# Effect of Fly Ash on Physical Properties of Concrete

by Steven H. Gebler and Paul Klieger

Synopsis: Tests of portland cement concretes containing Class F and Class C fly ashes from ten different sources were conducted to evaluate mixing water requirement, time of setting, bleeding, compressive strength, drying shrinkage, abrasion resistance, and absorption. The effects of moisture availability and temperature during curing were also examined. Mixing water requirement was reduced for concretes with Class C fly ash. There was no consistent water reduction when Class F fly ashes were used. Slight to significant retardation of setting time was noted for concretes with fly ash. Setting time generally increased as concrete mixing water requirement increased. Concretes with fly ash showed less bleeding than control concretes. Concretes with Class C fly ash showed less bleeding than concretes with Class F fly ash. Concretes containing Class C fly ash developed higher early age compressive strength than concretes with Class F fly ash. Compressive strengths of concretes with Class F fly ash were more susceptible to low curing temperatures than those for concretes with Class C fly ash. At early ages, compressive strength of concretes with fly ash, regardless of class, was essentially unaffected by moisture availability. Abrasion resistance of control concretes and concretes containing fly ash was dependent on compressive strength. Drying shrinkage and absorption of the concretes were generally unaffected by the use of fly ash.

Keywords: abrasion resistance; absorption; admixtures; bleeding (concrete); cold weather construction; compressive strength; concretes; curing; drying shrinkage; fly ash; hardened concretes; mineral admixtures; pozzolans; setting (hardening); water content.

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## INTRODUCTION

Currently, the American Society for Testing and Materials(1)* (ASTM) and Canadian Standards Association(2) (CSA) divide fly ashes into two classes, F and C. Criteria within these standard specifications require only limited chemical and physical tests for these mineral admixtures. They do not require tests of fly ashes in concrete.

This project was primarily directed toward obtaining a better understanding of those characteristics of fly ash that influence concrete mixing water requirements, bleeding, setting time, concrete strength development, shrinkage, abrasion resistance, and absorption. Data were developed to understand how physical properties of concretes with fly ashes are affected by moisture availability, temperature during curing.

Data in this paper are part of a broad program of tests to evaluate and characterize the effects of ten different fly ashes on concrete performance. Companion papers present data on air-void stability, and on durability with respect to freezing and thawing, deicer scaling resistance, chloride ion permeability, sulfate resistance, and alkali-aggregate reactivity (3,4,5).

*Numbers in parentheses designate references at the end of this paper.

## OBJECTIVES AND SCOPE

The main objective of work described in this paper was to evaluate the effect fly ash in concrete has on compressive strength development under different curing conditions, including the effects of low temperature and moisture availability. Concrete mixing water requirement, time of setting, drying shrinkage, bleeding, abrasion resistance, and absorption were other properties evaluated. The investigation was also directed towards obtaining a better understanding of how the composition and various ASTM characterization tests of fly ash can be used to predict performance in concrete.

To this end, for each fly ash evaluated, three sets of compressive strength concrete specimens were fabricated and cured as described below. One set of compressive strength specimens was cured at 73°F (23°C) and 100% relative humidity (conventional moist curing), a second set was cured at 40°F (4.4°C) and 100% relative humidity for 7 days followed by air storage at 40°F (4.4°C) and 95% relative humidity until testing, and the third set was stored at 73°F (23°C) and 50% relative humidity with no initial moist curing.

For comparison, two control concretes (with no fly ash) were also tested. One set of controls was made to achieve an equivalent strength level to the fly ash mixes. The other control was made at a cement content equivalent to the total cementitious material content in the fly ash mixes.

Drying shrinkage specimens were initially cured as follows: one set was cured for seven days at 73°F (23°C) and 100% relative humidity and another set for seven days at 40°F (4.4°C) and 100% relative humidity. After initial curing, each set was stored in 73°F (23°C) laboratory air at 50% relative humidity.

Abrasion resistance and absorption specimens were moist cured at 73°F (23°C) for 14 days followed by storage in 73°F (23°C) laboratory air at 50% relative humidity for 14 days.

Fly ashes were selected to represent a wide range of chemical and physical compositions and geographical locations. Both ASTM Designation: C 618(1) Class F and Class C fly ashes were used.

## FINDINGS AND CONCLUSIONS

The following findings and conclusions are based in large part on an arbitrary separation of the fly ashes used in this study into ASTM Designation: C 618(1) Class F and Class C designations based on 10% CaO content as a dividing line as discussed in this Standard. Therefore, this arbitrary division based on 10% CaO probably results in exceptions to some of these general observations. The findings and conclusions are presented below.

1. Concretes containing Class C fly ash and that were moist cured at 73°F (23°C) developed higher early age (1 to 14 days) compressive strengths than concretes with Class F fly ash.

2. Moist-cured concretes containing Class F fly ash developed lower strength at early ages than either control concrete without fly ash. In this respect, the Class C fly ashes performed somewhat better.

3. The long-term (90 days and greater) compressive strength of concrete containing fly ash was not significantly influenced by the class of fly ash.

4. Air-cured concretes containing Class F fly ash did not develop strengths equivalent to air-cured control concretes.

5. Air-cured concretes containing Class C fly ash developed relatively greater compressive strengths than air-cured concretes containing Class F fly ash. In comparison with the control concretes, some Class C fly ashes developed greater strengths and others lower.

6. Air-cured concretes gained little or no strength after 14 to 28 days. This was the case for concretes with or without fly ash.

7. Concretes containing Class F fly ashes required more moist curing for long-term compressive strength development than did concretes with Class C fly ashes or concretes without any fly ash.

8. At early ages, compressive strengths of concretes with fly ash, relative to controls,

were essentially unaffected by moisture availability during curing.

9. For concretes containing either class of fly ash, compressive strengths at 7 days increased with an increase in curing temperature. For concretes with Class F fly ash compressive strengths at one year increased with an increase in curing temperature. The use of some fly ashes appears to have been beneficial with respect to the effect of higher temperatures on later age strength development.

10. Certain chemical and physical properties of fly ash can be used to indicate the following properties: relative compressive strength development for concretes cured under different conditions, bleeding and shrinkage. Each of these factors are presented in the section DISCUSSION OF TEST RESULTS.

11. Drying shrinkage results for concretes containing fly ash were essentially the same as for control concretes without fly ash, regardless of initial curing temperature. Drying shrinkage results for concretes with Class F fly ash were, on the average, generally slightly less than for concretes with Class C fly ash.

12. Lower initial moist-curing temperatures reduced drying shrinkages of concretes with or without fly ash.

13. Abrasion resistance of the concretes was essentially dependent on compressive strength.

14. Absorptions of concretes with fly ash were essentially the same as for the control concretes.

15. Concretes with Class C fly ash showed reduced mixing water requirements, while there was no consistent water reduction when Class F fly ashes were used.

16. As concrete mixing water requirement increased, setting time increased.

17. Time of setting of most of the concretes with fly ash was retarded.

18. Concretes with fly ash showed less bleeding than control mixtures. Further, concretes with Class C fly ash showed less bleeding than concretes with Class F fly ash.

## MATERIALS

### Cement

Two different cements were used in this study. A blend of three commercial ASTM Type I cements, Lot No. 21833, was used for laboratory concretes and for most of the mortar physical tests. Cement Lot No. 21841, a high-alkali Type I cement was used for the reactivity with cement alkalies tests. Calculated potential compound compositions and other pertinent data are presented in Table 1 for both cements.

### Aggregates

Natural sand from Elgin, Ill., consisting of carbonate (dolomitic) and siliceous particles, and gravel from Eau Claire, Wis., a highly siliceous, partially crushed coarse aggregate, were used in all concretes. Coarse aggregate was dry-sieved and recombined to obtain the desired gradation. Pertinent data for aggregates are given in Table 2.

### Air-Entraining Admixture

Neutralized Vinsol resin in 2.27% aqueous solution was used as the air-entraining admixture.

### Fly Ashes

Ten different fly ashes that are commercially available for use in concrete were chosen for this study.

Selected fly ashes represent a wide range of chemical and physical properties and geographic origin within North America. Chemical properties of all fly ashes are shown in Table 3; physical properties are shown in Table 4. Inspection of Tables 3 and 4 indicates that several fly ashes meet ASTM Designation:

C 618(1), or CSA CAN3-A23.5-M82(2) while a number of these commercially available fly ashes do not meet some of the chemical or physical requirements of these specifications. For purposes of discussions that follow, fly ashes having a lime content in excess of 10% expressed as CaO, were classified as Class C fly ash; ashes with less than 10% CaO were classified as Class F fly ash. Although ASTM Designation: C 618(1) does not specify CaO content for either Class F or Class C fly ash, there is an inference in Section 3.3 of the Standard that CaO content is being considered as a criterion.

## DESCRIPTION OF CONCRETE MIXTURES

### Concrete Mixture Proportions

Concretes with fly ash were proportioned for a nominal cementitious material content of 517 pounds per cubic yard (pcy) (307 kg/m$^3$) with 75% Type I portland cement and 25% fly ash by weight of cementitious material.

Two control concretes without fly ash were also prepared. One control concrete had a nominal cement content of 517 pcy (307 kg/m$^3$); the other control concrete had a nominal cement content of 474 pcy (281 kg/m$^3$). The latter was used to provide early age strength development more nearly equal to concretes containing fly ash.

The concretes with fly ash contain 388 pcy (230 kg/m$^3$) cement and 129 pcy (77 kg/m$^3$) of fly ash. Relative to the two control concretes, this fly ash concrete can be considered as a 25% by weight cement replacement concrete to be compared with the 517 pcy (307 kg/m$^3$) control, or as a partial replacement plus admixture for comparison with the 474 pcy (281 kg/m$^3$) control. In the latter case, 86 pcy (51 kg/m$^3$) of cement (17%) is considered replaced by fly ash and 43 pcy (26 kg/m$^3$) of fly ash (8%) is used as an admixture.

All concrete mixtures were proportioned to have a slump of 3 in. ± 1 in. (75 mm ± 25 mm), with sufficient neutralized Vinsol resin to obtain a nominal air content of 6% ± 1% in the plastic concrete.

Selected mixture proportions and properties of freshly mixed concrete are presented in Table 5.

Results are the mean of replicate mixtures that were used for the entire fly ash test program.

### Mixing Procedure

All concretes were mixed in a 1.5-ft$^3$ (0.042-m$^3$) open-pan counter-current type mixer. Cement and fly ash were blended by hand. Charging sequence of the concrete materials was coarse aggregate, fine aggregate, cement and fly ash, mixing water, and air-entraining admixture. After all ingredients were in the mixer, they were mixed for 3 min., followed by a 3-min. rest, followed by 2 min. of final mixing. All concrete mixing was conducted in a laboratory maintained at approximately 73°F (23°C) and approximately 50% relative humidity.

## APPARATUS AND TECHNIQUES

### Time of Setting

Mortars, wet sieved from concretes, were consolidated and tested as outlined in ASTM Designation: C 403, "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance" (6). Consolidation and penetration measurements were conducted in laboratory air at approximately 73°F (23°C) and approximately 50% relative humidity.

### Bleeding

Concretes were consolidated by standard rodding techniques and bleeding measurements were conducted in accordance with ASTM Designation: C 232, "Standard Test Method for Bleeding of Concrete" (7). Consolidation and bleeding measurements were conducted in laboratory air at approximately 73°F (23°C) and approximately 50% relative humidity.

### Compressive Strength

For each concrete, three sets of 3x6-in. (75x 150-mm) cylindrical concrete specimens were cast and consolidated by standard rodding techniques. Specimens were cured in the following manner:

Set No. 1: 73°F ± 3°F (23°C ± 1.7°C) and 100% relative humidity (conventional moist curing in fog room),

Set No. 2: 40°F ± 3°F (4.4°C ± 1.7°C) and 100% relative humidity for 7 days followed by air storage at 40°F ± 3°F (4.4°C ± 1.7°C) and 95% ± 5% relative humidity, and

Set No. 3: 73°F ± 3°F (23°C ± 1.7°C) and 50% ± 5% relative humidity (no moist curing).

The above conditions were used for casting and storage until testing. Concretes were tested in accordance with procedures outlined in ASTM Designation: C 39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" (8).

## Drying Shrinkage

Two sets of concrete prisms, 3x3x11-1/4 in. (75x75x285 mm), were cast and consolidated by standard rodding techniques. Prisms were initially cured for 7 days in the following manner:

Set No. 1: 73°F ± 3°F (23°C ± 1.7°C) and 100% relative humidity, and

Set No. 2: 40°F ± 3°F (4.4°C ± 1.7°C) and 100% relative humidity.

Subsequently, these concretes were stored in laboratory air at 73°F ± 3°F (23°C ± 1.7°C) and 50% ± 5% relative humidity, and were measured periodically for length change in accordance with ASTM Designation: C 157, "Standard Test Method for Length Change of Hardened Cement Mortar and Concrete"(9).

## Abrasion Resistance

Concrete slabs, 12x12x3 in. (305x305x75 mm), were cast and consolidated by standard rodding procedures. Surfaces were finished with a steel trowel. Slabs were cured at 73°F ± 3°F (23°C ± 1.7°C) and 100% relative humidity for 14 days followed by laboratory air storage at 73°F ± 3°F (23°C ± 1.7°C) and 50% ± 5% relative humidity for 14 days. After this cure cycle, slabs were tested for abrasion resistance at approximately 28 days, using revolving disks in accordance with ASTM Designation: C 779, "Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces," Procedure A (10). Depth of wear was measured at 30 and 60 minutes.

### Absorption

Cylindrical concrete specimens, 3x6 in. (75x150 mm), were consolidated by standard rodding techniques. The cylinders were cured at 73°F ± 3°F (23°C ± 1.7°C) and 100% relative humidity for 14 days followed by laboratory air storage at 73°F ± 3°F (23°C ± 1.7°C) and 50% ± 5% relative humidity for 14 days. On the 29th day, specimens were tested for absorption using the 5-hour boiling test in accordance with methods outlined in ASTM Designation: C 642, "Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete" (11).

## DISCUSSION OF TEST RESULTS

### Freshly-Mixed Concrete Properties

Mixing Water Requirement--Data presented in Table 6 indicate that seven of ten concretes containing fly ash required less mixing water for the same nominal slump as compared to control concretes. In these tests, the four concretes with Class C fly ash showed reduced mixing water requirements, and three of the concretes with Class F fly ash showed reduced mixing water requirements. Two concretes with Class F fly ash required more mixing water, while one concrete with Class F fly ash required no change in mix water.

Setting Time--Time of setting results, presented in Table 7, show that some fly ashes have a mild retarding effect on initial and final setting time of concrete relative to control concrete mixtures.

Relative to the 517 pcy (307 kg/m$^3$) control concrete without fly ash, retardation ranged from 10 to 55 minutes for initial set and 5 to 130 minutes for final set.

Compared to the 474 pcy (281 kg/m$^3$) control concrete, some fly ashes had no effect on initial and