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PRELIMINARY INVESTIGATION OF CEMENTITIOUS MATERIALS FOR OLMSTED LOCK AND DAM

by

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The effect of four fly ashes on strength development and heat-of-hydration characteristics of portland cement-fly ash mixtures was investigated. These comprised three Class F and one Class C fly ash. Mixtures containing Class C fly ash gained strength more rapidly than mixtures containing Class F fly ash. At 2 days, heat of hydration was reduced by all fly ashes, but the Class C fly ash contributed substantial heat at later ages, exceeding pure portland cement in some mixtures. The consequences of using Class C fly ash in mass concrete were investigated. Keywords: Concrete/construction materials; Chemical properties; Strength mechanics; Dams/locks waterways. (MM)

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Preface

The investigation described in this paper was conducted for the US Army Engineer District, Louisville, as part of a preliminary investigation of cementitious materials and concrete design pursuant to construction of Olmsted Lock and Dam. Funding was under Intra-Army Order for Reimbursable Services (DA Form 2544) No. RM-B-89-984, dated 7 September 1989.

The work was performed at the US Army Engineer Waterways Experiment Station (WES) by the Cement and Pozzolan Group (CPG), Engineering Sciences Branch (ESB), Concrete Technology Division (CTD), Structures Laboratory (SL).

The investigation was completed under the general supervision of Messrs. Bryant Mather, Chief, SL; Kenneth L. Saucier, Chief, CTD; and Richard L. Stowe, former Chief, ESB. Mr. Toy S. Poole, CPG, directed the investigation assisted by Mr. Melvin C. Sykes and Ms. Shirley D. Griffin, CPG, who conducted the laboratory work.

Commander and Director of WES during the preparation of this report was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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Conversion Factors, Non-SI To SI (Metric)

Unit Of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
calories per gram	4184	joules per kilogram
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
inches	25.4	millimetres
pounds per square inch	0.006894757	megapascals
pounds (force)	4.448222	newtons

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain Kelvin (K) readings, use: K = (5/9)(F - 32) + 273.15.

PRELIMINARY INVESTIGATION OF CEMENTITIOUS MATERIALS FOR OLMSTED LOCK AND DAM

Introduction

1. The purpose of this work is to compare strength development and heat-of-hydration properties among four fly ashes being considered for use in portland-cement concrete construction of the Olmsted Lock and Dam by the US Army Engineer District, Louisville.

2. One of the candidate materials is a Class C fly ash, as defined by the American Society for Testing and Materials (ASTM) in specification C 618 (ASTM 1989a). There has been abundant experience in the Corps of Engineers' construction in the use of Class F (ASTM C 618) fly ash in mass concrete, but the use of Class C fly ash is relatively new. Class C fly ash is noted for early strength development and high heat of hydration relative to similar mixtures containing Class F fly ash. The heat evolution property of the Class C material poses a potential problem in mass concrete.

3. In this work, strength development and heat of hydration are compared, among mixtures containing the candidate fly ashes, using results of tests of mortar and paste specimens. Such tests do not describe properties that are immediately translatable into concrete strength and heat rise, but these results should be proportional to these concrete properties, making them useful for relative comparisons among materials.

Materials

4. One Type II portland cement, as defined by ASTM C 150-89 (ASTM 1989b) and four fly ashes were used in this work. The fly ashes comprised one Class C (C1) and three Class F (F1, F2, F3) pozzolans. These are materials currently marketed in the vicinity of the proposed construction. General physical and chemical descriptions of these materials are summarized in Tables 1 through 5.

5. Sand was from Ottawa Silica Company, Ottawa, IL. Deionized water was used throughout.

Methods

6. Mortars were prepared and cubes were fabricated according to ASTM C 311-88 (ASTM 1989c), paragraphs 23 through 25. This procedure calls for adjusting the water content of mortars to a specified flow. Because of this constant-flow restriction, mortars could have different water-cement ratios (w/c) if there is much variation in the water requirement among the cementitious materials. The w/c of mortars made with three of the fly ashes in this study (Cl, F2, and F3) was held to a constant value (0.46), and flows still fell within the specified limits. Fly ash F1 had a higher water requirement than the others, consequently, a w/c of 0.49 was required to meet the flow specification of the method. The effect of change in the w/c on strength was investigated by repeating two of the mixtures at slightly modified w/c. These were: fly ash Cl at 30 percent replacement (w/c = 0.46 and 0.41) and fly ash F1 at 30 percent replacement (w/c = 0.49 and 0.54).

7. Cubes were demolded at 24 hr and cured in saturated lime water at $23^{\circ}C$* until tested. Compressive strengths were measured at 2, 7, 28, and 90 days. Each reported strength result represents the mean strength of three cubes. A Tinius-Olsen Super L (60,000-lb capacity) testing machine was used for strength determinations.

8. Fly ash Cl was proportioned at 25, 30, 35, and 45 percent replacement of portland cement, by solid volume. Fly ashes F1, F2, and F3 were proportioned at 30 percent replacement. These replacement levels were requested by the sponsor.

9. Heat of hydration was determined according to ASTM C 186-86 (ASTM 1989d), with duplicate determinations made at 2, 7, and 28 days. Fly ash Cl mixtures were proportioned at 25, 35, and 45 percent replacement. The Class F fly ash mixtures were proportioned at 30 percent replacement.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

Results

Strength

10. Complete data for 2-, 7-, 28-, and 90-day strengths are summarized in Table 6. Strength development patterns were similar among Class F fly ash mixtures. These differed, however, from the Class C mixtures, and all fly ash mixtures differed from the strength gain pattern of the control mixture. In general, Class F mixtures developed strength much more slowly than the Class C or the control mixtures. Class C mixtures were slower in strength gain than control at very early ages, but faster than control at later ages. Details are described in the following paragraphs.

11. Figure 1 illustrates strength versus time for the pure portland cement (control) and the four fly ash mixtures at 30 percent replacement. At 2 and 7 days, all mixtures containing fly ash have developed similar compressive strengths to within at least a few hundred pounds per square inch of each other, and all are substantially lower in strength than the control. The 28-day data show the Class C mixture to be gaining strength faster than the Class F mixtures, all of which showed about the same strength-gain pattern. The slightly lower strength gain of ash F1 was probably due to the higher w/c necessitated by its higher water requirement. After 28 days, all of the fly ash mixtures appeared to be gaining strength at a relatively constant rate, so that the relative strength advantage expressed by the Class C mixture at early ages continues to persist at 90 days. The rate-of-strength gain between 28 and 90 days of all of the fly ash mixtures is greater than the portland-cement mixture, suggesting that the fly ash mixtures will probably surpass the latter at some point beyond 90 days.

12. Expressing strength as a percentage of the control allows a more detailed look at relative strength-contribution behavior among the fly ashes at early ages (Figure 2). As expected, early-age strengths are considerably less than 100 percent of control. It is known that fly ash contributes little if any strength at very early ages, so that the relative depression in strength is at least partially a reflection of the dilution of portland cement by fly ash. However, there is some evidence that fly ash sometimes affects portland-cement hydration, so that observed strengths of cement-fly ash mortars may not be the simple sum of the individual cement and pozzolan

properties (Dnir et al. 1988).

13. From the earliest age, the mortar mixture containing Class C fly ash steadily gained strength with respect to the control, while the three mortar mixtures containing Class F fly ash tended to exhibit a dormant period from 2 to 7 days (Figure 2). The Class F fly ashes appear to be inhibiting the strength development of the portland-cement fraction of the paste at early ages. Mixtures containing fly ashes F1 and F3 actually declined in strength relative to the control. This same phenomenon has been observed in another comparison involving Class F fly ash (Poole et al in preparation). The 28-day strengths then showed an increase relative to the control, but at a slower rate than the mixture containing C1. After 28 days, strength-gain rate is relatively constant among all of the fly ashes, as discussed in paragraphs 10 through 12.

14. Figure 3 illustrates the effect of changing replacement levels on the strength development of the Class C fly ash mixtures. Note that at 25 percent and 35 percent replacement, 90-day strengths are greater than the control mixture, while at 45 percent replacement, strength still lags the control mixture. The slope of the strength-gain curve for the 45 percent mixture between 28 and 90 days is greater than the control, suggesting that higher strength will be attained at some point beyond 90 days. However, past work has shown that this does not always occur, particularly for lean concretes at high water-cement ratios (Mather 1965).

15. Figure 4 is a representation of the same data illustrated in Figure 3, except that percent replacement is shown as the independent variable, with a curve for each test age. Strength appears to decrease in linear proportion to the fly ash replacement level at both 2 and 7 days. This simple relationship does not appear to continue to hold at 28 days. By this time, the Class C fly ash is apparently reacting with the portland cement, so that strength is not a simple function of fraction of cement. At 90 days, there appears to be an optimum replacement of about 25 percent (optimum being taken as the replacement level that gives the highest strength).

16. A decrease in water-cement ratio (0.46 to 0.41) in the 30 percent Class C mixture caused strength to increase, as would be expected. The enhanced-strength effect tended to diminish with time. The increase was 24.3

percent (relative to the strength at w/c = 0.46) at 2 days, 17.5 percent at 7 days, 12.6 percent at 28 days, and 8.6 percent at 90 days. The 30 percent Class F mixture showed an abnormal effect for a similar change in w/c. The strengths at 2 and 7 days were little affected, while the strengths at 28 and 90 days were actually lower for the lower w/c mixture. These mixtures were not replicated, so no conclusions should be based on this phenomenon.

Heat of Hydration

17. Complete data for 2-, 7-, and 28-day heats of hydration are summarized in Table 7. Heat-evolution patterns among types of materials are similar to the patterns observed for strength. The Class F mixtures, the Class C mixtures, and the control all showed different patterns of heat evolution. The effect of Class F fly ash on all mixtures was to reduce the heat of hydration, at least through 28 days. Heat of hydration at very late ages would probably be similar or greater than control. The Class C mixtures tended to reduce early heat, but 7- and 28-day heats were often equal to or greater than the control. These patterns are detailed in the following paragraphs.

18. Figure 5 represents heat evolution versus time for the control and the four fly ash mixtures at thirty percent replacement. Figure 6 represents the same data expressed as percent of control. Heat of hydration was not actually measured on the 30 percent C1 mixtures, but values were calculated by interpolation between the results from 25 and 35 percent mixtures.

19. Two-day heat of hydration varies little among fly ashes at the 30 percent replacement level. Each one gives a reduction in heat relative to the pure portland cement that is about in proportion to the amount of cement replaced. By 7 days, the Class C fly ash and the pure portland-cement heats of hydration were about the same, within expected laboratory error. The 7-day heats of hydration for Class F mixtures continued to be reduced relative to the pure portland cement. This reduction persisted at about the same level at 28 days, while the Class C mixture evolved more heat than the control.

20. Figure 7 illustrates the effect of changing replacement levels on heat evolution of Class C fly ash mixtures. More heat was evolved by the low-replacement mixtures than by the control.

21. In a replot of the data presented in Figure 7, Figure 8 illustrates

the heat of hydration obtained with increasing percentages of the Class C fly ash. At 2 days, there was an approximately linear decrease with increasing replacement level. At 7 and 28 days, the linearity of the relationship disappeared, indicating that the fly ash was beginning to make a contribution to the total heat at the lower replacement levels. Again, notice that the heat evolved by the 25 percent mixture exceeded the control level at both 7 and 28 days.

Discussion

22. Class C fly ashes are reputed to contribute more to early strength gain than equivalent replacements of Class F fly ashes. Strength-gain behavior of these materials generally conforms to this pattern, except that this Class C fly ash did not exhibit quite as high a strength-gain rate as have some Class C fly ashes evaluated in past work. For example, two Class C fly ashes were evaluated for use at Red River Lock and Dam 3 (Poole et al 1990). Mixtures containing these fly ashes at 30 percent replacement for portland cement exhibited about 70 percent of control strength at 7 days compared with the 60 percent of control exhibited by the Class C ash in this study. At 28 days, the Red River ashes had gained >90 percent of control, while the ash used in this study had gained to 82 percent of control. This difference may not be totally due to differences among fly ash sources since different portland cements were used. It is known that variations in cement properties do affect strength gain in cement-fly ash mixtures.

23. A concern associated with the use of Class C fly ash in mass concrete is that excessive heat evolution could cause thermal stress problems. In this study, the Class C fly ash showed a reduction in heat of hydration comparable to Class F fly ashes at 2 days, but evolved about as much heat as pure portland cement at 7 days, and more heat than portland cement at 28 days for some replacement levels. This behavior is consistent with other Class C fly ashes that have been examined.

24. That early-age strength and heat of hydration varies linearly with percent replacement is quite convenient. This allows a relatively simple prediction of changes in early strength and heat of hydration for a given

change in replacement level.

Recommendations

25. The decision concerning whether to use Class C fly ash in a mass concrete application in lieu of the more traditional Class F fly ash when both are nearly equally economically available probably depends on the reduction in heat of hydration of the portland cement that is needed and on the importance of the timing of heat evolution. For example, if the portland cement is inherently a low heat-of-hydration material, then Class C fly ash probably would not significantly worsen the heat-of-hydration picture. If, on the other hand, the portland cement evolves so much heat that a pozzolan is needed to reduce this to acceptable levels, then it is questionable whether a Class C fly ash is suitable. This work has shown that no reduction in heat of hydration at 7 days is obtained at conventional replacement levels of 25 to 35 percent. However, 7-day heat of hydration may not be the critical criterion. Results of thermal stress analysis of other structures have indicated that heat of hydration at earlier ages is more important than heat evolved at later ages. If this is substantiated in the thermal analysis of this structure, then use of Class C fly ash may be acceptable. Another alternative would be to use the Class C fly ash at higher replacement levels, e.g. 45 percent, where heat evolution is still reduced relative to control, even at 28 days. However, this approach would result in a considerable sacrifice in strength unless other adjustments were made to the mixture.

26. If thermal considerations indicate use of Class C fly ash to be acceptable, then strength problems that sometimes occur during mass concrete construction could possibly be avoided. These problems occur as a result of the relatively low, and sometimes variable, strength development typical of some sources of Type II cement that has been modified to meet the 70-cal/g optional limit in ASTM C 150-89 (1989b). This sometimes variable property of cements is a result of the fact that most commercially marketed Type II cements will not meet the 70-cal/g limit. The reformulation necessary to reduce the heat of hydration necessarily also reduces the strength. The resultant cement is now in effect a specialty product, which often means that

quality control is not as good as with normal commercial cements. As a result, strength variation often becomes a problem. A strength decline of 30 percent or more has been observed on sequential lots of cement. Low-strength problems in the cement may become amplified when Class F fly ash is used because of the nonreactive nature of such fly ash at early ages, although this phenomenon has not been substantiated.

References

American Society for Testing and Materials. 1989. 1989 Annual Book of ASTM Standards, Philadelphia, PA.

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b. Designation C 150-89. "Standard Specification for Portland Cement."

c. Designation C 311-88. "Standard Test Method for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete."

d. Designation C 186-86. "Standard Test Method for Heat of Hydration of Hydraulic Cement."

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Table 1

Chemical and Properties of Portland Cement

Company: Lone Star Industries
Location: Cape Girardeau, MO
Specification: ASTM C 150,II,LA,FS,HH
Project: Olmsted Dam

Test Report No.: ORL-204-89
Program: Single Sample

Date Sampled: 15 Sep 89

10/30/89 Tests complete, material X does, ____ does not meet specification

Chemical Analysis	Result	Spec Limits Type II
SiO_2, %	23.6	20.0 min
Al_2O_3, %	2.7	6.0 max
Fe_2O_3, %	3.5	6.0 max
CaO, %	61.8	*
MgO, %	3.4	6.0 max
SO_3, %	2.5	3.0 max
Loss on ignition, %	0.9	3.0 max
Insoluble residue, %	0.24	0.75 max
Na_2O, %	0.07	*
K_2O, %	0.52	*
Alkalies-total as Na_2O,%	0.41	0.60 max
TiO_2, %	0.19	*
P_2O_5, %	0.07	*
C_3A, %	2	8 max
C_3S, %	40	*
C_2S, %	42	*
C_4AF, %	11	*

Physical Tests	Result	Spec Limits Type II
Heat of hydration, 7-day, cal/g	59	70 max
Surface area, m^2/kg (air permeability)	304	280 min
Autoclave expansion, %	0.06	0.80 max
Initial set, min. (Gillmore)	170	60 min
Final set, min. (Gillmore)	285	600 max
Air content, %	10	12 max
Compressive strength, 3-day, psi	1,700	1,000 min
Compressive strength, 7-day, psi	2,205	1,700 min
False set (final penetration), %	94	50 min

* ASTM C 150 contains no specification requirements for these properties.

Table 2

Chemical and Physical Properties of Fly Ash C1

Company: Indiana Michigan Power
Location: Rockport, Indiana
Specification: ASTM C 618, Class C
Project: Olmsted Dam

Test Report No.: ORL-231C-89
Program: Single Sample

Date Sampled: unknown

12/12/89 Tests complete, material X does, ____ does not meet specification

Chemical Analysis	Result	Spec Limits Class C
SiO_2, %	43.2	*
Al_2O_3, %	18.2	*
Fe_2O_3, %	7.3	*
Sum, %	68.7	50.0 min
MgO, %	4.4	*
SO_3, %	1.5	5.0 max
Moisture content, %	0.0	3.0 max
Loss on ignition, %	0.4	6.0 max
Available alkalies (28-day), %	0.8	1.5 max

Physical Tests	Result	Spec Limits Class C
Fineness (45 micrometre), % retained	25	34 max
Water requirement, %	91	105 max
Density, Mg/m^3	2.65	*
Autoclave expansion, %	-0.07	0.80 max
Pozzolanic activity w/cement (28-day), %	94	75 min

Laboratory cement used: Lone Star Industries, Cape Girardeau, MO
Laboratory lime used: Chemstone

* ASTM C 618 contains no specification requirements for these properties.

Table 3

Chemical and Physical Properties of Fly Ash F1

Company: Louisville Millcreek Power
Location: Louisville, Kentucky
Specification: ASTM C 618, Class F
Project: Olmsted Dam

Test Report No.: ORL-207F-89
Program: Single Sample
CTD No.:
Date Sampled: unknown

12/12/89 Tests complete, material X does, ____ does not meet specification

Chemical Analysis	Result	Spec Limits Class F
SiO_2, %	48.5	*
Al_2O_3, %	19.8	*
Fe_2O_3, %	17.6	*
Sum, %	85.9	70.0 min
MgO, %	0.8	*
SO_3, %	1.1	5.0 max
Moisture content, %	0.2	3.0 max
Loss on ignition, %	3.2	6.0 max
Available alkalies (28-day), %	1.1	1.5 max

Physical Tests	Result	Spec Limits Class F
Fineness (45-micrometre), % retained	24	34 max
Water requirement, %	103	105 max
Density, Mg/m^3	2.38	*
Autoclave expansion, %	0.02	0.80 max
Pozzolanic activity w/lime, psi	1,020	900 min
Pozzolanic activity w/cement (28-day), %	119	75 min

Laboratory cement used: Lone Star Industries, Cape Girardeau, MO
Laboratory lime used: Chemstone

* ASTM C 618 contains no specification requirements for these properties.

Table 4

Chemical and Physical Properties of Fly Ash F2

Company: American Fly Ash
Location: Baldwin, Illinois
Specification: ASTM C 618, Class F
Project: Olmsted Dam

Test Report No.: ORL-232F-89
Program: Single Sample
CTD No.:
Date Sampled: unknown

12/12/89 Tests complete, material X does, ____ does not meet specification

Chemical Analysis	Result	Spec Limits Class F
SiO_2, %	55.7	*
Al_2O_3, %	18.8	*
Fe_2O_3, %	16.1	*
Sum, %	90.6	70.0 min
MgO, %	1.0	*
SO_3, %	1.1	5.0 max
Moisture content, %	0.1	3.0 max
Loss on ignition, %	1.2	6.0 max
Available alkalies (28-day), %	0.8	1.5 max

Physical Tests	Result	Spec Limits Class F
Fineness (45-micrometre), % retained	22	34 max
Water requirement, %	96	105 max
Density, Mg/m^3	2.35	*
Autoclave expansion, %	0.02	0.80 max
Pozzolanic activity w/lime, psi	1,110	900 min
Pozzolanic activity w/cement (28-day), %	106	75 min

Laboratory cement used: Lone Star Industries, Cape Girardeau, MO
Laboratory lime used: Chemstone

* ASTM C 618 contains no specification requirements for these properties.

Table 5

Chemical and Physical Properties of Fly Ash F3

Company: American Fly Ash
Location: North Bend, Ohio
Specification: ASTM C 618, Class F
Project: Olmsted Dam

Test Report No.: ORL-233F-89
Program: Single Sample
CTD No.:
Date Sampled: 11 October 1989

12/12/89 Tests complete, material X does, ____does not meet specification

Chemical Analysis	Result	Spec Limits Class F
SiO_2, %	50.5	*
Al_2O_3, %	24.4	*
Fe_2O_3, %	14.8	*
Sum %	90.0	70.0 min
MgO, %	0.9	*
SO_3, %	0.4	5.0 max
Moisture content, %	0.1	3.0 max
Loss on ignition, %	1.1	6.0 max
Available alkalies (28-day), %	0.7	1.5 max

Physical Tests	Result	Spec Limits Class F
Fineness (45-micrometre), % retained	21	34 max
Water requirement, %	92	105 max
Density, Mg/m^3	2.45	*
Autoclave expansion, %	-0.09	0.80 max
Pozzolanic activity w/lime, psi	920	900 min
Pozzolanic activity w/cement (28-day), %	111	75 min

Laboratory cement used: Lone Star Industries, Cape Girardeau, MO
Laboratory lime used: Chemstone

* ASTM C 618 contains no specification requirements for these properties.

Table 6

Strength Development for Control (Cement) and Four Fly Ashes Using 2- by 2-in. Cubes

Fly Ash	Replacement %	Age	PSI	Control %	W/C
None	0	2	1,595	N/A	0.46
		7	2,690	N/A	0.46
		28	4,990	N/A	0.46
		90	5,915	N/A	0.46
C1	25	2	990	62	0.46
		7	1,737	65	0.46
		28	4,444	89	0.46
		90	6,595	112	0.46
C1	30	2	895	56	0.46
		7	1,644	61	0.46
		28	4,110	82	0.46
		90	6,130	104	0.46
C1	30	2	1,113	70	0.41
		7	1,932	72	0.41
		28	4,628	93	0.41
		90	6,660	113	0.41
C1	35	2	797	50	0.46
		7	1,441	54	0.46
		28	3,418	68	0.46
		90	6,300	107	0 46
C1	45	2	545	34	0.46
		7	1,080	40	0.46
		28	2,132	43	0.46
		90	5,355	91	0.46
F1	30	2	875	55	0.49
		7	1,434	53	0.49
		28	3,260	65	0.49
		90	5,420	92	0.49
F1	30	2	877	55	0.54
		7	1,336	50	0.54
		28	3,780	76	0.54
		90	6,040	102	0.54
F2	30	2	1,015	64	0.46
		7	1,730	64	0.46
		28	3,583	72	0.46
		90	5,560	96	0.46
F3	30	2	998	63	0.46
		7	1,511	56	0.46
		28	3,525	71	0.46
		90	5,760	97	0.46

Table 7

Heat of Hydration for Control (Cement) and Mixtures Containing Four Fly Ashes

Fly Ash	Replacement %	Age	Heat of Hydration cal/g	Control %
None	0	2	48.9	N/A
		7	59.2	N/A
		28	71.0	N/A
C1	25	2	45.3	93
		7	62.1	105
		28	80.4	113
C1	30*	2	41.9	86
		7	59.0	100
		28	77.3	109
C1	35	2	38.4	78
		7	55.8	94
		28	74.1	104
C1	45	2	36.5	75
		7	49.5	84
		28	67.9	96
F1	30	2	42.4	87
		7	50.0	84
		28	61.1	86
F2	30	2	40.1	82
		7	49.2	83
		28	59.5	84
F3	30	2	39.8	81
		7	48.8	82
		28	60.9	86

* Calculated by interpolation between results obtained at 25 percent and 35 percent replacement levels.

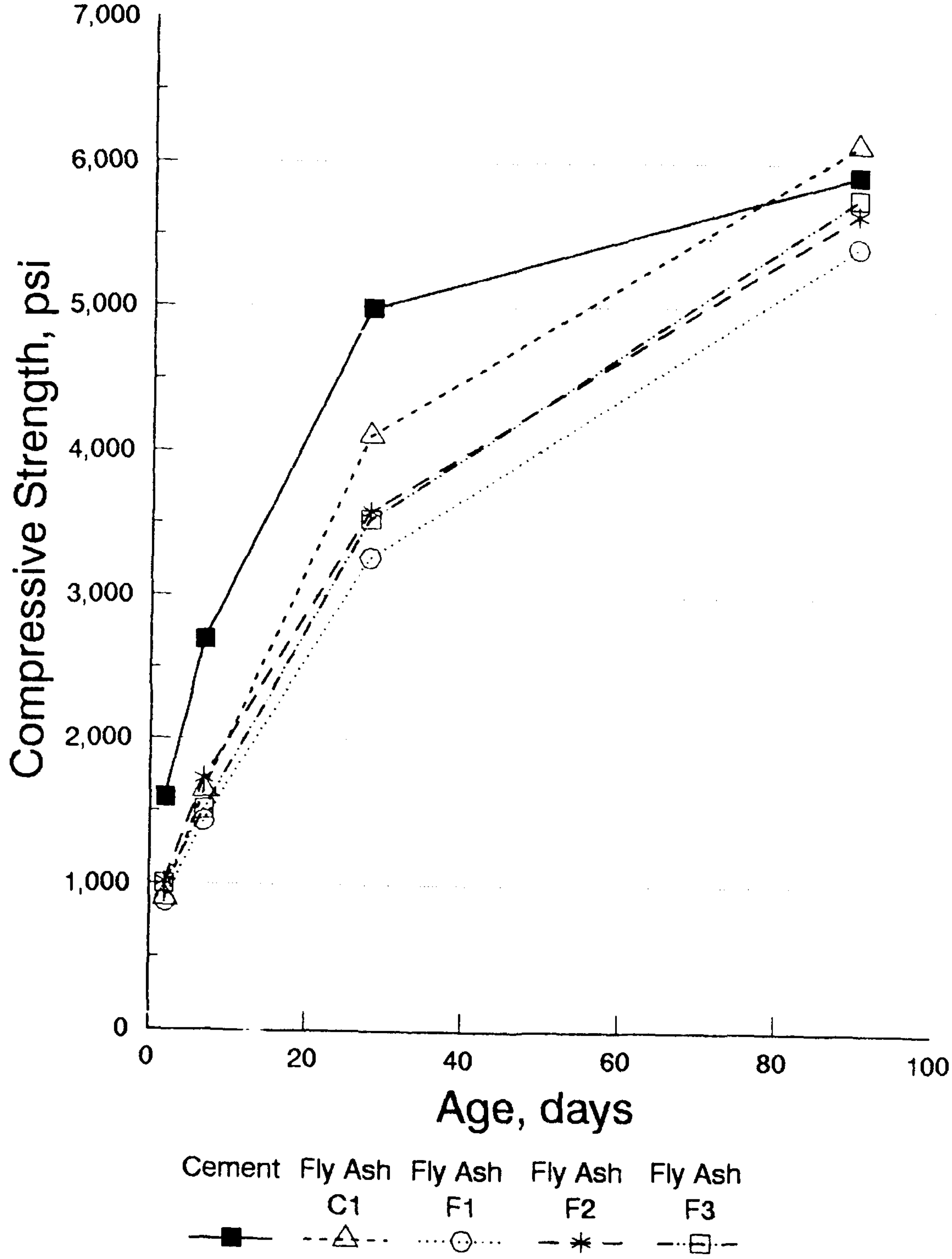

Figure 1. Compressive strength of 2- by 2-in. mortar cubes versus age for cement alone and for four cement-fly ash blends at 30 percent (by volume)

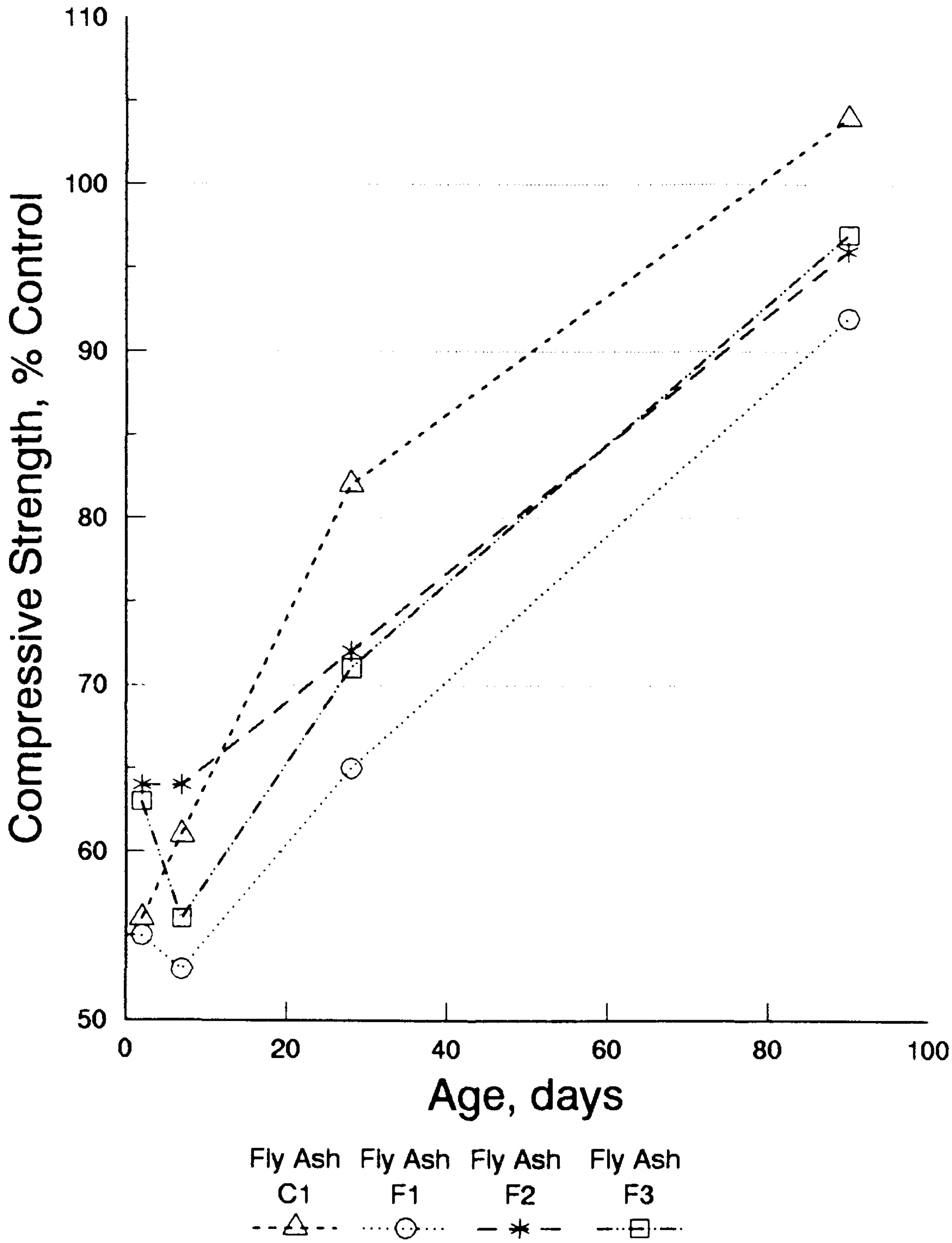

Figure 2. Compressive strength of 2- by 2-in. mortar cubes, expressed as percent of control, versus age for four cement-fly ash blends at 30 percent

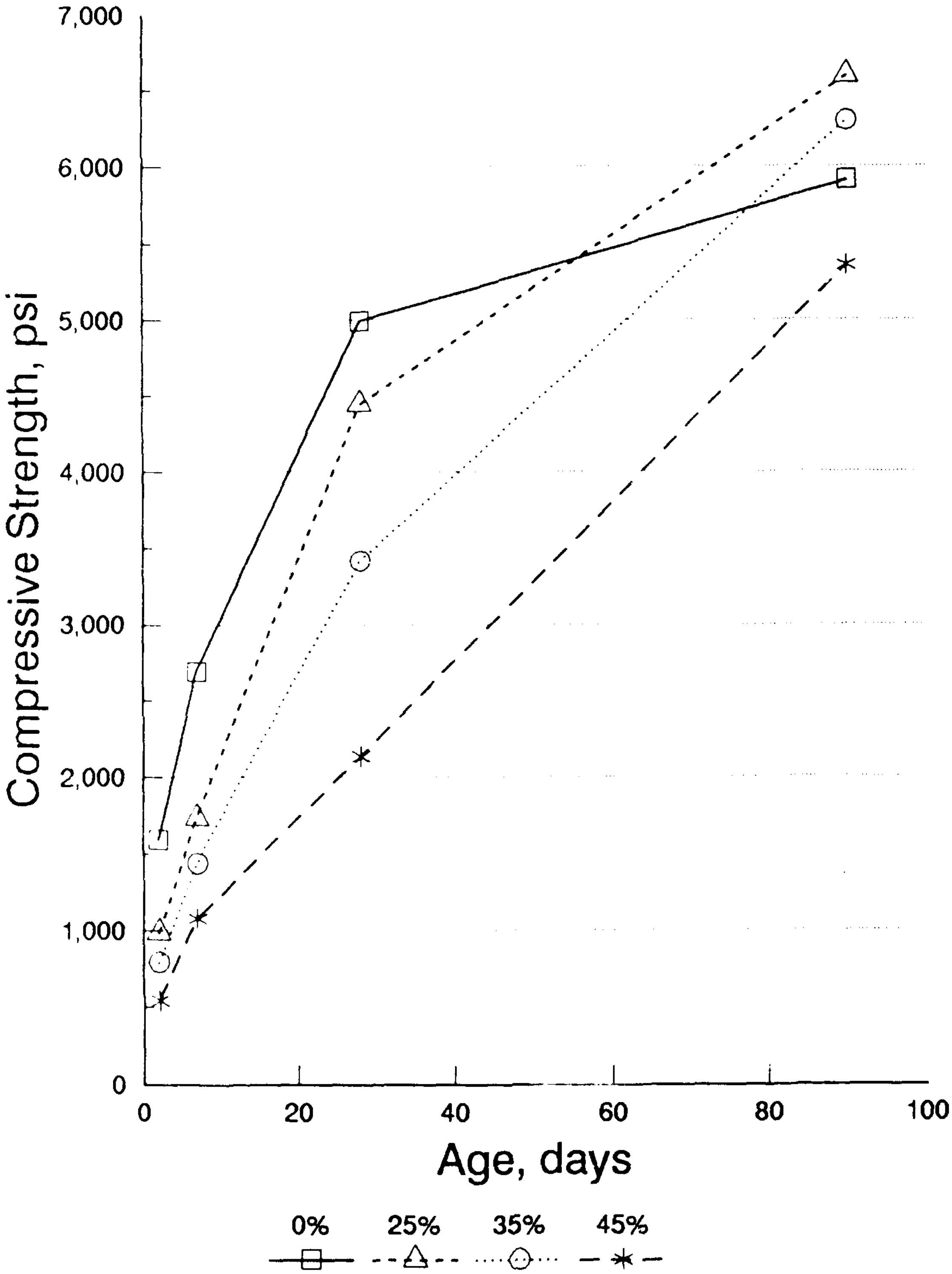

Figure 3. Compressive strength of 2- by 2-in. mortar cubes versus age using the Class C fly ash (C1) at five replacement levels

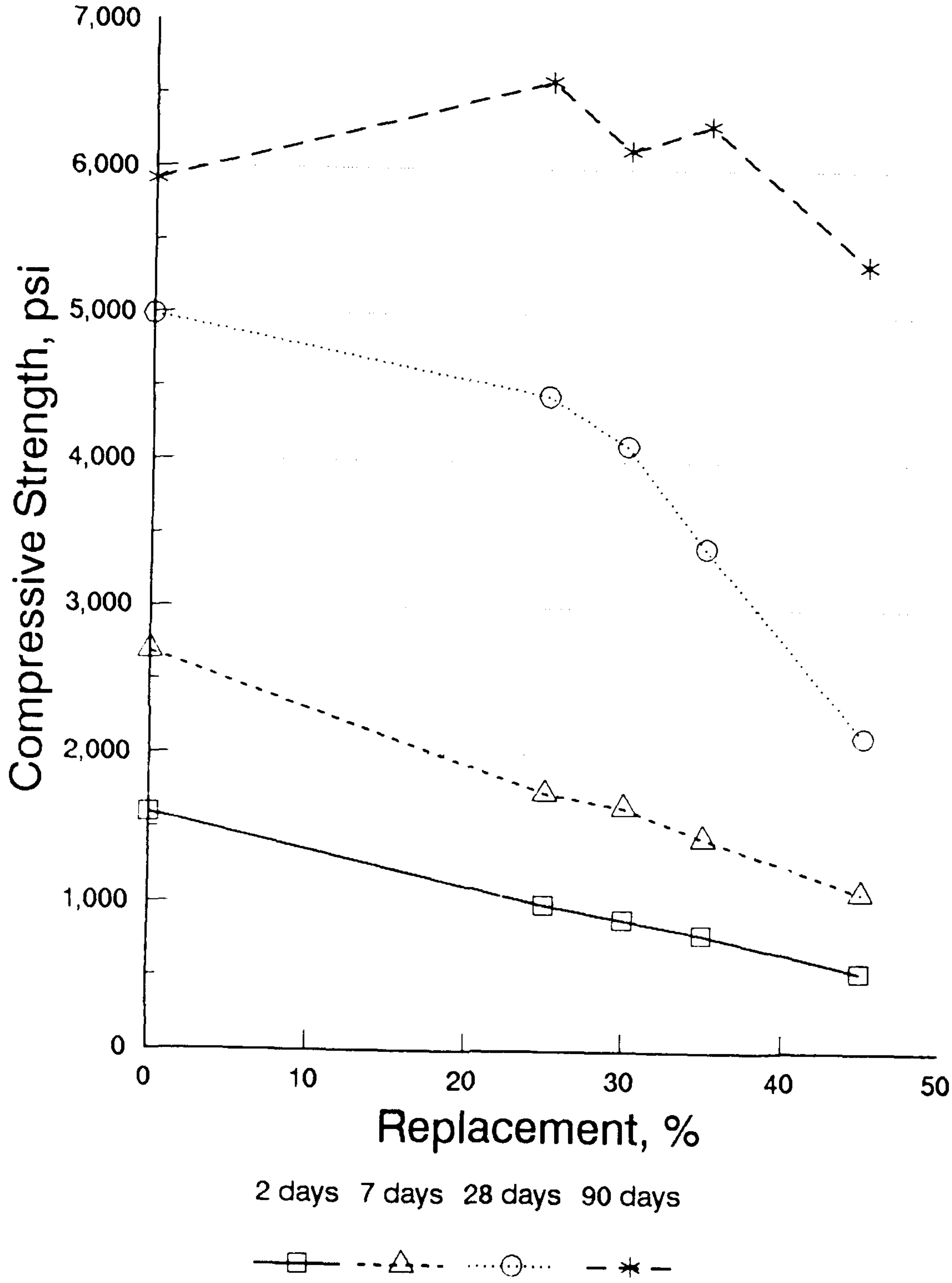

Figure 4. Compressive strength of 2- by 2-in. mortar cubes versus percent replacement for the Class C fly ash (C1) at four ages

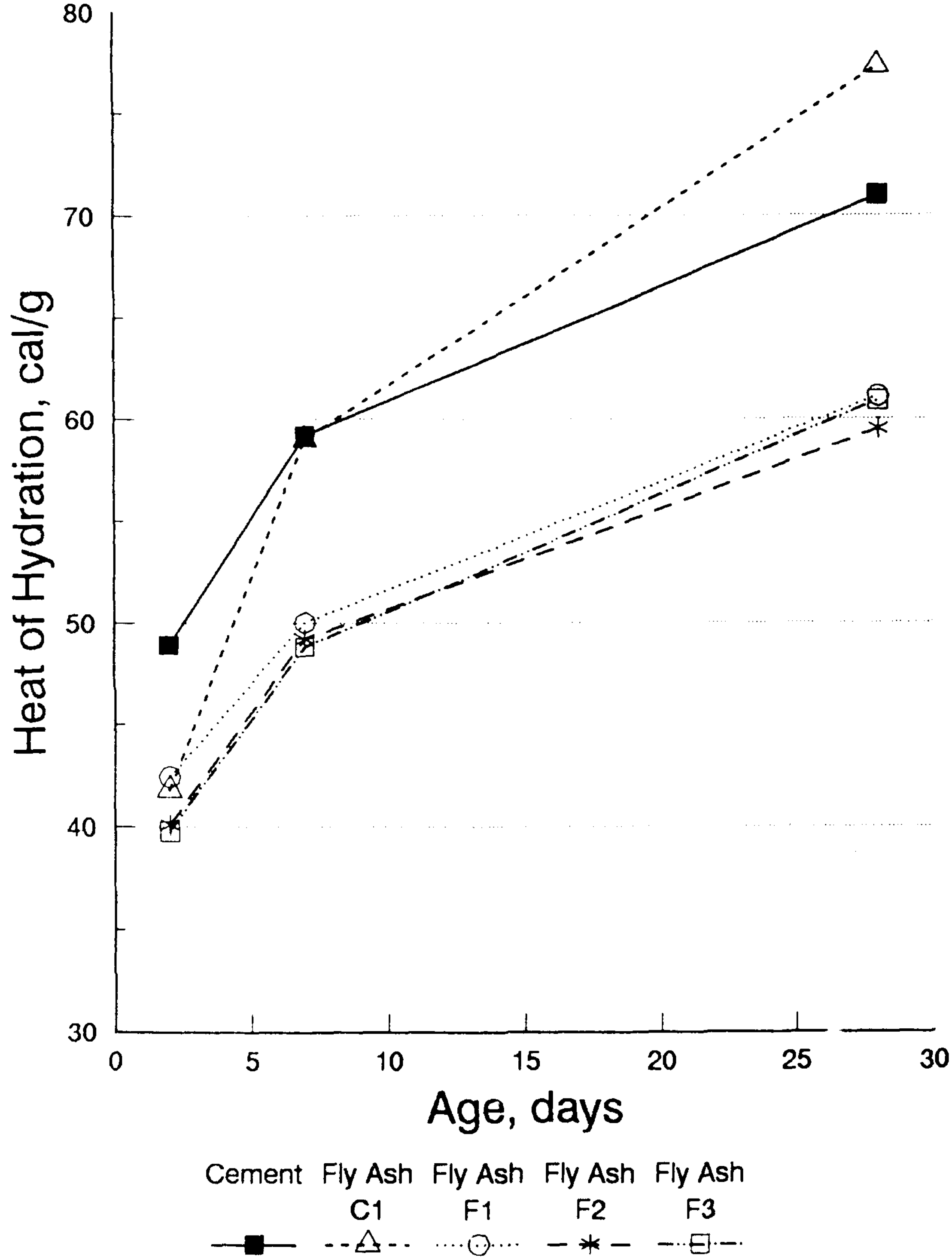

Figure 5. Heat of hydration versus age for cement alone and four cement-fly ash blends at 30 percent (by volume)

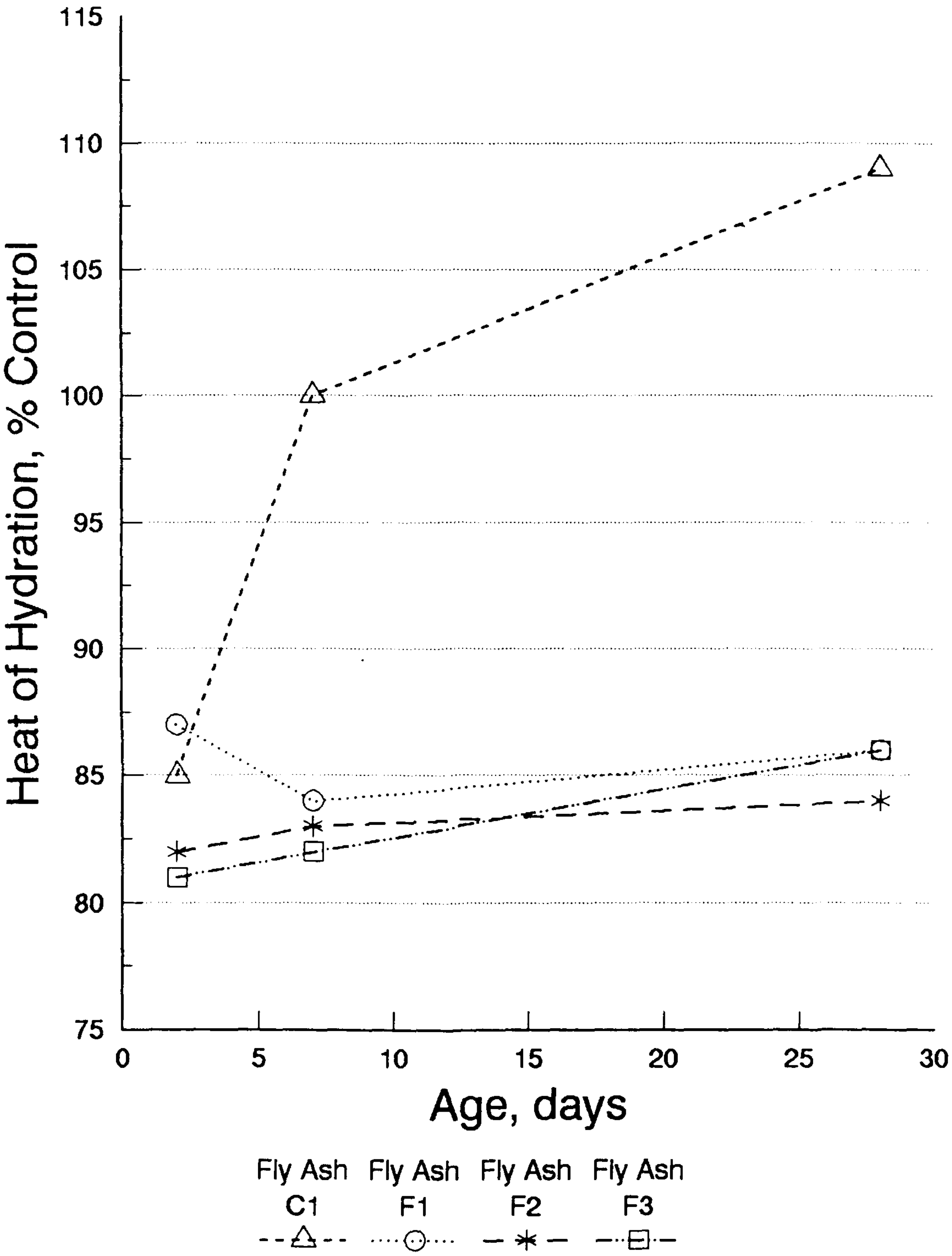

Figure 6. Heat of hydration, expressed as percent of control, versus age for four cement-fly ash blends at 30 percent

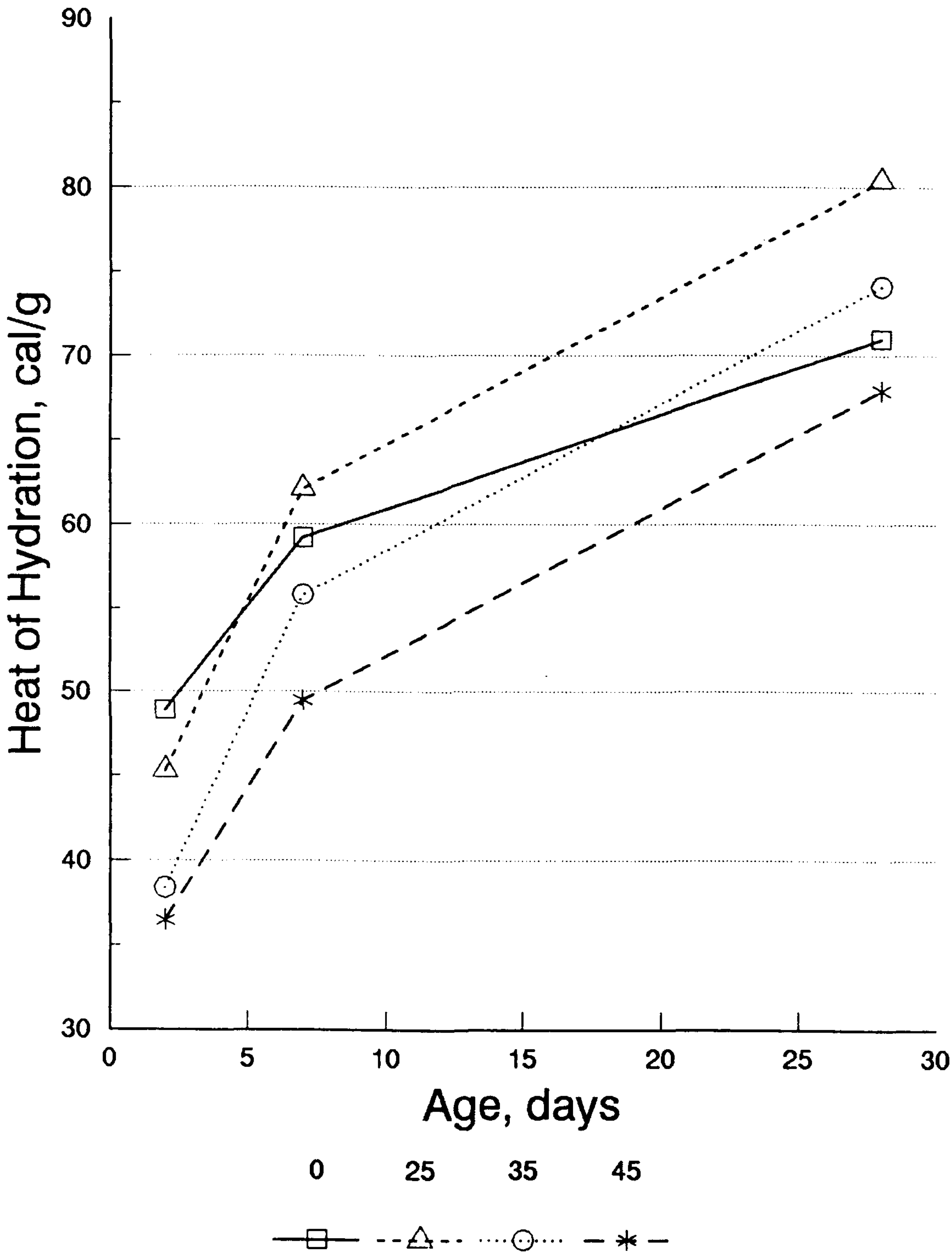

Figure 7. Heat of hydration versus age using the Class C fly ash (C1) at four replacement levels

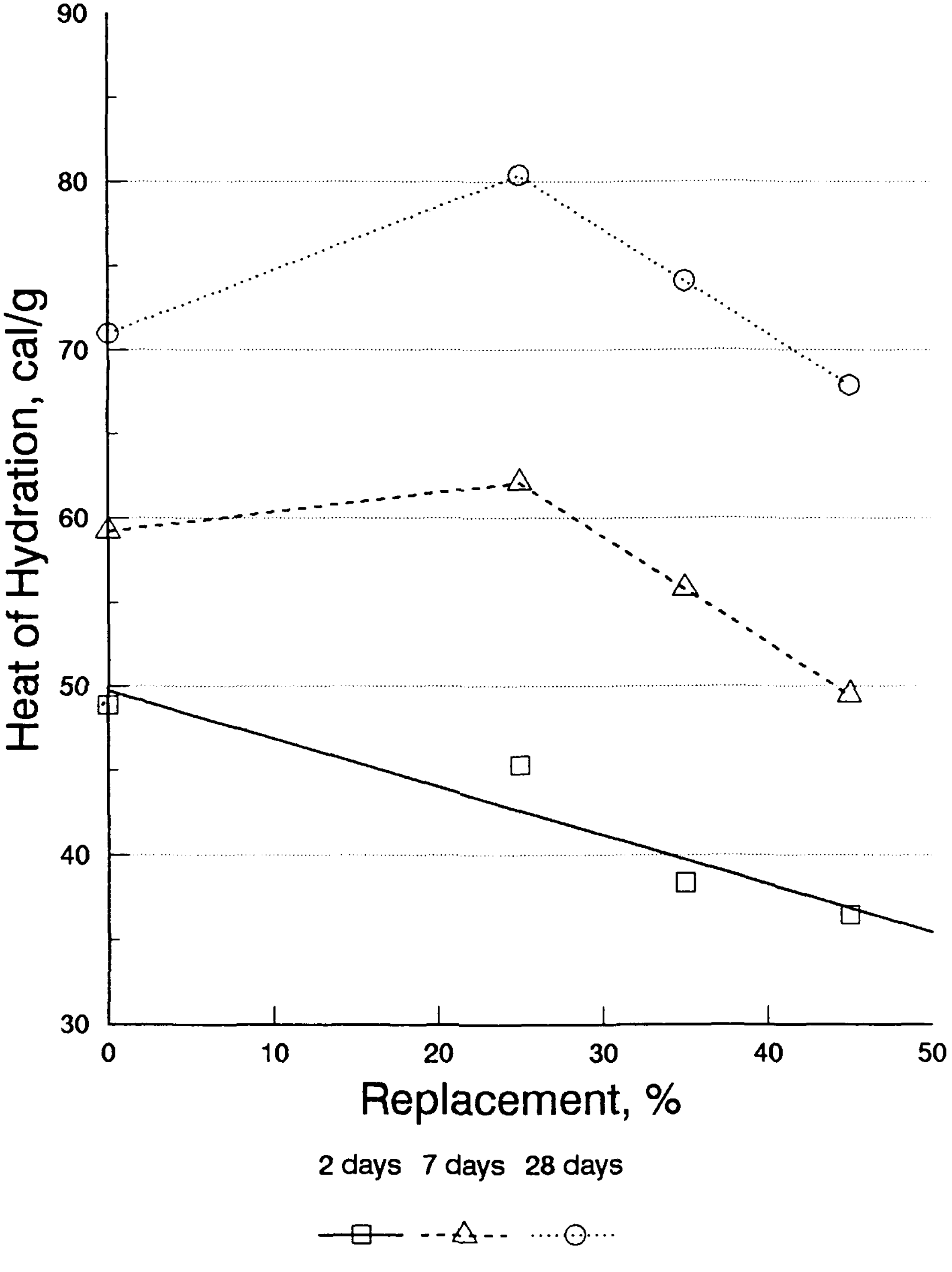

Figure 8. Heat of hydration versus percent replacement for the Class C fly ash at three ages