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EFFECTS OF VARIOUS FLY ASHES ON COMPRESSIVE STRENGTH, RESISTANCE TO FREEZING AND THAWING, RESISTANCE TO SULFATE ATTACK, AND ADIABATIC TEMPERATURE RISE OF CONCRETE

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13. ABSTRACT ***(Maximum 200 words)***
The evaluation of the effects of fly ash on compressive strength, resistance to freezing and thawing, resistance to sulfate attack, and adiabatic temperature rise of concrete is part of a research program conducted by the Bureau of Reclamation's Materials Engineering Branch. The impact of fly ash on strength, durability, and temperature rise of concrete have been areas of major interest in the concrete materials field.

The report presents results of a study of the effects of several fly ashes used in concrete on the subject properties. The fly ashes used represented a range of calcium oxide contents mixed at different replacement percentages of portland cement for two cementitious materials contents.

The quantity of each fly ash used ranged from 10 to 100 percent, by weight, of the total cementitious materials (cement plus fly ash). Comparisons with control mixtures are made, and the test results are discussed with regard to type and quantity of fly ash used, strength and durability of the concrete specimens, and adiabatic temperature rise of concrete.

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by

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Denver, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

U.S. Department of the Interior
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INTRODUCTION

This report presents results from a research program that was designed to determine the effects of fly ash replacement of cement in concrete on the following properties:

- compressive strength,
- resistance to freezing and thawing,
- resistance to sulfate attack,
- adiabatic temperature rise, and
- alkali reactivity.

Laboratory operational constraints required deleting the alkali reactivity portion of the study and reducing the scope of the temperature rise study.

The effects of three fly ashes—representing a range of calcium oxide contents and mixed at different replacement percentages of portland cement in concrete for two cementitious (cement plus fly ash) contents—were determined on a range of concrete properties. The influence on test results of two different curing methods was also investigated in one of the studies. Some information in this paper was presented earlier (Druhushak-Crow, 1987; von Fay and Pierce, 1989; von Fay et al., 1993).

The quantity of each fly ash used ranged from 10 to 100%, by weight, of the total cementitious materials. Comparisons with control mixtures are made, and test results are discussed with regard to type and quantity of fly ash used, curing method, and impact of fly ash replacement of cement in concrete on the specified properties.

This report is divided into several sections. The summary section presents summary findings from the various studies. The materials used are described next. Mixing procedures are then described, followed by discussions of each of the study areas. Conclusions resulting from a particular study are presented in their corresponding section.

SUMMARY

As expected, higher cementitious levels and/or longer curing times in comparable mixtures provided more resistance to freeze-thaw and sulfate attack. As fly ash replacement increased, freeze-thaw durability, compressive strength, and adiabatic temperature rise (except for the high lime class C specimens) decreased. However, as fly ash replacement increased for sulfate durability test specimens, expansion increased, up to about 50% replacement, and then expansion decreased as fly ash replacement levels increased further.

For freeze-thaw specimens cured using a 28-day fog cure, the class F fly ash mixtures with fly ash replacement levels of 10% and below for the lean mixture and 50% and below for the richer mixture were more durable than the control. The low lime class C fly ash mixtures with fly ash replacement levels of 50% and below provided more freeze-thaw resistance than the control at both cementitious materials levels. The high lime class C fly ash mixtures with 50% and below replacement for the lean mixtures and 75% and below for the richer mixtures were more durable than the control specimens.

For freeze-thaw specimens cured using a longer curing method, the control specimens tended to be more durable than the fly ash specimens. However, the class F fly ash specimens provided good durability (more than 800 freeze-thaw cycles with less than 25% weight loss) at both cementitious materials levels with replacement levels of 50% and below. The low lime class C fly ash specimens provided good freeze-thaw durability at replacement levels of 50% and below for the lean mixture and 75% and below for the richer mixtures. The high lime class C fly ash specimens provided good freeze-thaw durability at replacement levels of 30% and below for the lean mixtures and 50% and below for the richer mixtures.

Differences in freeze-thaw durability corresponding to type of fly ash were most notable at the lowest replacement and cementitious levels. Both the class C fly ashes performed about the same, and the class F fly ash tended to have lower freeze-thaw durability compared to the other test specimens.

Depending on fly ash replacement level, both the low lime class C and class F fly ashes were effective as cement replacements in resisting sulfate attack. Class F fly ash is most effective in reducing expansion at the lower cementitious level, and its expansion compares favorably with that of the control mixture. For the lower cementitious level, 50% or more low lime class C must be used; all replacement levels were effective for the richer mixtures.

The high lime class C fly ash mixtures generally performed much worse than the control and were least effective in reducing expansion. For high lime class C fly ash concretes, replacement levels should be 75% or more.

High fly ash replacement levels (more than 50%) tended to improve sulfate durability when compared to the control and decrease freeze-thaw durability. For sulfate durability, as the lime content of the replacement fly ash increased (going from class F to a high lime class C fly ash), within a given replacement level, the more the specimen expanded.

Replacing cement with fly ash reduced the rate of adiabatic temperature rise for all the cases studied. Class F fly ash and low lime class C ash also reduced the maximum adiabatic temperature rise as well as compressive strengths when compared to the control. High lime class C fly ash replacement increased maximum adiabatic temperature rise and reduced compressive strength.

MATERIALS

The fly ashes selected for the study complied with the requirements of ASTM C 618 (1986a) and included a class F from the Navajo Generating Station in Page, Arizona; a class C with a mid-range calcium oxide content from the White Bluff Powerplant in Little Rock, Arkansas; and a high calcium oxide content class C from the Pawnee Powerplant in Brush, Colorado. Chemical and physical properties of these ashes and the cement are listed in table 1.

The cement used in the study was an ASTM C 150 (1986b), type II, low-alkali cement (table 1). The aggregates complied with ASTM C 33 (1986c) requirements and were a Denver area river sand and gravel supplemented with some crushed gravel from the same source. The coarse aggregate and sand were stored in the laboratory for a long period of time and had a constant moisture content. The temperature was held constant for all the materials at 23 ±2 °C (73 ±3 °F). The air-entraining admixture was a proprietary neutralized vinsol resin.

Table 1.-Chemical and physical properties of cementitious materials.

Parameter	Navajo	White Bluff	Pawnee	Portland Cement
Silicon dioxide, %	52.4	40.2	32.8	23.2
Aluminum oxide, %	20.5	7.8	17.6	3.7
Ferric oxide, %	4.5	6.0	6.1	3.1
Calcium oxide, %	1.0	21.4	28.6	65.0
Magnesium oxide, %	2.1	4.7	6.0	1.0
Sulfur trioxide, %	0.7	1.6	3.3	2.2
Alkalies (Na_20 eq), %	1.1	0.8	1.2	0.39
Loss on ignition, %	1.2	0.20	.31	.2
Specific gravity	2.39	2.63	2.69	3.16
Insoluble residue, %	-	-	-	0.10
Retained on 45-µm (No. 325) sieve, %	21.1	12.0	13.0	7.0
Blaine fineness, cm^2/g	3612	3710	5060	3680
*Pozzolanic activity with cement (28 days), %	104	105	100	-
*Water requirement, % of control	97	95	94	-
Compressive/Strength (lbf/in^2)				
3 days	-	-	-	2850
7 days	-	-	-	3700

* These tests are modified; i.e., the ash percentage is 20% by weight rather than the volume replacement specified in ASTM C 311 (1986d), "Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete."

MIXING PROCEDURE

Concrete mixing was performed in a 0.32-m^3 (9-ft^3), manually-operated, tilting drum mixer. The mixer was primed or "buttered" (a trial mixture was performed to coat the inside of the mixture) prior to mixing. The batching sequence of adding all of the dry ingredients at once to the rotating mixer, which contained most of the batch water and all of the air-entraining admixture, was used for the compressive strength, freeze-thaw and sulfate durability portions of the research program. The mixing procedure used for these studies was: mix for 2 minutes, rest for 1 minute, and remix for 2 minutes. During the last 2 minutes of mixing, water was added to the batch if needed to adjust the slump.

Upon discharge from the mixer, each batch was tested for slump, air content, temperature, and unit weight. Tolerances for slump and air were adhered to with all mixtures except those containing 100% class C fly ash. Because class C ashes have a tendency to harden in less than 15 minutes, the total mixing time for these mixtures was reduced to 2-1/2 minutes to provide time to cast cylinders. Slump and unit weight tests were conducted simultaneously with cylinder casting. Because of problems associated with 100% fly ash mixtures, specimens were still used even though the slump and/or air content did not meet the requirements.

Exceptions to this general mixing procedure are noted in the separate sections describing the specific studies performed.

COMPRESSIVE STRENGTH STUDY

Thirty-five concrete mixes were made and cylinders were cast to determine compressive strengths at 7, 28, 90, and 365 days of age. Cylinders were cast and cured according to Bureau of Reclamation Test Procedure USBR 4192 (1992), "Making and Curing Concrete Test Specimens in the Laboratory." Compressive strength testing was performed according to USBR 4039, "Compressive Strength of Cylindrical Concrete Specimens." The ends of the compressive strength specimens were capped with a sulfur compound to achieve end tolerances according to USBR 4617, "Capping Cylindrical Concrete Specimens."

For comparison, five control mixtures were made containing various quantities of portland cement and no fly ash, as shown in table 2. The five different cement quantities were selected in an attempt to establish a relationship among the quantity of cement, compressive strength, and durability of the concrete. The quantity of cement used in the control mixtures was varied to approximate the amount of portland cement contained in the fly ash mixtures. For example, a mixture with 251.5 kg/m^3 (424 lbm/yd^3) of cementitious materials, 75% of which was fly ash, contained only 62.9 kg/m^3 (106 lbm/yd^3) of cement. A control mixture with 59.3 kg/m^3 (100 lbm/yd^3) of cement was attempted, but workability and other problems made this mixture unusable. Therefore, the lowest cement content used in the control series was 82.5 kg/m^3 (139 lbm/yd^3). Although the workability of this mixture was poor, it was used for base-level comparisons.

Mixtures developed for the adiabatic temperature rise study were proportioned differently than those of the other studies. Those data are presented in the adiabatic temperature rise section of this report.

Table 2 shows mixture proportions and compressive strength test results for the specimens tested for resistance to freezing and thawing and resistance to sulfate attack. The mixtures were proportioned to have a slump of 100 ±25 millimeters (4 ±1 in) and an air content of 6 ±1%. However, several of the 100% fly ash mixes did not meet these tolerances.

Compressive strength specimens shown in table 2 were cast and tested in conjunction with the freeze-thaw and sulfate durability studies, so test result discussions and conclusions appear in those sections. A relationship to assess and accurately predict the impact on concrete compressive strength caused by replacing fly ash with cement was not developed.

FREEZE-THAW STUDY

Six 75- by 150-millimeter (3- by 6-in) cylinders were cast from each mixture for freeze-thaw durability testing. Three of these cylinders were cured for 28 days at 100% humidity and 22.8 ±1.7 °C (73 ±3 °F) (referred to as fog-cured, USBR 4192) and the other three were cured for 14 days at 100% humidity and 22.8 ±1.7 °C, followed by 76 days at 50% humidity and 22.8 ±1.7 °C (referred to as alternate cure). After curing was completed, the cylinders were subjected to alternate cycles of freezing and thawing, according to USBR 4666, "Resistance of Concrete to Rapid Freezing and Thawing." The test procedure consists of freezing in water for 1-1/2 hours at -12.2 °C (10 °F) and thawing in water for 1-1/2 hours at about 22.2 °C (72 °F). The failure criterion for this study was a 25% weight loss of the original weight of the specimen.

Table 2. - Concrete mixture yield per cubic yard and properties.

Fly ash (%)	W/C+p by wt.	Water (lbm)	Cement (lbm)	Fly ash (lbm)	Sand (lbm,SSD)	Coarse aggregate (lbm,SSD)	Air content (% grav)	AEA* (cc)	Slump (in.)	Unit weight (lbm/ft^3)	Compressive Strength (lbf/in^2) Age (days) 7	28	90	365
							Control							
	0.36	309	855	0	1,048	1,654	5.0	337	4.75	142.9	5,085	6,610	7,590	8,050
	0.44	281	645	0	1,254	1,622	6.7	287	4.00	140.8	3,580	4,740	6,030	6,025
	0.63	265	424	0	1,455	1,663	6.4	166	3.50	141.0	1,725	2,865	3,610	4,035
	1.06	306	289	0	1596	1574	5.4	118	3.00	139.5	635	1,090	1,575	1,760
	2.34	325	139	0	1577	1634	6.2	45	5.00	136.2	130	160	310	315
							Navajo (Class F) Fly Ash							
10	0.64	273	382	42	1,458	1,628	6.4	177	3.50	140.1	1,425	2,325	3,185	4,045
30	0.64	273	299	128	1,453	1,640	5.7	278	4.25	140.4	990	1,680	2,960	3,850
50	0.61	263	214	214	1,464	1,642	5.4	368	4.75	140.7	615	1,055	2,315	3,585
75	0.59	250	105	317	1,467	1,628	6.0	497	5.00	139.5	215	335	1,185	1,805
100	0.56	248	0	440	1,502	1,692	2.7	747	4.25	143.8	n/t	n/t	30	n/a
10	0.42	269	583	65	1,271	1,628	6.4	365	3.50	141.4	3,210	4,380	5,365	6,165
30	0.40	260	458	196	1,271	1,644	5.7	446	3.75	141.8	2,680	4,455	5,765	5,580
50	0.38	246	325	325	1,259	1,634	6.3	522	4.75	140.4	1,760	3,105	5,100	n/a
75	0.36	233	161	491	1,259	1,646	5.8	671	4.50	140.5	855	1,400	3,185	4,315
100	0.34	231	0	673	1,318	1,796	2.0	576	5.00	145.1	n/t	n/t	160	n/a
							White Bluff (Low Lime Class C) Fly Ash							
10	0.64	275	385	42	1,484	1,642	5.4	167	3.50	141.8	1,575	2,590	3,430	3,830
30	0.63	269	297	127	1,473	1,632	6.0	156	4.00	140.7	1,070	1,930	3,135	3,800
50	0.59	255	216	216	1,478	1,654	5.7	157	4.00	141.4	800	1,305	2,780	3,640
75	0.56	239	106	322	1,520	1,650	5.5	190	3.50	142.1	225	1,160	1,895	3,155
100	0.56	239	0	430	1,551	1,654	4.3	177	3.50	143.5	70	95	125	165
10	0.41	272	591	66	1,295	1,650	5.2	291	3.50	143.5	3,795	5,395	6,135	7,075
30	0.40	256	452	194	1,287	1,622	6.7	275	4.50	151.2	2,755	4,495	5,570	6,035
50	0.37	241	326	326	1,307	1,638	6.2	267	4.50	142.1	2,370	4,075	6,020	7,035
75	0.34	223	165	493	1,319	1,652	6.0	292	4.00	142.7	595	1,630	3,985	5,735
100	0.38	248	0	654	1,328	1,644	4.3	268	6.50	143.5	150	185	255	400
							Pawnee (High Lime Class C) Fly Ash							
10	0.65	269	375	41	1,495	1,602	6.7	163	3.50	140.0	1,720	2,835	3,690	3,825
30	0.65	278	298	128	1,446	1,638	6.0	167	3.75	140.3	1,310	2,475	3,185	3,645
50	0.64	273	214	214	1,475	1,640	5.2	167	4.50	141.4	735	1,630	2,470	3,235
75	0.56	242	107	324	1,504	1,664	5.1	192	4.00	142.3	175	1,160	2,285	3,235
100	0.55	236	0	427	1,534	1,640	5.4	167	3.50	142.1	175	235	455	1,805
10	0.41	271	591	66	1,283	1,650	5.6	269	3.75	143.0	3,760	5,345	6,075	6,605
30	0.40	258	457	196	1,306	1,640	5.7	267	3.75	142.9	3,345	4,850	5,870	6,700
50	0.38	247	327	327	1,317	1,640	5.7	267	3.75	142.9	2,705	4,440	5,600	6,435
75	0.37	241	165	492	1,317	1,648	5.3	291	4.00	143.1	245	2,505	4,445	5,440
100	0.35	226	0	652	1,325	1,640	5.7	290	4.00	142.4	400	1,430	3,765	4,665

* Air-entraining admixture
n/a - not available
n/t - insufficient strength to test at these ages

The fly ash mixtures included five replacement levels: 10, 30, 50, 75, and 100%, by weight, of the cementitious materials. This series was repeated for each of the three fly ashes at two different cementitious materials levels, 424 lbm/yd^3 and 645 lbm/yd^3, resulting in a total of 30 fly ash mixtures for this study.

Discussion of Test Results

The results of freeze-thaw testing of both the control and fly ash mixes are listed in table 3. In general, specimens cured for 14 days with fog and 76 days with 50% humidity had better durability than those cured with 100% humidity for 28 days, probably because of the increased maturity of these specimens and their corresponding strength gain. As shown in table 2, none of the Navajo fly ash mixes with 100% replacement were tested because even after the curing period, the concrete could not be removed intact from the molds because of very low strength.

Table 3.-Freeze-thaw durability of control and fly ash mixes.

Quantity of Cementitious Materials (lbm)	Percent Fly Ash	Cycles to Failure	
		28-day Fog Cure	14-day Fog Cure and 76-day 50% Humidity
Control Mixes			
424	0	693	2048*
645	0	1323*	3971*
Navajo (Class F) Fly Ash Mixes			
424	10	798	1600*
	30	473	1000*
	50	332	856*
	75	269	410
	100	n/t	n/t
645	10	1550*	3979*
	30	1658*	3504*
	50	1345*	1775*
	75	504	686
	100	n/t	n/t
White Bluff (Low Lime Class C) Fly Ash Mixes			
424	10	688	1118*
	30	900*	1119*
	50	730	841*
	75	323	415
	100	49	79
645	10	2085*	4430*
	30	1871*	3360*
	50	2246*	2739*
	75	835*	823*
	100	240	255
Pawnee (High Lime Class C) Fly Ash Mixes			
424	10	768	1951*
	30	849*	1029*
	50	710	680
	75	515	431
	100	76	43
645	10	1650*	3952*
	30	1729*	3194*
	50	1742*	2852*
	75	1393*	540
	100	385	277

* good freeze-thaw durability
n/t - insufficient strength to test these specimens

A Bureau of Reclamation survey revealed that most concrete with good freeze-thaw durability endures an average of 800 cycles of freezing and thawing before failing. Of the 424-lbm/yd^3 cementitious materials level specimens that were fog cured, only the class C specimens with 30% fly ash endured more than 800 freeze-thaw cycles. Of the 424-lbm/yd^3 specimens that were alternately cured, only the specimens with 75% or more fly ash failed to exceed 800 freeze-thaw cycles. The only exception to this case was the high lime class C ash, where good freeze-thaw durability resulted for specimens with 30% fly ash replacement or less.

At the 645-lbm/yd^3 cementitious materials level, freeze-thaw durability improved compared to lower cementitious level specimens. Fog cured class F fly ash specimens exhibited good freeze-thaw durability at replacement levels of 50% and below. Both types of class C fly ash specimens that were fog-cured at replacement levels of 75% and below exhibited good freeze-thaw durability. Results were similar for the alternately cured specimens.

Test results are shown on figures 1 through 10. Figures 1 and 2 are graphs of fly ash replacement versus durability (cycles to failure) for the fog-cured specimens at 424 and 645 lbm/yd^3 of cementitious material, respectively. The class F fly ash was only somewhat more durable than the control at the 10% replacement level. Durability progressively decreased as the fly ash replacement percentage increased. Both class C fly ashes were about as durable to slightly more durable than the control for low to mid-range replacement levels. However, as the replacement level increased above 50%, the durability of the class C fly ash concretes progressively decreased and worsened when compared to the control.

Using the criterion of 800 freeze-thaw cycles before failure with figure 1 reveals that the class F and high lime class C mixtures at 10% replacement have good durability. Both class C mixes were durable at the 30% replacement level. With the same criterion in mind, examining figure 2 reveals that mixtures with class F fly ash with replacement levels up to about 60 to 70% have good durability, and that both class C mixtures have good durability up to about 80 to 90% replacement.

Figures 3 and 4 are graphs of fly ash replacement versus durability for specimens cured using the alternate (14-day fog) cure containing 424 lbm/yd^3 and 645 lbm/yd^3 of cementitious material, respectively. These specimens, especially the leaner mixtures, do not compare well to the control, and for the most part, have considerably lower durabilities than the control specimens. However, all three fly ashes provide mixtures with good freeze-thaw durability up to about 65 to 75% fly ash replacement.

Figures 5 through 10 compare the impact of the different curing methods on freeze-thaw durability. As can be seen, the durability of the specimens cured using the alternate cure is generally better than the durability of the specimens that were fog cured. However, as fly ash replacement levels increase, the differences of durability resulting from the different curing methods decrease. This decrease is probably due to lower compressive strength caused by increasing fly ash percentages. These trends are most notable in the class C fly ash specimens, and less pronounced with the class F fly ash specimens.

As would be expected, the durability improves as cementitious levels and strength levels increase (see table 2).

Conclusions

Based on data from this study, the following conclusions were made:

- As expected, higher cementitious levels in comparable mixtures provide more resistance to freeze-thaw.

- In general, durability decreased as percent fly ash replacement increased. This decrease is related to strength development rates associated with increasing fly ash replacement levels.

- Longer curing time with the alternate cure leads to higher strength development and lower saturation levels providing more resistance to freeze-thaw.

- For the fog-cured concrete with 424 lbm/yd^3 of cementitious material:

  - The class C fly ash mixtures with fly ash replacement levels of 50% and below were more durable than the control. The only class C fly ash mixtures that provided good freeze-thaw durability were those containing 30% fly ash replacement.

  - The class F fly ash mixtures with fly ash replacement levels of 10% and below provide better freeze-thaw durability than the control.

- For the fog-cured concrete with 645 lbm/yd^3 of cementitious material:

  - Freeze-thaw durability of the mixtures was good except for very high replacement levels for all fly ashes.

  - For the high lime class C fly ash, freeze-thaw durability was better than the control mixture for replacement levels of about 75% and below.

  - For the low lime class C fly ash, freeze-thaw durability was better than the control mixture for replacement levels of about 75% and below.

  - For the class F fly ash, freeze-thaw durability was better than the control for replacement levels of about 50% and below.

- For specimens cured using the alternate cure:

  - Freeze-thaw durability was best at low replacement levels, but was generally less than the control mixtures. All fly ashes had comparable durability performance for a given replacement level.

  - At 424 lbm/yd^3 of cementitious material, fly ash replacement levels of 50% and below for the class F and low lime class C fly ashes, and 30% and below for the high lime class C fly ash produced mixtures with good freeze-thaw durability. At 645 lbm/yd^3 of cementitious material, fly ash replacement levels of about 50% and below for all three fly ashes, and 75% and below for the low lime class C fly ash, produced mixtures with good freeze-thaw durability.

RESISTANCE TO SULFATE ATTACK

Long-time Reclamation procedures were used (test procedure is not published) for sulfate resistance testing of concrete mixtures to facilitate comparisons with our existing data base. All specimens were cured for 14 days in a 100%-humidity room and 14 days in a 50%-humidity room before testing started. Two different procedures were used because actual field conditions will vary from site to site: 10% sodium sulfate continuous soaking (soak test), and 2.1% sodium sulfate cyclic soaking and drying phases (accelerated test). Each cycle included 16 hours of soaking at 21 to 32 °C (70 to 90 °F) and 8 hours of drying at 54 °C (130 °F). In both procedures, the specimens "failed" when they had expanded 0.5%. Reclamation experience shows that extrapolation of test data yields a field service life of about 6 to 10 years for each year of laboratory exposure for both of these tests.

Mixture Proportions

Table 2 contains the yield quantities per cubic yard for all mixtures in this study. The mixtures were proportioned to have a slump of 100 ±25 millimeters (4 ±1 in) and an air content of 6 ±1%. However, several of the 100% fly ash mixtures exceeded these tolerances.

The fly ash mixtures included five replacement levels: 10, 30, 50, 75, and 100%, by weight, of the cementitious materials. This series was repeated for each of the three fly ashes at two different cementitious materials levels, 424 lbm/yd^3 and 645 lbm/yd^3, resulting in a total of 30 fly ash mixtures in the program.

Discussion of Test Results

The results of sulfate resistance testing for both the control and fly ash mixtures are shown on figures 11 through 37. As shown, neither of the Navajo fly ash mixtures with 100% replacement was tested because even after the curing period, the concrete could not be removed intact from the molds.

Figure 11 shows the impact of different test methods on control specimen expansion. The figure shows that the accelerated test procedure is a much more aggressive test.

Figures 12 through 15 show maximum expansions through about 5 years of age for the different test procedures, fly ash classes, and cementitious levels for the five fly ash replacement levels tested. When comparing the accelerated and soak test results, the accelerated test caused much greater expansions for the specimens that had relatively high expansions and comparable expansions for those specimens with lower level expansions.

In general, specimens exhibited the highest expansions at the middle to lower replacement levels. At higher replacement levels, maximum expansions were comparable with the control specimens in the soak test and were significantly less than the control specimens in the accelerated test.

Figures 16 through 37 are plots of expansion versus time for all the specimens that were tested. Figures 16 and 17 show the expansion of the various control specimens. As discussed earlier, the accelerated test caused higher and more rapid expansion than the soak test. In general, higher cementitious levels delayed and/or reduced expansion. However, notable exceptions to these effects are the mixtures containing 139 and 306 lbm/yd^3 of cement tested using the accelerated test method. For reasons unknown, these specimens started to expand rapidly, as would be expected, but then leveled off.

Figures 18 through 22 show expansion versus time for specimens containing 424 lbm/yd^3 of cementitious materials tested using the accelerated method. The figures show that in general, the class F fly ash specimens performed better than the class C fly ash specimens. Low replacement levels (10%) of all three ashes produced results comparable to the control specimen; mid-level (30% to 50%) replacements of the class C ashes expanded more than the control. Higher lime contents corresponded to higher expansions for mid-level replacements. Replacement levels above 50% reduced expansions for all specimens compared to the control.

Figures 23 through 27 show expansion versus time for specimens containing 424 lbm/yd^3 of cementitious materials tested using the soak method. In general, expansion trends from the soak test are similar to the accelerated test results, except the magnitude of expansion and rates of expansion are lower for the soak test. Unfortunately, the control specimen for this series of tests was misplaced near the end of testing.

Figures 28 through 32 show expansion versus time for specimens containing 645 lbm/yd^3 of cementitious materials tested using the accelerated method. In general, the higher the lime content of the fly ash, within a given replacement level, the more the specimen expanded. At the 10% replacement level, the high lime class C specimen performed comparably with the control specimens. The low lime class C and the class F expanded at a lower rate than the control. As the replacement levels increased to 50%, the fly ash specimens exhibited higher expansions. At 75% replacement, all the fly ash specimens expanded less than the control.

Figures 33 through 37 show expansion versus time for specimens containing 645 lbm/yd^3 of cementitious materials tested using the soak method. As with the accelerated test specimens, the higher the lime content, the more the specimens expanded, within a given replacement level. Overall, all the fly ash specimens on these figures expanded about the same or more than the control specimen.

Figures 25 and 35 reflect the distinct difference in performance of the high lime content class C fly ash mixture with 50% replacement. To control sulfate expansions to a level comparable to the control, more than 50% fly ash is required. Figures 27 and 37 show examples of specimens at both cementitious levels with 100% replacement performing about the same as the control specimens, confirming that more than 50% replacement with the high lime content fly ash is effective. Conversely, figures 19 and 29 reflect rapid failures and ineffectiveness of 30% replacements for both class C fly ashes at the lower cementitious level and only the high lime content at the higher cementitious level. On figures 21 and 31, the effectiveness of all fly ashes is shown for the 75% replacement level.

Conclusions

- As expected, higher cementitious levels in comparable mixtures provided more resistance to sulfate attack.
- The accelerated (wetting and drying) test provides a more severe test of the concrete than does the 10% soak (continuous wetting) test.

- The expansion trends for each cementitious level are the same, although of different magnitudes, for both test procedures.

- A service life estimate at the upper limit of 10 years for every year of laboratory exposure in the accelerated test is appropriate because of the comparative severity of the accelerated test. A service life estimate of 6 years for every year of laboratory exposure is appropriate for the 10% soak test results.

- In the soak test:

  - Both the low lime class C and class F fly ashes can be effective cement replacements. Class F fly ash is most effective in reducing expansion at the lower cementitious level, and its expansion compares favorably with that of the control mixture with 424 lbm/yd^3 of cement. At the higher cementitious level, class F is most effective with 30% fly ash. For the lower cementitious level, 50% or more low lime class C must be used; all replacement levels were effective for the richer mixture.

  - The high lime class C fly ash mixture generally performed much worse than the control and was least effective in reducing expansion. Replacement levels should be 75% or more for high lime class C fly ash concretes.

- In the accelerated test:

  - Class F fly ash is the most effective pozzolan. It improved the sulfate durability for the replacements and cementitious levels tested.

  - For low lime class C fly ash, replacement levels need to be 30% or more to achieve the most improved sulfate durability.

  - For high lime class C fly ash, replacement levels need to be 75% or more to achieve the most improved sulfate durability.

ADIABATIC TEMPERATURE RISE STUDY

The last of the series of fly ash studies conducted was the adiabatic temperature rise study. Operational constraints required reduction of the number of mixtures tested. Because temperature rise is mainly a concern for mass concrete placements, only the lower cementitious level of 424 lbm/yd^3 was studied. Two fly ash replacement levels of 30 and 75% were used, and one control test with no fly ash was tested. The 75% replacement level of the high lime class C fly ash also was not tested.

Table 4 contains the yield quantities per cubic yard of materials and compressive strength test results for all mixtures used in this portion of the study. The mixtures were proportioned with a constant water to cementitious materials ratio of 0.63 and an air content of 6 ±1%. Slump varied between mixtures. Mass cure refers to the specimens that were cured in the temperature rise rooms as the temperature rise test was performed.

Reclamation test procedure USBR 4911, "Temperature Rise of Concrete," was followed for the temperature rise tests. One specimen from each series was cast in a 21½- by 21½-inch steel cylindrical mold. Thermometers were inserted into the concrete in the mold through ports in the mold's lid. The test specimen was then wrapped in an insulating fiberglass blanket.

Table 4.-Concrete mixture yield per cubic yard and properties.

Fly ash (%)	W/C+P by wt.	Water (lbm)	Cement (lbm)	Fly ash (lbm)	Sand (lbm, SSD)	Coarse Aggregate (lbm, SSD)	Air Content (%, grav.)	AEA (cc)	Slump (in.)	Unit Weight (lbf/ft^3)	Cure	Compressive Strength, lbf/in^2 3	7	14	28	90	180	365
							Control											
0	0.63	264	420	0	1282	1835	6.9	533	1.75	140.7	*Fog Room*	1687	2500	3163	3650	4270	4240	4450
											Mass	2577	3005	n/t	n/t	n/t	n/t	n/a
							Navajo(Class F) Fly Ash											
30	0.63	268	298	128	1286	1840	5.6	503	1.25	141.5	*Fog Room*	990	1487	1760	2423	3340	3800	4130
											Mass	1293	2517	3343	3820	n/t	n/t	3973
75	0.63	266	105	316	1253	1793	6.5	654	6.75	138.3	*Fog Room*	167	257	323	413	1100	n/a	1577
											Mass	156	259	500	1317	n/t	n/t	1573
							White Bluff (Low Lime Class C) Fly Ash											
30	0.63	268	298	128	1291	1847	5.6	538	7	141.9	*Fog Room*	990	1560	2013	2380	3560	3817	3790
											Mass	1043	2140	2887	2930	n/t	n/t	3760
75	0.63	264	105	315	1260	1804	6.8	397	7.25	138.8	*Fog Room*	n/t	50	60	450	n/a	n/a	n/a
											Mass	n/t	65	70	100	n/t	n/t	n/a
							Pawnee (High Lime Class C) Fly Ash											
30	0.63	265	295	126	1279	1831	6.5	535	3	140.7	*Fog Room*	1063	1580	2130	2590	3245	3070	3410
											Mass	1323	2320	2700	2710	n/t	n/t	3080

n/t - specimen not tested because of insufficient strength or no specimen was cast
n/a - specimen not available for testing

The temperature of the room was automatically adjusted to match the temperature of the concrete; thus, the concrete neither gained nor lost heat from its surroundings.

Companion 6- by 12-inch concrete cylinders were cast in plastic cylinder molds for compressive strength tests. Three cylinders were cast and tested for each test age. Cylinders were cast and cured according to USBR 4192, "Making and Curing Concrete Test Specimens in the Laboratory." Compressive strength testing was performed according to USBR 4039, "Compressive Strength of Cylindrical Concrete Specimens." The ends of the compressive strength specimens were capped with a sulfur compound to achieve end tolerances according to USBR 4617, "Capping Cylindrical Concrete Specimens." Several cylinders were sealed in their molds and placed in the temperature rise room along with the temperature rise specimen. They were tested at 3, 7, 14, 28, and 90 days, or until the adiabatic temperature rise test was completed, whichever occurred first. Three of any remaining 6- by 12-inch cylinders were placed in the fog room and tested at one year of age. Additional 6- by 12-inch cylinders were cast for testing at 3, 7, 14, 28, 90, 180, and 365 days, and were cured using the fog room cure (100% humidity and 22.8 °C ±1.7 [73 ±3 °F], USBR 4192).

Mixing Procedure

Concrete mixing was performed in a 9-ft^3 (0.32-m^3) manual tilting drum mixer. The mixer was primed or "buttered" (a batch was mixed to coat the mixer interior) prior to mixing. The batching sequence of adding all of the aggregates at once to the rotating mixer, which contained the batch water and air-entraining admixture, was kept constant throughout the study. Aggregates were chilled to 55 °F and sufficient ice was used in the mix water so that the concrete had a temperature between 55 and 60 °F when it was discharged from the mixer. The mixing procedure was: mix aggregate and water for 1 minute, add cementitious material and mix for 3 minutes, rest for 3 minutes, and remix for 2 minutes.

Upon discharge from the mixer, each batch was tested for slump, air content, temperature, and unit weight simultaneously with cylinder casting.

Test Results and Discussion

Table 5 and figure 38 show the temperature rise data for the test. Table 6 shows the maximum adiabatic temperature rise and how many days elapsed before the maximum temperature was recorded.

Test results show the control specimen (no fly ash) generated heat faster than any of the specimens containing fly ash (fig. 38). Total temperature rise was reduced when cement was replaced with the class F fly ash or the low lime content Class C fly ash. Similarly, compressive strengths were reduced. However, the maximum adiabatic temperature rise was higher than the control specimen, and compressive strengths were lower when cement was replaced with the high lime content class C fly ash.

A 9% reduction in adiabatic temperature rise and a 7% reduction in 1-year strength resulted when 30% of cement was replaced with the class F fly ash. The specimen with 30% replacement of low lime class C fly ash saw a 4% reduction in temperature rise and a 15% reduction in 1-year strength. The 30% high lime class C fly ash replacement specimen saw a 2% higher temperature than the control specimen and a 24% decrease in 1-year compressive strength.

Table 5.-Temperature rise data for tested mixtures.

Time (Days)	Temperature Rise					
	Control	Class F 30%	Class F 75%	Low lime C, 30%	Low lime C, 75%	High lime C, 30%
1	46.6	30.5	15.7	18.8	9.7	24.6
2	62.8	43.5	21.1	33.4	10.7	41.3
3	67.1	50.5	23.6	45.9	11.2	56.7
4	68.6	54.3	25.5	55.6	11.4	64.6
5	69.5	57.0	27.0	60.6	11.7	68.0
6	70.0	59.2	28.0	63.3	12.5	69.6
7	70.4	60.8	28.9	65.0	12.7	70.6
8	70.7	61.9	29.6	66.6	12.9	71.3
9	70.8	62.5	30.3	67.2	12.9	71.9
10	70.9	63.2	31.3	67.8	13.0	72.2
11	70.9	63.5	32.5	68.1	13.0	72.4
12	70.5	63.8	33.7	68.3	13.1	72.5
13	70.3	64.0	35.0	68.3	13.2	72.6
14	70.3	64.2	36.2	68.3	13.3	72.6
15	70.1	64.3	37.3	68.2	13.4	72.6
16	70.1	64.3	38.1		13.5	72.5
17		64.2	38.7		13.7	72.4
18		64.2	39.2		13.8	
19			39.5		13.9	
20			39.8		14.1	
21			40.1		14.3	
23			40.3		14.7	
25			40.4		15.5	
28			40.5		17.6	
31			40.4		25.7	
32					29.6	
33					34.0	
34					39.7	
35					45.5	
36					49.8	
38					56.3	
40					59.5	
41					60.4	
42					60.9	
43					61.3	
47					61.7	
49					61.6	

Table 6.-Maximum adiabatic temperature rise and time to highest temperature.

Mixture	Adiabatic Temp Rise, °F	Time, Days
Control	70.9	10
Class F, 30%	64.3	15
Class F, 75%	40.5	28
Low C, 30%	68.3	12
Low C, 75%	61.7	47
High C, 30%	72.6	13

When the fly ash replacement of cement was increased to 75%, adiabatic temperature rise was reduced even more compared to the control specimen, and 1-year compressive strengths were also reduced. A 75% replacement of cement with the class F fly ash reduced the maximum temperature by 43% and reduced strength by 65%.

When 75% of the cement was replaced with low lime class C fly ash, total adiabatic temperature rise was reduced by 13%. No data were available for 1-year compressive strength comparisons. In addition, the temperature rise was substantially delayed by almost one month. A partial repeat of this test was performed, and similar results were obtained. At the time of this report, the cause of this delay in heat generation and strength gain was not determined. This anomaly was not experienced in the other studies in this research program.

Results from this study show that for each 10% replacement of cement with a class F fly ash, a 3.5% reduction in maximum adiabatic temperature rise was obtained. For each 10% replacement of cement with a low-lime class C fly ash, a 1.5% reduction in a maximum temperature rise was achieved. Data were not available to make similar observations for the high lime class C fly ash. These values are rough approximations over the range of values resulting from the mixtures tested.

Six- by 12-inch compressive strength test specimens were cast and cured in sealed plastic cylinder molds in the adiabatic temperature room. The specimens were subjected to the same temperature rise as their companion adiabatic temperature rise test specimen. Sufficient compressive strength test specimens were cast to be tested at 3, 7, 14, 28, and 90 days of age. None of the temperature rise tests ran long enough to test all the specimens, so extras were placed in the fog room and tested at 1 year of age. Comparison of fog room cured test specimens and mass cured test specimens revealed that, for the most part, the compressive strength of the mass cured specimens increased faster than the fog room specimens. However, at 1 year of age, the compressive strength of mass cured specimens was equal to or less than the compressive strength of fog room cured specimens. The only exception to this situation was the low-lime class C ash at the 75% replacement level. In that case, the temperature rise room temperature was below the fog room temperature for about the first month of the test; consequently, the compressive strengths of the mass cured specimens were lower than the fog room cured specimens.

Conclusions

Based on the data gathered from this study, the following conclusions were made:

- As expected, higher curing temperatures experienced by the mass cured specimens accelerated compressive strength gain. However, 1-year compressive strengths of the mass cured specimens were about equal to or lower than comparable fog room cured specimens.

- Replacement of cement with fly ash reduced the initial rate of temperature rise when compared to the control specimen.

- Replacing cement with class F fly ash and low lime class C fly ash reduced the maximum adiabatic temperature rise.

  - For each 10% replacement of cement with a class F fly ash, a 3.5% reduction in maximum adiabatic temperature rise was obtained.

  - For each 10% replacement of cement with a low-lime class C fly ash, a 1.5% reduction in maximum temperature rise was achieved.

- Replacing cement with class F fly ash and low lime class C fly ash reduced the compressive strengths compared to the control specimens (no fly ash).

- Replacing cement with the high lime class C fly ash increased the maximum adiabatic temperature rise and reduced compressive strength compared to the control specimens.

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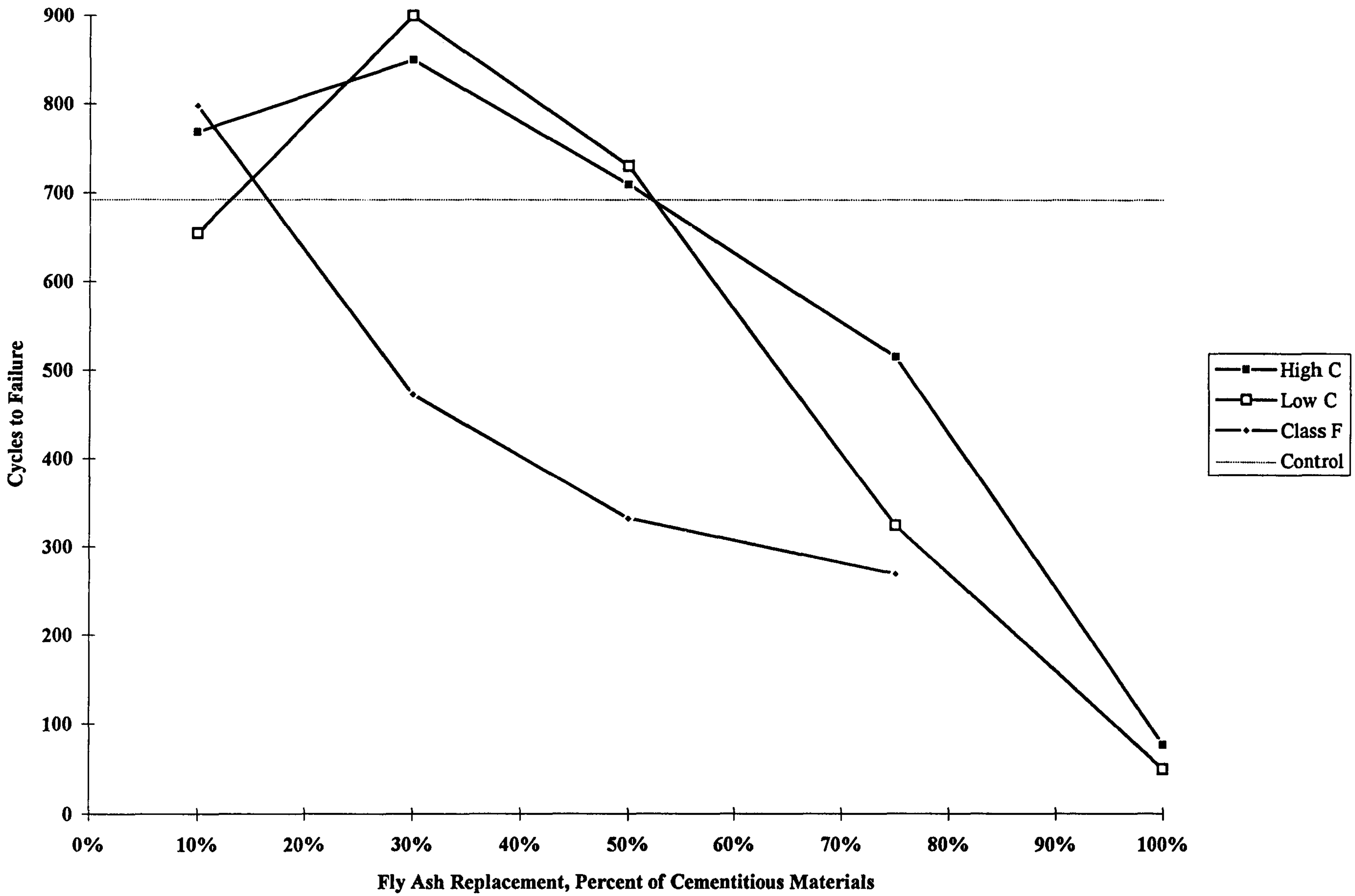

Figure 1. - Fly ash replacement versus freeze-thaw durability (28-day fog cure, 424-lbm/yd^3 cementitious material).

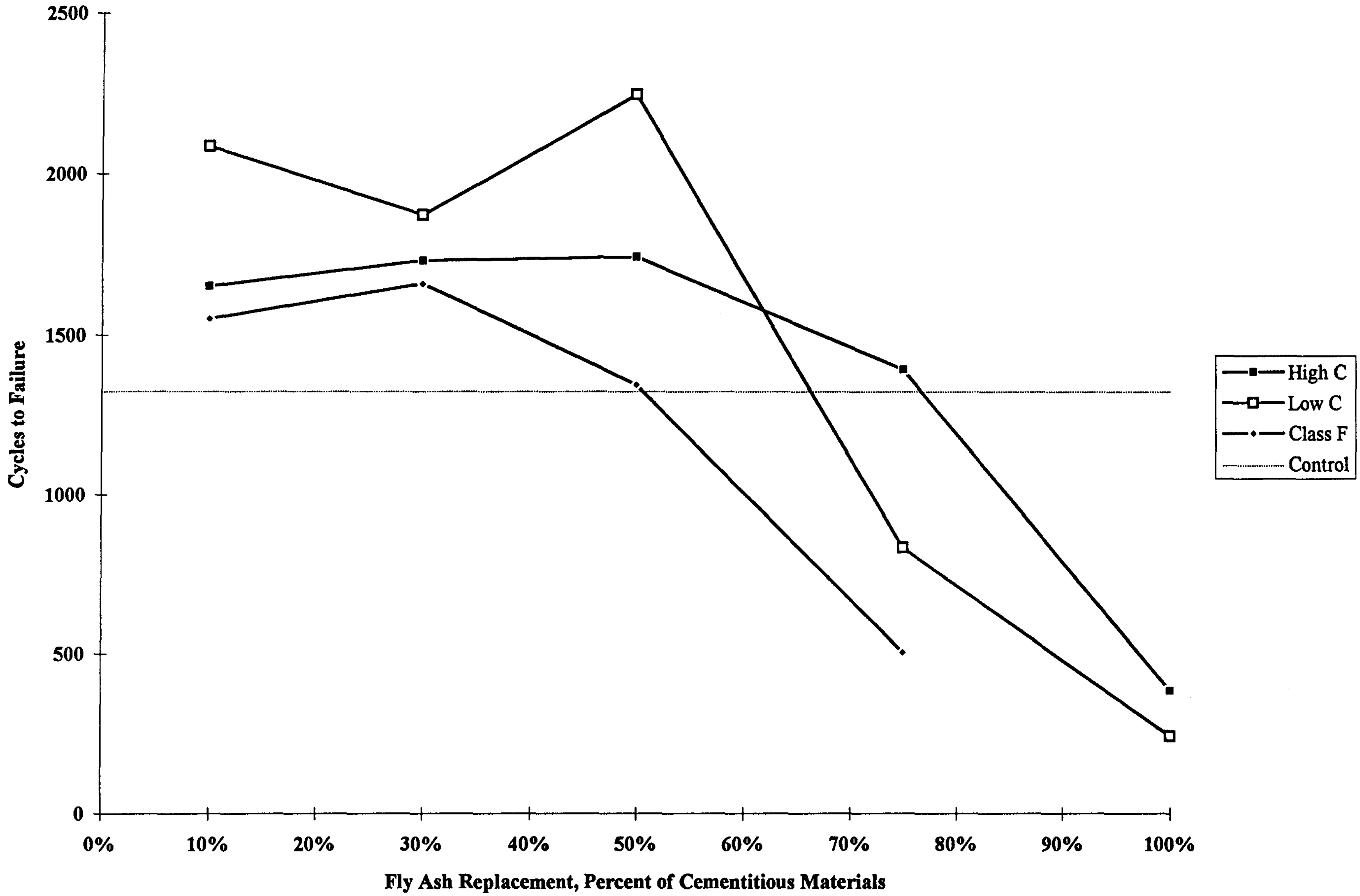

Figure 2. - Fly ash replacement versus freeze-thaw durability (28-day fog cure, 645-lbm/yd^3 cementitious material).

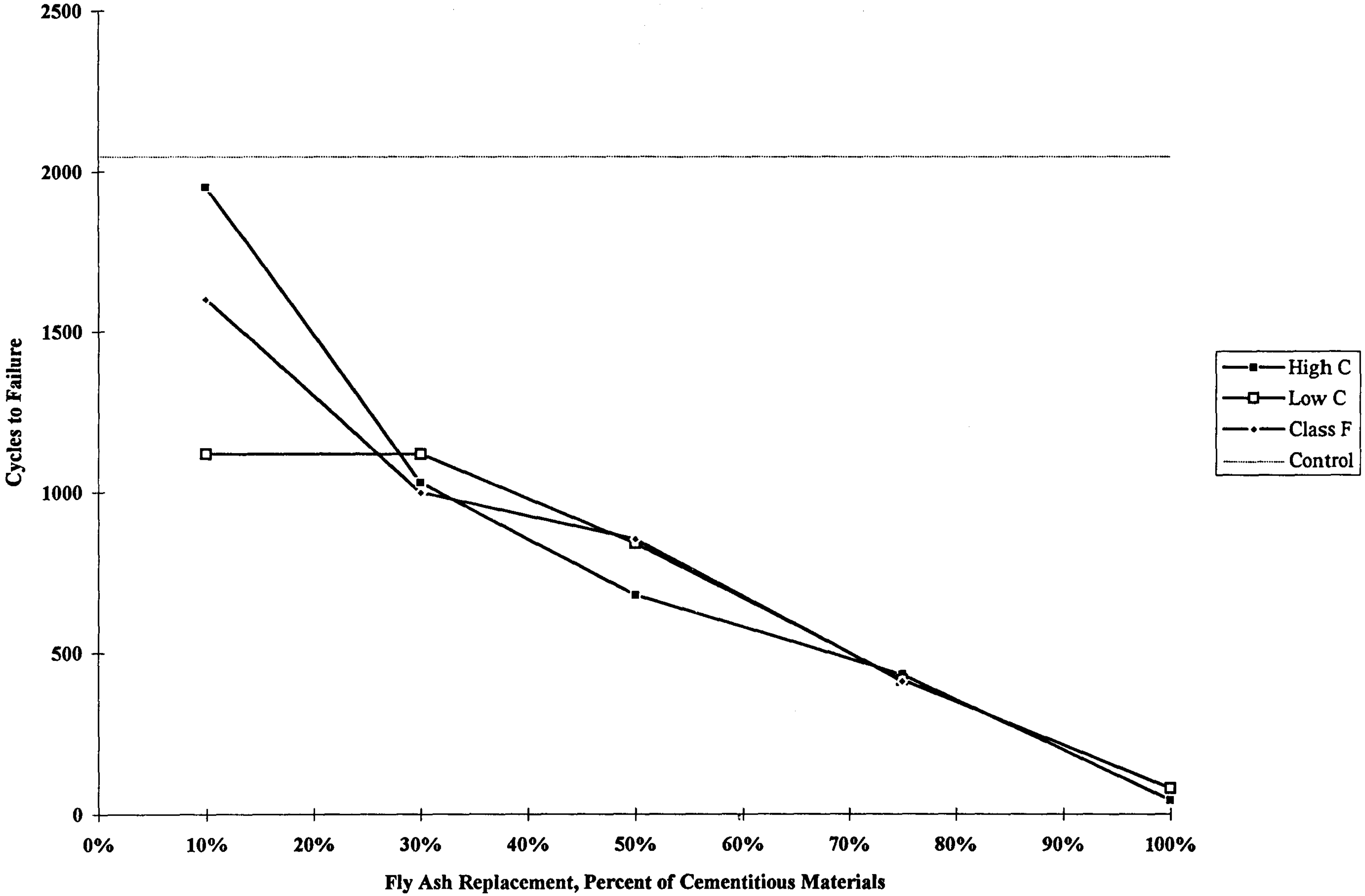

Figure 3. - Fly ash replacement versus freeze-thaw durability (14-day fog cure, 76-day 50% cure, 424-lbm/yd^3 cementitious material).

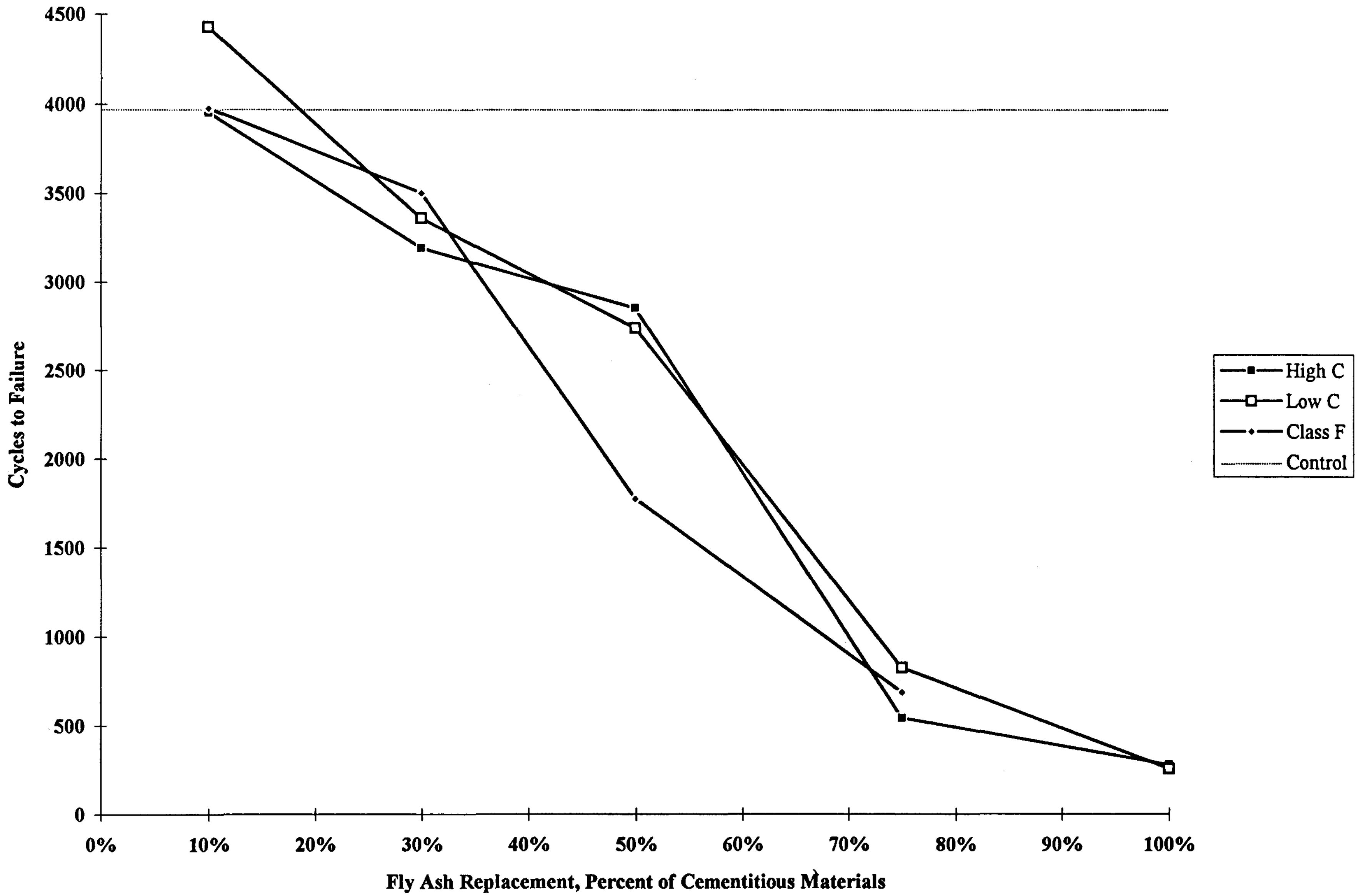

Figure 4. - Fly ash replacement versus freeze-thaw durability (14-day fog cure, 76-day 50% cure, 645-lbm/yd^3 cementitious material).

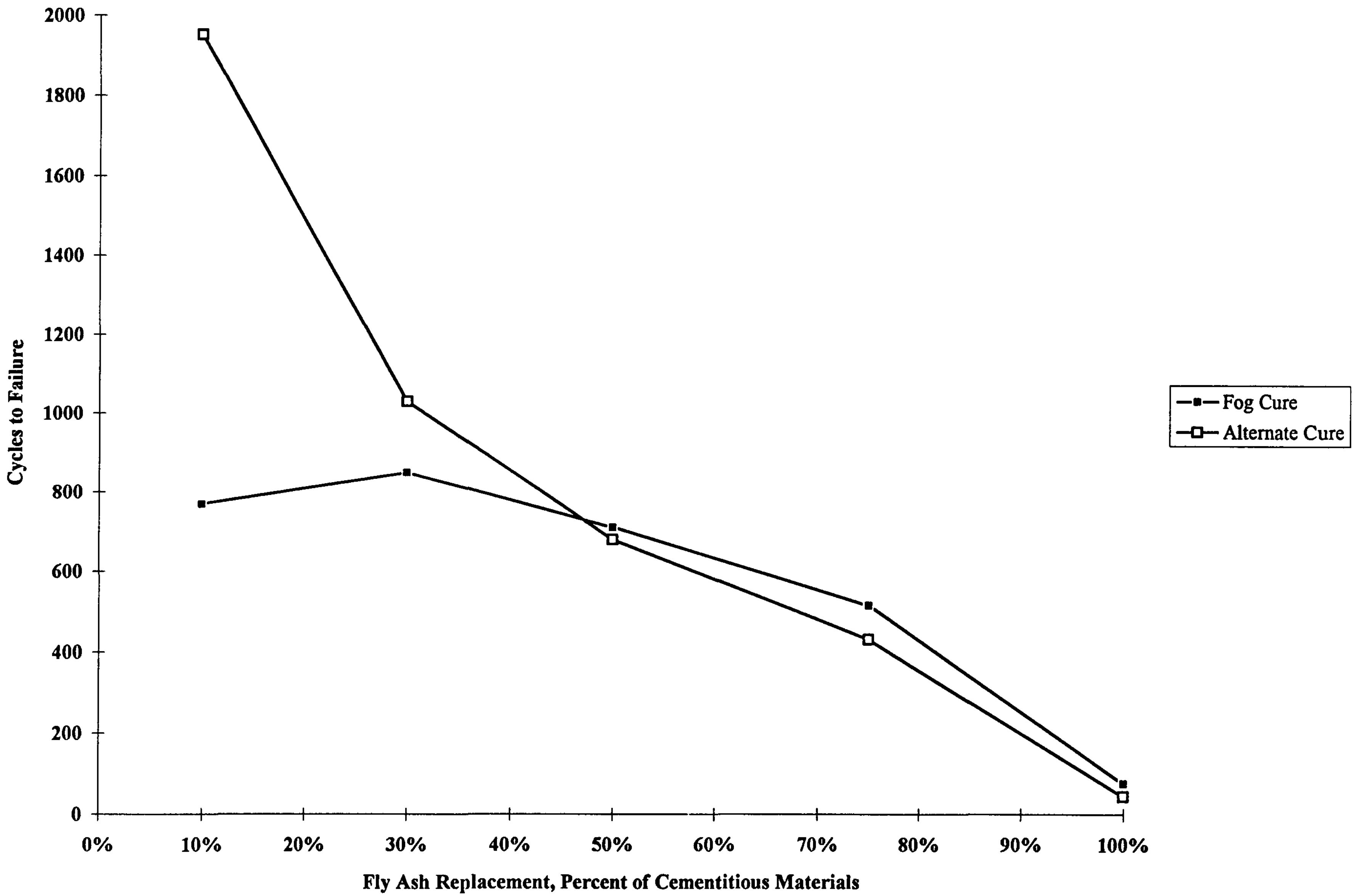

Figure 5. - Comparison of different curing methods, fly ash replacement versus freeze-thaw durability (424-lbm/yd^3 cementitious material, high lime class C fly ash).

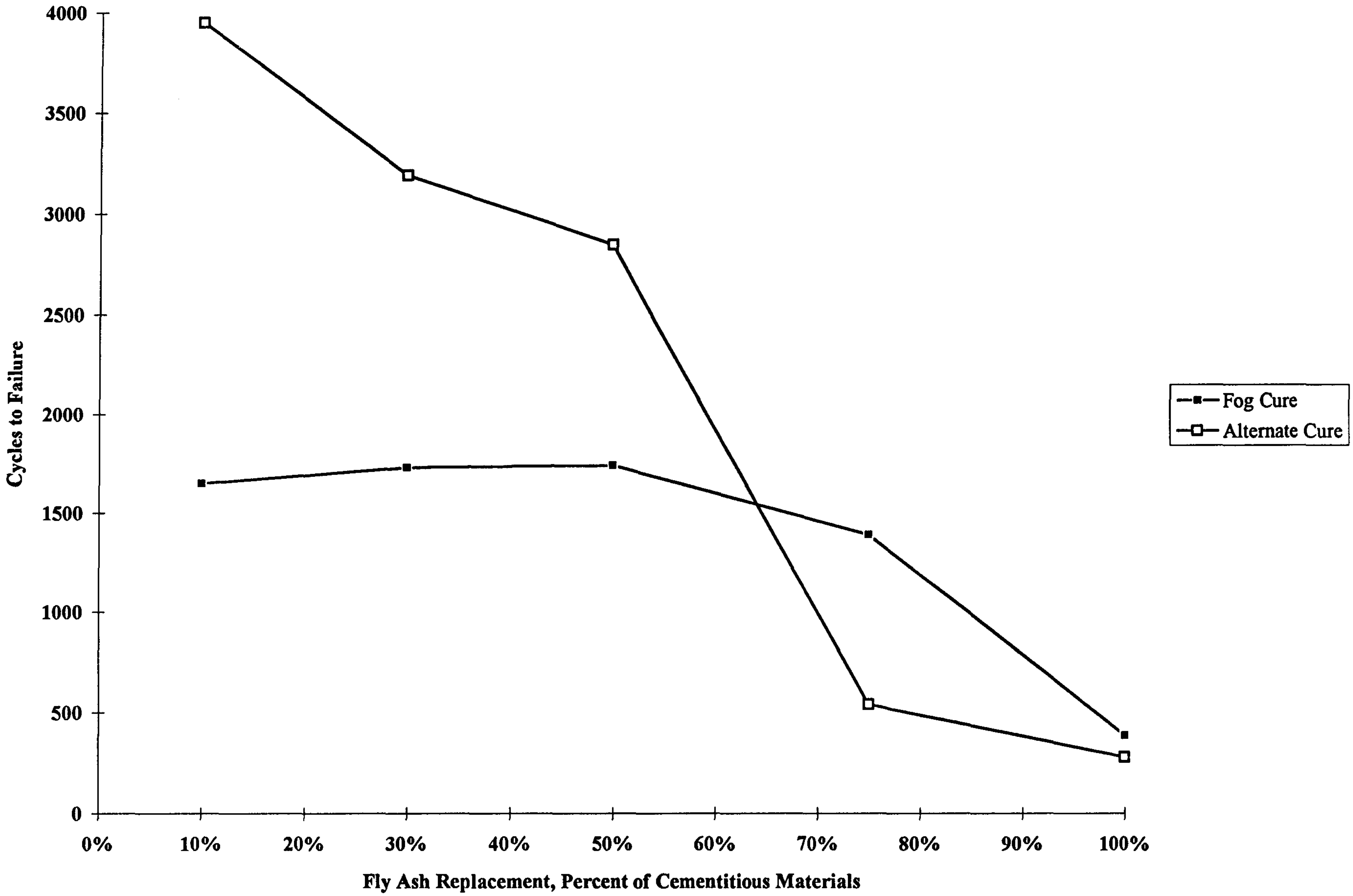

Figure 6. - Comparison of different curing methods, fly ash replacement versus freeze-thaw durability (645-lbm/yd[3] cementitious material, high lime class C fly ash).

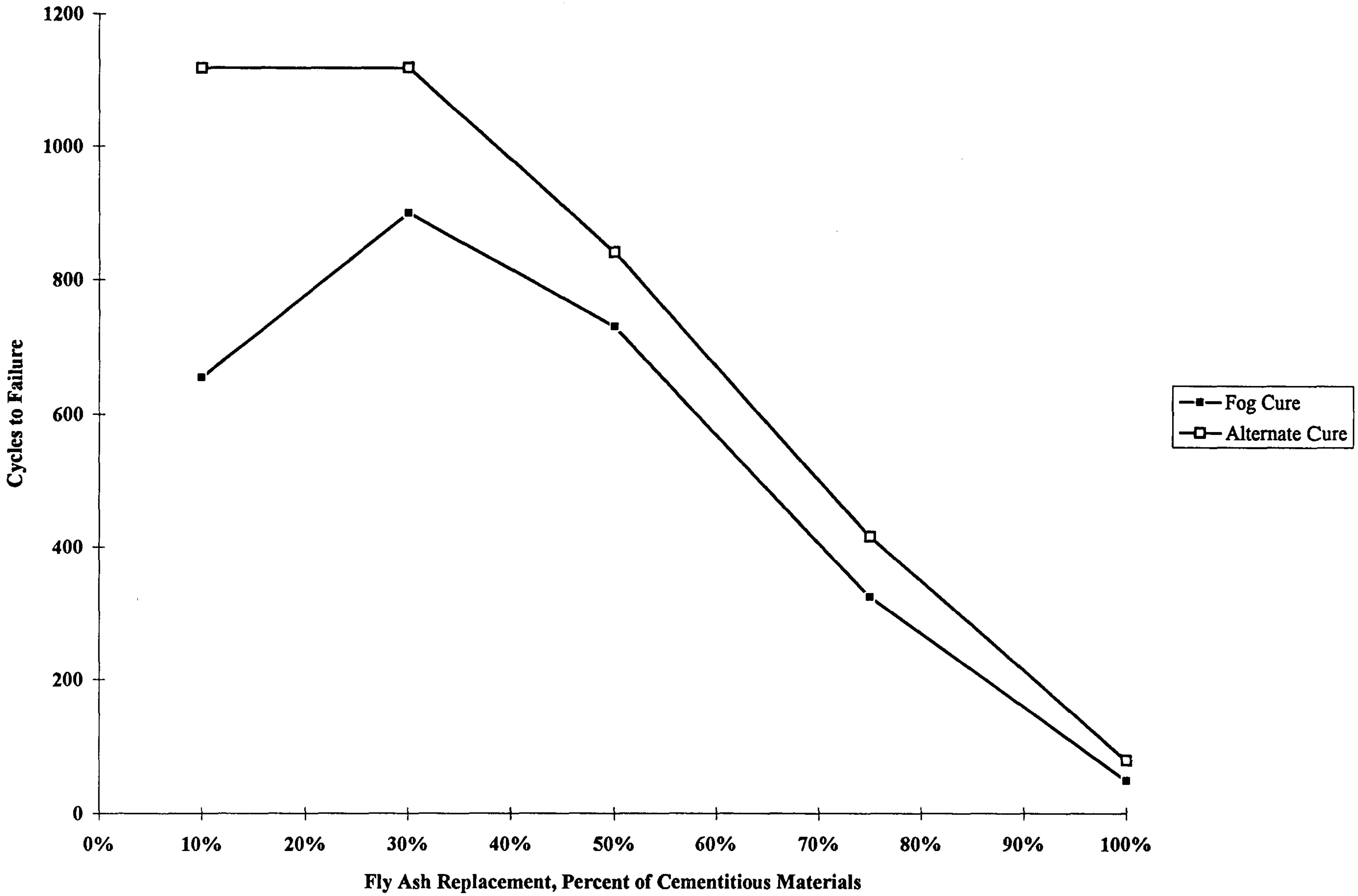

Figure 7. - Comparison of different curing methods, fly ash replacement versus freeze-thaw durability (424-lbm/yd^3 cementitious material, low lime class C fly ash).

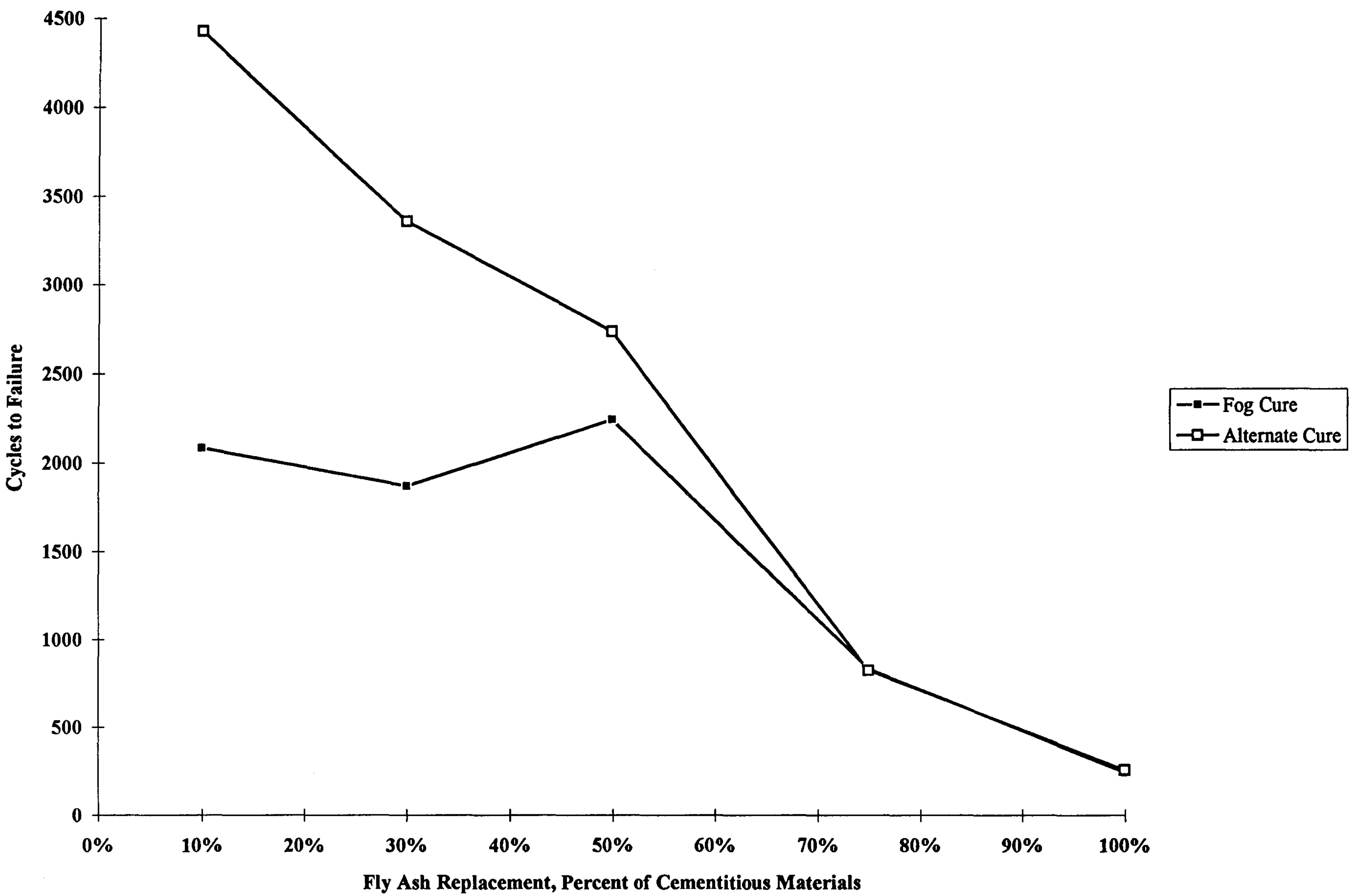

Figure 8. - Comparison of different curing methods, fly ash replacement versus freeze-thaw durability (645-lbm/yd^3 cementitious material, low lime class C fly ash).

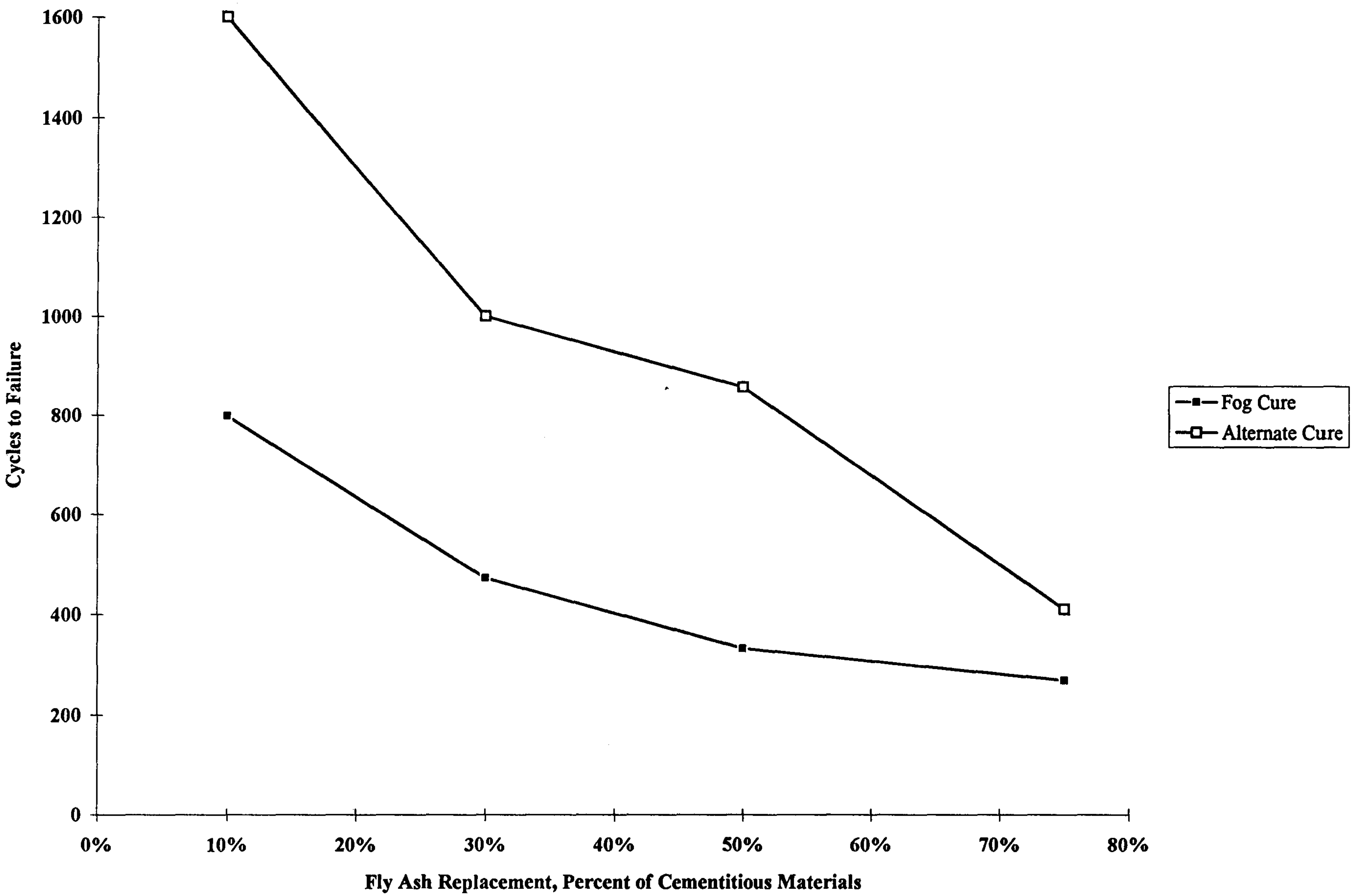

Figure 9. - Comparison of different curing methods, fly ash replacement versus freeze-thaw durability (424-lbm/yd^3 cementitious material, class F fly ash).

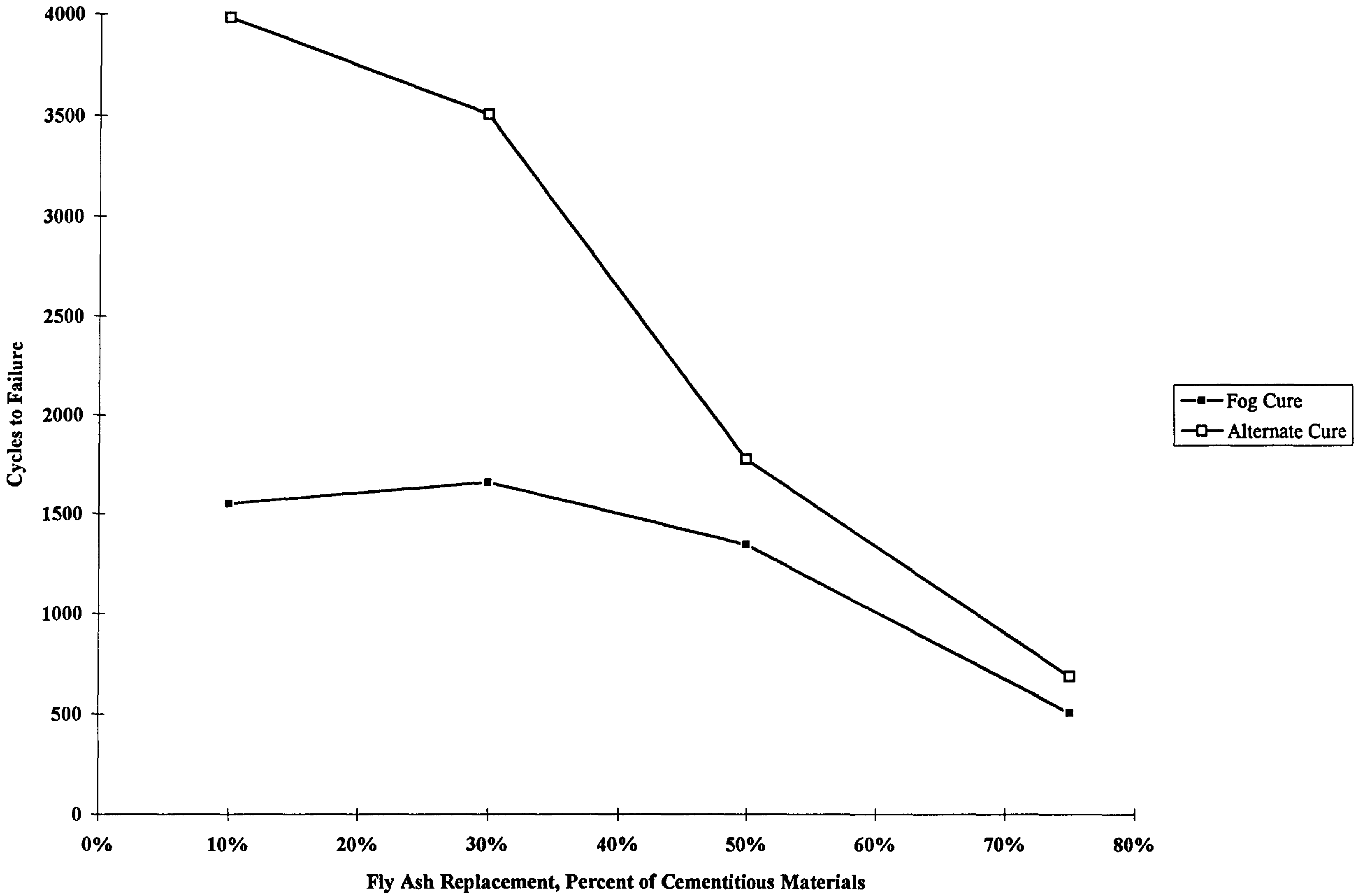

Figure 10. - Comparison of different curing methods, fly ash replacement versus freeze-thaw durability (645-lbm/yd^3 cementitious material, class F fly ash).

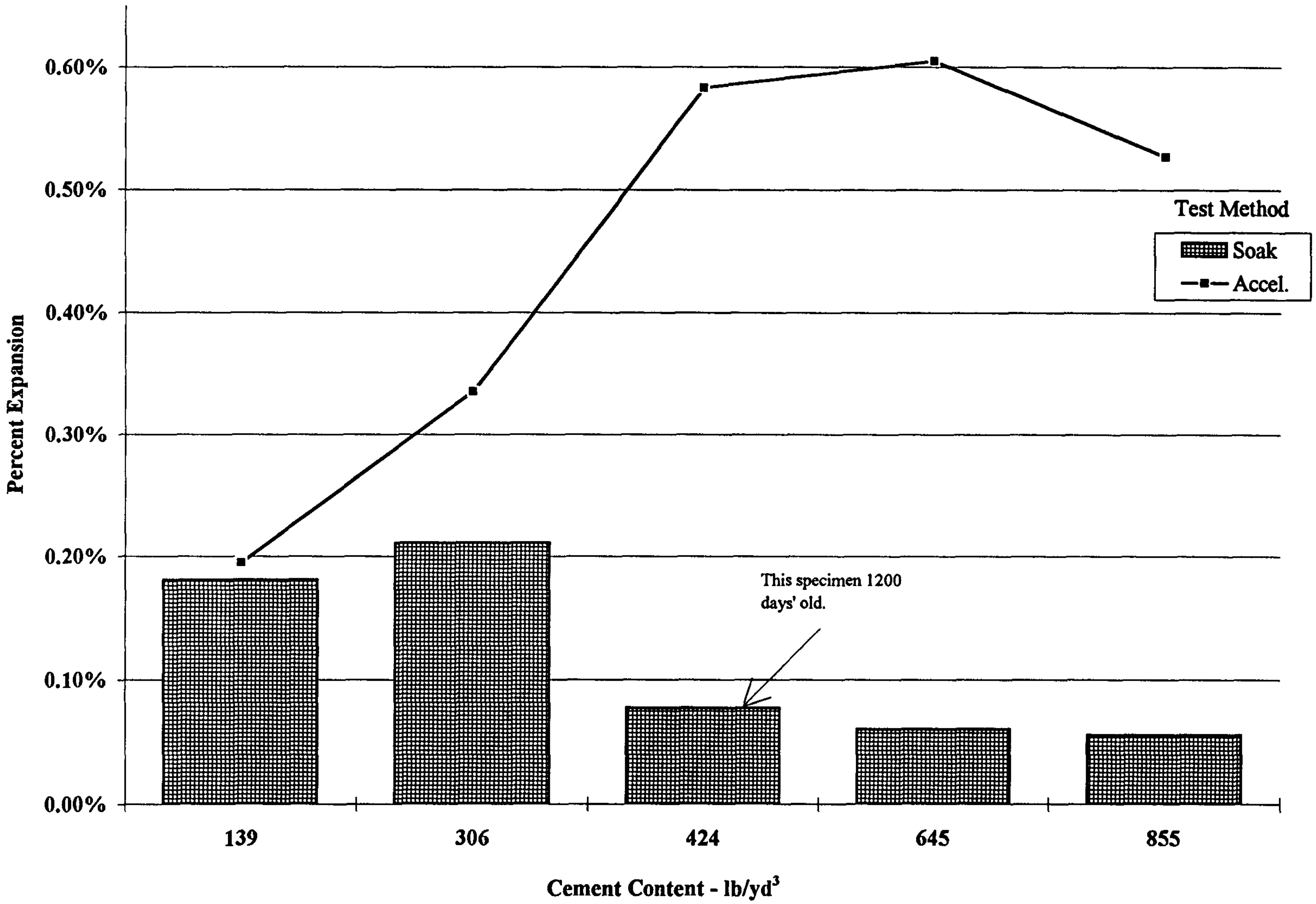

Figure 11. - Expansion versus cement content for the control specimens at about 1650 to 1750 days.

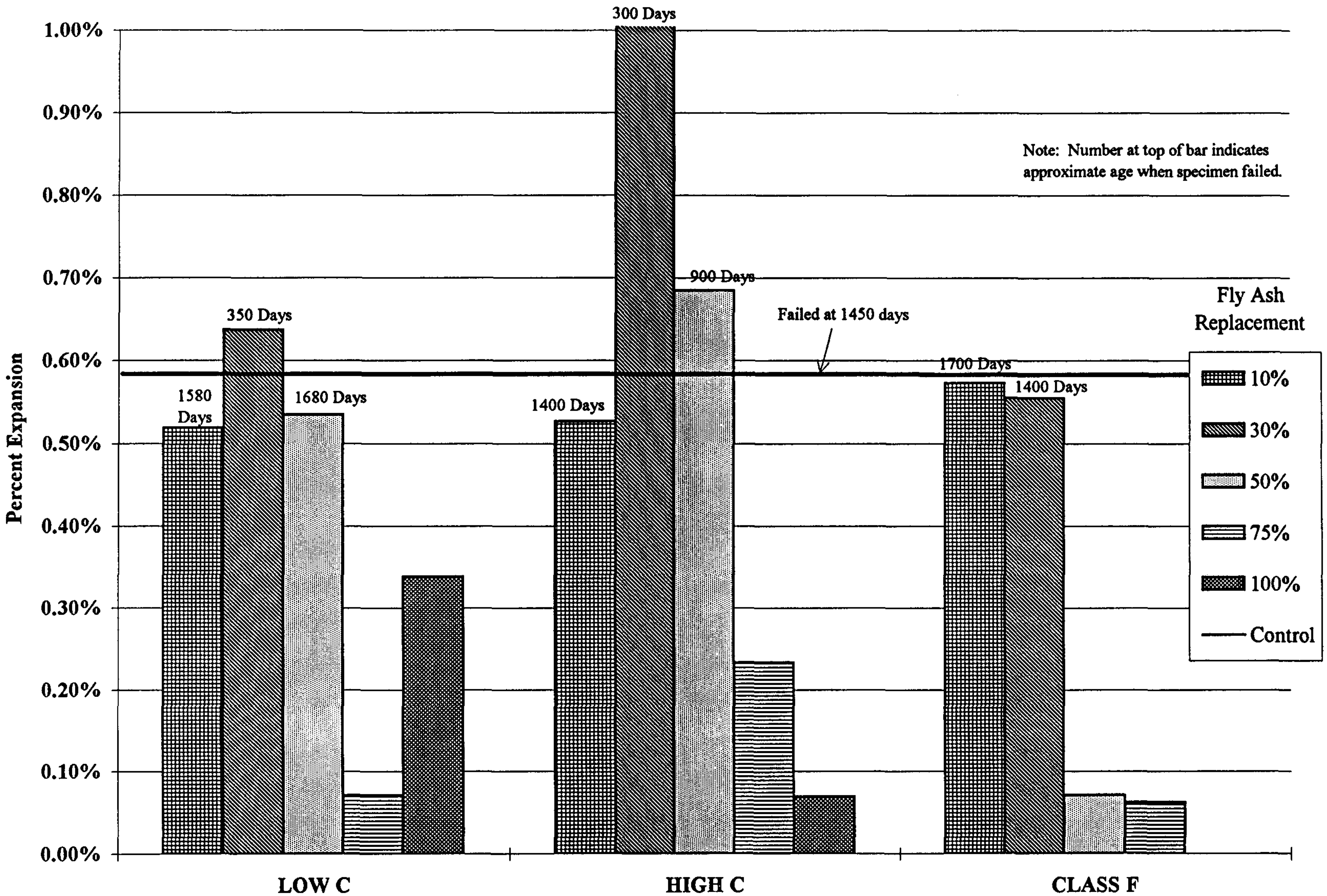

Figure 12. - Expansion of fly ash mixtures with 424 lbm/yd^3 of cementitious materials at about 1650 to 1750 days (accelerated test).

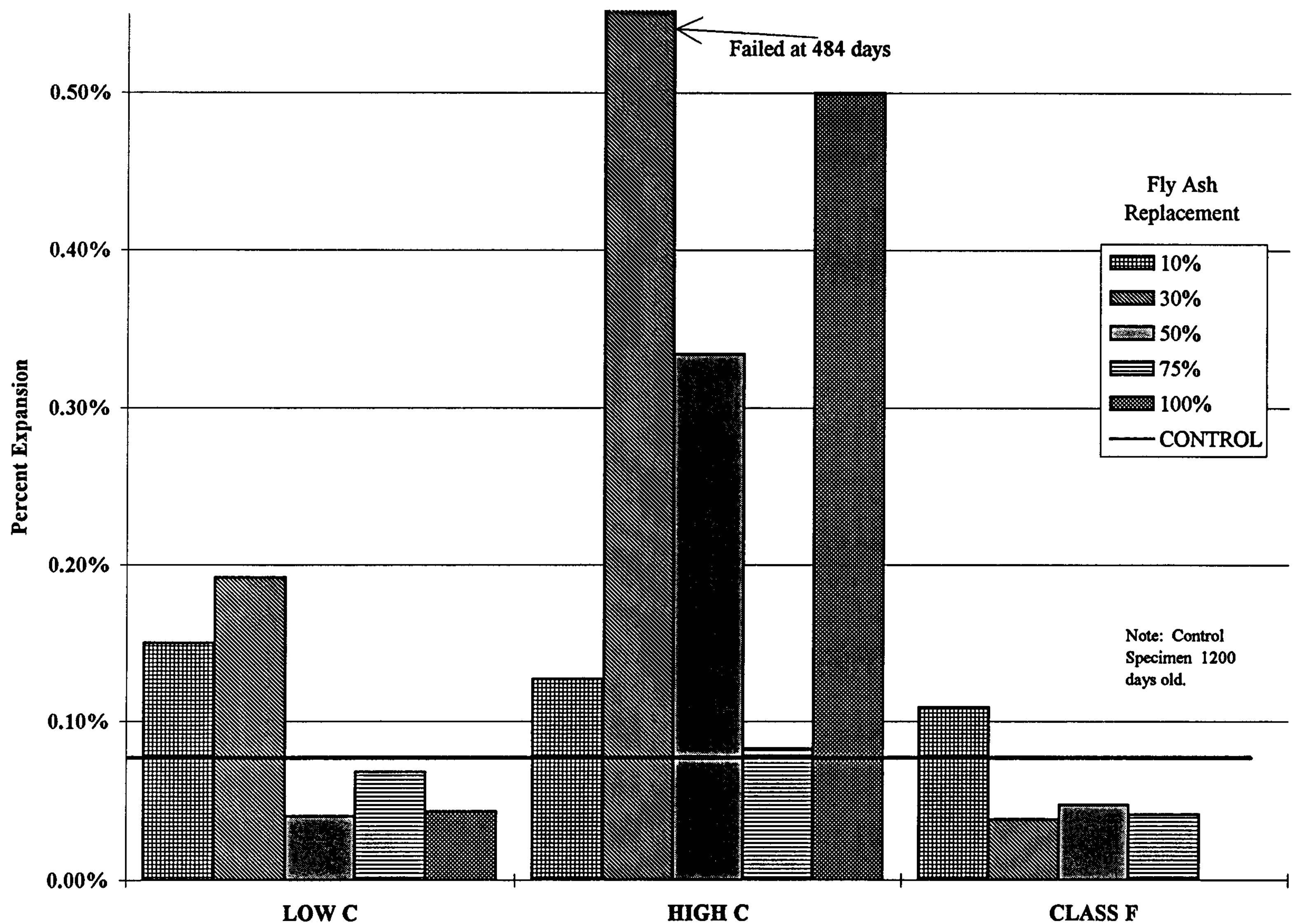

Figure 13. - Expansion of fly ash mixtures with 424 lbm/yd^3 of cementitious materials at about 1650 to 1750 days (soak test).

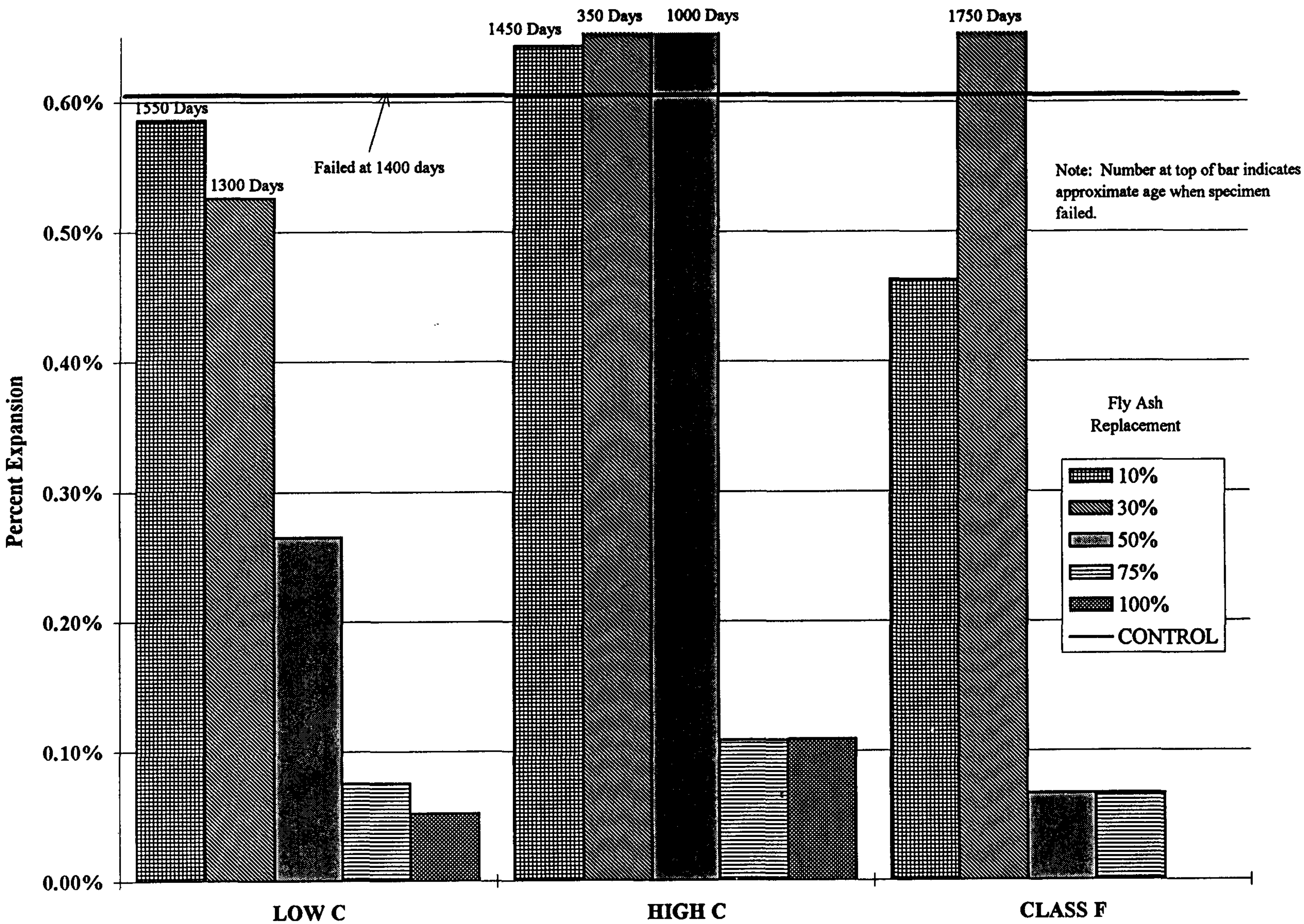

Figure 14. - Expansion of fly ash mixtures with 645 lbm/yd^3 of cementitious materials at about 1650 to 1750 days (accelerated test).

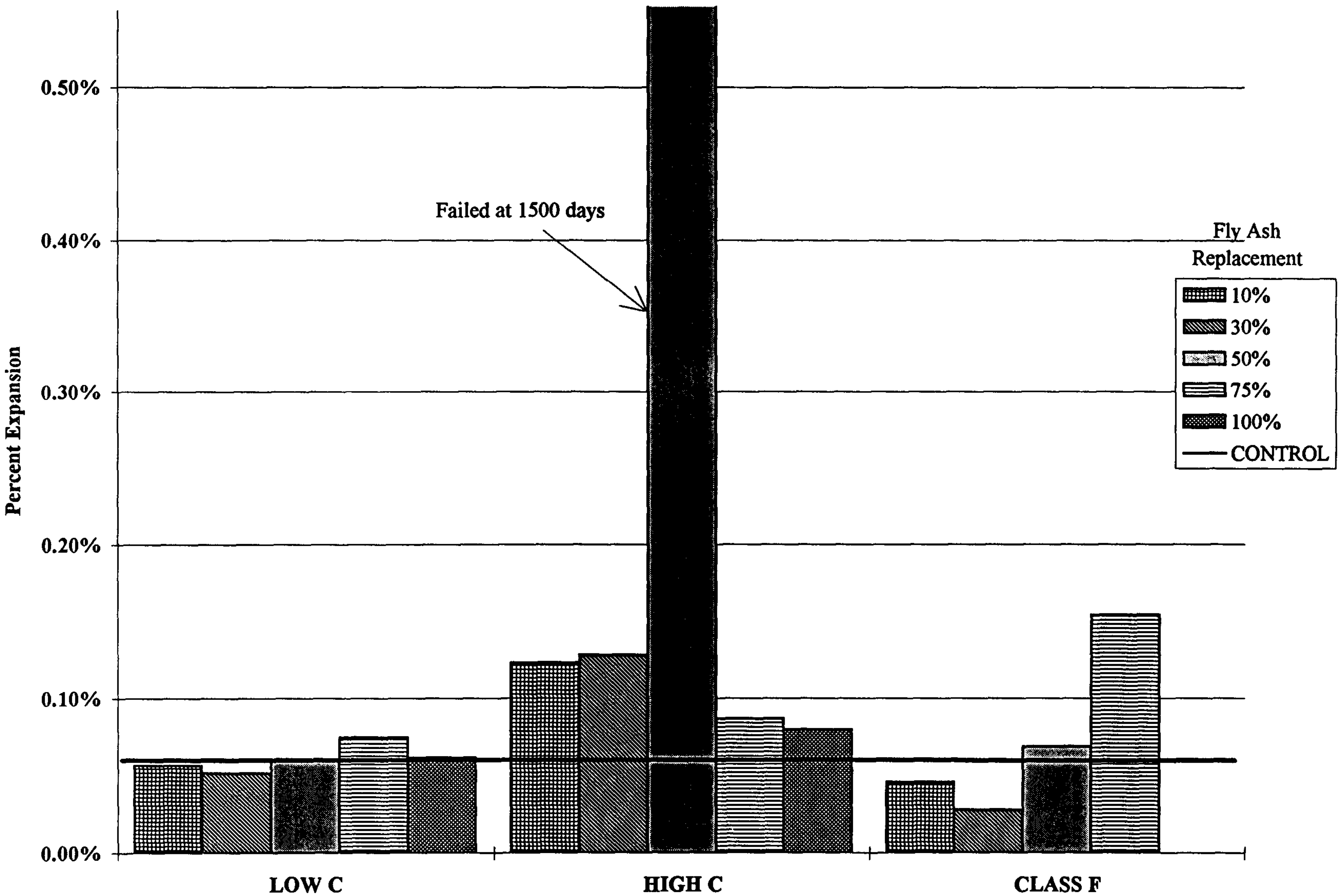

Figure 15. - Expansion of fly ash mixtures with 645 lbm/yd^3 of cementitious materials at about 1650 to 1750 days (soak test).

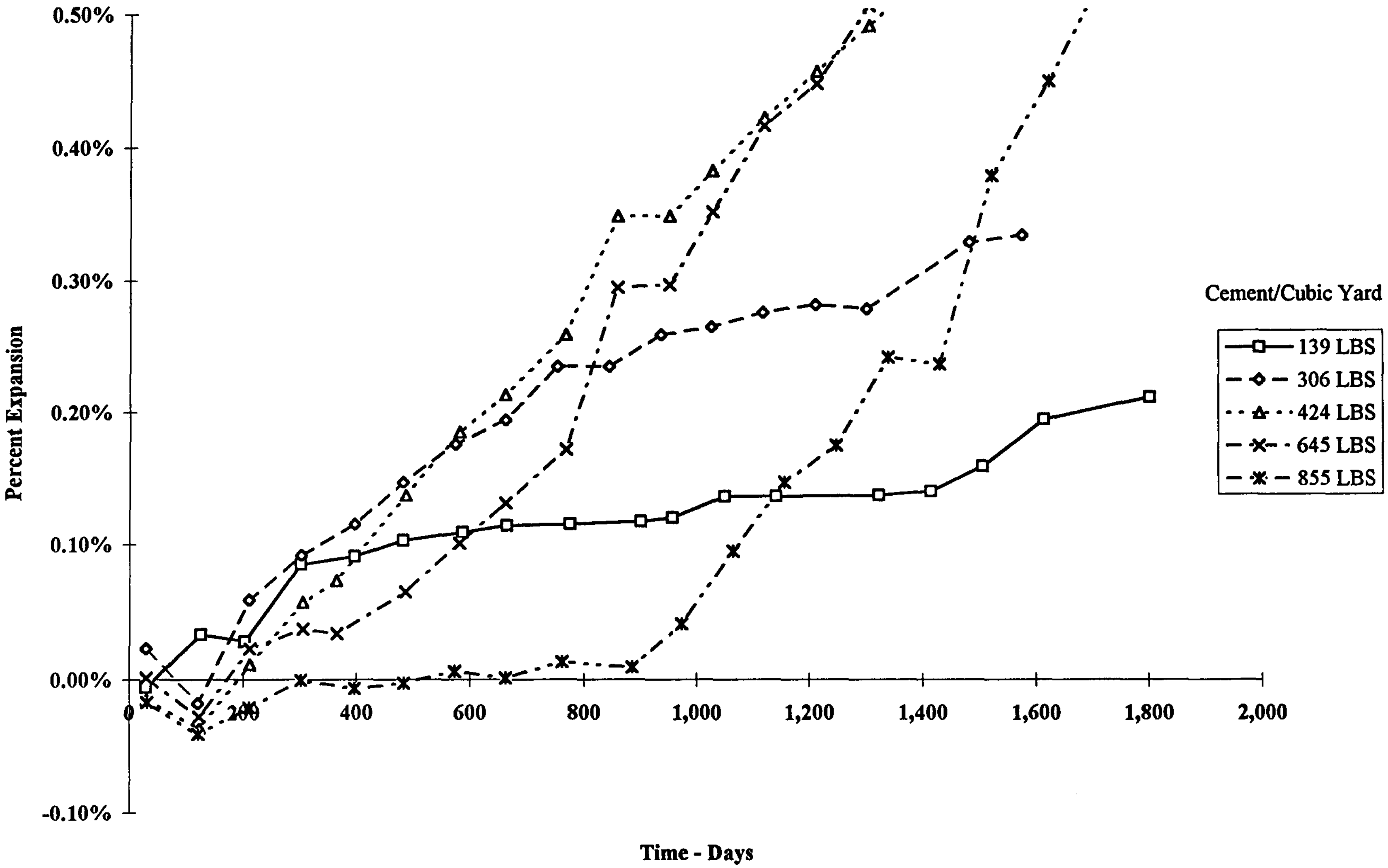

Figure 16. - Expansion versus time for control specimens (accelerated test; 100% cement).

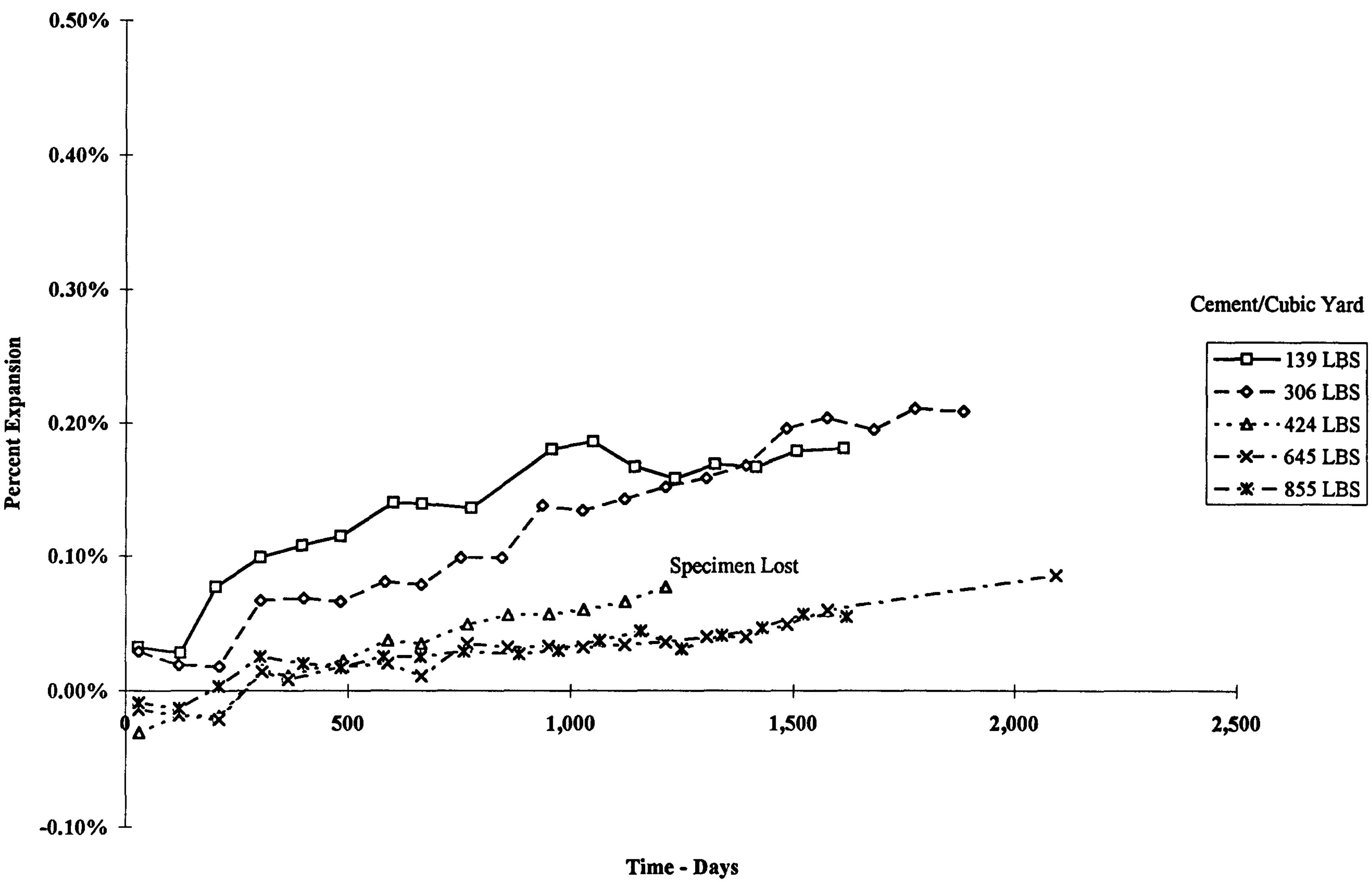

Figure 17. - Expansion versus time for control specimens (soak test; 100% cement).

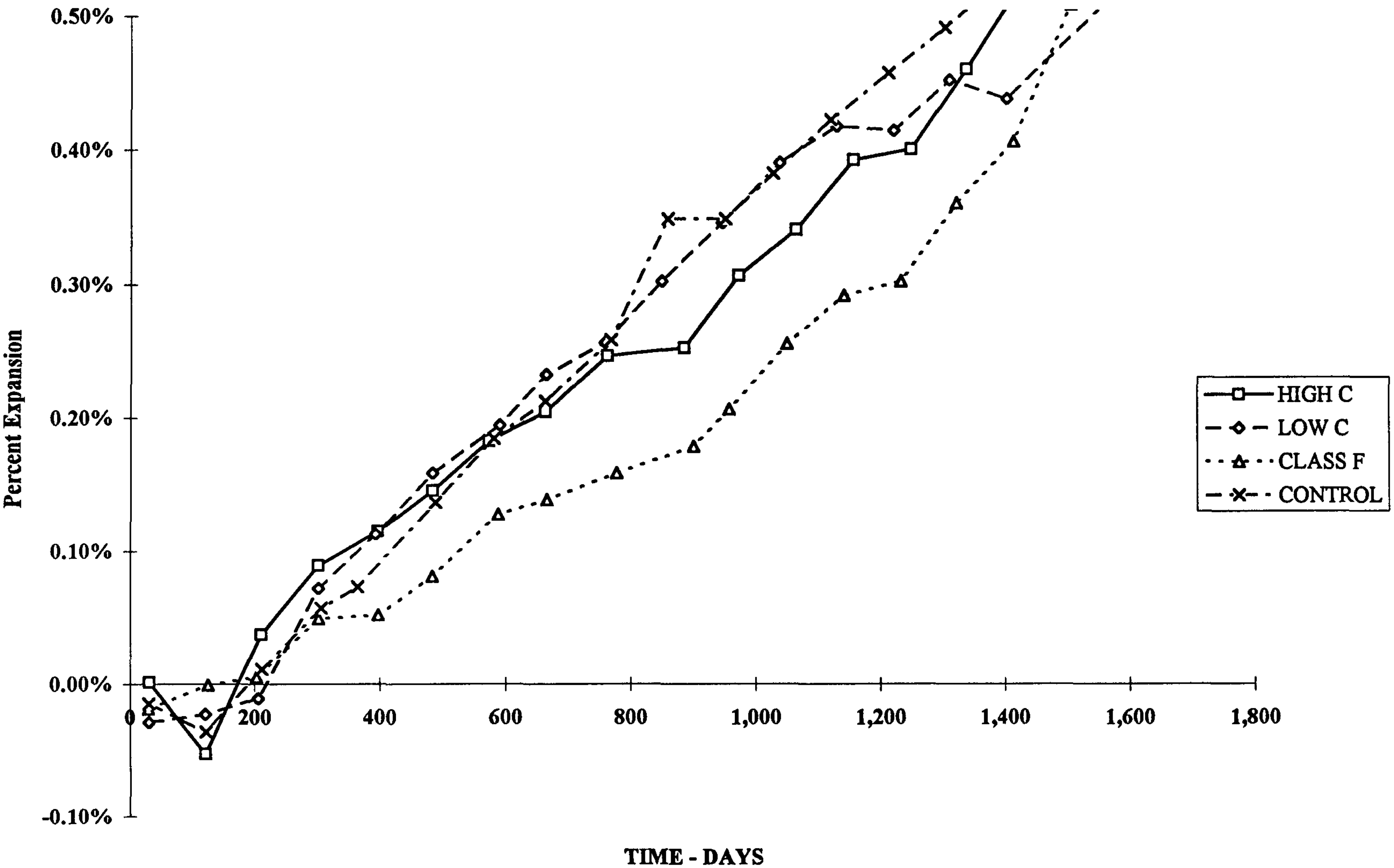

Figure 18. - Expansion versus time for 424 lbm/yd^3 of cementitious materials (accelerated test; 10% replacement level).

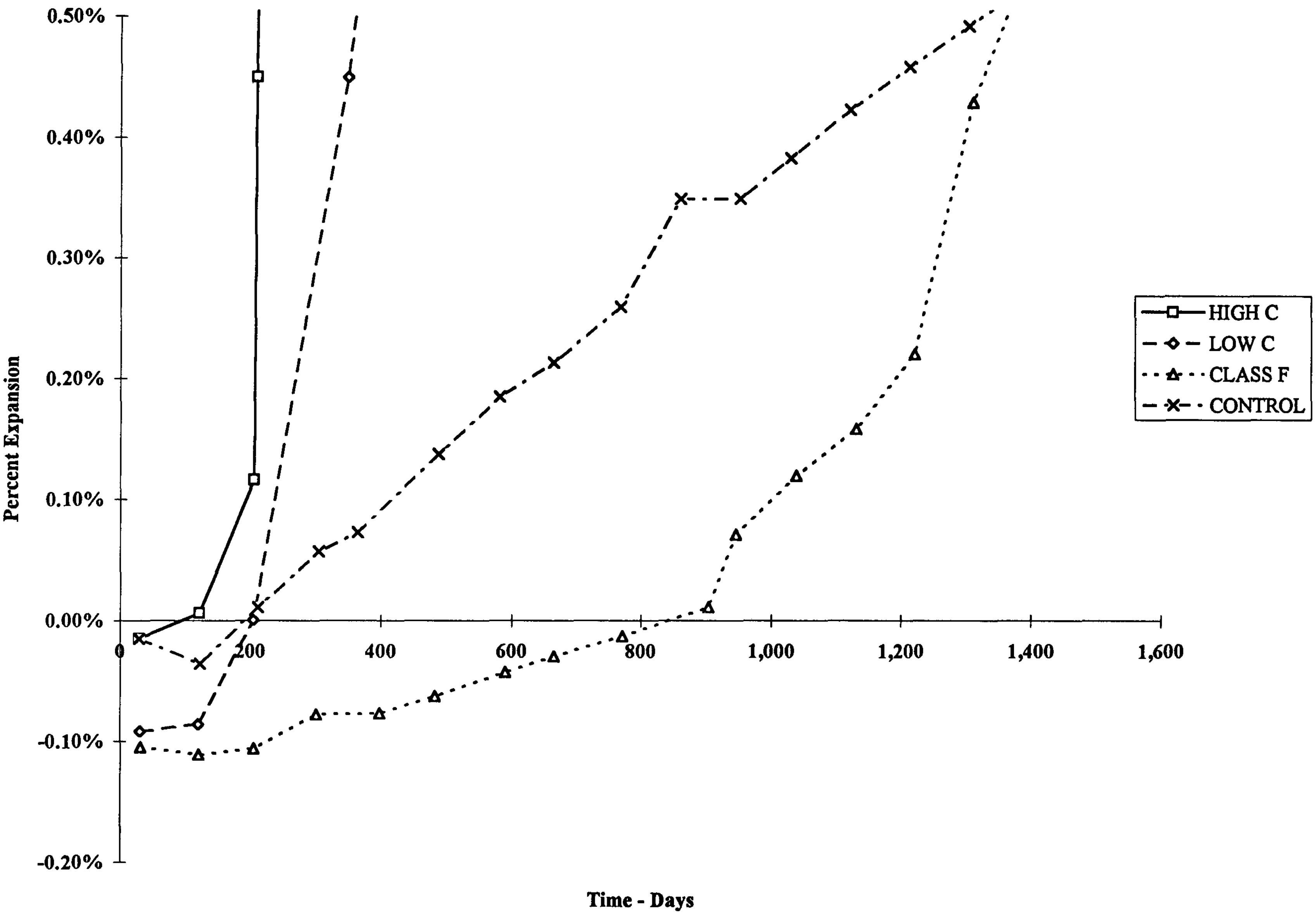

Figure 19. - Expansion versus time for 424 lbm/yd^3 of cementitious materials (accelerated test; 30% replacement level).

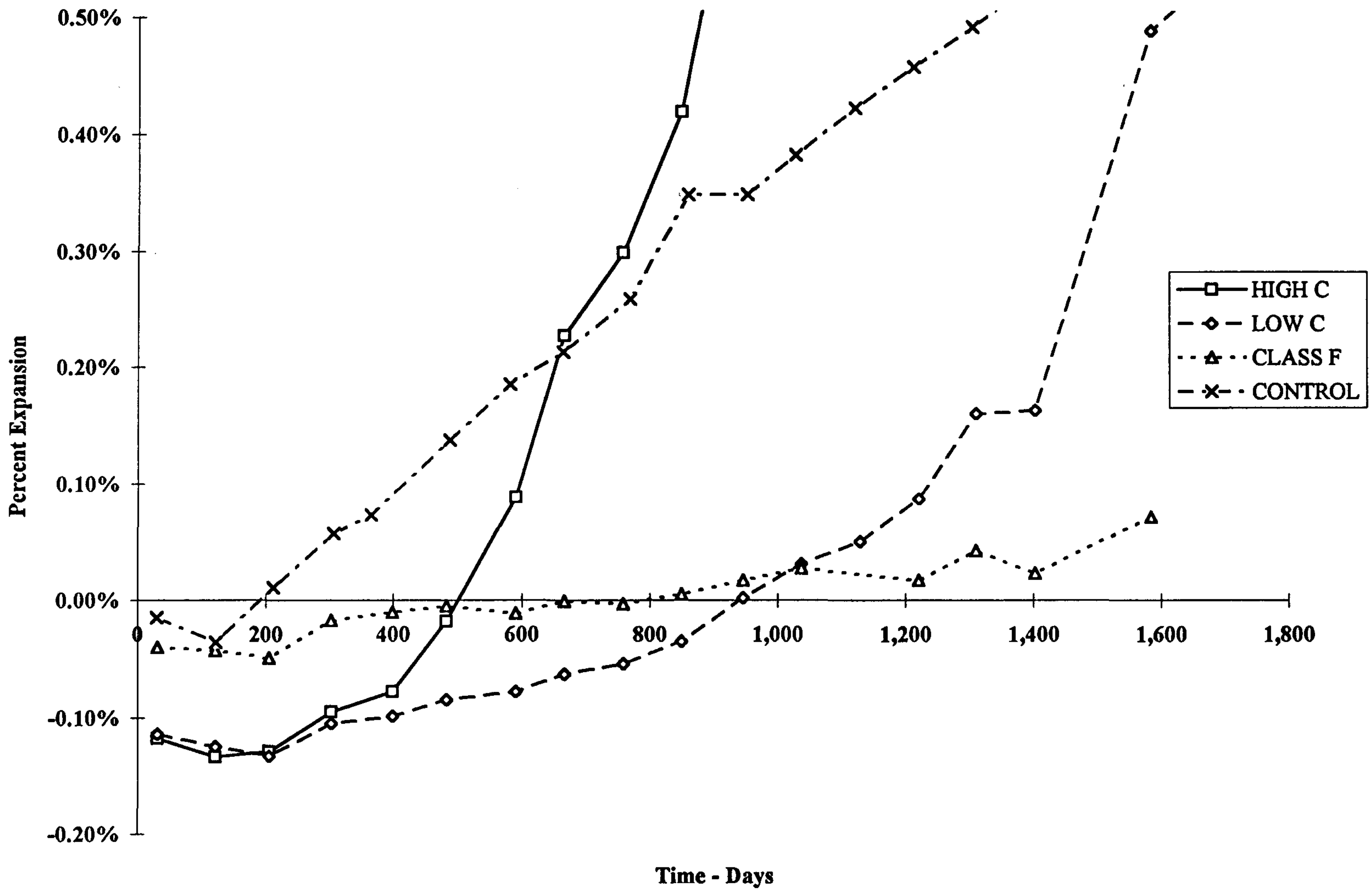

Figure 20. - Expansion versus time for 424 lbm/yd³ of cementitious materials (accelerated test; 50% replacement level).

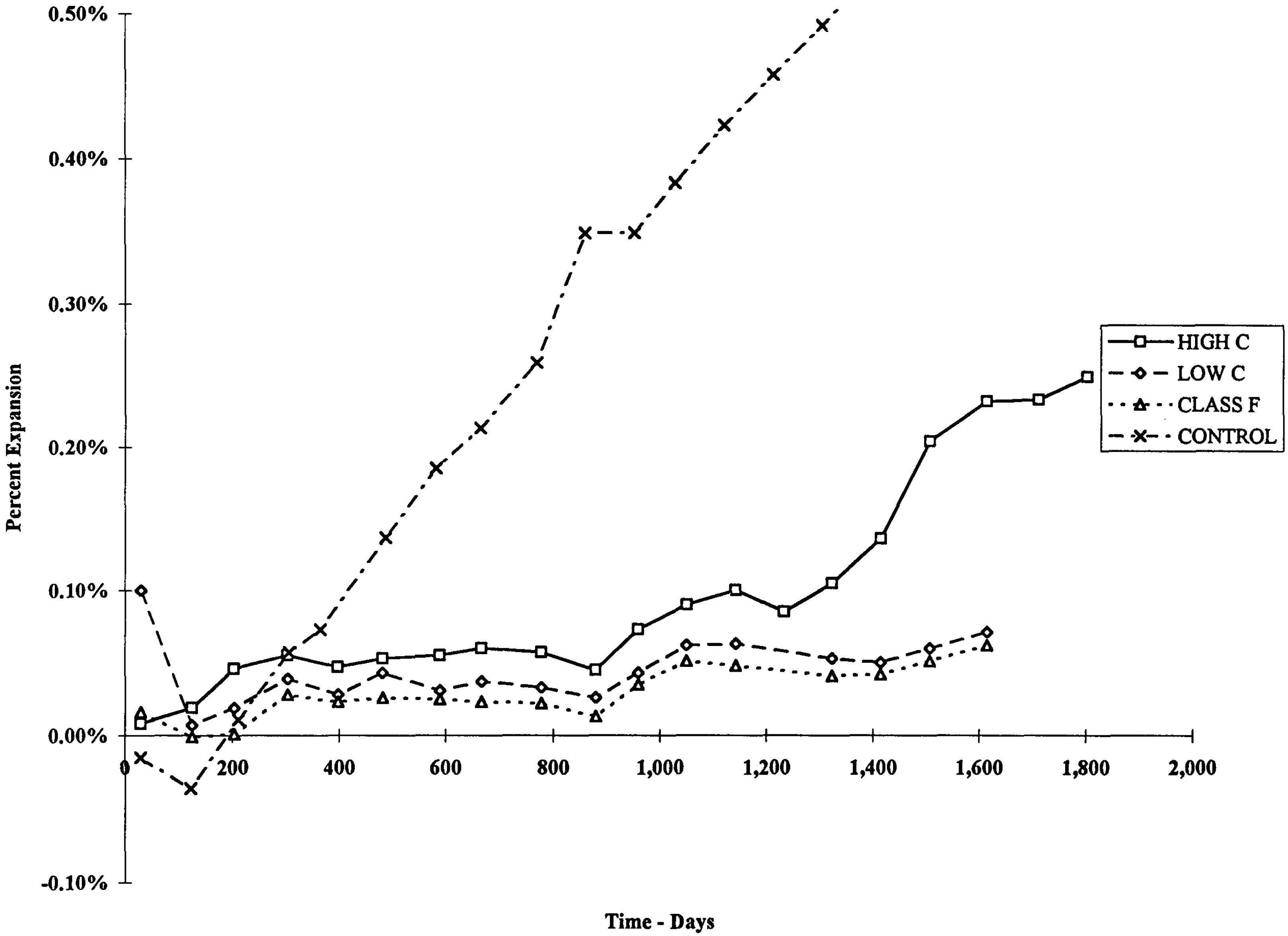

Figure 21. - Expansion versus time for 424 lbm/yd^3 of cementitious materials (accelerated test; 75% replacement level).

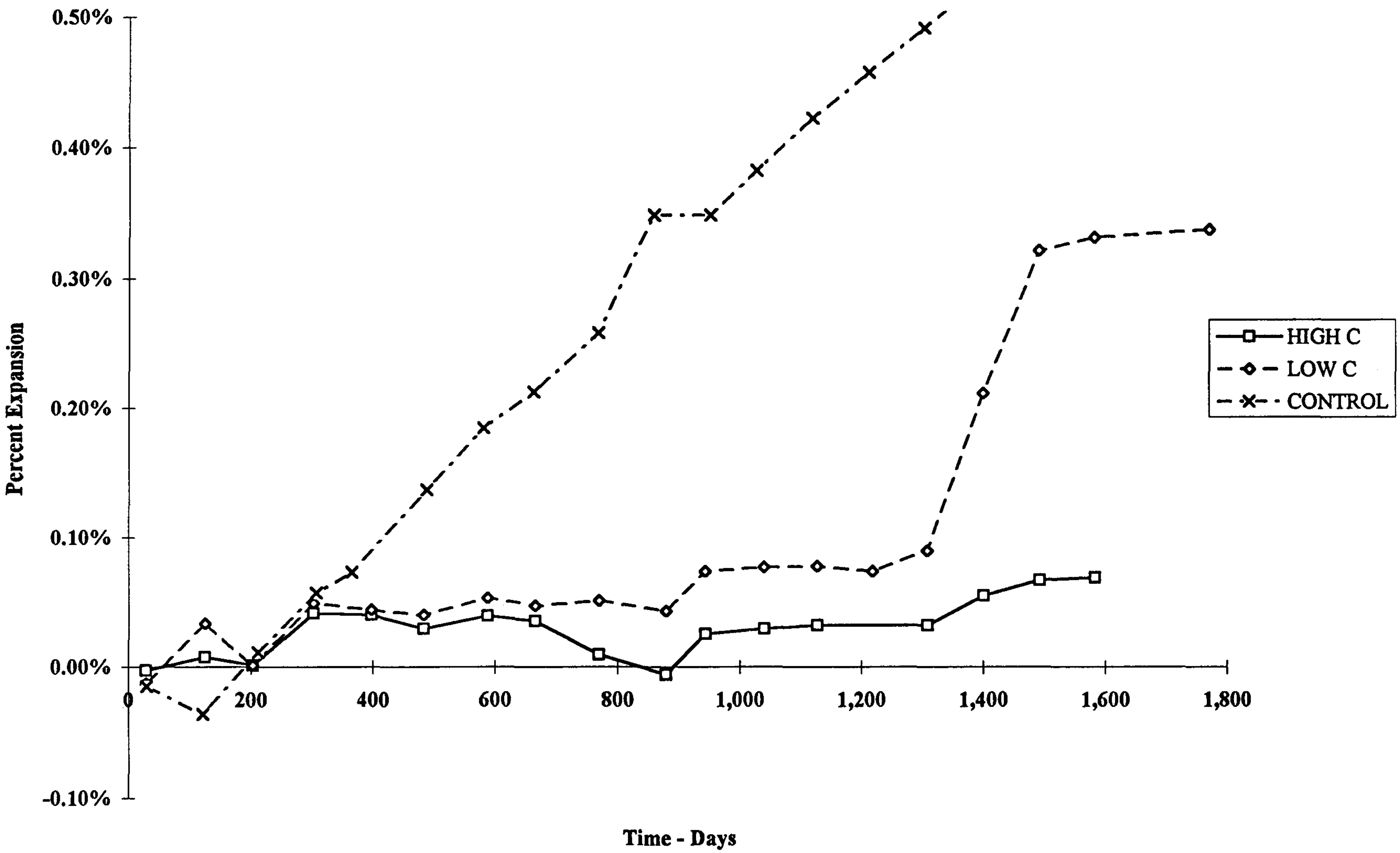

Figure 22. - Expansion versus time for 424 lbm/yd³ of cementitious materials (accelerated test; 100% replacement level).

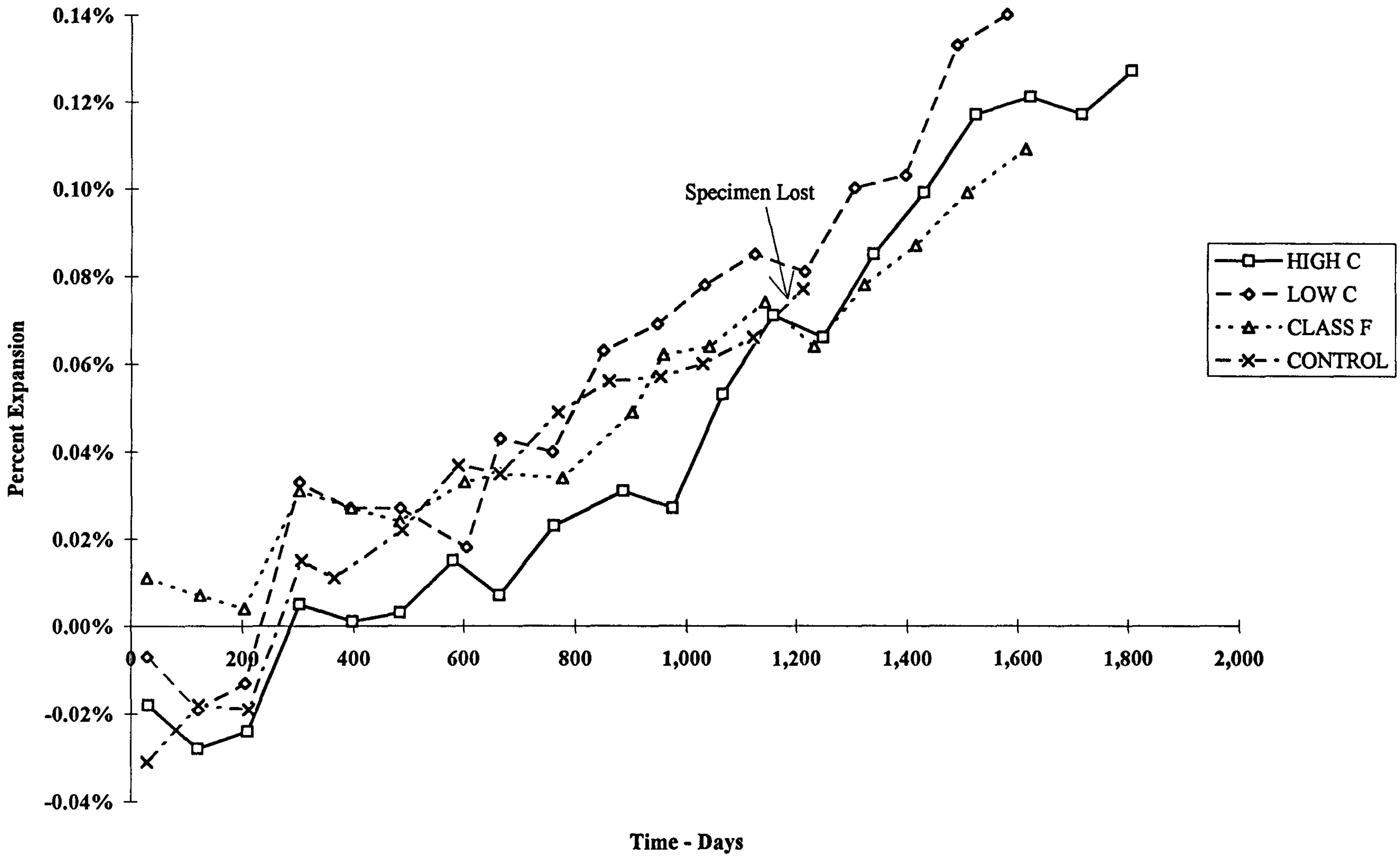

Figure 23. - Expansion versus time for 424 lbm/yd³ of cementitious materials (soak test; 10% replacement level).

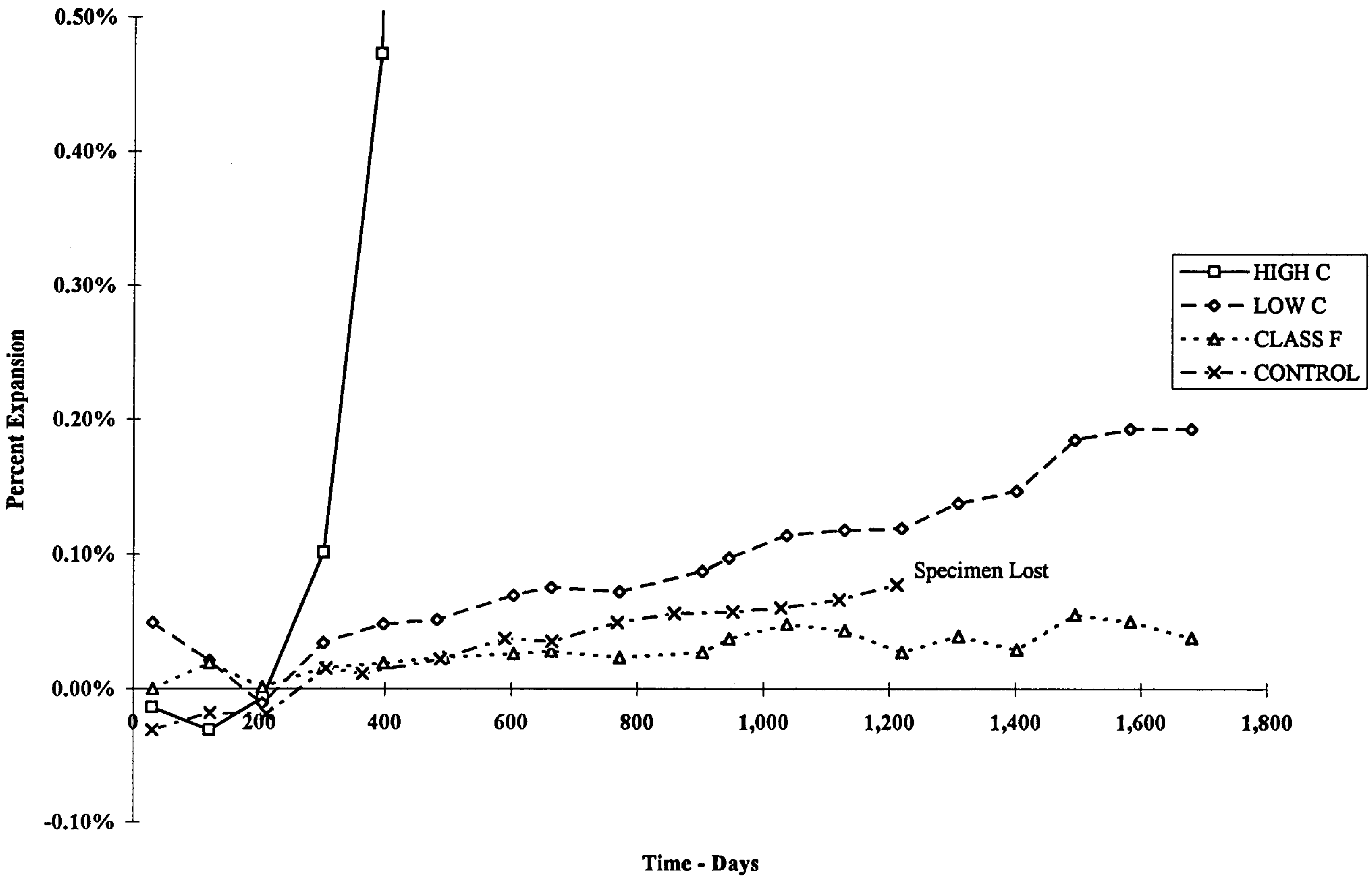

Figure 24. - Expansion versus time for 424 lbm/yd^3 of cementitious materials (soak test; 30% replacement level).

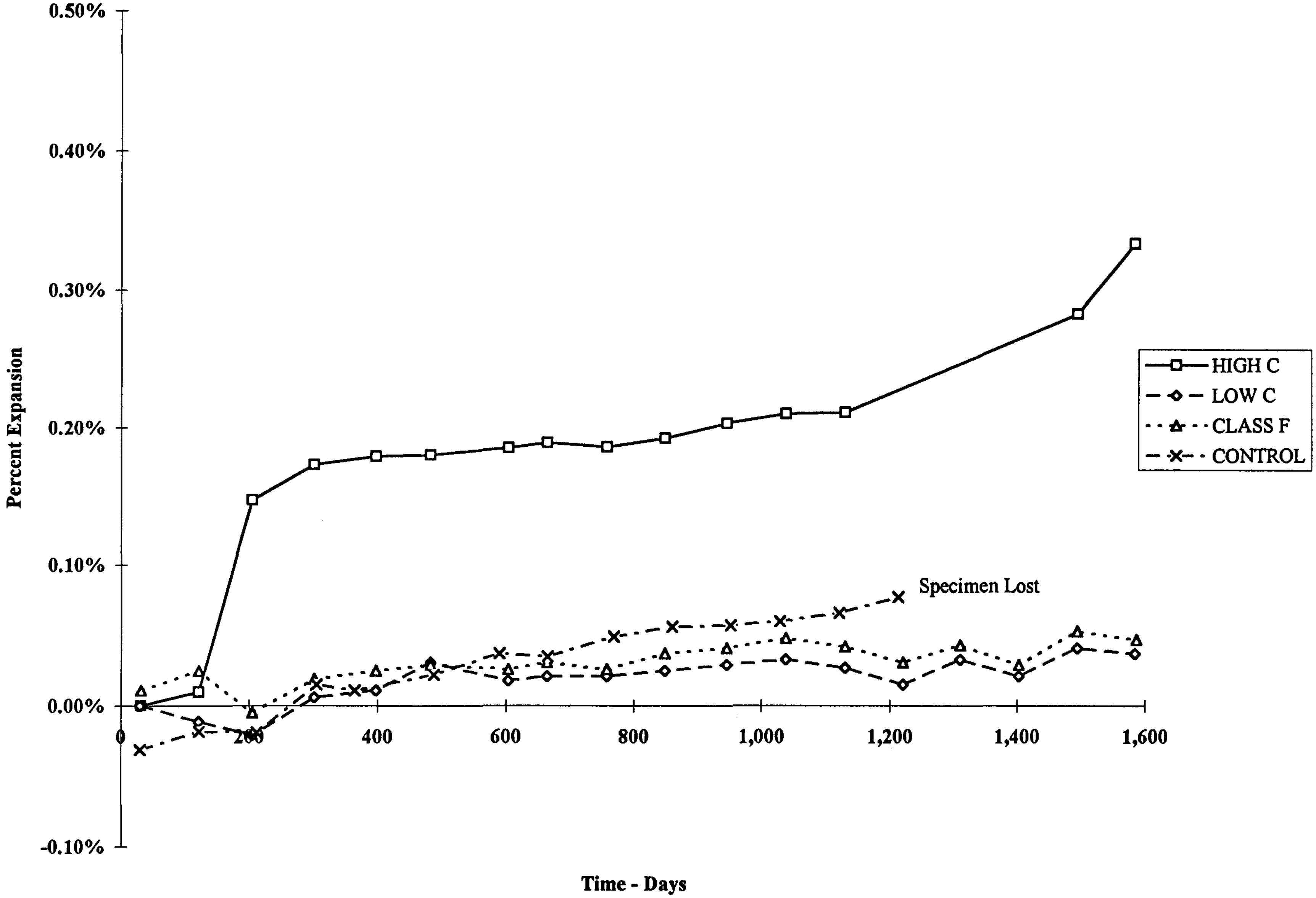

Figure 25. - Expansion versus time for 424 lbm/yd[3] of cementitious materials (soak test; 50% replacement level).

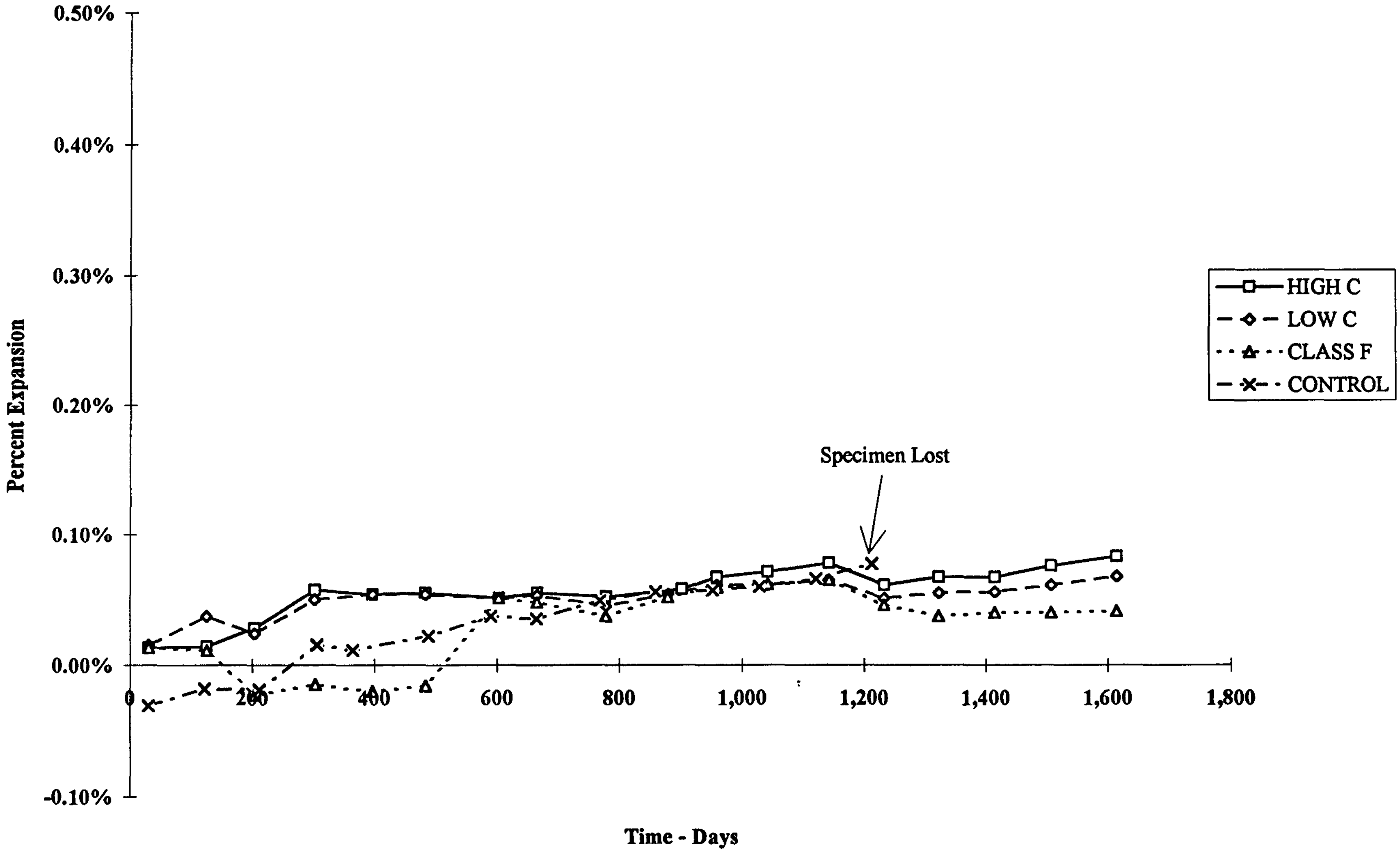

Figure 26. - Expansion versus time for 424 lbm/yd^3 of cementitious materials (soak test; 75% replacement level).

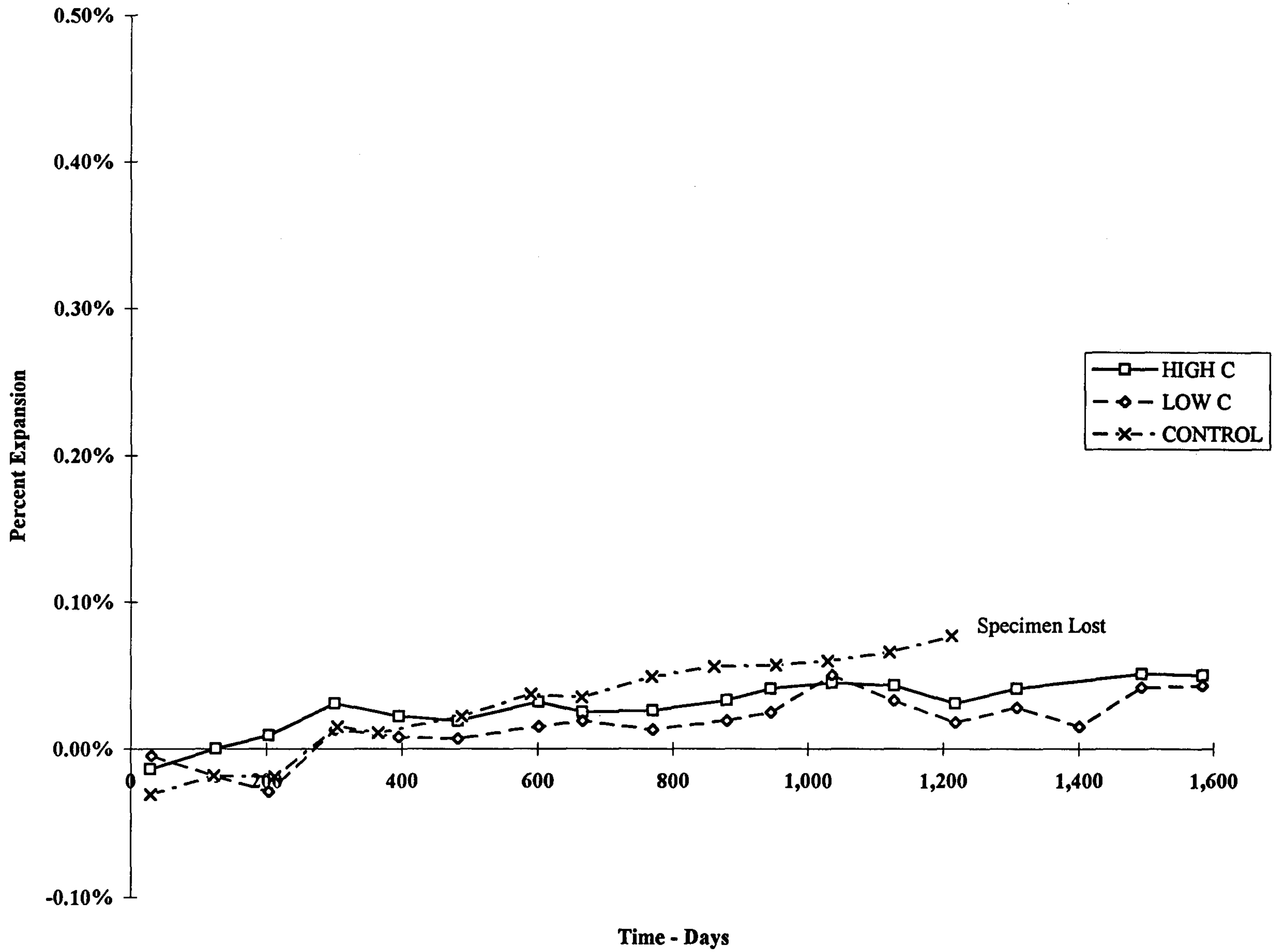

Figure 27. - Expansion versus time for 424 lbm/yd^3 of cementitious materials (soak test; 100% replacement level).

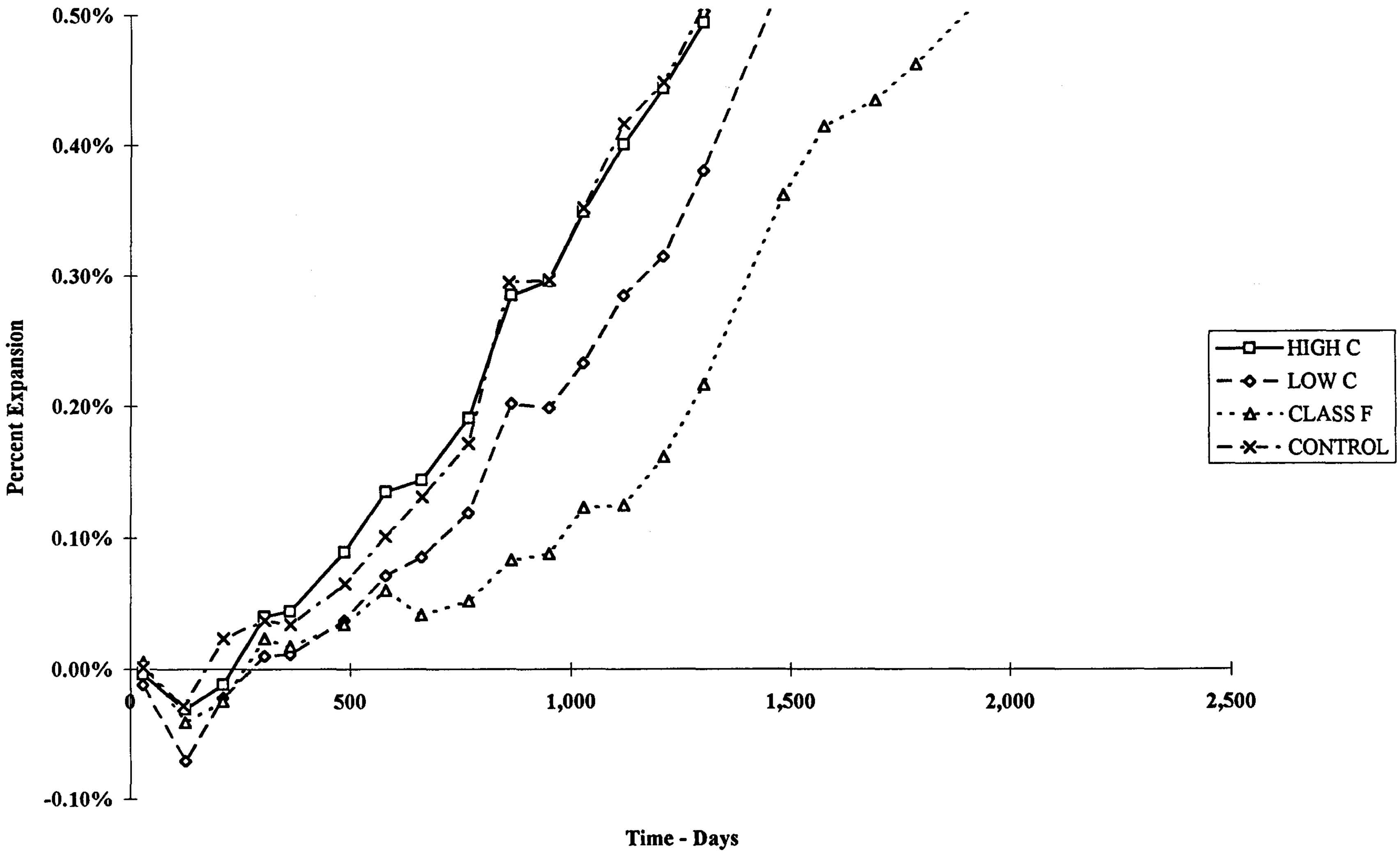

Figure 28. - Expansion versus time for 645 lbm/yd^3 of cementitious materials (accelerated test; 10% replacement level).

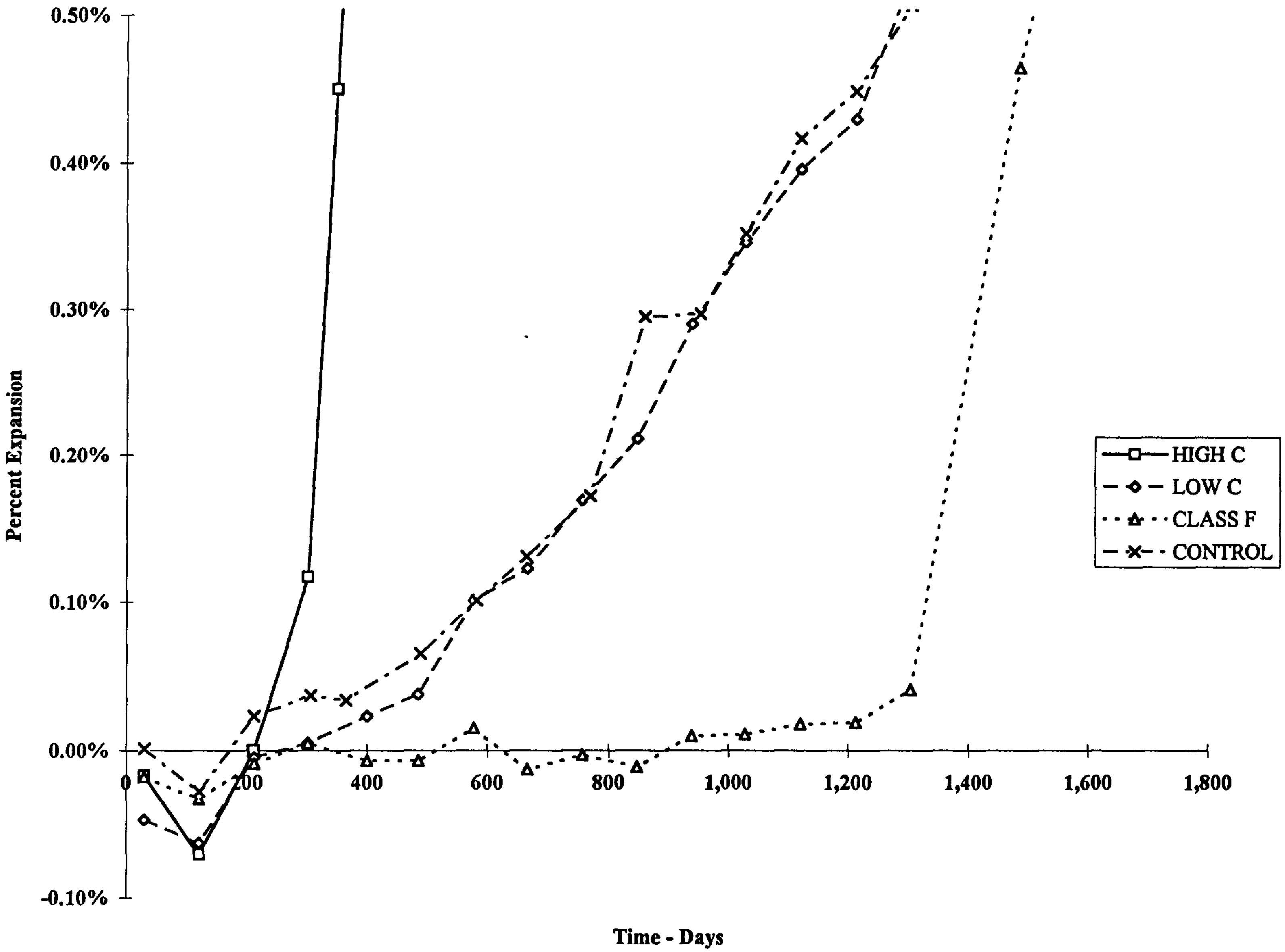

Figure 29. - Expansion versus time for 645 lbm/yd^3 of cementitious materials (accelerated test; 30% replacement level).

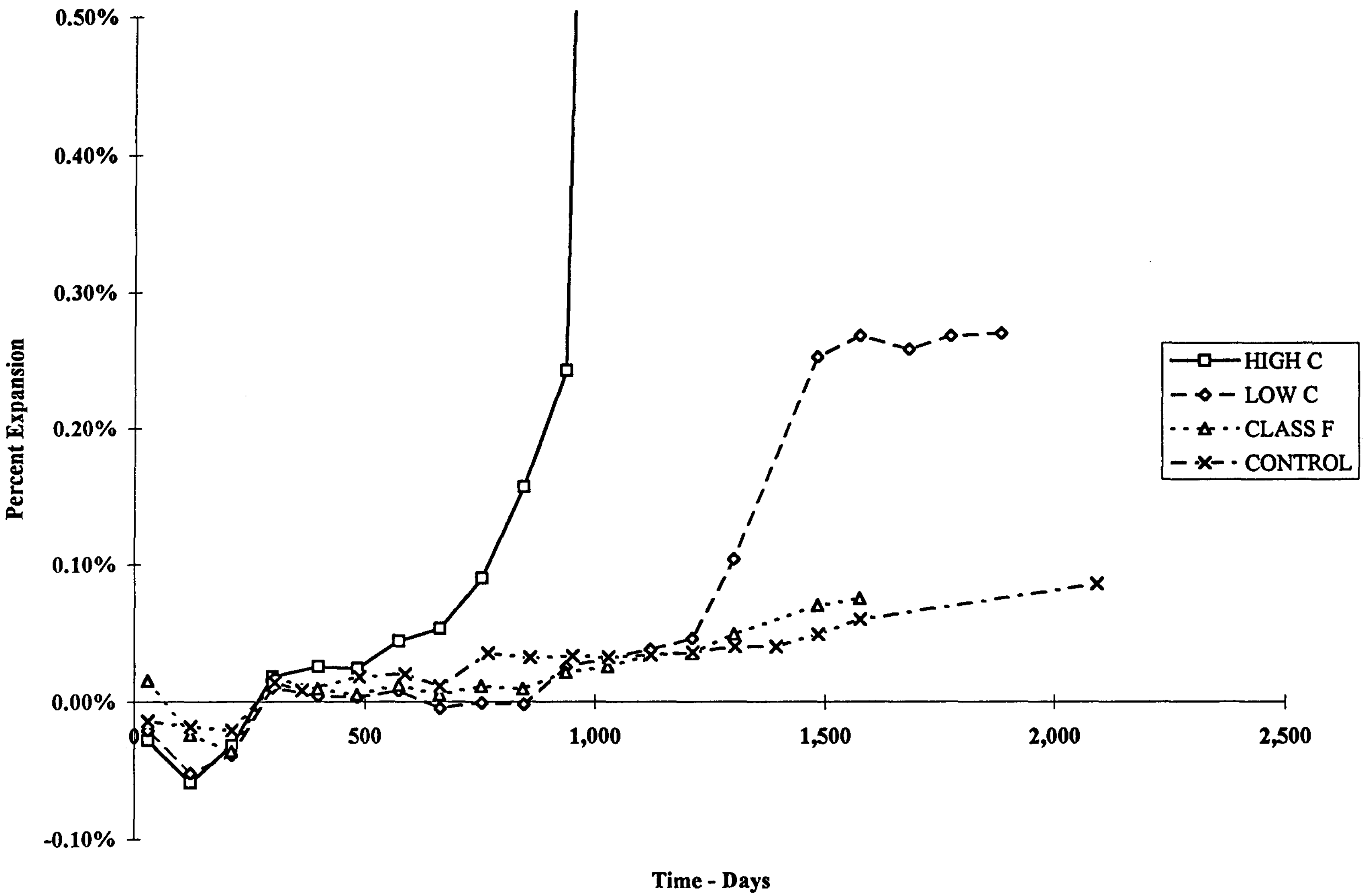

Figure 30. - Expansion versus time for 645 lbm/yd^3 of cementitious materials (accelerated test; 50% replacement level).

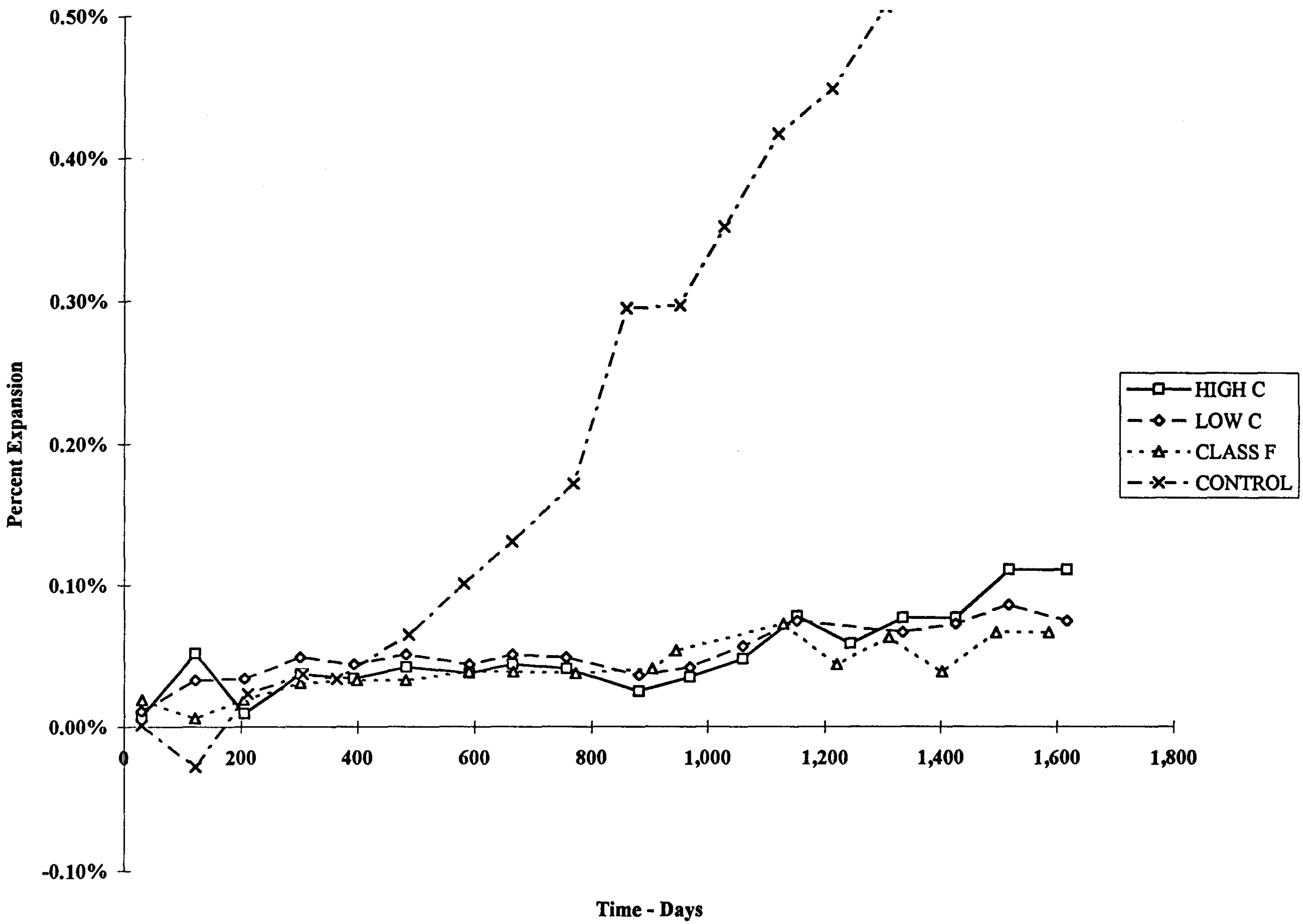

Figure 31. - Expansion versus time for 645 lbm/yd³ of cementitious materials (accelerated test; 75% replacement level).

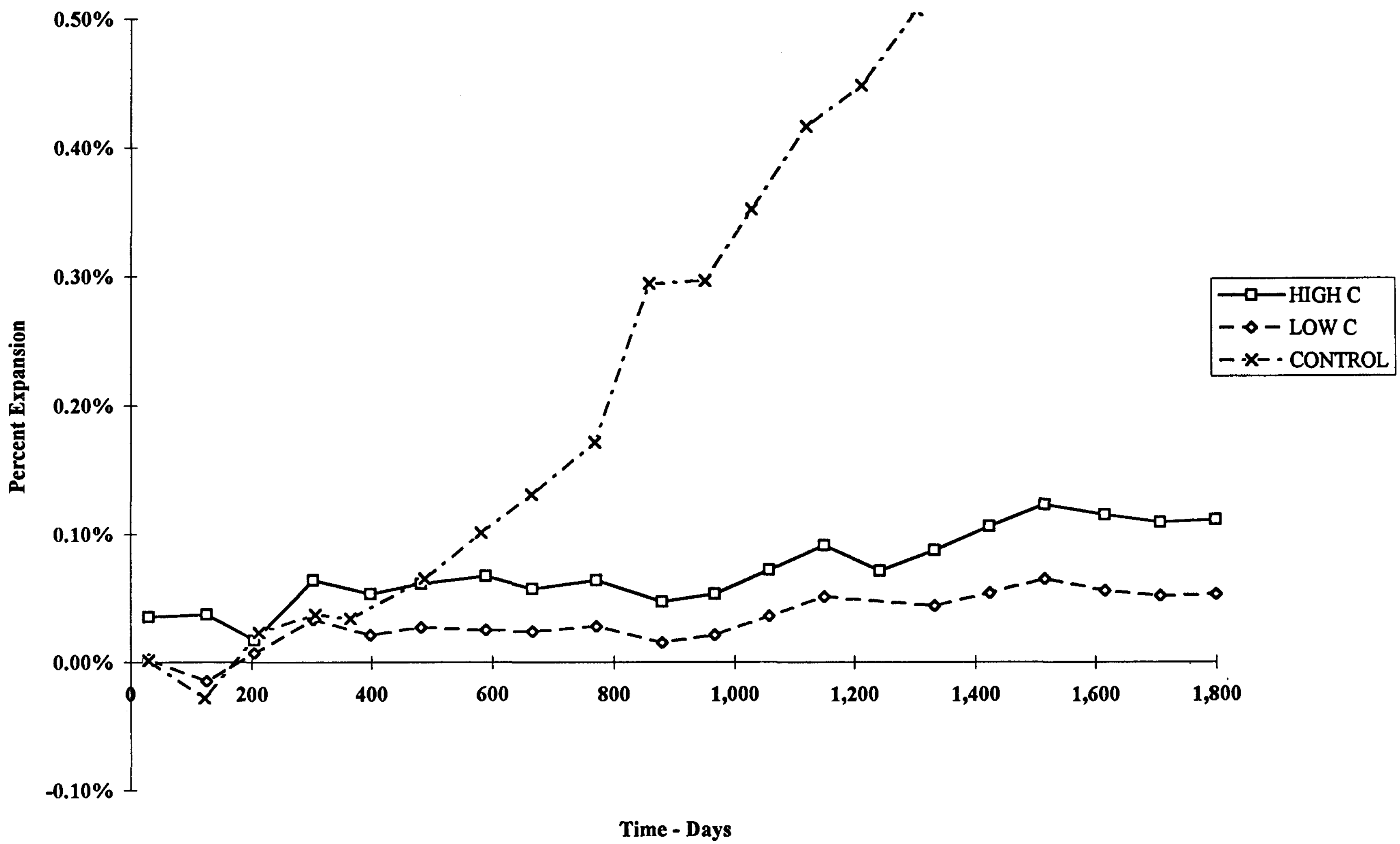

Figure 32. - Expansion versus time for 645 lbm/yd^3 of cementitious materials (accelerated test; 100% replacement level).

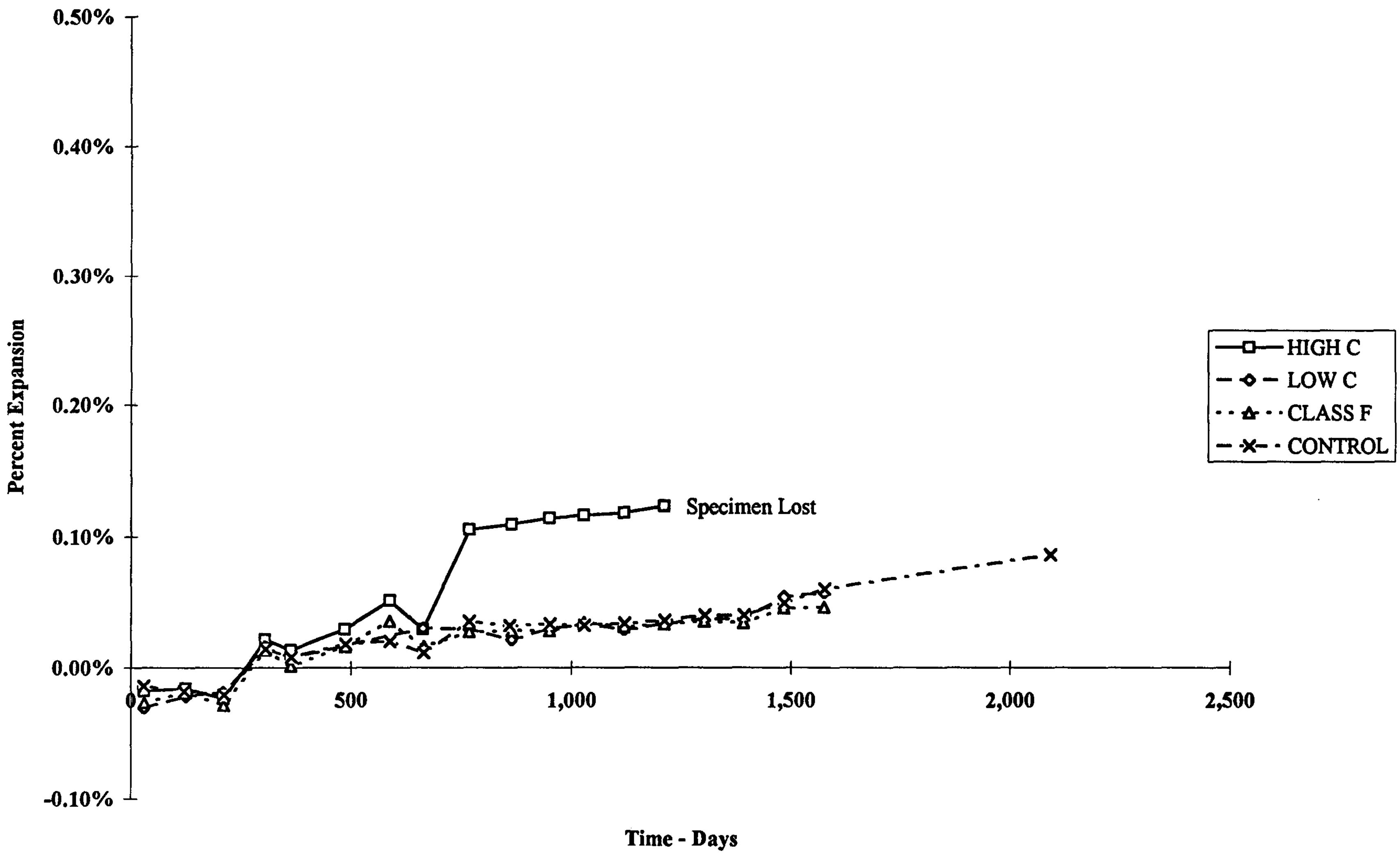

Figure 33. - Expansion versus time for 645 lbm/yd³ of cementitious materials (soak test; 10% replacement level).

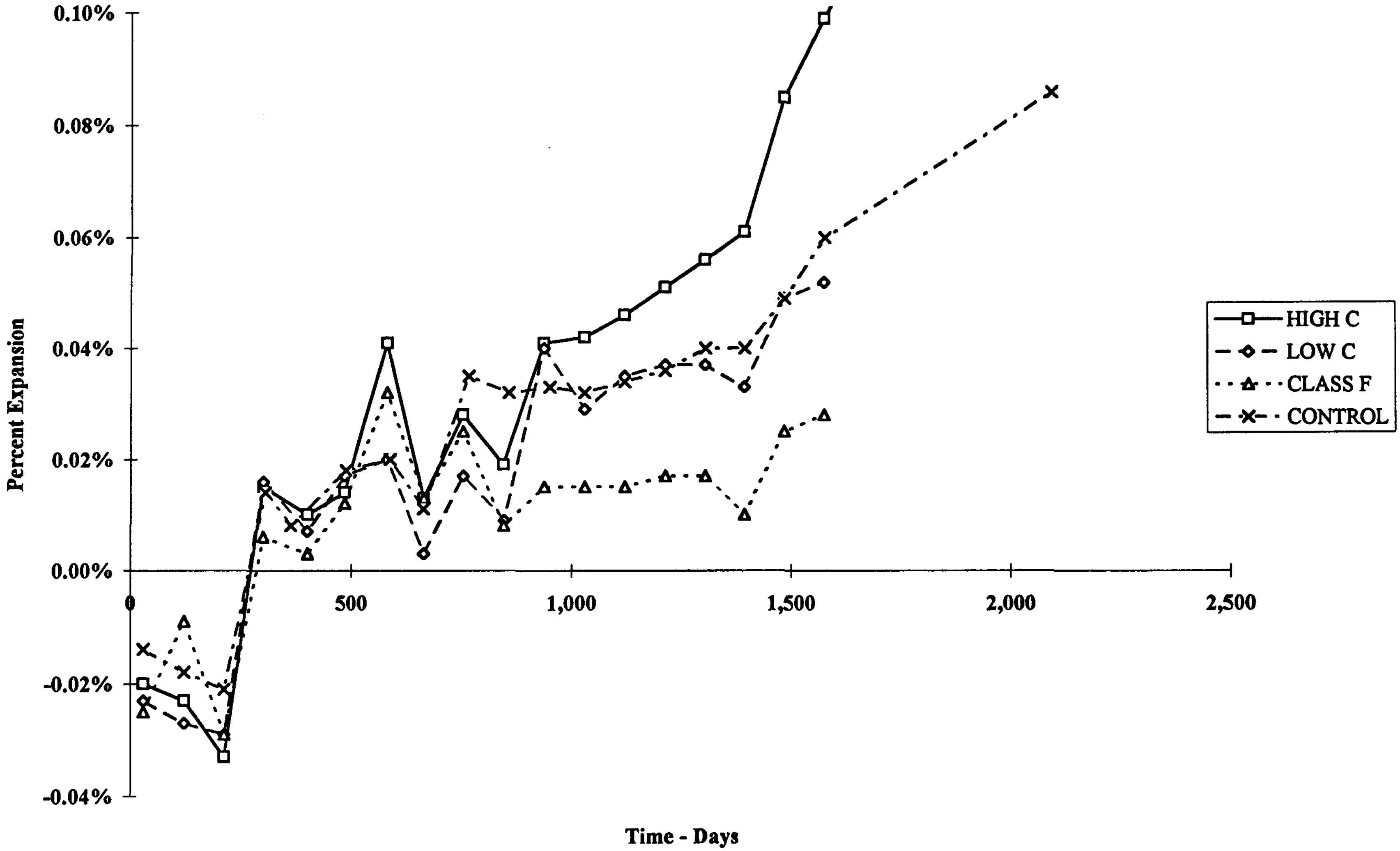

Figure 34. - Expansion versus time for 645 lbm/yd³ of cementitious materials (soak test; 30% replacement level).

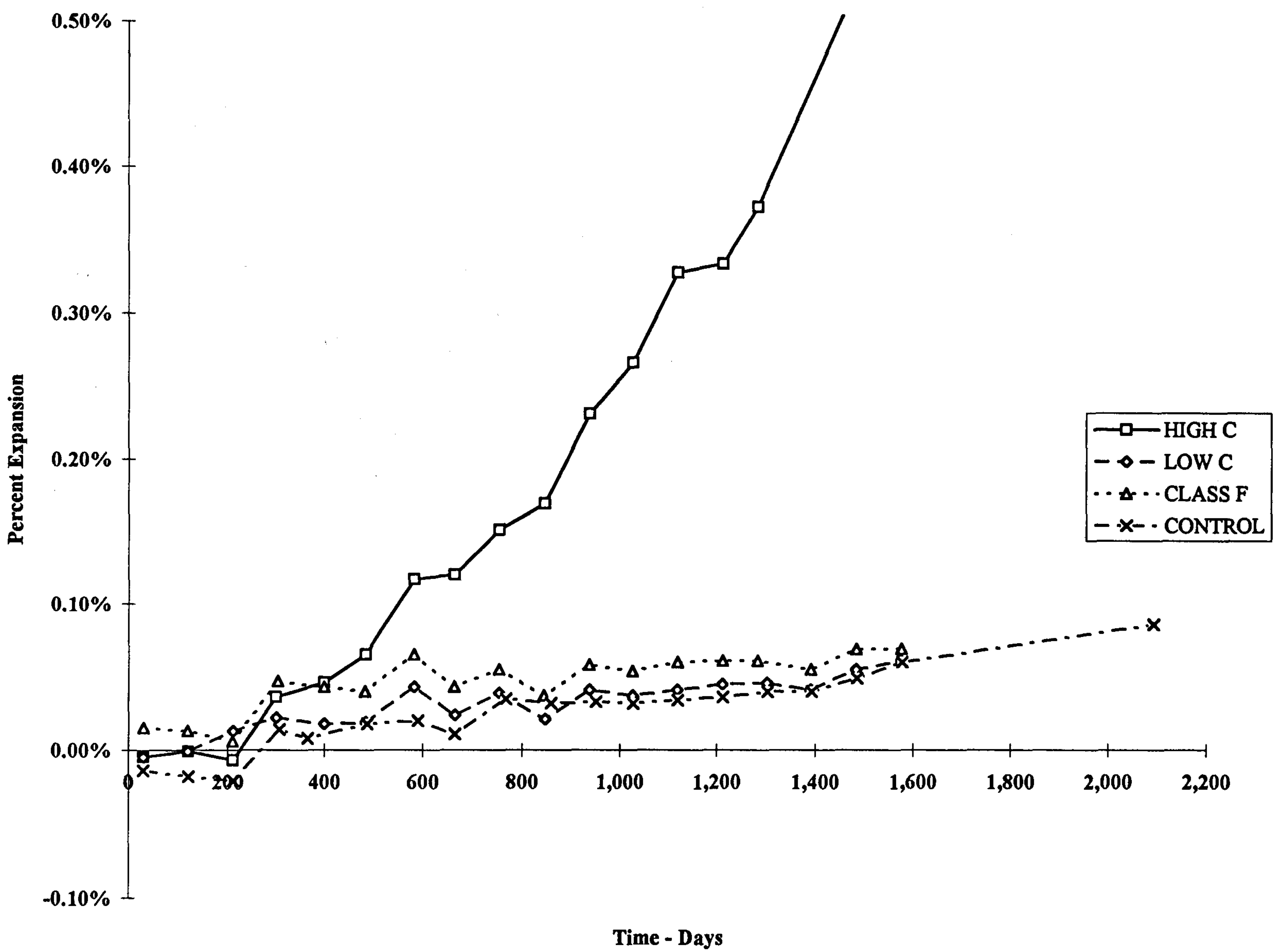

Figure 35. - Expansion versus time for 645 lbm/yd^3 of cementitious materials (soak test; 50% replacement level).

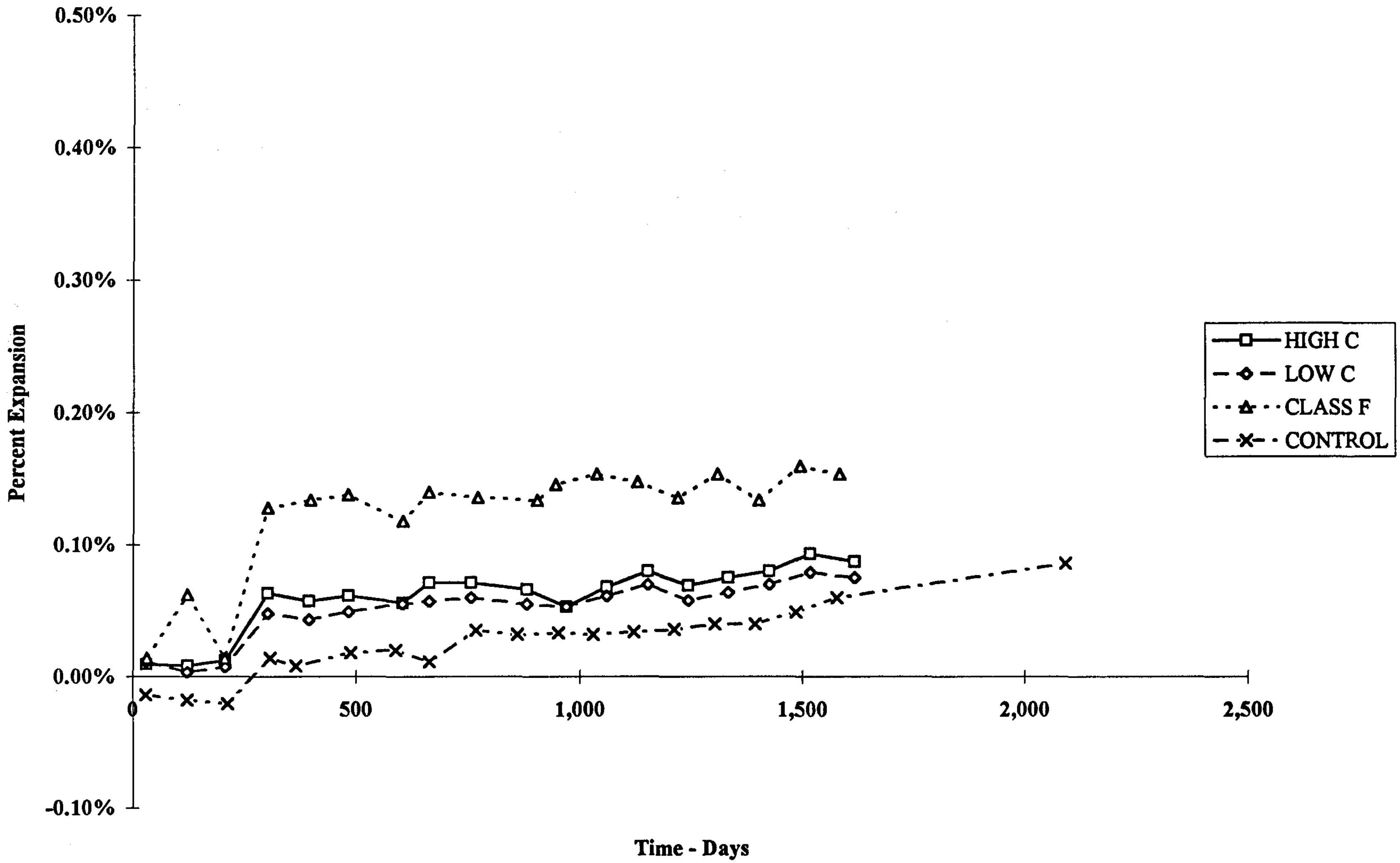

Figure 36. - Expansion versus time for 645 lbm/yd³ of cementitious materials (soak test; 75% replacement level).

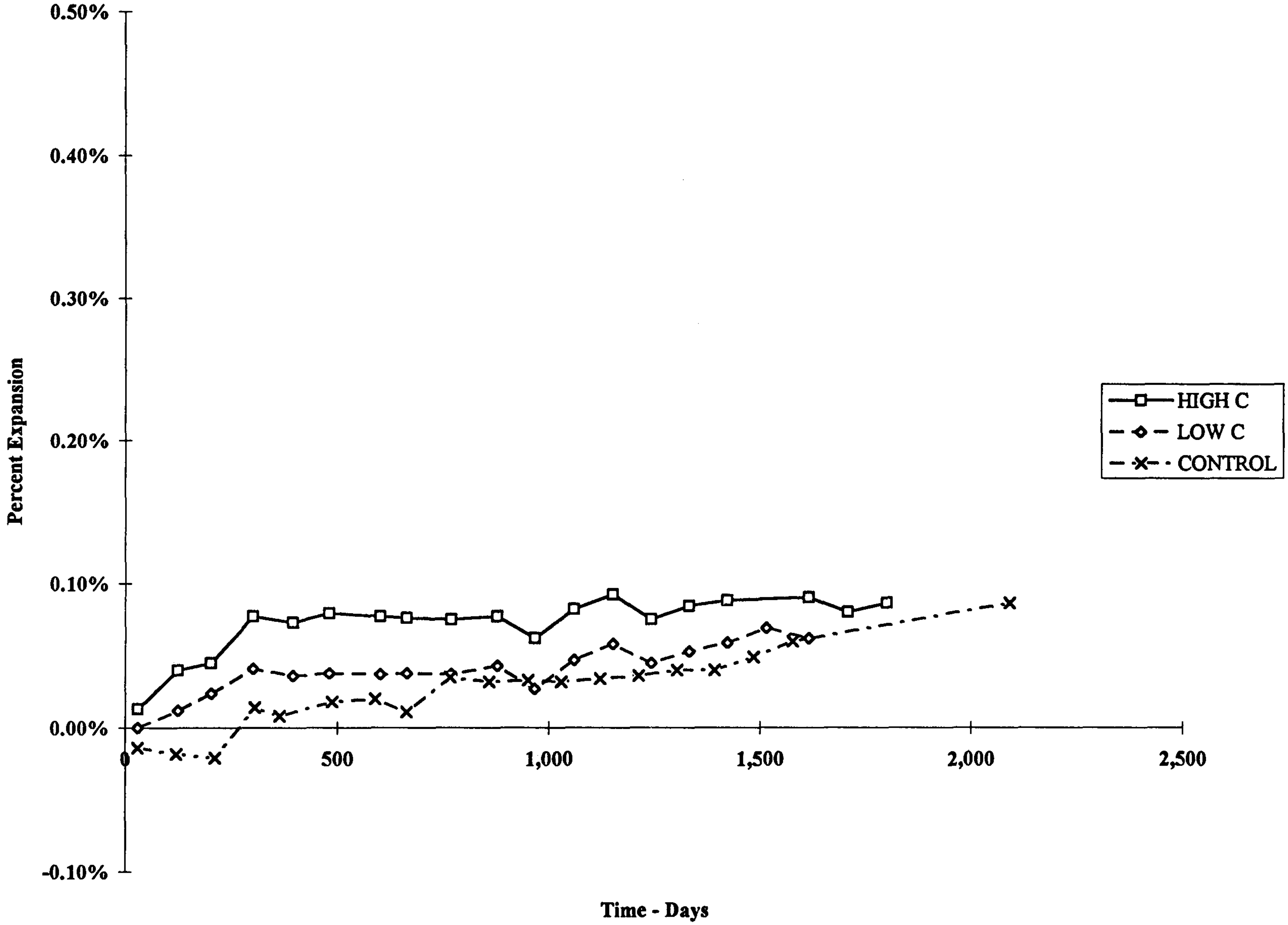

Figure 37. - Expansion versus time for 645 lbm/yd³ of cementitious materials (soak test; 100% replacement level).

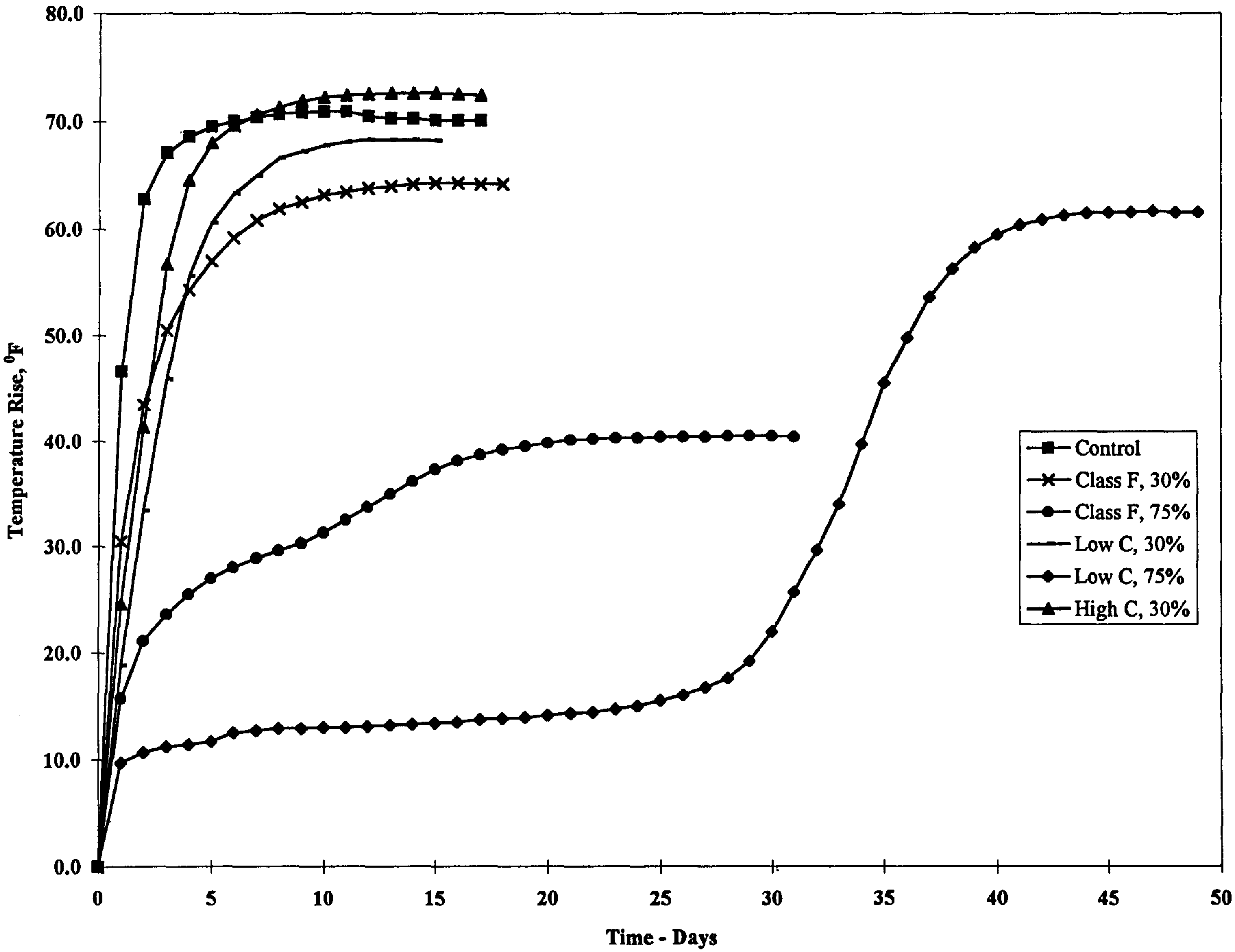

Figure 38. - Adiabatic temperature rise versus time.

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American Public.