

# 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.

## 2 Gebler and Klieger

Steven Gebler is a Senior Research Engineer at the Construction Technology Laboratories, PCA. He joined the Association in 1979 and his activities have been in various phases of concrete materials research. He is an ASME/ACI 359 Level III Concrete Inspector and a member of ACI Committee 214, 308, 309, 506, and 517.

Paul Klieger is Consultant, Research and Development/Construction Technology Laboratories Group, PCA. He joined the Association in 1941 and has been engaged in research activities involving concrete strength development, resistance to freezing and thawing, and other aspects of concrete technology. He is currently Chairman of ACI Committee 201 on Durability.

### 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.



## 6 Gebler and Klieger

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) ( $307 \text{ kg/m}^3$ ) 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 ( $307 \text{ kg/m}^3$ ); the other control concrete had a nominal cement content of 474 pcy ( $281 \text{ kg/m}^3$ ). 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 ( $230 \text{ kg/m}^3$ ) cement and 129 pcy ( $77 \text{ kg/m}^3$ ) 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 ( $307 \text{ kg/m}^3$ ) control, or as a partial replacement plus admixture for comparison with the 474 pcy ( $281 \text{ kg/m}^3$ ) control. In the latter case, 86 pcy ( $51 \text{ kg/m}^3$ ) of cement (17%) is considered replaced by fly ash and 43 pcy ( $26 \text{ kg/m}^3$ ) of fly ash (8%) is used as an admixture.

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

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



## 8 Gebler and Klieger

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<sup>3</sup> (0.042-m<sup>3</sup>) 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. (75x150-mm) cylindrical concrete specimens were cast and consolidated by standard rodding techniques. Specimens were cured in the following manner:



**Documents**

Document Sharing Hub

Set No. 1:  $73^{\circ}\text{F} \pm 3^{\circ}\text{F}$  ( $23^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$ ) and 100% relative humidity (conventional moist curing in fog room),

Set No. 2:  $40^{\circ}\text{F} \pm 3^{\circ}\text{F}$  ( $4.4^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$ ) and 100% relative humidity for 7 days followed by air storage at  $40^{\circ}\text{F} \pm 3^{\circ}\text{F}$  ( $4.4^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$ ) and  $95\% \pm 5\%$  relative humidity, and

Set No. 3:  $73^{\circ}\text{F} \pm 3^{\circ}\text{F}$  ( $23^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$ ) and  $50\% \pm 5\%$  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,  $3 \times 3 \times 11\text{-}1/4$  in. ( $75 \times 75 \times 285$  mm), were cast and consolidated by standard rodding techniques. Prisms were initially cured for 7 days in the following manner:

Set No. 1:  $73^{\circ}\text{F} \pm 3^{\circ}\text{F}$  ( $23^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$ ) and 100% relative humidity, and

Set No. 2:  $40^{\circ}\text{F} \pm 3^{\circ}\text{F}$  ( $4.4^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$ ) and 100% relative humidity.

Subsequently, these concretes were stored in laboratory air at  $73^{\circ}\text{F} \pm 3^{\circ}\text{F}$  ( $23^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$ ) and  $50\% \pm 5\%$  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,  $12 \times 12 \times 3$  in. ( $305 \times 305 \times 75$  mm), were cast and consolidated by standard rodding procedures. Surfaces were finished with a steel trowel. Slabs were cured at  $73^{\circ}\text{F} \pm 3^{\circ}\text{F}$  ( $23^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$ ) and 100% relative humidity for 14 days followed by laboratory air storage at  $73^{\circ}\text{F} \pm 3^{\circ}\text{F}$  ( $23^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$ ) and  $50\% \pm 5\%$  relative humidity for 14 days. After this cure cycle,



## 10 Gebler and Klieger

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  $73^{\circ}\text{F} \pm 3^{\circ}\text{F}$  ( $23^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$ ) and 100% relative humidity for 14 days followed by laboratory air storage at  $73^{\circ}\text{F} \pm 3^{\circ}\text{F}$  ( $23^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$ ) and 50%  $\pm$  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 ( $307 \text{ kg/m}^3$ ) 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 ( $281 \text{ kg/m}^3$ ) control concrete, some fly ashes had no effect on initial and

final setting. In fact, one fly ash slightly accelerated the final set. Maximum initial set retardation was 45 minutes, and the maximum final set retardation was 110 minutes.

The data in Tables 6 and 7 generally indicate that as concrete water requirement increased, the setting time increased. This fact is consistent with Sprouse and Peppler(12) in that they found as slump (as a measure of water requirement) increased, setting was retarded.

Bleeding--Results in Table 8 indicate that concretes containing fly ash generally showed reduced bleeding capacity compared to control concretes without fly ash. The data indicate that concretes with Class C fly ash generally showed less bleeding than concretes with Class F fly ash.

Comparison of Tables 6 and 8 show that as mixing water requirement for concrete with fly ash decreased, bleeding decreased. This last observation is not surprising in that lower bleeding values would be expected when less mixing water is used. Bleeding occurs when excess mix water is displaced by settlement of solid material. Therefore, the more mixing water used that is above that needed for hydration (the mix water for convenience workability), the greater the bleeding. This observation can also be seen in the correlation between the ASTM Designation: C 618(1) water requirement test and bleeding capacity results as shown in Fig. 1.

### Hardened Concrete Properties

Compressive Strength--Compressive strength data are shown in Figs. 2 through 7. The data are also presented in Tables 9 through 12, which list compressive strengths and the strengths as a percentage of control concrete strengths (mixtures without fly ash).

Moist Curing at 73°F (23°C). Fig. 2 and Table 9 indicate that 73°F (23°C) moist-cured concrete containing Class F fly ash developed strength at a slower rate than either control concrete. At later ages, concretes with four of the Class F fly ashes had strengths that were approximately equal to or greater than the 474 pcy (281 kg/m<sup>3</sup>) control concrete.

Figure 3 and Table 9 show that except for one fly ash, concretes containing Class C fly ash developed approximately equal or greater early age compressive



## 12 Gebler and Klieger

strength than the 474 pcy ( $281 \text{ kg/m}^3$ ) control concrete. At later ages, concrete with two Class C fly ashes showed higher strengths or were approximately equal to the 474 pcy ( $281 \text{ kg/m}^3$ ) control concrete, while the other two showed lower strengths. Moist-cured concretes with Class C fly ash developed slightly higher early strengths than concretes with Class F fly ash.

The long-term (91 days and greater) compressive strength of concrete containing fly ash was not significantly different for the two classes of fly ash.

The concretes with fly ash (Classes F and C) had lower strengths than the 517 pcy ( $307 \text{ kg/m}^3$ ) control except for mix Designation "F" at 1 and 3 days.

Curing at 40°F (4.4°C). Data in Tables 10 and 11, and Figs. 4 and 5, show that concretes with Class F fly ash generally are more susceptible to low curing temperatures than concretes with conventional portland cement or concretes containing Class C fly ash. Later age strengths for concretes with Class C fly ash (except in one case) were generally not affected by low curing temperatures.

Lower curing temperatures for portland cement concrete without fly ash produced higher long-term strength than did 73°F (23°C) moist-curing. This suggests that an optimum curing temperature, something less than 73°F (23°C), exists for long-term strength development. This finding is consistent with Klieger's(13) research in which it was found that "there is a temperature during the early life of concrete which is considered optimum with regard to strength at later ages." The later age effect of low curing temperatures was not found for concretes with fly ash except in one instance (fly ash mix Designation "F").

Air Storage at 73°F (23°C). This portion of the study was conducted to evaluate the effects of moisture availability during curing on compressive strength development. Table 12 and Figs. 6 and 7 show that air-cured concretes containing Class F fly ash did not develop equivalent compressive strengths compared to both control concretes. Table 12 and Fig. 7 show that concretes with three of the four Class C fly ashes developed greater strengths compared to the concretes with the Class F fly ashes.

One Class C fly ash mix (mix Designation "F" in Table 12) developed considerably higher strengths than the other concretes including the control concretes

without fly ash. This fly ash had the highest free lime content of all the fly ashes tested in this investigation.

As expected, the data show that after 7 days, strengths of air-cured concretes did not increase significantly, as did moist-cured concretes. Some air-cured concretes showed minor regression in strength. Obviously, the air-cured concretes suffered from lack of moisture to sustain hydration.

The air-cured strength data show that concrete exposed continuously to laboratory air following removal from molds gained essentially no strength between 14 and 28 days. This finding is consistent with work reported by Chamberlain (14). The air-cured strength data confirm the importance of moisture for continued hydration of concrete with or without fly ash.

Effect of Moisture Availability During Curing on Strength Development--To illustrate the effects of moisture availability on compressive strength, Table 13 presents the air-cured concrete strengths relative to companion moist-cured concretes. The relationships are presented graphically in Figs. 8 and 9. The data in Figs. 8 and 9 are normalized in the sense that each set of concrete strengths is presented as ratios of strength developed at one day in the molds for the particular concrete mix.

The data illustrate that concretes containing Class F fly ashes would require slightly more moist curing for long-term compressive strength development equivalent to concretes with Class C fly ash. One Class C fly ash (mix Designation "F") had relatively high air-cured strengths at all ages. At early ages, compressive strength of concretes with fly ash were not greatly affected by moisture availability, regardless of class of fly ash.

In general, the data also show that the long-term strengths of the control concretes (without fly ash) were slightly less sensitive to the unavailability of moisture during the curing period than concretes with fly ash. At early ages, the control concretes responded essentially in a manner similar to the concretes with fly ash.

At age one year concrete exposed continuously to laboratory air after removal from molds without moist curing had 45% to 60% of the moist-cured concrete compressive strength. This finding is essentially consistent with Chamberlain's (14) findings.



## 14 Gebler and Klieger

The data illustrate the importance of moisture availability for long-term compressive strength development for all concretes. Strength development for concretes with Class C fly ashes subject to air curing was similar to the control concretes. Concretes with Class F fly ashes showed lower later age strengths than control concretes or concretes with Class C fly ashes.

Effect of Curing Temperature on Strength Development--To illustrate the effect of curing temperature on compressive strength, Figs. 10 through 13 are presented. Figures 10 and 11 show 7-day compressive strengths versus curing temperature for concretes containing Class F and Class C fly ash, respectively. Figures 10 and 11 show that conventional portland cement concretes and concretes with fly ash developed greater 7-day compressive strength as the curing temperature increases. Figures 12 and 13 show one-year compressive strengths as a function of curing temperature for concretes containing Class F and Class C fly ash, respectively. Figures 12 and 13 show that, except for one Class C fly ash, only the portland cement concretes without fly ash developed lower one-year compressive strength as the curing temperature increased. These two findings regarding the control concretes are consistent with Klieger's (13), which showed that increasing the initial and curing temperatures for concrete without fly ash resulted in higher early strengths and lower strengths at 3 months and 1 year. The use of certain fly ash appears to have been beneficial with respect to the effect of higher temperatures on later age strength development.

Drying Shrinkage--Data presented in Table 14 show that the shrinkage of concrete containing fly ash and initially moist cured at 73°F (23°C) was not significantly different from that for the control portland cement concretes. This finding is consistent with results reported by Perenchio and Klieger (15).

The data shown in Table 14 also indicate that drying shrinkage of 40°F (4.4°C) moist-cured (initial 7 days) concrete with fly ash was essentially the same as the control concretes. The class of fly ash did not substantially influence the magnitude of drying shrinkage.

The magnitude of drying shrinkage of concretes with or without fly ash was significantly affected by initial curing temperature. As the initial curing temperature decreased, the drying shrinkage decreased.

Abrasion Resistance--Depth of wear results are presented in Table 15 and Fig. 14. The data generally show that as compressive strength increased, the abrasion resistance increased. Further study of these data indicate that abrasion resistance was only dependent on the class of fly ash to the extent that the fly ash affected strength. The observation that abrasion resistance is primarily a function of compressive strength is consistent with findings of Witte and Backstrom(16) with respect to conventional portland cement concretes.

Absorption--Results of five-hour boiling tests for absorption are presented in Table 16. Results indicate that some fly ashes influenced the absorption as compared to the conventional portland cement concretes. The absorption values shown in Table 16 are relatively low. Some fly ash concretes showed a 20% decrease in absorption while others showed no effect. The data indicate that class of fly ash did not measurably influence absorption.

#### Correlation of Fly Ash Characteristics with Concrete Properties

Regression analyses using standard statistical techniques were made to see if there were correlations between chemical and physical properties of the fly ash and concrete performance. Table 17 shows the trends between relevant properties and concrete performance. Table 17 presents only those relationships having at least a 0.77 correlation coefficient which equates to a 99% confidence level for a sample size of 10 observations (a correlation of 1.00 is considered a perfect correlation).

Inspection of Table 17 shows that the most frequent correlations occur between concrete performance and the following fly ash parameters:  $MgO$ ,  $SO_3$ ,  $CaO$  and the sum of the major oxides ( $SiO_2$ ,  $Al_2O_3$  and  $Fe_2O_3$ ). These fly ash properties can be useful indicators for prediction of concrete performance. The pozzolanic activity index with lime was also a good predictor of concrete strength performance with the cement used in this study. It is interesting to note, however, that the pozzolanic activity index with cement did not show consistent significant correlations with compressive strength. Intuitively, one would expect that this test should show a strong correlation with concrete strength development. It may be that in the test procedure, ASTM Designation: C 311, "Standard Methods of Sampling and Testing Fly

Ashes Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete"(17), the mix proportions or the accelerated curing may reduce the test's ability to be a useful tool in predicting compressive strength development of concrete with fly ash at normal temperatures.

It is suggested that future research be aimed at developing further improvements in the laboratory test with lime as the principal ingredient for predicting compressive strength development of concrete containing fly ash. The U.S. Army Corps of Engineers has increased the minimum requirement for pozzolanic activity index with lime from 800 psi (5.5 MPa) to 900 psi (6.2 MPa) in their specifications (18).

#### SUMMARY AND RECOMMENDATIONS

The following summary and recommendations 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. Therefore, there may be exceptions to these general comments which should be considered in applying these results. 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.

These tests indicate that concrete with fly ash has the potential to produce satisfactory compressive strength development, abrasion resistance, and absorption. The long-term compressive strength of concrete with fly ash was not significantly affected by the class of fly ash. Generally, compressive strength development of concretes with Class F fly ash was more susceptible to low curing temperature than concretes with Class C fly ash or concretes without fly ash.

Concrete containing Class F fly ashes required more initial moist curing for long-term air-cured compressive strength development than did concretes with Class C fly ashes or concretes without any fly ash. At early ages, compressive strength of concretes with fly ash, regardless of class, was essentially unaffected by moisture availability during curing relative to the control concretes. These compressive strength data illustrate the importance of proper curing for strength development of concrete with or without fly ash. In general, concretes without fly



ash were less sensitive to moisture unavailability at later ages than concrete mixes with fly ash.

#### ACKNOWLEDGMENTS

This work was funded by the Portland Cement Association (PCA) as part of Projects HR-1150 and HR-1212. The authors would like to thank personnel of the Concrete Materials/Technical Services Department who prepared and tested these concretes. The authors also wish to thank Julie Dugo, Administrative Assistant and Secretary, Concrete Materials/Technical Services Department, and PCA's Word Processing Department for editing and typing the manuscript. Appreciation is expressed to representatives of electric utilities and fly ash brokers who provided fly ash used in this project.

#### REFERENCES

1. "Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete," ASTM Designation: C 618-83, Annual Book of ASTM Standards, Section 4-Construction, Volume 04.02 Concrete and Mineral Aggregates, American Society for Testing and Materials, Philadelphia, PA, 1983, pp. 376-379.
2. "Supplementary Cementing Materials and Their Use in Concrete Construction," CSA Standard CAN3-A23.5-M82, Canadian Standards Association, Rexdale, ON, Canada, 1982.
3. Gebler, S., and Klieger, P., "Effect of Fly Ash on the Air-Void Stability of Concrete," ACI Special Publication SP-79, American Concrete Institute, Detroit, MI, 1983, pp. 103-142. Preprinted as PCA Research and Development Bulletin RD085.
4. Gebler, S. and Klieger, P. "Effect of Fly Ash on the Durability of Concrete," ACI Special Publication SP-91, American Concrete Institute, Detroit, MI, 1986. Preprinted as PCA Research and Developments Bulletin RD090. (In print).



5. Gebler, S. and Klieger, P., "Effect of Fly Ash on the Alkali-Aggregate and Sulfate Resistance of Concrete" (In Print), 1986.
6. "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance," ASTM Designation: C 403-80, Annual Book of ASTM Standards, Volume 04.02 Concrete and Mineral Aggregates, American Society for Testing and Materials, Philadelphia, PA, 1983, pp. 269-272.
7. "Standard Test Method for Bleeding of Concrete," ASTM Designation: C 232-71, Annual Book of ASTM Standards, Volume 04.02 Concrete and Mineral Aggregates, American Society for Testing and Materials, Philadelphia, PA, 1983, pp. 174-179.
8. "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," ASTM Designation: C 39-81, Annual Book of ASTM Standards, Section 4-Construction, Volume 04.02 Concrete and Mineral Aggregates, American Society for Testing and Materials, Philadelphia, PA, 1983, pp. 25-28.
9. "Standard Test Method for Length Change of Hardened Cement Mortar and Concrete," ASTM Designation: C 157-80, Annual Book of ASTM Standards, Volume 04.02 Concrete and Mineral Aggregates, American Society for Testing and Materials, Philadelphia, PA, 1983, pp. 120-126.
10. "Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces," ASTM Designation: C 779-82, Annual Book of ASTM Standards, Volume 04.02 Concrete and Mineral Aggregates, American Society for Testing and Materials, Philadelphia, PA, 1983, pp. 457-464.
11. "Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete," ASTM Designation: C 642-82, Annual Book of ASTM Standards, Volume 04.02 Concrete and Mineral Aggregates, American Society for Testing and Materials, Philadelphia, PA, 1983, pp. 395-397.
12. Sprouse, J., and Peppler, R., "Setting Time," Chapter 9 Significance of Tests and Properties of Concrete and Concrete-Making Materials, STP-169B, American Society for Testing and Materials, Philadelphia, PA, 1978, pp. 15.

13. Klieger, P., "Effect of Mixing and Curing Temperature on Concrete Strength, "Journal of the American Concrete Institute, Proceeding, Vol. 54, pages 1063-1081, 1958. Reprinted Research and Department Laboratories of the Portland Cement Association, Research Department Bulletin 103.
14. Chamberlain, W., "Effect of Air Drying on the Compressive Strength of Concrete," Concrete Laboratory Report No. C-796, Engineering Laboratories, United States Department of the Interior Bureau of Reclamation, Denver, CO, 1955.
15. Perenchio, W., and Klieger, P., "Further Laboratory Studies of Portland-Pozzolan Cements," Research and Development Department Bulletin RDO41, Portland Cement Association, 1976.
16. L. P. Witte, and J. E. Backstrom, "Some Properties Affecting The Abrasion Resistance of Air-Entrained Concrete," Proceedings, Amer. Soc. Testing Mat., vol. 51, 1951, p. 1141.
17. "Standard Methods of Sampling and Testing Fly Ash or Natural Pozzolan for use as a Mineral Admixture in Portland Cement Concrete," ASTM Designation: C 311-77, Annual Book of ASTM Standards, Part 14, Concrete and Mineral Aggregates, American Society for Testing and materials, Philadelphia, PA, 1981, pp. 228-235.
18. Lamond, J. F., "Twenty-Five Years' Experience Using Fly Ash in Concrete," ACI Special Publication SP-79, American Concrete Institute, Detroit, MI, pp. 47 to 69.

TABLE 1. Composition of Cements

| Item                                               | Cement Lot Number |         |
|----------------------------------------------------|-------------------|---------|
|                                                    | 21833             | 21841   |
| <u>Chemical Properties</u>                         |                   |         |
| CaO, %                                             | 63.76             | 62.66   |
| SiO <sub>2</sub> , %                               | 21.24             | 20.29   |
| Al <sub>2</sub> O <sub>3</sub> , %                 | 4.64              | 5.53    |
| Fe <sub>2</sub> O <sub>3</sub> , %                 | 2.74              | 1.97    |
| MgO, %                                             | 2.35              | 2.47    |
| SO <sub>3</sub> , %                                | 2.55              | 3.31    |
| Loss on ignition, %                                | 1.63              | 1.22    |
| Insoluble residue, %                               | 0.23              | 0.26    |
| Na <sub>2</sub> O, %                               | 0.25              | 0.25    |
| K <sub>2</sub> O, %                                | 0.66              | 1.27    |
| Total alkalis<br>(as Na <sub>2</sub> O), %         | 0.68              | 1.09    |
| Water soluble alkalis<br>(as Na <sub>2</sub> O), % | 0.34              | 0.70(a) |
| C <sub>3</sub> S, %                                | 56                | 52      |
| C <sub>2</sub> S, %                                | 18                | 19      |
| C <sub>3</sub> A, %                                | 8                 | 11      |
| C <sub>4</sub> AF, %                               | 8                 | 6       |
| <u>Physical Properties</u>                         |                   |         |
| Air content, %                                     | 8.9               | NR(b)   |
| Air permeability<br>fineness, m <sup>2</sup> /kg   | 383               | 357     |
| Autoclave expansion, %                             | 0.03              | NR(b)   |
| Compressive<br>strength, psi(c)                    |                   |         |
| 3 days                                             | 3330              | NR(b)   |
| 7 days                                             | 4320              | NR(b)   |
| 28 days                                            | 5530              | NR(b)   |
| Time of setting                                    |                   |         |
| Vicat test                                         |                   |         |
| Initial set, h:m                                   | 1:58              | NR(b)   |
| Final set, h:m                                     | 2:30              | NR(b)   |

(a) The value reported in Table 1 in Reference No. 3 is in error. The value shown in this Table is the correct value.

(b) Test not performed.

(c) To convert from pounds per square inch to megapascals, multiply by  $6.895 \times 10^{-3}$ .

TABLE 2. Data on Aggregates

## Fine Aggregate

| Source      | Grading, cumulative % retained on sieve indicated |                    |                     |                         |                         |                          |                     | Specific gravity<br>s.s.d. | 24-hour<br>absorption,<br>% by weight |
|-------------|---------------------------------------------------|--------------------|---------------------|-------------------------|-------------------------|--------------------------|---------------------|----------------------------|---------------------------------------|
|             | No. 4<br>(4.75 mm)                                | No. 8<br>(2.36 mm) | No. 16<br>(1.18 mm) | No. 30<br>(600 $\mu$ m) | No. 50<br>(300 $\mu$ m) | No. 100<br>(150 $\mu$ m) | Fineness<br>modulus |                            |                                       |
| Elgin, Ill. | 2                                                 | 16                 | 31                  | 55                      | 84                      | 97                       | 2.85                | 2.65                       | 1.70                                  |

## Coarse Aggregate

| Source              | Grading, % retained on<br>sieve size indicated |                     |                   | Bulk<br>specific<br>gravity<br>s.s.d. | 24-hour<br>absorption,<br>% by weight |
|---------------------|------------------------------------------------|---------------------|-------------------|---------------------------------------|---------------------------------------|
|                     | 3/4 in.<br>(19.0 mm)                           | 3/8 in.<br>(9.5 mm) | No. 4<br>4.75 mm) |                                       |                                       |
| Eau<br>Claire, Wis. | 0                                              | 50                  | 100               | 2.66                                  | 1.40                                  |

TABLE 3. Chemical Composition of Fly Ash<sup>(a)</sup>

| Fly ash identification | SiO <sub>2</sub><br>(%) | Al <sub>2</sub> O <sub>3</sub><br>(%) | Fe <sub>2</sub> O <sub>3</sub><br>(%) | Total SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub><br>(%) | SO <sub>3</sub><br>(%) | MgO<br>(%) | CaO<br>(%) | Free lime <sup>(b)</sup><br>(%) | Loss on Ignition<br>(%) | Total carbon <sup>(c)</sup><br>(%) | Organic matter <sup>(d)</sup><br>(%) | Na <sub>2</sub> O <sup>(e)</sup><br>(%) | K <sub>2</sub> O <sup>(e)</sup><br>(%) | Total alkalis as Na <sub>2</sub> O <sup>(e)</sup><br>(%) | Available alkalis as Na <sub>2</sub> O <sup>(f)</sup><br>(%) | Moisture content<br>(%) | Classification of fly ash <sup>(g)</sup> |
|------------------------|-------------------------|---------------------------------------|---------------------------------------|-------------------------------------------------------------------------------------------------|------------------------|------------|------------|---------------------------------|-------------------------|------------------------------------|--------------------------------------|-----------------------------------------|----------------------------------------|----------------------------------------------------------|--------------------------------------------------------------|-------------------------|------------------------------------------|
| A                      | 35.70                   | 20.30                                 | 5.76                                  | 61.76                                                                                           | 3.05                   | 4.26       | 17.32      | 0.63                            | 0.36                    | 0.14                               | 0.09                                 | 6.50                                    | 0.84                                   | 7.05                                                     | 4.10                                                         | 0.03                    | C                                        |
| B                      | 46.70                   | 25.00                                 | 8.40                                  | 80.10                                                                                           | 0.94                   | 2.81       | 7.00       | 0.71                            | 2.92                    | 2.75                               | 0.29                                 | 1.04                                    | 1.63                                   | 2.11                                                     | 0.95                                                         | 0.03                    | F                                        |
| C                      | 56.00                   | 22.00                                 | 11.02                                 | 89.02                                                                                           | 0.64                   | 1.71       | 8.70       | 1.23                            | 2.01                    | 1.80                               | 1.04                                 | 1.75                                    | 0.91                                   | 2.34                                                     | 1.04                                                         | 0.01                    | F                                        |
| D                      | 52.60                   | 24.00                                 | 9.80                                  | 86.40                                                                                           | 0.30                   | 1.30       | 1.20       | 0.20                            | 4.30                    | 4.02                               | 0.54                                 | 0.37                                    | 3.19                                   | 2.47                                                     | 0.86                                                         | 0.10                    | F                                        |
| E                      | 57.70                   | 23.40                                 | 5.84                                  | 86.54                                                                                           | 0.53                   | 1.62       | 6.30       | 1.13                            | 0.93                    | 0.75                               | 0.24                                 | 1.79                                    | 1.19                                   | 2.57                                                     | 1.05                                                         | 0.00                    | F                                        |
| F                      | 23.13                   | 13.29                                 | 9.65                                  | 48.07                                                                                           | 8.32                   | 7.54       | 24.86      | 2.02                            | 0.74                    | 0.29                               | 0.15                                 | 7.28                                    | 0.58                                   | 7.66                                                     | 2.41                                                         | 0.11                    | C                                        |
| G                      | 48.90                   | 21.30                                 | 3.74                                  | 73.94                                                                                           | 0.33                   | 2.68       | 11.70      | 0.66                            | 0.60                    | 0.49                               | 0.15                                 | 6.40                                    | 0.94                                   | 7.02                                                     | 2.73                                                         | 0.06                    | C                                        |
| H                      | 51.40                   | 24.50                                 | 13.86                                 | 89.76                                                                                           | 0.87                   | 0.95       | 2.90       | 0.86                            | 1.83                    | 1.20                               | 0.21                                 | 0.49                                    | 2.24                                   | 1.96                                                     | 0.31                                                         | 0.06                    | F                                        |
| I                      | 31.10                   | 17.00                                 | 5.60                                  | 53.70                                                                                           | 4.77                   | 3.79       | 29.00      | 1.08                            | 0.28                    | 0.16                               | 0.09                                 | 3.17                                    | 0.37                                   | 3.41                                                     | 2.34                                                         | 0.02                    | C                                        |
| J                      | 46.10                   | 20.10                                 | 16.96                                 | 83.16                                                                                           | 1.36                   | 1.33       | 5.10       | 1.49                            | 4.86                    | 4.19                               | 0.62                                 | 0.53                                    | 2.23                                   | 2.00                                                     | 0.65                                                         | 0.15                    | F                                        |
| ASTM C618              | -                       | -                                     | -                                     | 70 min.                                                                                         | 5.0 max.               | 5.0 max.   | -          | -                               | 12.0 max.               | -                                  | -                                    | -                                       | -                                      | -                                                        | 1.50 max.                                                    | 3.0 max.                | F                                        |
| ASTM C618              | -                       | -                                     | -                                     | 50 min.                                                                                         | 5.0 max.               | 5.0 max.   | -          | -                               | 6.0 max.                | -                                  | -                                    | -                                       | -                                      | -                                                        | 1.50 max.                                                    | 3.0 max.                | C                                        |
| CSA CAN3-A23.5-MB2     | -                       | -                                     | -                                     | -                                                                                               | 5.0 max.               | -          | -          | -                               | 12.0                    | -                                  | -                                    | -                                       | -                                      | -                                                        | -                                                            | 3.0                     | F                                        |
| CSA CAN3-A23.5 MB2     | -                       | -                                     | -                                     | -                                                                                               | 5.0 max.               | -          | -          | -                               | 6.0 max.                | -                                  | -                                    | -                                       | -                                      | -                                                        | -                                                            | 3.0 max                 | C                                        |

(a) All numerical values in percentages and tests conducted in accordance with ASTM C 311-77 unless otherwise noted.

(b) Franke free lime test method.

(c) Calculated from the determination of CO<sub>2</sub> by Leco Furnace Method.

(d) Organics by University of Maryland method for evaluating soils using sodium dichromate and sulfuric acid.

(e) Percent total alkalis calculated as follows - Na<sub>2</sub>O + 0.658 K<sub>2</sub>O, tested in accordance with ASTM C114.

(f) Tested in accordance with ASTM C311-77 Section 18.

(g) Class of fly ash arbitrarily established based on total lime content, i.e., fly ashes containing at least 10% CaO are considered Class C fly ashes, those containing less than 10% are considered Class F fly ashes.

TABLE 4. Physical Properties of Fly Ash

| Fly ash identification | Retained on No. 325 (45 $\mu\text{m}$ ) sieve (a) | Fineness air permeability (b) ( $\text{m}^2/\text{kg}$ ) | Pozzolanic activity index (c) |            | Water requirement (d,e) (%) | Autoclave expansion (d,f) (%) | Specific gravity (g) | Increase of drying shrinkage (d,h) (%) | Reactivity with cement alkalis (i,j) (%) |                             | Classification of fly ash |
|------------------------|---------------------------------------------------|----------------------------------------------------------|-------------------------------|------------|-----------------------------|-------------------------------|----------------------|----------------------------------------|------------------------------------------|-----------------------------|---------------------------|
|                        |                                                   |                                                          | Cement (d) (%)                | Lime (psi) |                             |                               |                      |                                        | Reduction of mortar expansion at 14 days | Mortar expansion at 14 days |                           |
| A                      | 11.24                                             | 418                                                      | 89                            | 2355       | 92                          | 0.01                          | 2.67                 | 0.00                                   | 36                                       | 0.204                       | C                         |
| B                      | 31.56                                             | 427                                                      | 82                            | 715        | 100                         | 0.01                          | 2.46                 | 0.00                                   | 70                                       | 0.095                       | F                         |
| C                      | 28.25                                             | 530                                                      | 82                            | 775        | 103                         | 0.02                          | 2.35                 | -0.01 (k)                              | 65                                       | 0.113                       | F                         |
| D                      | 23.70                                             | 296                                                      | 68                            | 700        | 103                         | 0.00                          | 2.19                 | -0.01                                  | 65                                       | 0.111                       | F                         |
| E                      | 23.51                                             | 634                                                      | 81                            | 870        | 98                          | 0.01                          | 2.32                 | -0.02                                  | 72                                       | 0.090                       | F                         |
| F                      | 11.62                                             | 324                                                      | 73                            | 2450       | 95                          | 0.14                          | 2.86                 | -0.01                                  | 3                                        | 0.310                       | C                         |
| G                      | 38.45                                             | 318                                                      | 64                            | 590        | 98                          | 0.06                          | 2.31                 | -0.01                                  | 55                                       | 0.176                       | C                         |
| H                      | 22.32                                             | 241                                                      | 70                            | 825        | 98                          | 0.01                          | 2.44                 | -0.01                                  | 60                                       | 0.127                       | F                         |
| I                      | 14.63                                             | 604                                                      | 90                            | 1720       | 92                          | 0.09                          | 2.74                 | 0.01                                   | 37                                       | 0.202                       | C                         |
| J                      | 14.38                                             | 375                                                      | 90                            | 920        | 100                         | 0.02                          | 2.51                 | -0.01                                  | 67                                       | 0.105                       | F                         |
| ASTM C618              | 34 max.                                           | -                                                        | 75 min.                       | 800 min.   | 105 max.                    | 0.8 max.                      | -                    | 0.03 max.                              | -                                        | 0.020 max.                  | F&C                       |
| CSA CAN3-A23.5-M82     | 34 max.                                           | -                                                        | 68 <sup>(l)</sup> min.        | -          | -                           | 0.8 max.                      | -                    | 0.03 max.                              | 60 min.                                  | -                           | F&C                       |

(a) Tested in accordance with ASTM C 311-77, Section 21.

(b) Tested in accordance with ASTM C 204-79a.

(c) Tested in accordance with ASTM C 311-77, Sections 29 to 31, and 34.

(d) Cement lot No. 21833 used for mortar test.

(e) Calculated in accordance with ASTM C 311-77, Section 33.

(f) Tested in accordance with ASTM C 311-77, Section 25.

(g) Tested in accordance with ASTM C 311-77, Section 20.

(h) Tested in accordance with ASTM C 311-77, Sections 22 to 24.

(i) Tested in accordance with ASTM C 311-77, Section 35.

(j) Cement lot No. 21841 and Pyrex Glass No. 7740 Cullet was used for alkali reactivity test.

(k) "-" denotes decrease in drying shrinkage.

(l) May be increased to 75% minimum at 28 days.

TABLE 5. Concrete Mix Characteristics

| Test mixtures (a,b)     |                        | AEA<br>(ml/lb of<br>cementitious (c,d)<br>material) | Water-<br>cement +<br>fly ash<br>ratio(c) | Slump<br>(in.) (e) | Initial<br>plastic<br>concrete<br>air<br>content<br>(%) |
|-------------------------|------------------------|-----------------------------------------------------|-------------------------------------------|--------------------|---------------------------------------------------------|
| Fly Ash                 |                        |                                                     |                                           |                    |                                                         |
| Identification          | Class<br>of<br>fly ash |                                                     |                                           |                    |                                                         |
| A                       | C                      | 2.51                                                | 0.40                                      | 3.5                | 6.8                                                     |
| B                       | F                      | 4.14                                                | 0.42                                      | 3.5                | 6.5                                                     |
| C                       | F                      | 10.95                                               | 0.42                                      | 3.0                | 6.3                                                     |
| D                       | F                      | 4.73                                                | 0.45                                      | 4.0                | 6.7                                                     |
| E                       | F                      | 3.76                                                | 0.41                                      | 3.0                | 6.0                                                     |
| F                       | C                      | 3.43                                                | 0.40                                      | 3.5                | 6.2                                                     |
| G                       | C                      | 3.14                                                | 0.42                                      | 3.0                | 6.3                                                     |
| H                       | F                      | 3.37                                                | 0.44                                      | 3.25               | 6.0                                                     |
| I                       | C                      | 2.96                                                | 0.42                                      | 3.0                | 6.4                                                     |
| J                       | F                      | 8.61                                                | 0.43                                      | 3.0                | 5.9                                                     |
| <u>Control Mixtures</u> |                        |                                                     |                                           |                    |                                                         |
| 517 pcy <sup>(f)</sup>  |                        | 1.98                                                | 0.43                                      | 3.25               | 6.4                                                     |
| 474 pcy <sup>(g)</sup>  |                        | 1.73                                                | 0.48                                      | 3.25               | 6.2                                                     |

- (a) Test mixtures contained 75% cement and 25% fly ash by weight of cementitious material, based on 517 pcy (307 kg/m<sup>3</sup>) cementitious content mixture, or 82% cement and 18% fly ash by weight of cementitious material based on 474 pcy (281 kg/m<sup>3</sup>) cementitious content mixture.
- (b) Fine aggregate to coarse aggregate ratio of test mixtures was 42.5:57.5 based on 517 (307 kg/m<sup>3</sup>) pcy cementitious content mixture or 43.3:56.7 based on 474 pcy (281 kg/m<sup>3</sup>) cementitious content mixture.
- (c) Based on 517 pcy (307 kg/m<sup>3</sup>) cementitious content mixture; also based on initial water-cement + fly ash ratio before retempering.
- (d) To convert from millilitres per pound to milliliters per kilogram, multiply by 2.205.
- (e) To convert from inches to millimetres, multiply by 25.4.
- (f) Fine aggregate to coarse aggregate ratio was 42.5:57.5.
- (g) To convert from pounds per cubic yard to kilograms per cubic meter, multiply by 0.594.

TABLE 6. Mixing Water Requirement for Concretes

| Test Mixture<br>Fly Ash<br>Identification | Class<br>of<br>Fly Ash | Change in mixing water<br>requirement compared<br>to 517 pcy <sup>(a)</sup><br>control, % |
|-------------------------------------------|------------------------|-------------------------------------------------------------------------------------------|
| A                                         | C                      | -7.0                                                                                      |
| B                                         | F                      | -2.3                                                                                      |
| C                                         | F                      | -2.3                                                                                      |
| D                                         | F                      | +4.6                                                                                      |
| E                                         | F                      | -4.7                                                                                      |
| F                                         | C                      | -7.0                                                                                      |
| G                                         | C                      | -2.3                                                                                      |
| H                                         | F                      | +2.3                                                                                      |
| I                                         | C                      | -2.3                                                                                      |
| J                                         | F                      | 0                                                                                         |

(a) To convert pounds per cubic yard to kilograms per cubic meter, multiply by 0.594.

TABLE 7. Setting Time of Concretes

| Test Mixture              |                     | Setting time<br>hr:min |       | Retardation<br>relative to<br>517 pcy <sup>(a)</sup><br>control,<br>hr:min |       | Retardation<br>relative to<br>474 pcy <sup>(a)</sup><br>control,<br>hr: min |                      |
|---------------------------|---------------------|------------------------|-------|----------------------------------------------------------------------------|-------|-----------------------------------------------------------------------------|----------------------|
| Fly Ash                   |                     |                        |       | Initial                                                                    | Final | Initial <sup>(b)</sup>                                                      | Final <sup>(b)</sup> |
| Identifi-<br>cation       | Class of<br>Fly Ash | Initial                | Final | Initial                                                                    | Final | Initial <sup>(b)</sup>                                                      | Final <sup>(b)</sup> |
| A                         | C                   | 4:30                   | 5:35  | 0:15                                                                       | 0:05  | 0:05                                                                        | -0:15                |
| B                         | F                   | 4:40                   | 6:15  | 0:25                                                                       | 0:45  | 0:15                                                                        | 0:25                 |
| C                         | F                   | 4:25                   | 6:15  | 0:10                                                                       | 0:45  | 0:00                                                                        | 0:25                 |
| D                         | F                   | 5:05                   | 7:15  | 0:50                                                                       | 1:45  | 0:40                                                                        | 1:25                 |
| E                         | F                   | 4:25                   | 5:50  | 0:10                                                                       | 0:20  | 0:00                                                                        | 0:00                 |
| F                         | C                   | 4:25                   | 6:00  | 0:10                                                                       | 0:30  | 0:00                                                                        | 0:10                 |
| G                         | C                   | 4:55                   | 6:30  | 0:40                                                                       | 1:00  | 0:30                                                                        | 0:40                 |
| H                         | F                   | 5:10                   | 7:10  | 0:55                                                                       | 1:40  | 0:45                                                                        | 1:20                 |
| I                         | C                   | 5:00                   | 6:50  | 0:45                                                                       | 1:20  | 0:35                                                                        | 1:00                 |
| J                         | F                   | 5:10                   | 7:40  | 0:55                                                                       | 2:10  | 0:45                                                                        | 1:50                 |
| Average of <sup>(c)</sup> |                     |                        |       |                                                                            |       |                                                                             |                      |
| Class C                   |                     | 4:40                   | 6:15  | 0:30                                                                       | 0:45  | 0:20                                                                        | 0:15                 |
| Class F                   |                     | 4:50                   | 6:45  | 0:35                                                                       | 1:15  | 0:25                                                                        | 0:55                 |
| Control Mixtures          |                     |                        |       |                                                                            |       |                                                                             |                      |
| 517 pcy <sup>(a)</sup>    |                     | 4:15                   | 5:30  | --                                                                         | --    | -0:10                                                                       | -0:20                |
| 474 pcy <sup>(a)</sup>    |                     | 4:25                   | 5:50  | 0:10                                                                       | 0:20  | --                                                                          | --                   |

(a) To convert from pounds per cubic yard to kilograms per cubic meter, multiply by 0.594.

(b) Minus sign means setting time accelerated compared to control.

(c) Rounded to nearest 5 minutes.



Documents

Document Sharing Hub

TABLE 8. Bleeding of Concretes

| Test mixtures           |                  | Bleeding |                               |
|-------------------------|------------------|----------|-------------------------------|
| Fly ash                 |                  | %        | ml/cm <sup>2</sup> of surface |
| Identification          | Class of fly ash |          |                               |
| A                       | C                | 0.22     | 0.007                         |
| B                       | F                | 1.11     | 0.036                         |
| C                       | F                | 1.61     | 0.053                         |
| D                       | F                | 1.88     | 0.067                         |
| E                       | F                | 1.18     | 0.035                         |
| F                       | C                | 0.13     | 0.004                         |
| G                       | C                | 0.89     | 0.028                         |
| H                       | F                | 0.58     | 0.022                         |
| I                       | C                | 0.12     | 0.004                         |
| J                       | F                | 1.48     | 0.051                         |
| <u>Average of</u>       |                  |          |                               |
| Class C                 |                  | 0.34     | 0.011                         |
| Class F                 |                  | 1.31     | 0.044                         |
| <u>Control Mixtures</u> |                  |          |                               |
| 517 pcy(a)              |                  | 1.75     | 0.059                         |
| 474 pcy(a)              |                  | 2.42     | 0.080                         |

(a) To convert pounds per cubic yard to kilograms per cubic meter, multiply by 0.594.

TABLE 9. Compressive Strength Development Moist Cured at 73°F (23°C) Mean of Three 3x6-in. (75x150-mm) Cylinders

| Test mixtures          |                     | Compressive strength, psi <sup>(a)</sup> |        |        |         |         |         |        |
|------------------------|---------------------|------------------------------------------|--------|--------|---------|---------|---------|--------|
| Fly ash                |                     |                                          |        |        |         |         |         |        |
| Identi-<br>fication    | Class of<br>fly ash | 1 day                                    | 3 days | 7 days | 14 days | 28 days | 91 days | 1 year |
| A                      | C                   | 1310                                     | 2750   | 3870   | 4570    | 5250    | 6360    | 7370   |
| B                      | F                   | 1060                                     | 2070   | 2990   | 3880    | 4770    | 5930    | 7070   |
| C                      | F                   | 1200                                     | 2360   | 3240   | 4130    | 5140    | 6530    | 7280   |
| D                      | F                   | 850                                      | 1630   | 2430   | 2980    | 3720    | 5020    | 6240   |
| E                      | F                   | 1240                                     | 2320   | 3190   | 3940    | 5010    | 6580    | 7680   |
| F                      | C                   | 1970                                     | 3210   | 3750   | 4260    | 4590    | 5750    | 6140   |
| G                      | C                   | 930                                      | 1840   | 2720   | 3400    | 4070    | 5570    | 6290   |
| H                      | F                   | 900                                      | 1770   | 2540   | 3230    | 4150    | 5500    | 6600   |
| I                      | C                   | 1440                                     | 2780   | 3610   | 4340    | 4550    | 5860    | 6660   |
| J                      | F                   | 950                                      | 1910   | 2510   | 2960    | 3580    | 5060    | 6280   |
| Average of             |                     |                                          |        |        |         |         |         |        |
| Class C                |                     | 1290                                     | 2760   | 3490   | 4140    | 4260    | 5880    | 6620   |
| Class F                |                     | 1030                                     | 2010   | 2820   | 3520    | 4400    | 5770    | 6860   |
| Control mixtures       |                     |                                          |        |        |         |         |         |        |
| 517 pcy <sup>(b)</sup> |                     | 1750                                     | 3070   | 4150   | 4910    | 5810    | 6670    | 7420   |
| 474 pcy <sup>(b)</sup> |                     | 1350                                     | 2790   | 3890   | 4280    | 4710    | 5870    | 6670   |

| Percent of Control Mixtures |                     |                                           |        |        |         |         |         |        |
|-----------------------------|---------------------|-------------------------------------------|--------|--------|---------|---------|---------|--------|
| Test mixtures               |                     | Percent of 474 pcy <sup>(b)</sup> control |        |        |         |         |         |        |
| Fly ash                     |                     |                                           |        |        |         |         |         |        |
| Identi-<br>fication         | Class of<br>fly ash | 1 day                                     | 3 days | 7 days | 14 days | 28 days | 91 days | 1 year |
| A                           | C                   | 97                                        | 98     | 99     | 107     | 111     | 108     | 110    |
| B                           | F                   | 78                                        | 74     | 77     | 91      | 101     | 101     | 106    |
| C                           | F                   | 89                                        | 84     | 83     | 96      | 109     | 111     | 109    |
| D                           | F                   | 63                                        | 58     | 62     | 70      | 79      | 86      | 94     |
| E                           | F                   | 92                                        | 83     | 82     | 92      | 106     | 112     | 115    |
| F                           | C                   | 146                                       | 115    | 96     | 100     | 97      | 98      | 92     |
| G                           | C                   | 69                                        | 66     | 70     | 79      | 86      | 95      | 94     |
| H                           | F                   | 67                                        | 63     | 65     | 75      | 88      | 94      | 99     |
| I                           | C                   | 107                                       | 100    | 93     | 101     | 97      | 100     | 100    |
| J                           | F                   | 70                                        | 68     | 64     | 69      | 76      | 86      | 94     |

| Test mixtures       |                     | Percent of 517 pcy <sup>(b)</sup> control |        |        |         |         |         |        |
|---------------------|---------------------|-------------------------------------------|--------|--------|---------|---------|---------|--------|
| Fly ash             |                     |                                           |        |        |         |         |         |        |
| Identi-<br>fication | Class of<br>fly ash | 1 day                                     | 3 days | 7 days | 14 days | 28 days | 91 days | 1 year |
| A                   | C                   | 75                                        | 90     | 93     | 93      | 90      | 95      | 99     |
| B                   | F                   | 60                                        | 67     | 72     | 79      | 82      | 89      | 95     |
| C                   | F                   | 68                                        | 77     | 78     | 84      | 88      | 98      | 98     |
| D                   | F                   | 48                                        | 53     | 58     | 61      | 64      | 75      | 84     |
| E                   | F                   | 71                                        | 76     | 77     | 80      | 86      | 99      | 104    |
| F                   | C                   | 112                                       | 104    | 90     | 87      | 79      | 86      | 83     |
| G                   | C                   | 53                                        | 60     | 66     | 69      | 70      | 84      | 85     |
| H                   | F                   | 51                                        | 58     | 61     | 66      | 71      | 82      | 89     |
| I                   | C                   | 82                                        | 90     | 87     | 88      | 78      | 88      | 90     |
| J                   | F                   | 54                                        | 62     | 60     | 60      | 62      | 76      | 85     |

(a) To convert from pounds per square inch to megapascals, multiply by  $6.895 \times 10^{-3}$ .

(b) To convert from pounds per cubic yard to kilograms per cubic meter, multiply by 0.594.



TABLE 10. Compressive Strength Development Cured at 40°F (4.4°C) (a) Mean of Three 3x6-in. (75x150-mm) Cylinders

| Test mixtures       |                     | Compressive strength, psi(b) |        |        |         |         |         |        |
|---------------------|---------------------|------------------------------|--------|--------|---------|---------|---------|--------|
| Fly ash             |                     |                              |        |        |         |         |         |        |
| Identi-<br>fication | Class of<br>fly ash | 1 day                        | 3 days | 7 days | 14 days | 28 days | 91 days | 1 year |
| A                   | C                   | 70                           | 1550   | 3010   | 4010    | 4950    | 6090    | 7160   |
| B                   | F                   | 70                           | 880    | 1990   | 2990    | 3860    | 4690    | 6130   |
| C                   | F                   | 60                           | 1110   | 2100   | 3370    | 3720    | 4990    | 6020   |
| D                   | F                   | 60                           | 850    | 1510   | 2340    | 3130    | 3870    | 4690   |
| E                   | F                   | 80                           | 1170   | 2340   | 3230    | 4050    | 5050    | 6560   |
| F                   | C                   | 70                           | 1630   | 3390   | 4610    | 4920    | 5350    | 6990   |
| G                   | C                   | 100                          | 870    | 1840   | 2600    | 3510    | 4300    | 5330   |
| H                   | F                   | 60                           | 760    | 1460   | 2330    | 2910    | 3830    | 4380   |
| I                   | C                   | 90                           | 1530   | 2750   | 4010    | 4470    | 5990    | 6730   |
| J                   | F                   | 70                           | 1070   | 1790   | 2610    | 3320    | 4100    | 4700   |
| Average of          |                     |                              |        |        |         |         |         |        |
| Class C             |                     | 80                           | 1400   | 2750   | 3810    | 4460    | 5430    | 6550   |
| Class F             |                     | 70                           | 970    | 1860   | 2810    | 3500    | 4470    | 5410   |
| Control mixtures    |                     |                              |        |        |         |         |         |        |
| 517 pcy(c)          |                     | 160                          | 1650   | 2900   | 4300    | 5050    | 6330    | 7850   |
| 474 pcy(c)          |                     | 90                           | 1360   | 2680   | 3640    | 4910    | 5690    | 6930   |

| Percent of Control Mixtures |                     |                               |        |        |         |         |         |        |
|-----------------------------|---------------------|-------------------------------|--------|--------|---------|---------|---------|--------|
| Test mixtures               |                     | Percent of 474 pcy(c) control |        |        |         |         |         |        |
| Fly ash                     |                     |                               |        |        |         |         |         |        |
| Identi-<br>fication         | Class of<br>fly ash | 1 day                         | 3 days | 7 days | 14 days | 28 days | 91 days | 1 year |
| A                           | C                   | 78                            | 114    | 112    | 110     | 101     | 107     | 103    |
| B                           | F                   | 78                            | 65     | 74     | 82      | 79      | 82      | 88     |
| C                           | F                   | 68                            | 82     | 78     | 92      | 76      | 88      | 87     |
| D                           | F                   | 68                            | 62     | 56     | 64      | 64      | 68      | 68     |
| E                           | F                   | 89                            | 86     | 87     | 89      | 82      | 89      | 94     |
| F                           | C                   | 78                            | 120    | 126    | 126     | 100     | 94      | 101    |
| G                           | C                   | 111                           | 64     | 69     | 71      | 71      | 76      | 77     |
| H                           | F                   | 68                            | 56     | 54     | 64      | 59      | 67      | 63     |
| I                           | C                   | 100                           | 112    | 96     | 110     | 91      | 105     | 97     |
| J                           | F                   | 78                            | 79     | 67     | 72      | 68      | 72      | 68     |

| Test mixtures       |                     | Percent of 517 pcy(c) control |        |        |         |         |         |        |
|---------------------|---------------------|-------------------------------|--------|--------|---------|---------|---------|--------|
| Fly ash             |                     |                               |        |        |         |         |         |        |
| Identi-<br>fication | Class of<br>fly ash | 1 day                         | 3 days | 7 days | 14 days | 28 days | 91 days | 1 year |
| A                   | C                   | 44                            | 94     | 104    | 93      | 98      | 96      | 91     |
| B                   | F                   | 44                            | 53     | 69     | 70      | 76      | 74      | 78     |
| C                   | F                   | 38                            | 67     | 72     | 78      | 74      | 79      | 77     |
| D                   | F                   | 38                            | 52     | 52     | 54      | 62      | 61      | 60     |
| E                   | F                   | 50                            | 71     | 81     | 75      | 80      | 80      | 84     |
| F                   | C                   | 44                            | 98     | 117    | 107     | 97      | 84      | 89     |
| G                   | C                   | 62                            | 53     | 63     | 60      | 70      | 68      | 68     |
| H                   | F                   | 38                            | 46     | 50     | 54      | 58      | 60      | 56     |
| I                   | C                   | 56                            | 93     | 89     | 93      | 88      | 95      | 86     |
| J                   | F                   | 44                            | 65     | 62     | 61      | 66      | 65      | 60     |

- (a) Moist cured at 40°F (4.4°C) for 7 days, followed by 40°F (4.4°C) air storage and 95% relative humidity.  
 (b) To convert from pounds per square inch to megapascals, multiply by  $6.895 \times 10^{-3}$ .  
 (c) To convert from pounds per cubic yard to kilograms per cubic meter, multiply by 0.594.

TABLE 11. Compressive Strength Development Percent of  
 40°F (4.4°C) Cured to Moist Cured at 73°F (23°C)

| Test Mixtures<br>Fly Ash |                     | Compressive Strength, percent of 40°F (4.4°C)<br>cured to moist cured at 73°F (23°C) |        |        |         |         |         |        |
|--------------------------|---------------------|--------------------------------------------------------------------------------------|--------|--------|---------|---------|---------|--------|
| Identi-<br>fication      | Class of<br>fly ash | 1 day                                                                                | 3 days | 7 days | 14 days | 28 days | 91 days | 1 year |
| A                        | C                   | 5                                                                                    | 56     | 78     | 88      | 94      | 96      | 97     |
| B                        | F                   | 7                                                                                    | 42     | 66     | 77      | 81      | 79      | 87     |
| C                        | F                   | 5                                                                                    | 47     | 65     | 82      | 72      | 76      | 83     |
| D                        | F                   | 7                                                                                    | 52     | 62     | 78      | 84      | 77      | 75     |
| E                        | F                   | 6                                                                                    | 50     | 73     | 82      | 81      | 88      | 85     |
| F                        | C                   | 4                                                                                    | 51     | 90     | 108     | 107     | 93      | 114    |
| G                        | C                   | 11                                                                                   | 47     | 68     | 76      | 86      | 77      | 85     |
| H                        | F                   | 7                                                                                    | 43     | 57     | 72      | 70      | 70      | 66     |
| I                        | C                   | 6                                                                                    | 55     | 76     | 92      | 98      | 102     | 101    |
| J                        | F                   | 7                                                                                    | 56     | 71     | 88      | 93      | 81      | 75     |
| <u>Average of</u>        |                     |                                                                                      |        |        |         |         |         |        |
| Class C                  |                     | 6                                                                                    | 52     | 77     | 91      | 96      | 92      | 99     |
| Class F                  |                     | 6                                                                                    | 48     | 66     | 80      | 80      | 78      | 78     |
| <u>Control Mixtures</u>  |                     |                                                                                      |        |        |         |         |         |        |
| 517 pcy <sup>(a)</sup>   |                     | 9                                                                                    | 54     | 70     | 88      | 87      | 95      | 106    |
| 474 pcy <sup>(a)</sup>   |                     | 7                                                                                    | 49     | 69     | 85      | 104     | 97      | 104    |

(a) To convert pounds per cubic yard to kilograms per cubic meter, multiply by 0.594.

TABLE 12. Compressive Strength Development Air Storage  
at 73°F (23°C) (a) Mean of Three 3x6 in. (75x150 mm) Cylinders

| Test mixtures          |                     | Compressive strength, psi <sup>(b)</sup> |        |        |         |         |         |        |
|------------------------|---------------------|------------------------------------------|--------|--------|---------|---------|---------|--------|
| Fly ash                |                     |                                          |        |        |         |         |         |        |
| Identifi-<br>cation    | Class of<br>fly ash | 1 day                                    | 3 days | 7 days | 14 days | 28 days | 91 days | 1 year |
| A                      | C                   | 1540                                     | 2680   | 3340   | 3510    | 3510    | 3560    | 3890   |
| B                      | F                   | 1290                                     | 1940   | 2550   | 2950    | 3070    | 2750    | 2870   |
| C                      | F                   | 1120                                     | 2110   | 2520   | 3060    | 2810    | 2820    | 3230   |
| D                      | F                   | 860                                      | 1510   | 2020   | 2380    | 2270    | 2410    | 2420   |
| E                      | F                   | 1210                                     | 2160   | 2900   | 3040    | 3100    | 3300    | 3340   |
| F                      | C                   | 2250                                     | 3410   | 4020   | 4380    | 4530    | 5100    | 4750   |
| G                      | C                   | 960                                      | 2000   | 2380   | 2420    | 2490    | 2480    | 2840   |
| H                      | F                   | 860                                      | 1580   | 2380   | 2460    | 2330    | 2510    | 2650   |
| I                      | C                   | 1460                                     | 2560   | 3030   | 3500    | 3470    | 3400    | 3450   |
| J                      | F                   | 990                                      | 1900   | 2500   | 2660    | 2600    | 2510    | 2770   |
| Average of             |                     |                                          |        |        |         |         |         |        |
| Class C                |                     | 1550                                     | 2660   | 3190   | 3450    | 3500    | 3640    | 3730   |
| Class F                |                     | 1060                                     | 1870   | 2480   | 2760    | 2700    | 2720    | 2880   |
| Control mixtures       |                     |                                          |        |        |         |         |         |        |
| 517 pcy <sup>(c)</sup> |                     | 1760                                     | 3060   | 3620   | 3830    | 3980    | 3990    | 4190   |
| 474 pcy <sup>(c)</sup> |                     | 1490                                     | 2720   | 3370   | 3480    | 3450    | 3580    | 3860   |

| Percent of Control Mixtures |                     |                                           |        |        |         |         |         |        |
|-----------------------------|---------------------|-------------------------------------------|--------|--------|---------|---------|---------|--------|
| Test mixtures               |                     | Percent of 474 pcy <sup>(c)</sup> control |        |        |         |         |         |        |
| Fly ash                     |                     |                                           |        |        |         |         |         |        |
| Identifi-<br>cation         | Class of<br>fly ash | 1 day                                     | 3 days | 7 days | 14 days | 28 days | 91 days | 1 year |
| A                           | C                   | 103                                       | 98     | 98     | 101     | 102     | 99      | 101    |
| B                           | F                   | 86                                        | 71     | 76     | 85      | 89      | 77      | 74     |
| C                           | F                   | 75                                        | 78     | 75     | 88      | 81      | 79      | 84     |
| D                           | F                   | 58                                        | 56     | 60     | 68      | 80      | 67      | 89     |
| E                           | F                   | 81                                        | 79     | 86     | 87      | 90      | 92      | 86     |
| F                           | C                   | 151                                       | 125    | 119    | 125     | 131     | 142     | 123    |
| G                           | C                   | 64                                        | 74     | 71     | 70      | 72      | 69      | 74     |
| H                           | F                   | 58                                        | 58     | 83     | 71      | 68      | 70      | 69     |
| I                           | C                   | 98                                        | 94     | 90     | 100     | 100     | 95      | 89     |
| J                           | F                   | 66                                        | 70     | 74     | 76      | 75      | 70      | 72     |

| Test mixtures       |                     | Percent of 517 pcy <sup>(c)</sup> control |        |        |         |         |         |        |
|---------------------|---------------------|-------------------------------------------|--------|--------|---------|---------|---------|--------|
| Fly ash             |                     |                                           |        |        |         |         |         |        |
| Identifi-<br>cation | Class of<br>fly ash | 1 day                                     | 3 days | 7 days | 14 days | 28 days | 91 days | 1 year |
| A                   | C                   | 88                                        | 88     | 92     | 92      | 92      | 91      | 93     |
| B                   | F                   | 73                                        | 63     | 70     | 77      | 80      | 69      | 68     |
| C                   | F                   | 64                                        | 69     | 70     | 80      | 73      | 71      | 77     |
| D                   | F                   | 49                                        | 49     | 56     | 62      | 72      | 60      | 58     |
| E                   | F                   | 69                                        | 70     | 80     | 79      | 81      | 83      | 80     |
| F                   | C                   | 128                                       | 111    | 111    | 114     | 118     | 128     | 113    |
| G                   | C                   | 54                                        | 65     | 66     | 63      | 65      | 62      | 68     |
| H                   | F                   | 49                                        | 52     | 66     | 64      | 61      | 63      | 63     |
| I                   | C                   | 83                                        | 84     | 83     | 91      | 91      | 85      | 82     |
| J                   | F                   | 51                                        | 62     | 69     | 69      | 65      | 63      | 66     |

(a) Relative humidity was 50% ± 5%.

(b) To convert from pounds per square inch to megapascals, multiply by 6.895x10<sup>-3</sup>.

(c) To convert from pounds per cubic yard to kilograms per cubic meter, multiply by 0.594.

TABLE 13. Compressive Strength Development  
Percent of Air Cured<sup>(a)</sup> to Moist Cured<sup>(b)</sup> at 73°F (23°C)

| Test mixtures           |                     | Compressive strength, <sup>(c)</sup><br>percent of air cured to moist cured<br>normalized to the strength at one day |        |        |         |         |         |        |
|-------------------------|---------------------|----------------------------------------------------------------------------------------------------------------------|--------|--------|---------|---------|---------|--------|
| Fly ash                 |                     |                                                                                                                      |        |        |         |         |         |        |
| Identi-<br>fication     | Class of<br>fly ash | 1 day                                                                                                                | 3 days | 7 days | 14 days | 28 days | 91 days | 1 year |
| A                       | C                   | 100                                                                                                                  | 83     | 73     | 65      | 57      | 48      | 45     |
| B                       | F                   | 100                                                                                                                  | 76     | 70     | 62      | 53      | 38      | 33     |
| C                       | F                   | 100                                                                                                                  | 95     | 83     | 79      | 59      | 46      | 47     |
| D                       | F                   | 100                                                                                                                  | 92     | 82     | 79      | 60      | 47      | 38     |
| E                       | F                   | 100                                                                                                                  | 95     | 93     | 79      | 63      | 51      | 44     |
| F                       | C                   | 100                                                                                                                  | 93     | 94     | 90      | 86      | 78      | 67     |
| G                       | C                   | 100                                                                                                                  | 105    | 85     | 69      | 59      | 43      | 44     |
| H                       | F                   | 100                                                                                                                  | 93     | 98     | 80      | 59      | 48      | 42     |
| I                       | C                   | 100                                                                                                                  | 91     | 83     | 80      | 75      | 57      | 51     |
| J                       | F                   | 100                                                                                                                  | 96     | 95     | 86      | 70      | 48      | 42     |
| <u>Average of</u>       |                     |                                                                                                                      |        |        |         |         |         |        |
| Class C                 |                     | 100                                                                                                                  | 93     | 84     | 76      | 69      | 56      | 52     |
| Class F                 |                     | 100                                                                                                                  | 91     | 87     | 78      | 61      | 46      | 41     |
| <u>Control mixtures</u> |                     |                                                                                                                      |        |        |         |         |         |        |
| 517 pcy <sup>(d)</sup>  |                     | 100                                                                                                                  | 99     | 87     | 78      | 68      | 60      | 56     |
| 474 pcy <sup>(d)</sup>  |                     | 100                                                                                                                  | 88     | 78     | 74      | 66      | 55      | 52     |

(a) Relative humidity was 50% ± 5%.

(b) Relative humidity was 100%.

(c) For each mix normalized to the one-day strengths developed in the molds.

(d) To convert pounds per cubic yard to kilograms per cubic meter, multiply by 0.594.

TABLE 14. Drying Shrinkage Mean of Three Prisms

| Test mixtures           |                     | Drying shrinkage, %                              |         |         |          |          |          |
|-------------------------|---------------------|--------------------------------------------------|---------|---------|----------|----------|----------|
| Fly ash                 |                     | Initial curing - 7 days moist at 73°F (23°C) (a) |         |         |          |          |          |
| Identi-<br>fication     | Class of<br>fly ash | Age of concrete after initial curing             |         |         |          |          |          |
|                         |                     | 7 days                                           | 28 days | 8 weeks | 16 weeks | 32 weeks | 64 weeks |
| A                       | C                   | 0.030                                            | 0.066   | 0.076   | 0.084    | 0.092    | 0.092    |
| B                       | F                   | 0.026                                            | 0.053   | 0.062   | 0.072    | 0.075    | 0.074    |
| C                       | F                   | 0.026                                            | 0.051   | 0.059   | 0.069    | 0.077    | 0.076    |
| D                       | F                   | 0.023                                            | 0.050   | 0.059   | 0.069    | 0.077    | 0.075    |
| E                       | F                   | 0.025                                            | 0.051   | 0.061   | 0.070    | 0.076    | 0.073    |
| F                       | C                   | 0.019                                            | 0.046   | 0.054   | 0.070    | 0.076    | 0.081    |
| G                       | C                   | 0.028                                            | 0.055   | 0.058   | 0.069    | 0.072    | 0.074    |
| H                       | F                   | 0.027                                            | 0.053   | 0.059   | 0.068    | 0.070    | 0.071    |
| I                       | C                   | 0.031                                            | 0.056   | 0.064   | 0.074    | 0.077    | 0.079    |
| J                       | F                   | 0.027                                            | 0.051   | 0.059   | 0.065    | 0.070    | 0.068    |
| <u>Average of</u>       |                     |                                                  |         |         |          |          |          |
| Class C                 |                     | 0.027                                            | 0.056   | 0.063   | 0.074    | 0.079    | 0.082    |
| Class F                 |                     | 0.026                                            | 0.052   | 0.060   | 0.069    | 0.074    | 0.073    |
| <u>Control mixtures</u> |                     |                                                  |         |         |          |          |          |
| 517 pcy <sup>(b)</sup>  |                     | 0.024                                            | 0.055   | 0.066   | 0.075    | 0.082    | 0.082    |
| 474 pcy <sup>(b)</sup>  |                     | 0.027                                            | 0.052   | 0.065   | 0.073    | 0.080    | 0.076    |

| Test mixtures           |                     | Drying shrinkage, %                              |         |         |          |          |          |
|-------------------------|---------------------|--------------------------------------------------|---------|---------|----------|----------|----------|
| Fly ash                 |                     | Initial curing - 7 days moist at 40°F (44°C) (a) |         |         |          |          |          |
| Identi-<br>fication     | Class of<br>fly ash | Age of concrete after initial curing             |         |         |          |          |          |
|                         |                     | 7 days                                           | 28 days | 8 weeks | 16 weeks | 32 weeks | 64 weeks |
| A                       | C                   | 0.011                                            | 0.041   | 0.051   | 0.060    | 0.068    | 0.067    |
| B                       | F                   | 0.011                                            | 0.040   | 0.050   | 0.054    | 0.061    | 0.060    |
| C                       | F                   | 0.008                                            | 0.035   | 0.046   | 0.054    | 0.059    | 0.058    |
| D                       | F                   | 0.009                                            | 0.039   | 0.048   | 0.056    | 0.061    | 0.062    |
| E                       | F                   | 0.007                                            | 0.034   | 0.040   | 0.047    | 0.055    | 0.055    |
| F                       | C                   | 0.013                                            | 0.042   | 0.050   | 0.061    | 0.067    | 0.069    |
| G                       | C                   | 0.012                                            | 0.054   | 0.050   | 0.055    | 0.055    | 0.060    |
| H                       | F                   | 0.008                                            | 0.040   | 0.050   | 0.057    | 0.057    | 0.062    |
| I                       | C                   | 0.017                                            | 0.042   | 0.048   | 0.055    | 0.058    | 0.058    |
| J                       | F                   | 0.018                                            | 0.035   | 0.044   | 0.052    | 0.056    | 0.053    |
| <u>Average of</u>       |                     |                                                  |         |         |          |          |          |
| Class C                 |                     | 0.013                                            | 0.045   | 0.050   | 0.058    | 0.062    | 0.064    |
| Class F                 |                     | 0.010                                            | 0.037   | 0.046   | 0.053    | 0.058    | 0.058    |
| <u>Control mixtures</u> |                     |                                                  |         |         |          |          |          |
| 517 pcy <sup>(b)</sup>  |                     | 0.010                                            | 0.037   | 0.050   | 0.058    | 0.066    | 0.063    |
| 474 pcy <sup>(b)</sup>  |                     | 0.006                                            | 0.038   | 0.046   | 0.052    | 0.058    | 0.060    |

(a) Subsequent storage after initial curing was 73°F (23°C) and 50%±20% relative humidity.

(b) To convert pounds per cubic yard to kilograms per cubic meter, multiply by 0.594.



TABLE 15. Abrasion Resistance Mean of Three Tests

| Test mixtures           |                     | Depth of wear, in. <sup>(a)</sup> |        | 28-day<br>moist-cured,<br>compressive<br>strength,<br>psi <sup>(b)</sup> |
|-------------------------|---------------------|-----------------------------------|--------|--------------------------------------------------------------------------|
| Fly ash                 |                     | Duration of test                  |        |                                                                          |
| Identifi-<br>cation     | Class of<br>fly ash | 30 min                            | 60 min |                                                                          |
| A                       | C                   | 0.032                             | 0.051  | 5250                                                                     |
| B                       | F                   | 0.045                             | 0.065  | 4770                                                                     |
| C                       | F                   | 0.036                             | 0.061  | 5140                                                                     |
| D                       | F                   | 0.044                             | 0.068  | 3720                                                                     |
| E                       | F                   | 0.037                             | 0.061  | 5010                                                                     |
| F                       | C                   | 0.028                             | 0.047  | 4590                                                                     |
| G                       | C                   | 0.057                             | 0.080  | 4070                                                                     |
| H                       | F                   | 0.057                             | 0.084  | 4150                                                                     |
| I                       | C                   | 0.043                             | 0.063  | 4550                                                                     |
| J                       | F                   | 0.056                             | 0.070  | 3580                                                                     |
| <u>Control mixtures</u> |                     |                                   |        |                                                                          |
| 517 pcy <sup>(c)</sup>  |                     | 0.032                             | 0.056  | 5810                                                                     |
| 474 pcy <sup>(c)</sup>  |                     | 0.033                             | 0.054  | 4710                                                                     |

(a) To convert inches to millimeters, multiply by 25.4.

(b) To convert from pounds per square inch to megapascals, multiply by  $6.895 \times 10^{-3}$ .

(c) To convert from pounds per cubic yard to kilograms per cubic meter, multiply by 0.594.

**TABLE 16. Absorption of Hardened Concretes**  
Mean of Three Tests

| Test mixtures           |                  | 5-hr absorption by boiling, % |
|-------------------------|------------------|-------------------------------|
| Fly ash                 |                  |                               |
| Identification          | Class of fly ash |                               |
| A                       | C                | 6.7                           |
| B                       | F                | 6.7                           |
| C                       | F                | 6.5                           |
| D                       | F                | 7.0                           |
| E                       | F                | 6.0                           |
| F                       | C                | 6.2                           |
| G                       | C                | 4.9                           |
| H                       | F                | 5.1                           |
| I                       | C                | 5.1                           |
| J                       | F                | 6.2                           |
| <u>Average of</u>       |                  |                               |
| Class C                 |                  | 5.7                           |
| Class F                 |                  | 6.2                           |
| <u>Control Mixtures</u> |                  |                               |
| 517 pcy <sup>(a)</sup>  |                  | 6.8                           |
| 474 pcy <sup>(a)</sup>  |                  | 6.0                           |

(a) To convert pounds per cubic yards to kilograms per cubic meter, multiply 0.594.

Table 17. Effect of Fly Ash Properties on Concrete Performance

| Concrete Property                                            | Effect of Fly Ash Properties for Coefficient of Correlations Exceeding 0.77 As Fly Ash Property Increases in Magnitude (a) |                                |                                                                                                   |                 |     |     |              |                     |                 |                   |                   |                  |                                  |                              |      |                     |                                     |                                                 |                        |
|--------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|--------------------------------|---------------------------------------------------------------------------------------------------|-----------------|-----|-----|--------------|---------------------|-----------------|-------------------|-------------------|------------------|----------------------------------|------------------------------|------|---------------------|-------------------------------------|-------------------------------------------------|------------------------|
|                                                              | SiO <sub>2</sub>                                                                                                           | Al <sub>2</sub> O <sub>3</sub> | Total<br>SiO <sub>2</sub> +<br>Fe <sub>2</sub> O <sub>3</sub> +<br>Al <sub>2</sub> O <sub>3</sub> | SO <sub>3</sub> | MgO | CaO | Free<br>Lime | Loss on<br>Ignition | Total<br>Carbon | Organic<br>Matter | Na <sub>2</sub> O | K <sub>2</sub> O | Alkalies<br>As Na <sub>2</sub> O | Pozzolanic<br>Activity Index |      | Specific<br>Gravity | Mortar<br>Water<br>Require-<br>ment | Reduction<br>of Mortar<br>Expansion<br>Alkalies | Autoclave<br>Expansion |
|                                                              |                                                                                                                            |                                |                                                                                                   |                 |     |     |              |                     |                 |                   |                   |                  |                                  | Cement                       | Lime |                     |                                     |                                                 |                        |
| Water Requirement                                            |                                                                                                                            |                                |                                                                                                   |                 | D   | D   |              |                     |                 |                   | D                 | I                |                                  |                              |      |                     |                                     |                                                 |                        |
| Bleeding                                                     | I                                                                                                                          | I                              | I                                                                                                 | D               | D   | D   |              | I                   | I               | I                 |                   | I                |                                  |                              | D    | D                   | I                                   |                                                 |                        |
| Early Age Compressive Strength for 73°F (23°C) Moist Curing  | D                                                                                                                          | D                              | D                                                                                                 | I               | I   |     |              |                     |                 |                   |                   |                  |                                  |                              | I    |                     |                                     |                                                 |                        |
| Early age Compressive Strength for 40°F (4.4°C) Moist Curing | D                                                                                                                          | D                              | D                                                                                                 | I               | I   | I   |              |                     |                 |                   |                   |                  |                                  |                              | I    | I                   |                                     |                                                 |                        |
| Long-Term Compressive Strength for 40°F (4.4°C) Moist Curing |                                                                                                                            |                                |                                                                                                   |                 | I   | I   |              |                     |                 |                   | I                 | D                | I                                |                              |      |                     |                                     |                                                 |                        |
| 73°F (23°C) air-cured Compressive Strength at all ages       | D                                                                                                                          | D                              | D                                                                                                 | I               | I   | I   |              |                     |                 |                   |                   |                  |                                  |                              | I    | I                   |                                     | D                                               |                        |

(a) I = increases, D = decreases.

Table 17. Effect of Fly Ash Properties on Concrete Performance (continued)

| Concrete Property                                                             | Effect of Fly Ash Properties for Coefficient of Correlations Exceeding 0.77 As Fly Ash Property Increases in Magnitude (a) |                                |                                                                                                   |                 |     |     |              |                     |                 |                   |                   |                  |                                  |                              |      |                     |                                     |                                                 |                        |
|-------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|--------------------------------|---------------------------------------------------------------------------------------------------|-----------------|-----|-----|--------------|---------------------|-----------------|-------------------|-------------------|------------------|----------------------------------|------------------------------|------|---------------------|-------------------------------------|-------------------------------------------------|------------------------|
|                                                                               | SiO <sub>2</sub>                                                                                                           | Al <sub>2</sub> O <sub>3</sub> | Total<br>SiO <sub>2</sub> +<br>Fe <sub>2</sub> O <sub>3</sub> +<br>Al <sub>2</sub> O <sub>3</sub> | SO <sub>3</sub> | MgO | CaO | Free<br>Lime | Loss on<br>Ignition | Total<br>Carbon | Organic<br>Matter | Na <sub>2</sub> O | K <sub>2</sub> O | Alkalies<br>As Na <sub>2</sub> O | Pozzolanic<br>Activity Index |      | Specific<br>Gravity | Mortar<br>Water<br>Require-<br>ment | Reduction<br>of Mortar<br>Expansion<br>Alkalies | Autoclave<br>Expansion |
|                                                                               |                                                                                                                            |                                |                                                                                                   |                 |     |     |              |                     |                 |                   |                   |                  |                                  | Cement                       | Lime |                     |                                     |                                                 |                        |
| % Air to<br>Moist Cured<br>28-day<br>Compressive<br>Strength                  |                                                                                                                            |                                |                                                                                                   |                 |     |     | I            |                     |                 |                   |                   |                  |                                  |                              |      |                     |                                     |                                                 | I                      |
| % Air to<br>Moist Cured<br>28-day and<br>later age<br>Compressive<br>Strength | D                                                                                                                          | D                              |                                                                                                   | I               |     |     |              |                     |                 |                   |                   |                  |                                  |                              |      |                     |                                     |                                                 |                        |
| % Air to<br>Moist Cured<br>Long-Term<br>Compressive<br>Strength               |                                                                                                                            |                                | D                                                                                                 |                 |     |     |              |                     |                 |                   |                   |                  |                                  |                              |      |                     |                                     | D                                               |                        |
| 73°F (23°C)<br>Moist Cured<br>Long-Term<br>Drying<br>Shrinkage                |                                                                                                                            |                                |                                                                                                   |                 |     |     |              |                     | D               |                   |                   |                  | I                                |                              |      |                     |                                     |                                                 |                        |

(a) I = increases, D = decreases.

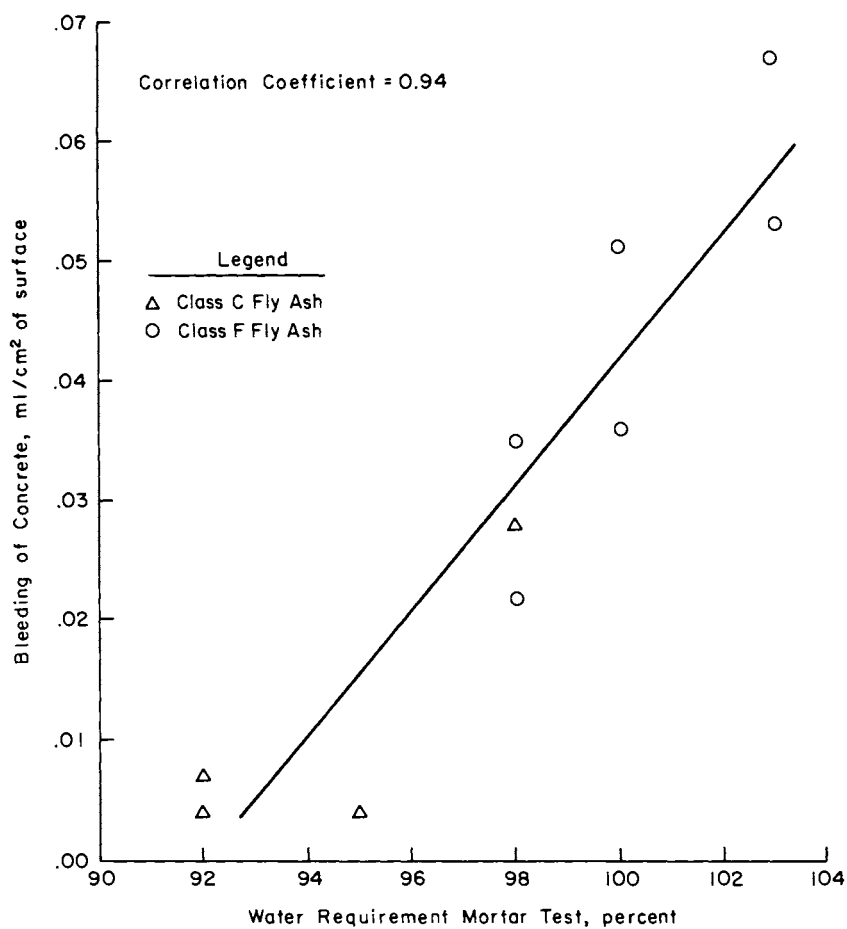


Fig. 1--Comparison of bleeding capacity and mortar water requirement values for fly ash

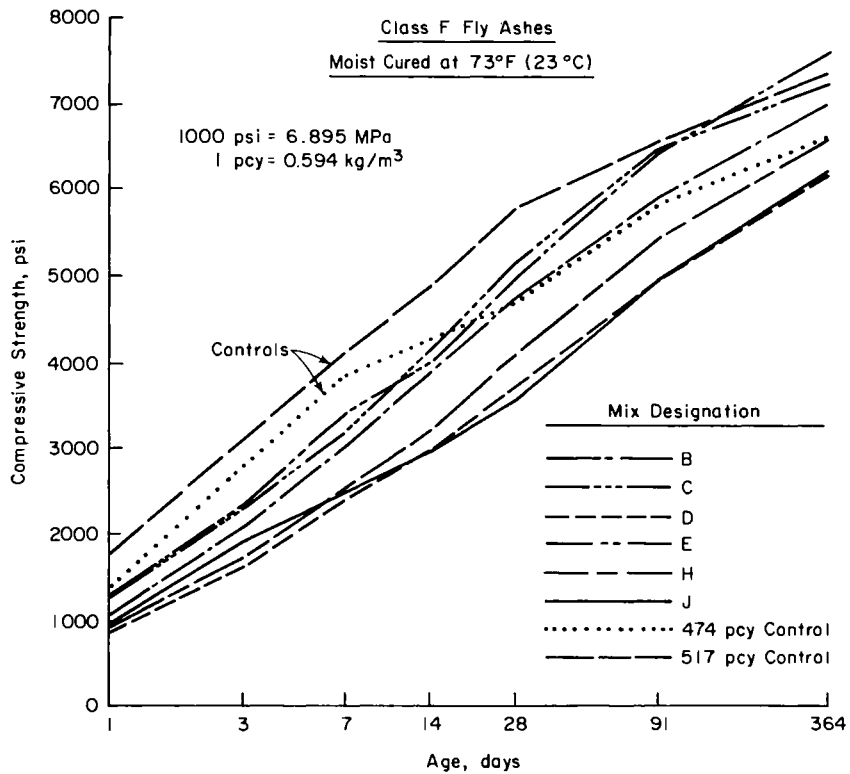


Fig. 2--Compressive strength development for concretes moist cured at 73 F (23 C)--Class F fly ashes

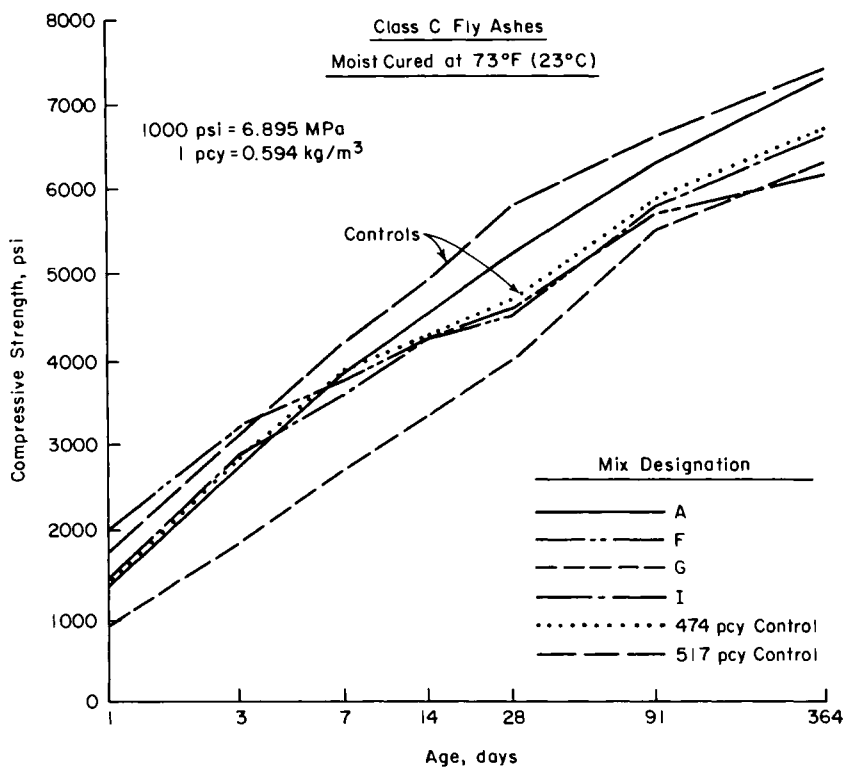


Fig. 3--compressive strength development for concretes moist cured at 73 F (23 C)--Class C fly ashes

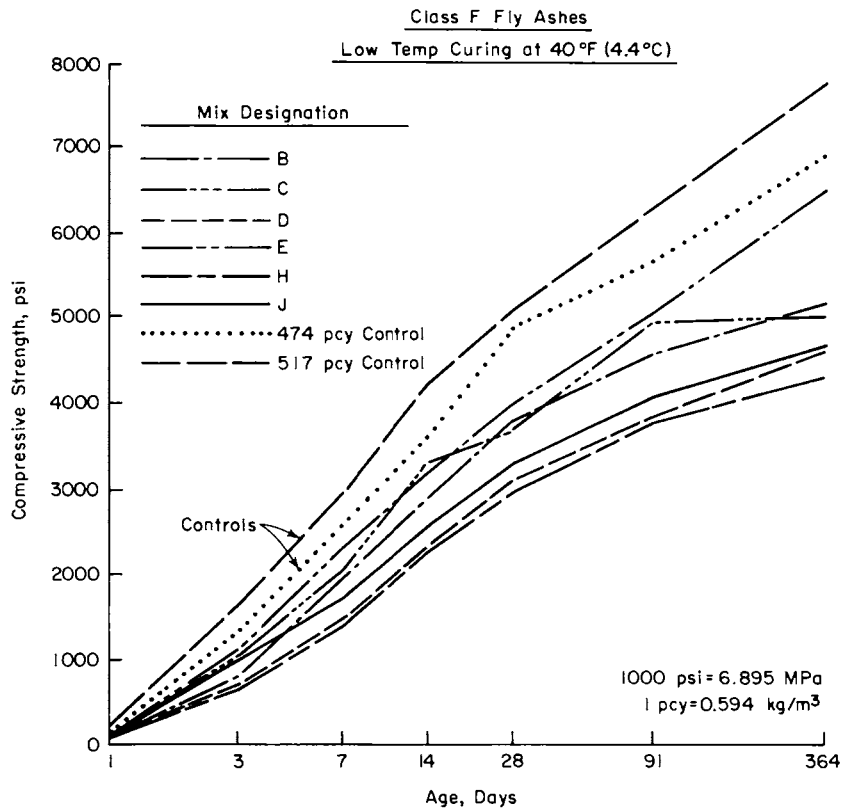


Fig. 4--Compressive strength development for curing at 40 F (4.4 C)--Class F fly ashes

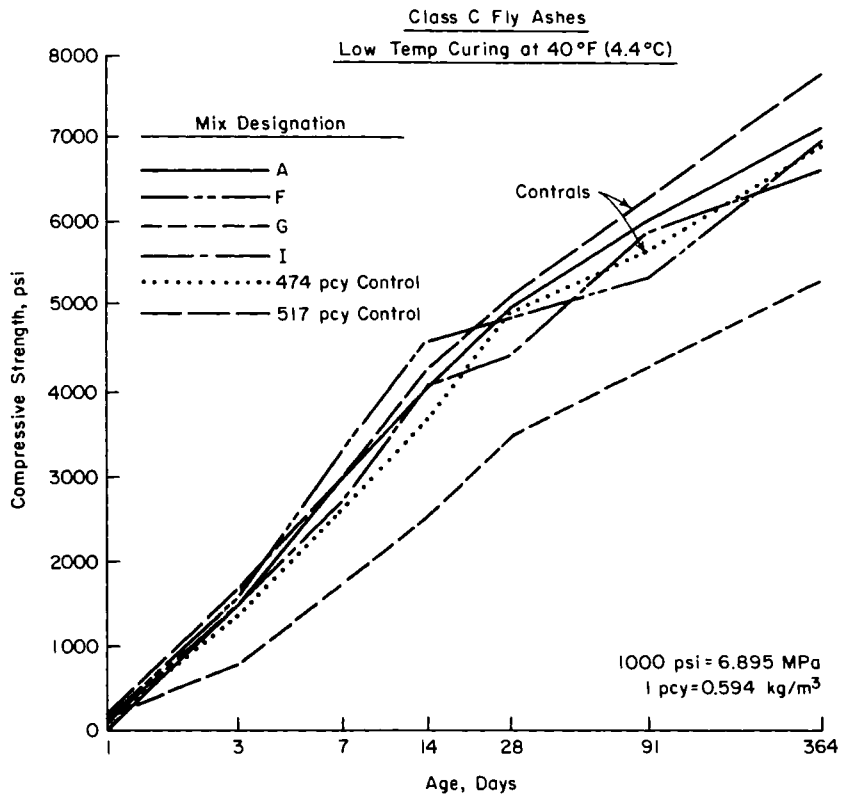


Fig. 5--Compressive strength development for curing at 40 F (4.4 C)--Class C fly ashes

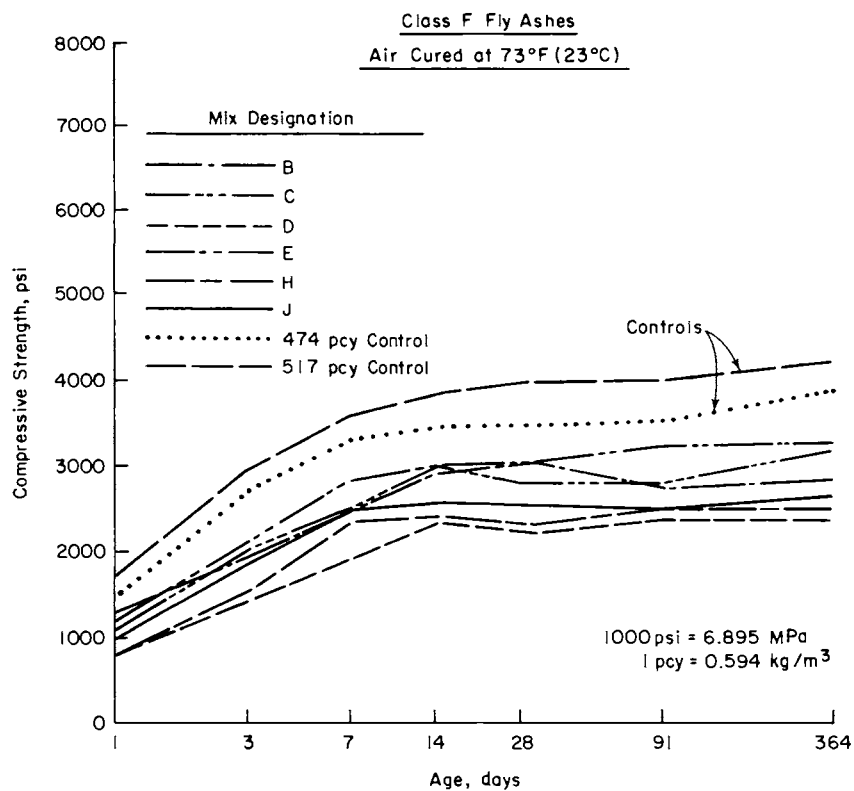


Fig. 6--Compressive strength development for air-cured concretes--Class F fly ashes

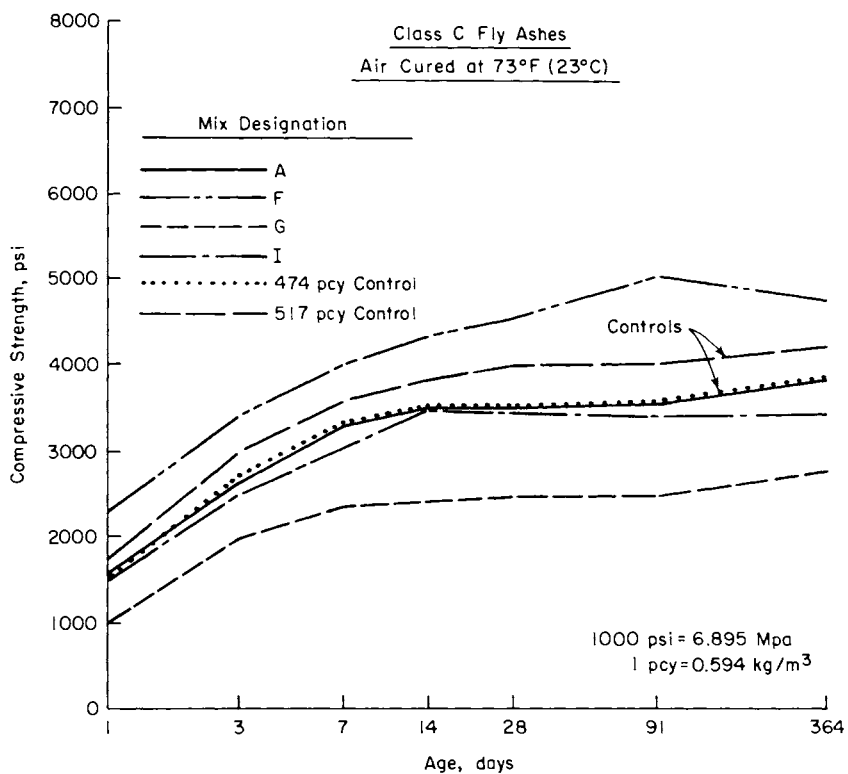


Fig. 7--Compressive strength development for air-cured concretes--  
Class C fly ashes

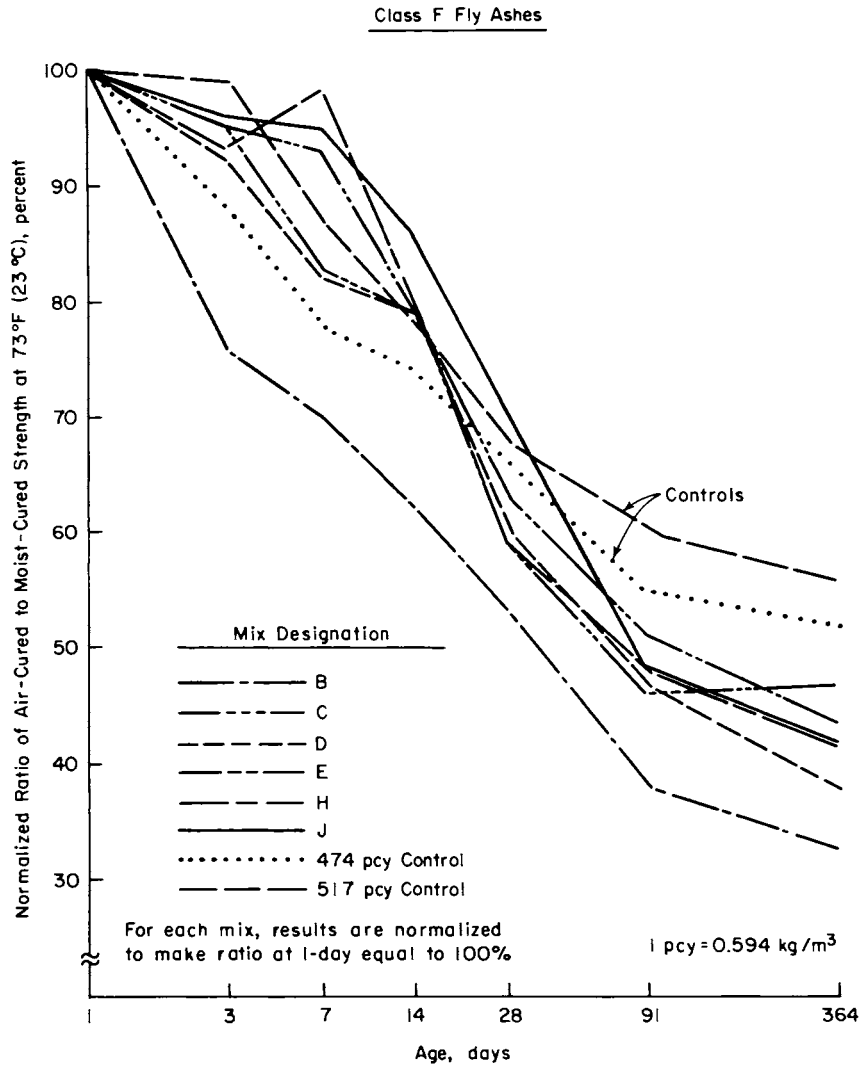


Fig. 8--Effect of moisture availability during curing on compressive strength of concretes with class F fly ashes

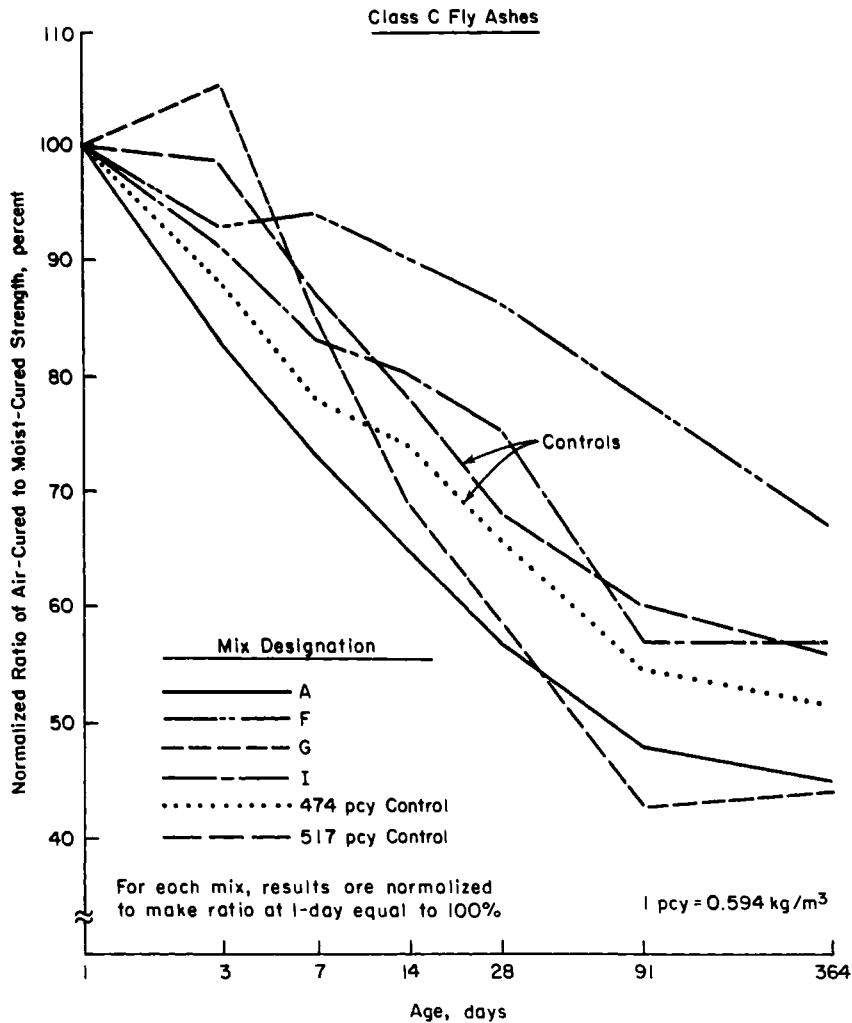


Fig. 9--Effect of moisture availability during curing on compressive strength of concretes with Class C fly ashes

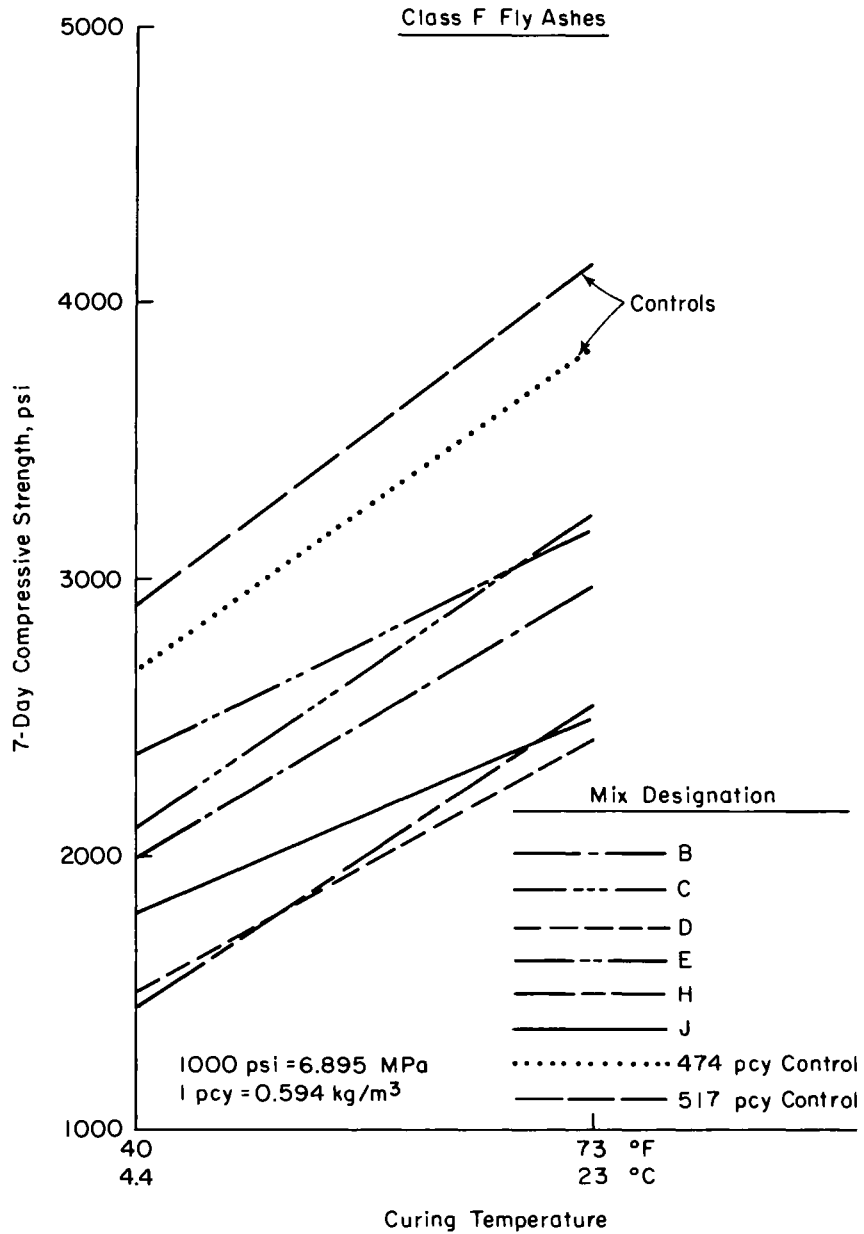


Fig. 10--Effect of curing temperature on 7-day compressive strengths of concretes with Class F fly ashes

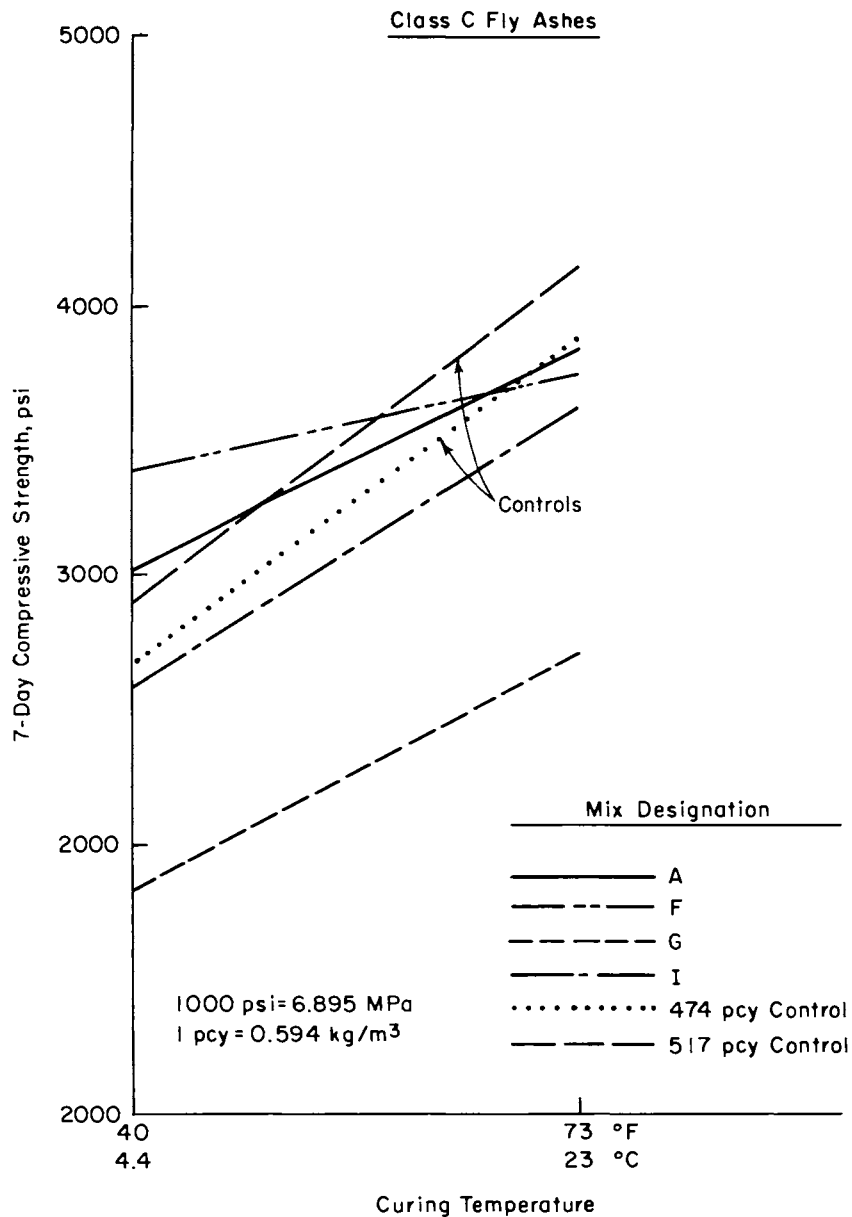


Fig. 11--Effect of curing temperature on 7-day compressive strengths of concretes with Class C fly ashes

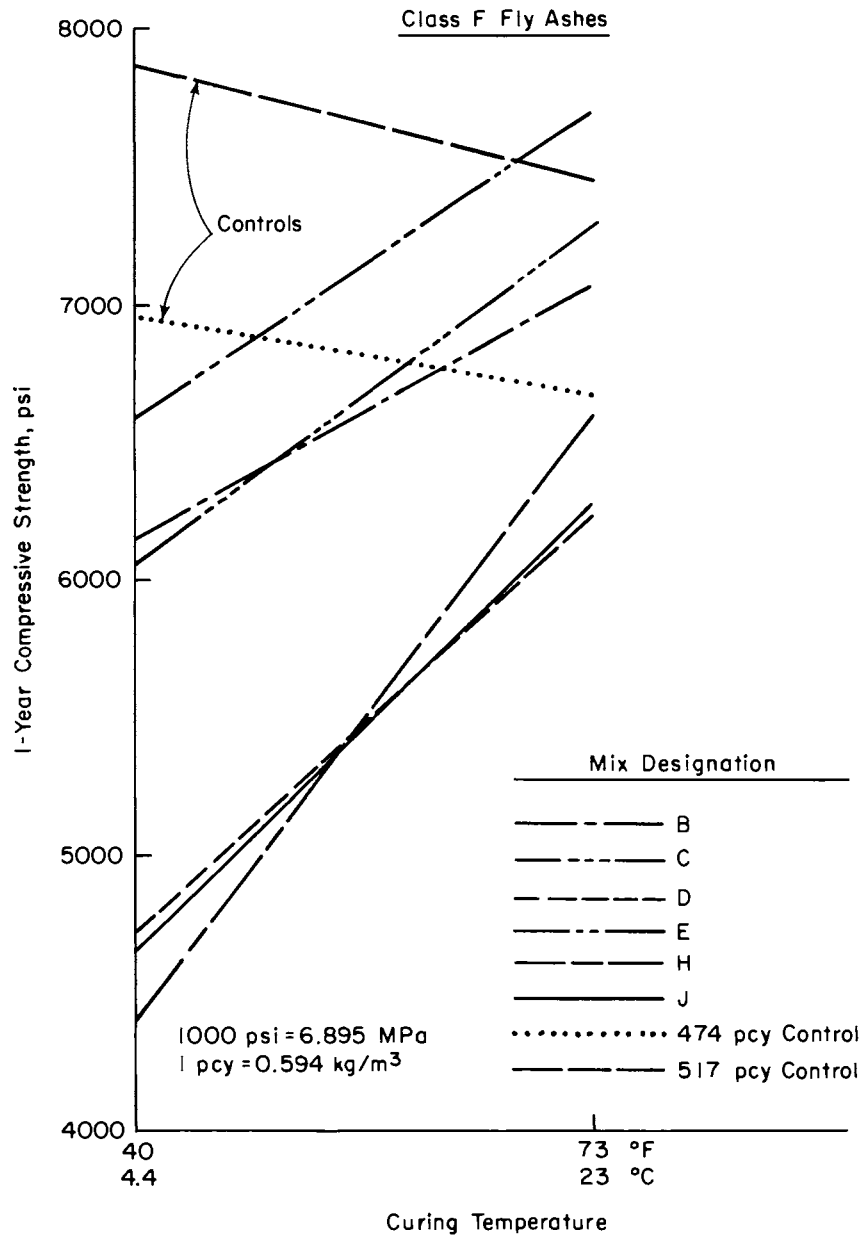


Fig. 12--Effect of curing temperature on 1-year compressive strengths of concretes with Class F fly ashes

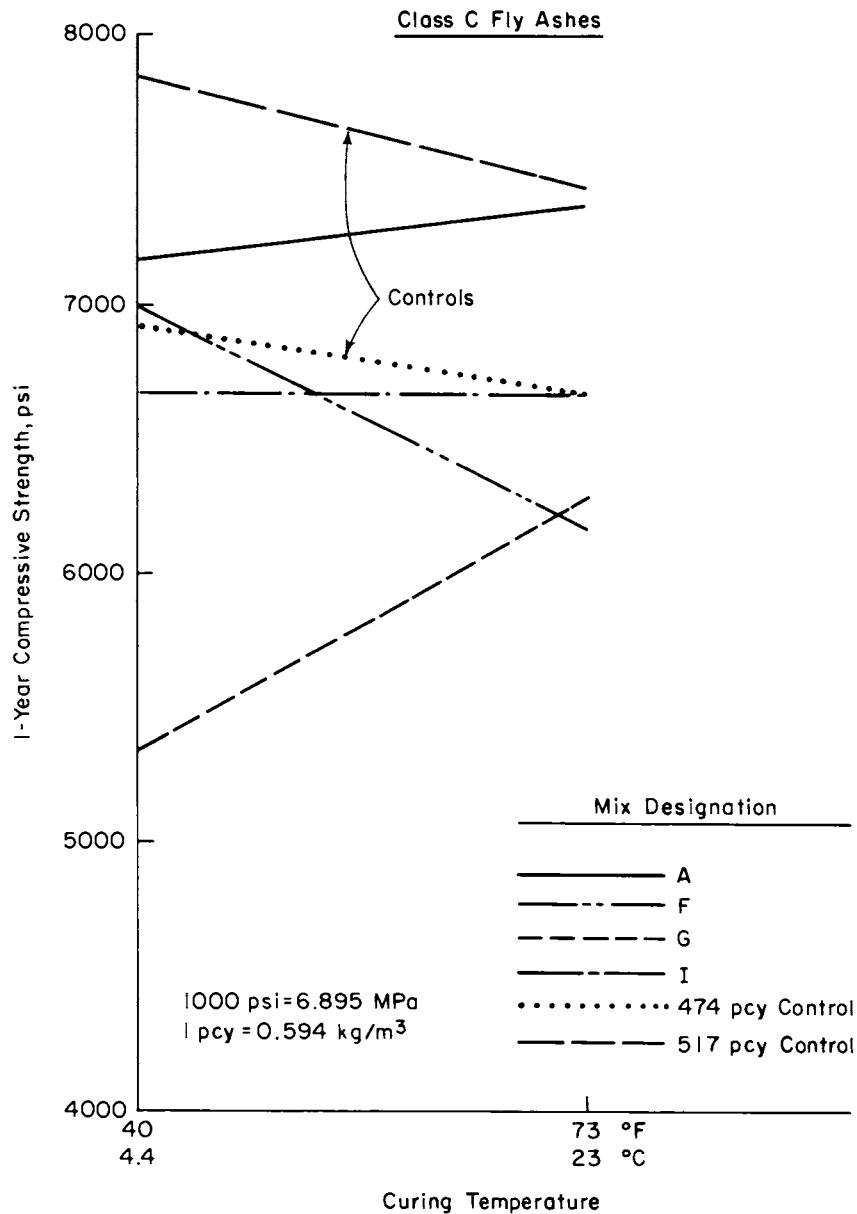


Fig. 13--Effect of curing temperature on 1-year compressive strengths of concretes with Class C fly ashes

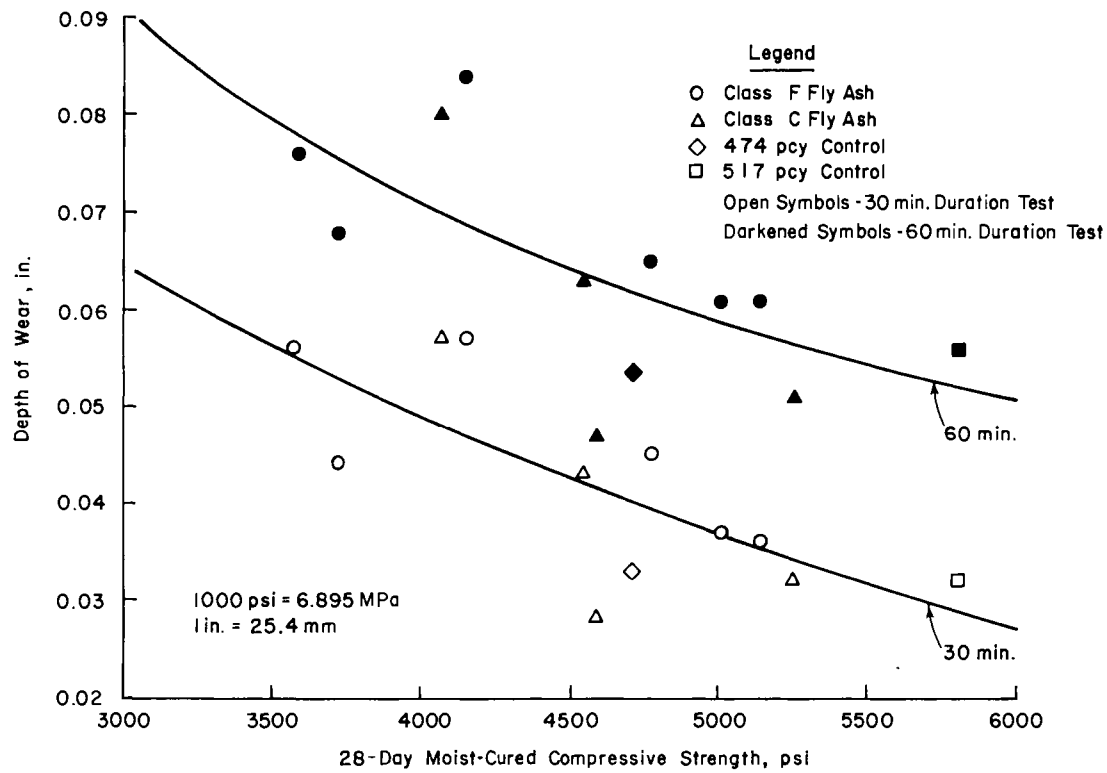


Fig. 14--Comparison of abrasion resistance (depth of wear) and compressive strength of concrete with fly ash