)
		90	57.4	108.6 (7.9)	183.2 (13.3)
		365	71.6	86.5 (7.4)	110.0 (9.3)
D	50	28	40.2	92.1 (17.0)	224.4 (41.3)
		60	46.0	74.1 (16.7)	103.1 (23.2)
		90	51.6	114.4 (20.4)	169.8 (30.3)
		365	59.0	67.0 (18.0)	96.0 (31.6)
Concrete	Fly Ash (%)	Age (days)	Fracture Toughness K_{Ic} (MPa $\sqrt{m}$) Critical Crack Tip Opening Displacement CTOD $_c$ (mm) (Average Values and Std Deviations)		
			K_{Ic}	CTOD $_c$	
A	0	28	1.704 (0.554)	0.0162 (0.0028)	
		60	2.877 (2.370)	0.0165 (0.0031)	
		90	1.676 (0.681)	0.0143 (0.0032)	
		365	2.556 (1.010)	0.0200 (0.0013)	
B	30	28	2.163 (1.206)	0.0218 (0.0053)	
		60	1.904 (0.520)	0.0171 (0.0004)	
		90	2.356 (0.056)	0.0160 (0.0008)	
		365	2.022 (0.620)	0.0142 (0.0015)	
C	40	28	2.011 (0.421)	0.0183 (0.0019)	
		60	2.062 (0.318)	0.0164 (0.0008)	
		90	1.994 (0.795)	0.0156 (0.0030)	
		365	1.710 (0.238)	0.0151 (0.0014)	
D	50	28	1.772 (0.678)	0.0187 (0.0025)	
		60	1.124 (0.121)	0.0140 (0.0016)	
		90	1.684 (0.076)	0.0184 (0.0016)	
		365	1.438 (0.292)	0.0129 (0.0019)	

TABLE 10 — RESISTANCE TO CHLORIDE-ION AND SULFATE-ION PENETRATION

Concrete	Fly Ash (%)	Depth of Chloride-Ion Penetration (Av. Values) (mm)	Depth of Sulphate-Ion Penetration (Av. Values) (mm)
A	0	12	3.5
B	30	no penetration	no penetration
C	40	no penetration	no penetration
D	50	no penetration	no penetration

TABLE 11 — AIR-VOID PARAMETERS

Concrete	Fly Ash (%)	Specific Surface (mm ⁻¹)	Air Void Content (%)	Spacing Factor (mm)	Average Chord Intercept (mm)
A	0	7.46	1.8	1.038	0.536
B	30	7.46	2.0	0.991	0.530
C	40	16.74	1.4	0.515	0.239
D	50	12.20	1.8	0.634	0.328

TABLE 12 — CONSTITUENT COSTS OF CONCRETE MIXTURES A, B, C, D

Constituents	Concrete			
	A	B	C	D
	Cost (\$/m ³) (Dosage (kg/m ³))			
Cement	26.5 (380)	18.5 (266)	16.0 (230)	13.2 (190)
Aggregates	24.3 (1910)	23.9 (1880)	23.8 (1870)	23.7 (1860)
Fly Ash	0 (0)	1.0 (114)	1.4 (150)	1.7 (190)
Superplasticizer	2.8 (3.8)	4.7 (6.4)	5.2 (7.2)	5.6 (7.6)
Total cost	53.6	48.1	46.4	44.2
% of Mixture A Cost	100	89	86	82

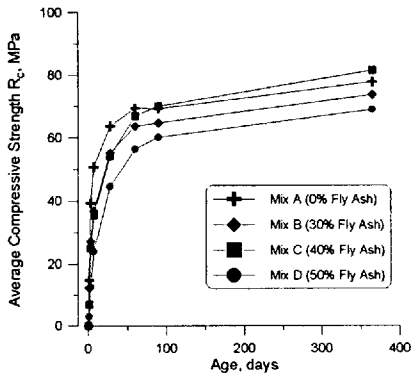


Fig. 1—Compressive strength versus age—Cubic specimens

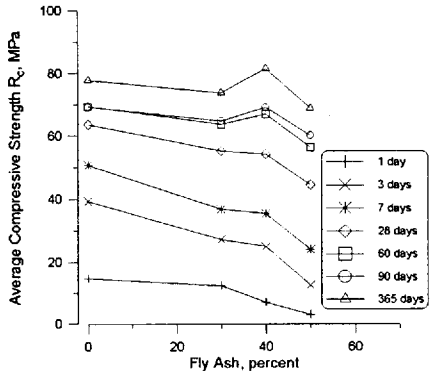


Fig. 2—Compressive strength versus percentage fly ash—Cubic specimens

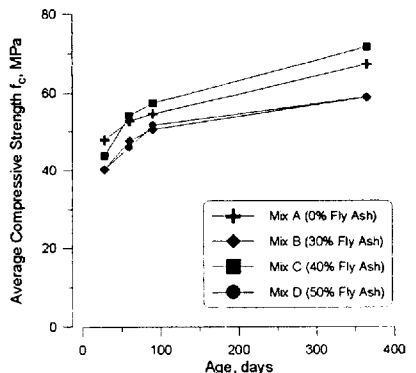


Fig. 3—Compressive strength versus age—Cylindrical specimens

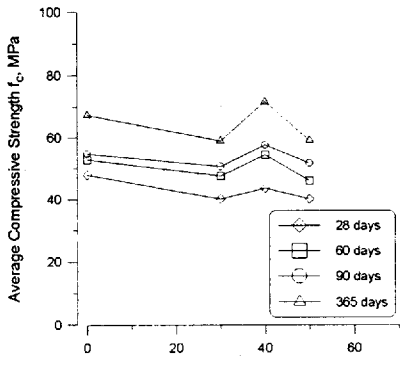


Fig. 4—Compressive strength versus percentage fly ash—Cylindrical specimens

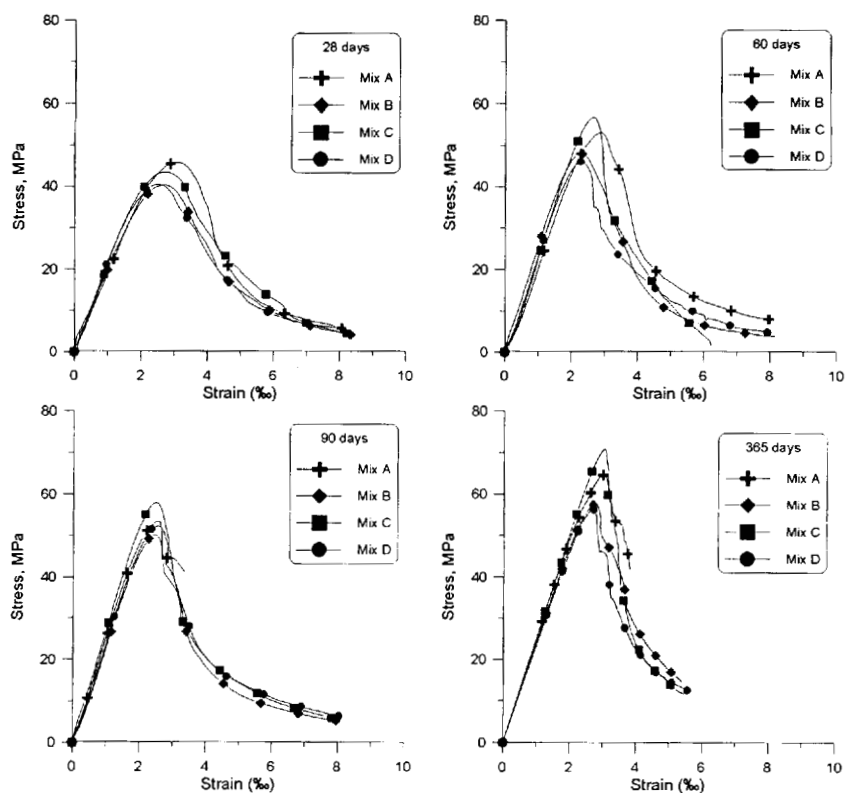


Fig. 5—Stress-strain curves (σ - ϵ) at 28, 60, 90, and 365 days—Cylindrical specimens

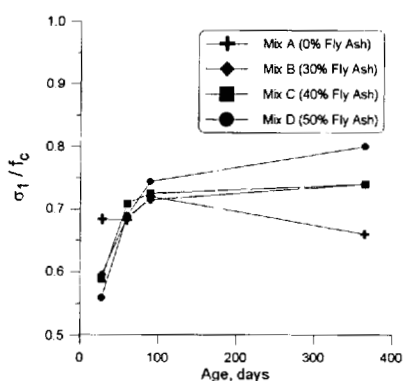


Fig. 6— σ_1/f_c ratio versus age

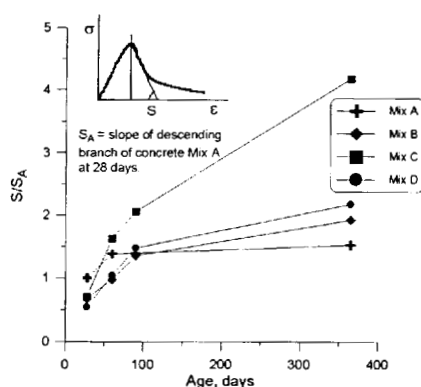


Fig. 7—Descending branch slope versus age for stress-strain curves

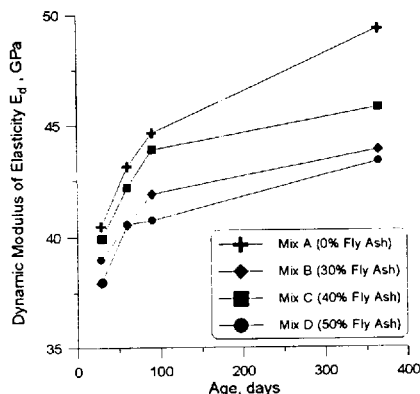


Fig. 8—Dynamic modulus of elasticity versus age

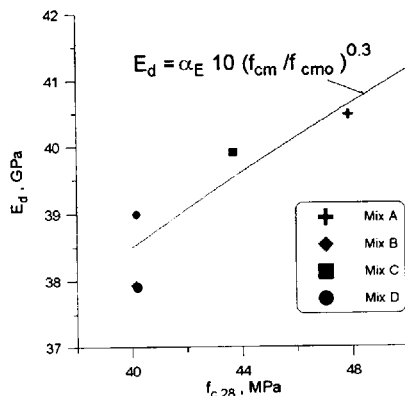


Fig. 9—Dynamic modulus of elasticity versus compressive strength at 28 days

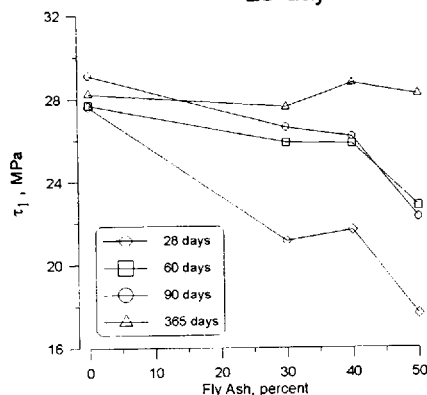


Fig. 10—Bond strength versus percentage fly ash

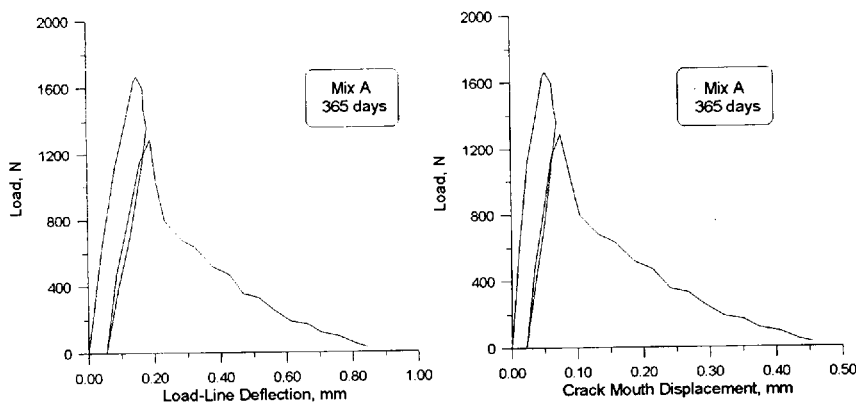


Fig. 11—Typical load-displacement and load-CMOD curves