Research Report No. 23 • A WATER RESOURCES TECHNICAL PUBLICATION

Fly Ash Increases Resistance of Concrete to Sulfate Attack

By
J. T. Dikeou
Division of Research
Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. administration.

First Printing: 1970
Revised Reprint: 1975

UNITED STATES GOVERNMENT PRINTING OFFICE
WASHINGTON : 1975

PREFACE

Fly ash is defined as "fine solid particles of noncombustible ash carried out of a bed of solid fuel by the draft." Pozzolan, originating from the Italian *pozzolana,* is a silicious or aluminous substance that reacts chemically with slacked lime in the presence of moisture to form a cementitious material.

The study reported in this booklet details the capabilities of bituminous coal fly ash as a pozzolan to combat resistance of concrete to sulfate attack. The tests showed that bituminous coal fly ashes consistently produce increased sulfate resistance over similar concrete without fly ash.

The findings and details of the tests should be of interest and value to water resource agencies, cement manufacturers and testing laboratories, colleges and universities, and other interested parties in the cement and concrete industries.

Included in this publication is an informative abstract with a list of decriptors, or keywords. The abstract was prepared as part of the Bureau of Reclamation's program of indexing and retrieving the literature of water resources development. The decriptors were selected from the *Thesaurus of Descriptors,* which is the Bureau's standard for listing of keywords.

NOTE TO READER

Preliminary results of studies presently (1975) underway by the Bureau of Reclamation on concretes containing subbituminous and lignite coal fly ashes indicate that in some cases the use of such fly ashes in concrete results in a decreased rather than an increased resistance to sulfate attack. When these studies are completed, a formal report will be published.

CONTENTS

TABLES

FIGURES

INTRODUCTION

The beneficial effect of bituminous coal fly ash or other pozzolans on improvement of sulfate resistance of concrete has been recognized for many years. As early as 1908, Jewett [1] reported that among the methods recognized by different authorities for combating sulfate attack was the use of a pozzolan to combine with the free lime which would otherwise be leached out.

Pozzolans have been used in many structures built by the Bureau of Reclamation. Justification for their use accrues from economies resulting and the significant improvement in the properties of mass concrete. These properties include increased impermeability, lower heat of hydration, reduced alkali-aggregate expansion, and improved workability. Inherent disadvantages to using pozzolan in structural concrete include generally slower strength development than straight portland cement concrete, and generally lower resistance to deterioration caused by freezing and thawing, unless longer than usual moist curing, which in most instances is not practicable, is provided.

A comprehensive investigation designed specifically to evaluate the sulfate resistant properties of concretes containing pozzolans has not been undertaken to date, since sulfate attack on concrete is not a major consideration in the dams using mass concrete, the only concrete in which pozzolan has been used by the Bureau. However, unrelated investigations performed over a number of years have included some sulfate resistance tests of concretes containing pozzolans. Results of these tests have shown a wide variation in effect of pozzolan on sulfate resistance, the effects ranging from significantly improved to marked decrease, depending principally on the type and properties of the pozzolan used. However, examination of test results indicated that bituminous coal fly ashes consistently produced a significant improvement in sulfate resistant properties of concrete over those of similar concrete but without fly ash.

The need for a concrete having maximum sulfate resistance has recently been emphasized in the development of specifications for concrete drain pipe for use where soluble sulfate concentrations of soils have been found to range as high as 5 to 6 percent, and concentrations of soluble sulfate in ground waters have been reported in excess of 150,000 ppm.

As mentioned previously, the use of pozzolan in concrete generally results in slower strength development and, under field curing conditions, lower resistance to deterioration caused by freezing and thawing. However, these potentially detrimental effects of pozzolan in concrete do not constitute adverse considerations in drain tile, since drainage installations are buried underground where tile is not subjected to freezing and thawing environment but only to chemical attack by soils and water with which it comes in contact. In addition, adequate early strength is provided by the increased cement content required for sulfate-resistant concrete pipe. Therefore, if sulfate resistance of concrete is significantly improved by the use of fly ash, maximum benefits will be derived from its use in concrete drain tile with none of the potentially adverse effects which are sometimes attributed to the use of pozzolan in concrete.

This report summarizes results to date of several unrelated Bureau of Reclamation investigations concerning the effect of bituminous coal fly ash on sulfate resistance of concrete.

[1] Jewett, J. Y., "The Effect of Alkali on Portland Cement," Engineering Record, vol. 58, July–December 1908, p. 105.

CONCLUSIONS

1. All of the bituminous coal fly ashes tested greatly improved the resistance of concrete to sulfate attack regardless of the type of cement used (table 3 and figures 1–8).

2. In the tests performed, improvement in resistance to sulfate attack due to the addition of fly ash generally is in the following order of cements used (table 4 and figure 9):

a. Type I cement (greatest improvement).

b. Type V cement.

c. Type II cement.

3. The degree of resistance of concrete to sulfate attack generally is in the following order of cementitious materials used (table 3 and figure 11):

a. Type V cement and fly ash (greatest resistance).

b. Type II cement and fly ash.

c. Type V cement.

d. Type II cement.

e. Type I cement and fly ash.

f. Type I cement.

4. Sulfate resistance of concretes may vary widely within each type of cement used. Resistance is primarily dependent upon the type of cement used, and to a lesser degree upon cement content, air content, and the variation of individual composition properties within each cement type (tables 1 and 3).

5. The degree of improvement in sulfate resistance of concrete accruing to the use of fly ash varies widely. However, all of the bituminous coal fly ashes tested, including those which failed to meet the composition requirements of Bureau of Reclamation specifications for pozzolan, greatly improved sulfate resistance (tables 2–4, and figures 1–9).

6. Exposure of concrete to the accelerated sulfate test is approximately equal in severity to continuous soaking in 10-percent Na_2SO_4 solution (figure 10).

7. The effectiveness of bituminous coal fly ash in improving sulfate resistance increases as the severity of exposure to sulfates is increased (table 4 and figure 9).

8. See NOTE TO READER in Preface.

TEST PROCEDURE

A total of 30 concrete mixes made from eight portland cements, three portland fly ash cements, and 12 fly ashes were included in the analysis of data for this report. These mixes were divided into eight series, A through H, with each cement representing a separate series. Concretes containing each of the eight cements without fly ash were made for control.

Test mixes contained partial replacements of cements with fly ash. In some instances, the same fly ashes were used in more than one series (tables 2 and 3). Test mixes utilized the following fly ash replacements of cement by weight: Series A, C, F, and G, all mixes contained 30-percent fly ash replacement; Series B, 25-percent fly ash replacement; Series D, four mixes contained 30-percent fly ash replacement, one mix contained 35-percent fly ash replacement; Series E, 15- and 30-percent replacements were used with one fly ash, 25-percent replacement was used with another fly ash; and Series H, portland fly ash cement mixes contained a Type II cement with 25-percent addition of fly ash.

Test specimens were 3- by 6-inch (7.62- by 15.24-cm.) concrete cylinders containing aggregate graded to ¾-inch (1.905-cm.) maximum size. Cylinders were fitted with stainless-steel gage studs for length measurements. After casting (three specimens per mix), specimens were fog cured for 14 days, followed by 14 days' drying at 50-percent relative humidity. At this time, initial length measurements were made, and the specimens were placed in sulfate resistance tests.

All specimens except those in Series E were cast and subjected to the soaking test (2.1-percent Na_2SO_4), which was the Bureau standard before the development of the accelerated wetting and drying test in 1954. At the time the accelerated test was initiated, one of the three specimens representing each mix was removed from the 2.1-percent sodium sulfate soaking test environment, and placed in the accelerated test apparatus. Expansion of specimens at the start of the accelerated test, due to their previous exposure to soaking, is listed in table 3. Series E specimens were placed directly in the accelerated test environment after completion of curing and drying periods.

The accelerated test consists of alternately soaking test specimens for 16 hours in a 2.1-percent (0.15 molar) solution of sodium sulfate at approximately

73° F. and drying for 8 hours in air under forced draft at 130° F. Specimens are measured for length in a surface dry condition. This accelerated test has been determined to produce failure in approximately one-sixth the time required by the 2.1-percent Na_2SO_4 soaking test.

Table 5 records results of tests performed on specimens made from concrete mixtures containing Types II and V cements without fly ash which were subjected both to the accelerated test and to a test environment consisting of continuous soaking in a 10-percent (100,000 p.p.m.) solution of Na_2SO_4. The latter test, which is about as rigorous in its action as the accelerated test, was adopted by the Bureau in 1960, specifically to study the performance of concrete subjected to a concentrated sulfate solution.

MATERIALS

Cement

Eight samples of portland cement and three samples of portland-fly ash cement used in these investigations are tabulated below:

Series No.	*Cement sample No.*	*Type*
A	M–1222	I.
B	M–1177	I.
C	A–777	II.
D	9458	II.
E	M–2400	II.
F	9249	V.
G	A–570	V.
H	A–705	II.
H	A–706	Portland fly ash.
H	A–695	Portland fly ash.
H	A–54	Portland fly ash.

Chemical composition, except for alkali content, was not determined on Series H cements (one Type II portland cement and three different portland-fly ash cements). Chemical compositions of the remaining cements are reported in table 1.

Fly Ash

Twelve samples of fly ash used in these investigations are:

Series No.	*Fly ash sample No.*	*Source*
A and F	A–464	Chicago, Northwest Station.
A, D, and F	M–1223	Blend, Corn Products, Argo, Ill.
B	A–1108	Chicago, Fisk Station.
C	A–1274	Philadelphia, Pa.
C	A–1326	Sewaren, N.J.
C	M–1178	Philadelphia, Pa.
D and G	9407	Chicago, Northwest Station.
D and H	9874	Chicago, Fisk Station.
D	A–223	Detroit, Mich.
D	A–463	Chicago, Calumet Station.
E	M–2564	Chicago, Northwest Station.
E	M–2343	Do.

Complete chemical analyses were not performed on all fly ashes; however, table 2 records the data available on chemical composition of the fly ashes used.

Aggregate

Sources of sand and coarse aggregate used in these investigations are as follows:

Series No.	*Aggregate source*
A	Grand Coulee Dam.
B	Palisades Dam.
C	Grand Coulee Dam.
D	Do.
E	Clear Creek (3 mixes). Glen Canyon Dam (2 mixes).
F	Clear Creek (1 control mix). Grand Coulee Dam (3 mixes).
G	Grand Coulee Dam.
H	Do.

TEST RESULTS

Tables 1 through 3 and figures 1 through 8 are tabular and graphic records of the data collected. Table 4 and figures 9 and 11 were prepared to show trends regarding the relationship between fly ash-portland cement combinations and sulfate resistance of concretes. Table 5 and figure 10 show the relationship between two different sulfate resistance tests, each representing severe exposure.

An 0.5-percent expansion of test specimens is the criterion for failure used here for evaluating sulfate resistance. An expansion of 0.2 percent is considered to be practically failure and is sometimes used for evaluation since internal disruption has definitely started and complete failure at 0.5 percent is imminent.

A long period of time is required to obtain significant sulfate deterioration of highly sulfate resistant concretes, as evidenced by some specimens reported herein which have continued in test for approximately 16 years without having reached failure. This necessitated that evaluation be made of sulfate resisting properties prior to 0.2 or 0.5 percent expansion in order to utilize test results presently available. Footnote 2 of table 3 explains the procedure used in making this evaluation, and reads as follows: "Where specimens have not reached 0.2 percent or 0.5 percent expansion, increased resistance of fly ash concrete is determined by comparison of length of time required for test specimen to reach expansion to date with the length of time required for the control (no fly ash) specimen to reach a similar expansion." Data in table 4 and figure 9, showing increased resistance to fly ash concretes, are based upon this criterion. Expansions range from less than 0.1 percent in some instances to complete failure (0.5 percent) in other cases.

Table 3 and figures 1–8 show that all fly ashes tested greatly improved the resistance of concrete to sulfate attack, regardless of the type of cement used. Table 4 shows that a considerable variation in improved resistance may be obtained with different cement-fly ash combinations. This variation apparently is due to a combination of factors, including water/cement ratio, cement content, air content, and permeability of the concretes. Other factors believed to influence sulfate resistance of concrete include variables in chemical composition within each cement type, unaccountable variation between cement sources, and differences in effectiveness of individual fly ashes in improving sulfate resistance. Table 4 and figure 9 show that the effect of fly ash in improving sulfate resistance of concrete decreases generally in the following order of cements used: Type I, Type V, and Type II. These data show that fly ash has a markedly greater effect in improving the sulfate resistance of Type I cement (least sulfate-resistant) concrete. The improvement in sulfate resistance due to fly ash in Type V cement concrete, which is not so great as that for Type I cement, is significant, averaging 405 percent greater than control in the 2.1-percent Na_2SO_4 soaking test and 1,430 percent greater than control in the accelerated sulfate resistance test, and the resulting concrete is many times more resistant than that containing Type I cement and fly ash.

A wide variation exists in length of time specimens have been in test, either due to early failure of some specimens, or to differences in time that tests were initiated. In order to obtain an overall comparison of the relative sulfate resistance of concretes included in this report, expansions of specimens obtained to date were extrapolated to a uniform age, 10,000 days (table 3). Figure 11 was prepared from these data and graphically shows average expansions due to sulfate attack. Concretes containing each of the three types of cement: I, II, and V, both with and without fly ash, are represented. These data indicate that the degree of resistance to sulfate attack of concrete in both the accelerated and the 2.1-percent soaking tests decreases generally in the following order of cementitious materials used: Type V cement and fly ash, Type II cement and fly ash, Type V cement, Type II cement,Type I cement and fly ash, and Type I cement.

Four of the 10 fly ashes used in combination with Type II cements exceeded the maximum specifications limit on ignition loss, indicating a high carbon content. Three of these four fly ashes produced comparatively low increase in sulfate resistance. However, the remaining fly ash with high ignition loss showed the greatest increase in sulfate resistance for Type II cements in both the accelerated and the 2.1-percent soaking tests. No reason for this behavior is readily apparent.

Of considerable interest is the markedly greater effectiveness of fly ash in increasing sulfate resistance of concrete subjected to the accelerated (more severe) test as compared to the 2.1-percent Na_2SO_4 soaking test. Table 4 shows that the average increased resistance due to fly ash for all tests in the 2.1-percent soaking test is 578 percent, while in the accelerated test, this average is 1,006 percent, or approximately 1.7 times greater.

Another comparison of interest shows the relative rate of deterioration of concrete in the accelerated test and the test consisting of continuous soaking in a 10-percent solution of sodium sulfate. The purpose of this comparison is to determine the relative effect of continuous soaking in a sulfate solution of higher concentration than 2.1 percent, since it may be argued that the accelerated test, with its continuous cycles of soaking and drying at elevated temperature, is not representative of the environment that concrete may be exposed to in service. Figure 10 shows a statistical comparison indicating approximately equal severity for the accelerated wetting and drying and the 10-percent Na_2SO_4 soaking test exposures. This comparison is based upon data reported in table 5, showing test results obtained on specimens of concrete made with Types II and V cements. The linear correlation coefficient, r, based upon 33 test values is 0.974. This is highly significant. A correlation coefficient of only 0.449 for 33 test values indicates a high level of significance, the possibility of chance occurrence being 1 or less in 100.

It may be concluded from this comparison and results of the miscellaneous unrelated tests that the effectiveness of fly ash in improving sulfate resistance is increased as the severity of exposure increases, i.e., when high soluble sulfate concentrations are encountered.

DISCUSSION

Increased sulfate resistance of concretes containing fly ash may be explained by the reaction of silica, alumina, and ferric oxide found in fly ash with calcium hydroxide liberated during the hydration of portland cement to form relatively stable cementitious compounds. Through this reaction, calcium hydroxide is reduced in amount compared to similar concrete without fly ash. The conversion of calcium hydroxide to complex compounds containing silica, alumina, and ferric oxide provides both physical and chemical bases for improved sulfate resistance.

The solubility characteristics of calcium hydroxide permit water to readily leach this compound out of concrete, leaving voids and thus, the concrete becomes more permeable. Since the calcium hydroxide content of fly ash concrete is lower than similar concrete without fly ash, it follows that fly ash concrete is less permeable. Greater impermeability of fly ash concrete reduces penetration of sulfate solutions and results in improved resistance to sulfate attack.

Disintegration of concrete due to sulfate attack may be caused by either of two chemical reactions. One is the reaction that occurs between sulfate and calcium hydroxide to form gypsum, and the other is a reaction between sulfate and the reactive alumina-bearing phases in hardened cement to produce calcium sulfo-aluminate. The products of both reactions occupy a greater volume than the compounds initially present, and in their formation cause disintegration of the concrete. In properly proportioned fly ash-portland cement concrete, the reduced availability of calcium hydroxide would permit a higher concentration of sulfate before gypsum would form with accompanying disintegration of the concrete.

TABLE 1.—*Chemical composition of cements*

Series	A	B	C	D	E	F	G	H	H	H	H
Type	I	I	II	II	II	V	V	II	Portland-fly ash	Portland-fly ash	Portland-fly ash
Lab No.	M–1222	M–1177	A–777	9458	M–2400	9249	A–570	[1] A–705	[2] A–706	[3] A–695	[4] A–54
SiO_2, percent	21. 59	22. 67	22. 48	22. 91	22. 70	23. 83	24. 39	...	...	...	...
Al_2O_3, percent	6. 66	5. 06	4. 80	5. 44	4. 81	4. 26	3. 10	...	...	...	...
Fe_2O_3, percent	2. 51	1. 80	4. 43	4. 41	3. 56	4. 20	2. 44	...	...	...	...
CaO, percent	65. 42	65. 34	63. 22	62. 24	62. 81	63. 39	64. 90	...	...	...	...
MgO, percent	1. 57	1. 55	1. 39	1. 63	2. 24	. 74	2. 64	...	...	...	...
SO_3, percent	1. 92	1. 57	1. 69	1. 68	1. 84	1. 89	1. 32	...	...	...	...
Loss on ignition, percent	. 81	. 95	1. 04	1. 43	1. 25	. 83	. 85	...	...	...	...
Insoluble residue, percent	. 12	. 26	. 23	1. 19	. 17	. 12	. 17	...	...	...	...
Na_2O, percent	. 11	. 10	. 14	. 16	. 22	. 10	. 13	. 07	. 19	. 19	. 16
K_2O, percent	. 41	. 59	. 50	. 46	. 47	. 32	. 32	. 23	. 22	. 26	. 26
Total alkalies, as Na_2O, percent	. 38	. 49	. 47	. 46	. 53	. 31	. 34	. 22	. 34	. 36	. 33
Compound composition:											
C_3S, percent	48. 4	52. 6	43. 0	40. 9	40. 5	56. 9	50. 7	...	...	...	...
C_2S, percent	25. 5	25. 4	32. 1	32. 9	34. 6	40. 5	31. 8	...	...	...	...
C_3A, percent	13. 4	10. 4	5. 2	6. 0	6. 7	4. 2	4. 1	...	...	...	...
C_4AF, percent	7. 6	5. 5	13. 5	13. 8	10. 8	12. 8	7. 4	...	...	...	...
$CaSO_4$, percent	3. 26	2. 67	2. 87	2. 86	3. 1	3. 21	2. 24	...	...	...	...

[1] Ground in the laboratory from Clinker No. 8148.
[2] Cement A–705 plus 25-percent addition of fly ash 9874—blended together.
[3] Cement clinker 8148 plus 25-percent fly ash 9874—interground.
[4] Cement clinker 8148 plus 25-percent fly ash 9874—interground. Fly ash was introduced into mill after clinker was partially ground.

TABLE 2.—*Chemical composition of fly ashes*

Series	A, F	A, D, F	B	C	C	C	D, G	D, H	D	D	E	E
Source	Chicago, Northwest Station	Blend, Corn Prod., Argo, Ill.	Chicago, Fisk Station	Philadelphia, Pa.	Sewaren, N.J.	Philadelphia, Pa.	Chicago, Northwest Station	Chicago, Fisk Station	Detroit, Mich.	Chicago, Calumet Station	Chicago, Northwest Station	Chicago, Northwest Station
Lab No.	A–464	M–1223	A–1108	A–1274	A–1326	M–1178	9407	9874	A–223	A–463	M–2564	M–2343
$SiO_2+Al_2O_3+Fe_2O_3$, percent	83. 75	...	...	[1] 58. 58	[1] 59. 88	[1] 60. 43	[1] 58. 36	[1] 70. 10	...	81. 71	78. 38	[1] 62. 98
MgO, percent	1. 48	...	...	1. 33	1. 59	. 07	1. 23	1. 25	...	1. 29	1. 25	1. 01
SO_3, percent	2. 49	...	...	1. 11	1. 60	1. 17	1. 72	2. 93	...	2. 16	3. 73	2. 47
Loss on ignition, percent	1. 84	...	1. 34	[2] 6. 35	[2] 10. 18	[2] 5. 45	2. 04	2. 47	4. 88	[2] 5. 56	1. 53	3. 18
Moisture content, percent	. 06	...	...	. 06	. 21	...	...	...	...	. 15	. 14	. 10
Exchangeable alkalies, as Na_2O, percent	2. 98	...	...	. 76	. 84	. 75	...	...	1. 82	[2] 2. 35	[2] 2. 29	...

[1] $SiO_2+Al_2O_3$ only.
[2] Fails to meet requirements of Bureau of Reclamation "Specifications for Pozzolan," dated Mar. 1, 1961.

TABLE 3.—*Sulfate resistance of concrete containing fly ash*

Series	Cement: Type	Cement: Sample No.	Fly ash sample No.	Mix data: W / C+P ratio	Mix data: Water, pounds per cubic yard	Mix data: Cement, pounds per cubic yard	Mix data: Pozzolan, pounds per cubic yard	Mix data: Slump, inches	Mix data: Air, percent	Sulfate resistance tests [1]: Continuous soaking, 2.1-percent Na_2SO_4, expansion results: Days to 0.2 percent	Continuous soaking: Increased resistance due to fly ash, percent	Continuous soaking: Days to 0.5 percent	Continuous soaking: Increased resistance due to fly ash, percent	Continuous soaking: Expansion at 10,000 days, percent [15]	Expansion at start of accelerated test, percent	Accelerated test, alternate soaking in 2.1-percent Na_2SO_4 and drying at 130° F., single specimens, expansion results: Days to 0.2 percent	Accelerated test: Increased resistance due to fly ash, percent	Accelerated test: Days to 0.5 percent	Accelerated test: Increased resistance due to fly ash, percent	Accelerated test: Expansion at 10,000 days, percent [15]
A	I	M-1222		0.52	313	596		3.9	2.1	250		310		16.12		Specimen failed in soaking.	Specimen failed in soaking.	Specimen failed in soaking.	Specimen failed in soaking.	
A	I	M-1222	A-464	.48	267	392	164	2.9	2.5	0.103 at 4,865.	(160) 3,041 [2]			.21	[3] .052	1,690		1,940		2.58
A	I	M-1222	M-1223	.54	300	387	172	3.0	1.7	1,775	716	0.466 at 4,865.	(300) 1,622 [2]	.92	[3] .102	175		295		16.95
B	I	M-1177		.51	286	561		3.1	3.5	1,170		3,450		1.45	[4] .052	135		195		25.64
B	I	M-1177	A-1108	.51	270	397	132	3.5	4.0	0.070 at 4,500.	(400) 1,125 [2]			.16	[4] .016	0.064 at 550 [17]	(20) 2,760 [2]			1.16
C	II	A-777		.50	294	588		2.0	2.4	5,025		0.208 at 5,355.		.39	[5] .058	630		1,030		4.85
C	II	A-777	A-1274	.53	292	389	165	3.2	1.7	0.087 at 4,815.	(2,200) 219 [2]			.18	[6] .044	1,780	282	1,980	193	2.53
C	II	A-777	A-1326	.51	288	395	171	2.3	1.4	0.072 at 4,815.	(1,850) 260 '			.15	[6] .042	2,200	348	2,360	230	2.12
C	II	A-777	M-1178	.50	286	396	17[illegible]	3.5	1.7	0.072 at 4,815.	(1,850) 260 [2]			.15	[6] .034	1,960	310	2,030	198	2.46
D	II	9458		.49	286	588		2.7	3.3	5,720		0.201 at 5,750.		.35	[7] .058	720		1,390		3.60
D	II	9458	9407	.47	260	391	166	3.5	3.7	0.072 at 6,150.	(2,100) 293 [2]			.12	[7] .064	0.162 at 4,015.	(560) 717 [2]			.40
D	II	9458	9874	.46	250	386	161	2.5	1.2	0.075 at 5,490.	(2,200) 250 [2]			.14	[8] .062	0.130 at 4,015.	(400) 1,004 [2]			.32
D	II	9458	A-233	.49	266	379	168	2.5	1.8	0.122 at 5,490.	(3,550) 155 [2]			.22	[8] .062	0.162 at 4,015.	(560) 717 [2]			.40
D	II	9458	A-463	.47	281	391	207	2.5	.8	0.064 at 5,490.	(1,850) 297 [2]			.12	[9] .052	0.084 at 4,015.	(160) 2,509 [2]			.21
D	II	9458	M-1223	.49	277	392	175	2.2	1.8	0.065 at 4,865.	(1,900) 256 [2]			.13	[3] .044	3,475	482	0.234 at 4,015.	(850) 472 [2]	.58
E	II	M-2400		.51	282	553		3.0	5.8	No tests	No tests	No tests	No tests			400*		1,260*		3.97
E	II	M-2400	M-2564	.51	272	452	80	3.4	6.0	do	do	do	do			1,530*	351	0.359 at 3,300*	(835) 395 [2]	1.09
E	II	M-2400	M-2564	.51	255	350	151	3.0	6.0	do	do	do	do			0.198 at 3,300.*	(430) 768 [2]			.60
E	II	M-2400		.51	261	511		2.5	5.2	do	do	do	do			370*		810*		6.17
E	II	M-2400	M-2343	.51	237	345	116	2.8	6.0	do	do	do	do			0.078 at 3,025.*	(150) 2,017 [2]			.26
F	V	9249		.44	290	654		3.5	6.8	0.157 at 5,190.				.30	[10] .062	390		1,530		3.27
F	V	9249	A-464	.44	250	399	164	2.1	2.7	0.046 at 4,900.	(1,450) 338 [2]			.09	[11] .032	0.126 at 4,200.	(175) 2,400 [2]			.30

See footnotes at end of table.

TABLE 3.—*Sulfate resistance of concrete containing fly ash*—Continued

Series	Cement: Type	Cement: Sample No.	Fly ash sample No.	Mix data: W/C+P ratio	Mix data: Water, pounds per cubic yard	Mix data: Cement, pounds per cubic yard	Mix data: Pozzolan, pounds per cubic yard	Mix data: Slump, inches	Mix data: Air, percent	Sulfate resistance tests[1] — Continuous soaking, 2.1-percent Na_2SO_4, expansion results: Days to 0.2 percent	Continuous soaking: Increased resistance due to fly ash, percent	Continuous soaking: Days to 0.5 percent	Continuous soaking: Increased resistance due to fly ash, percent	Continuous soaking: Expansion at 10,000 days, percent[18]	Expansion at start of accelerated test, percent	Accelerated test, alternate soaking in 2.1-percent Na_2SO_4 and drying at 130° F., single specimens, expansion results: Days to 0.2 percent	Accelerated test: Increased resistance due to fly ash, percent	Accelerated test: Days to 0.5 percent	Accelerated test: Increased resistance due to fly ash, percent	Accelerated test: Expansion at 10,000 days, percent[18]
F	V...........	9249	....	.49	290	590	......	3.0	2.9	0.184 at 5,790.	....		....	.32	[12].054	820........	....	1,480......	....	3.38
F	V...........	9249	M-1223	.48	271	394	174	2.0	1.7	0.067 at 4,810.	(2,050) 235[2]..	....	....	.14	[13].040	2,620......	319..........	0.300 at 4,200.	(1,125) 373[2]..	.71
G	V...........	A-570	....	.69	284	414	......	2.4	2.0	2,085......	....	0.492 at 5,140.	....	[19].96	[14].136	140........	....	315........	....	[19]15.87
G	V...........	A-570	9407	.67	262	275	115	2.7	2.0	0.077 at 5,140.	(800) 643[2]....	....	....	[19].15	[15].040	1,970......	1,409........	0.400 at 4,200.	(275) 1,527[2]..	[19].95
H	II...........	A-705	....	.47	277	597	......	2.1	1.4	4,860......	....	0.255 at 5,425.	....	.47	[16].048	775........	....	1,760......	....	2.84
H	Portland fly ash.	A-706	....	.49	290	592	......	2.9	1.9	0.074 at 5,425.	(2,000) 271[2]..	....	....	.14	[16].040	0.148 at 4,030.	(550) 732[2]....	....	....	.37
H	Portland fly ash.	A-695	....	.47	282	600	......	2.5	.7	0.112 at 5,425.	(3,100) 175[2]..	....	....	.21	[16].038	0.182 at 4,030.	(700) 575[2]....	....	....	.45
H	Portland fly ash.	A-54	....	.49	288	592	......	3.0	2.1	0.056 at 5,425.	(1,400) 388[2]..	....	....	.10	[16].038	4,030......	519..........	....	....	.50

[1] All specimens subjected to 14 days fog curing plus 14 days at 50-percent relative humidity prior to exposure to sulfate resistance tests.

[2] Where specimens have not reached 0.2- or 0.5-percent expansion, increased resistance of fly ash concrete is determined by comparison of length of time required for test specimen to reach expansion to date with the length of time required for the control (no fly ash) specimen to reach a similar expansion. Number of days required for the control specimen to reach this expansion is shown in parentheses.

Footnotes 3 through 16: Specimens soaked for varying periods of time in 2.1-percent Na_2SO_4 solution as follows, before being placed in the accelerated test: [3] 760 days; [4] 340 days; [5] 1,260 days; [6] 710 days; [7] 1,740 days; [8] 1,440 days; [9] 1,410 days; [10] 1,080 days; [11] 850 days; [12] 750 days; [13] 1,720 days; [14] 1,380 days; [15] 1,100 days; and [16] 1,320 days.

[17] Specimen removed from test for display.

[18] Values are extrapolated from expansions obtained to date.

[19] Due to high water-cement ratios of these concretes, these values are not included in averages for Type V cements, figure 11.

*Average of three specimens.

TABLE 4.—*Analysis of increased sulfate resistance due to fly ash*

Increased resistance, due to fly ash, of concrete exposed to continuous soaking in 2.1-percent Na_2SO_4, based upon age at expansion reached to date:

Cementitious material	Number of tests	Average increased resistance, percent	Maximum increased resistance, percent	Minimum increased resistance, percent
Type I, cement plus fly ash	3	1, 929	3, 041	1, 125
Type II, cement plus fly ash	8	249	297	155
Type V, cement plus fly ash	3	405	643	235
Type II, portland-fly ash cement	3	278	388	175
Average increase for all tests	......	578	....	....

Increased resistance, due to fly ash, of concrete exposed to the accelerated sulfate resistance test, based upon age at expansion reached to date:

Cementitious material	Number of tests	Average increased resistance, percent	Maximum increased resistance, percent	Minimum increased resistance, percent
Type I, cement plus fly ash	1	2, 760	....	....
Type II, cement plus fly ash	11	838	2, 509	193
Type V, cement plus fly ash	3	1, 433	2, 400	373
Type II, portland-fly ash cement	3	609	732	519
Average increase for all tests	......	1, 006	....	....

TABLE 5.—*Comparison of rates of expansion in the 10-percent Na_2SO_4 soaking test and in the accelerated test*

Cement sample No.	Cement type	Absorption of specimen	Continuous soaking—10-percent Na_2SO_4 expansion results		Accelerated wetting and drying test expansion results	
			Days to 0.2 percent	Days to 0.5 percent	Days to 0.2 percent	Days to 0.5 percent
M–3650	II	4. 48	448	802	527	805
M–3650	II	4. 60	464	699	442	613
M–3650	II	5. 42	428	768	358	644
M–3650	II	5. 56	429	684	532	774
M–3650	II	6. 37	292	397	138	250
M–3650	II	10. 31	116	169	72	128
M–3650	II	12. 07	30	40	24	41
M–3650	II	12. 16	41	64	27	50
Average	....	7. 62	281	453	265	413
M–3857	V	5. 51	1, 220	....	1, 210	[1] 1, 966
M–3857	V	6. 50	626	1, 399	1, 164	1, 885
M–3857	V	6. 97	360	866	461	736
M–3857	V	7. 40	371	637	337	686
M–3857	V	8. 36	296	486	330	500
M–3857	V	10. 90	34	65	42	70
M–3857	V	11. 88	14	39	30	44
M–3857	V	12. 37	176	355	286	429
M–3857	V	12. 66	63	136	57	99
M–3857	V	12. 76	17	31	34	56
Average	....	9. 53	318	446	395	501

[1] Not included in average.

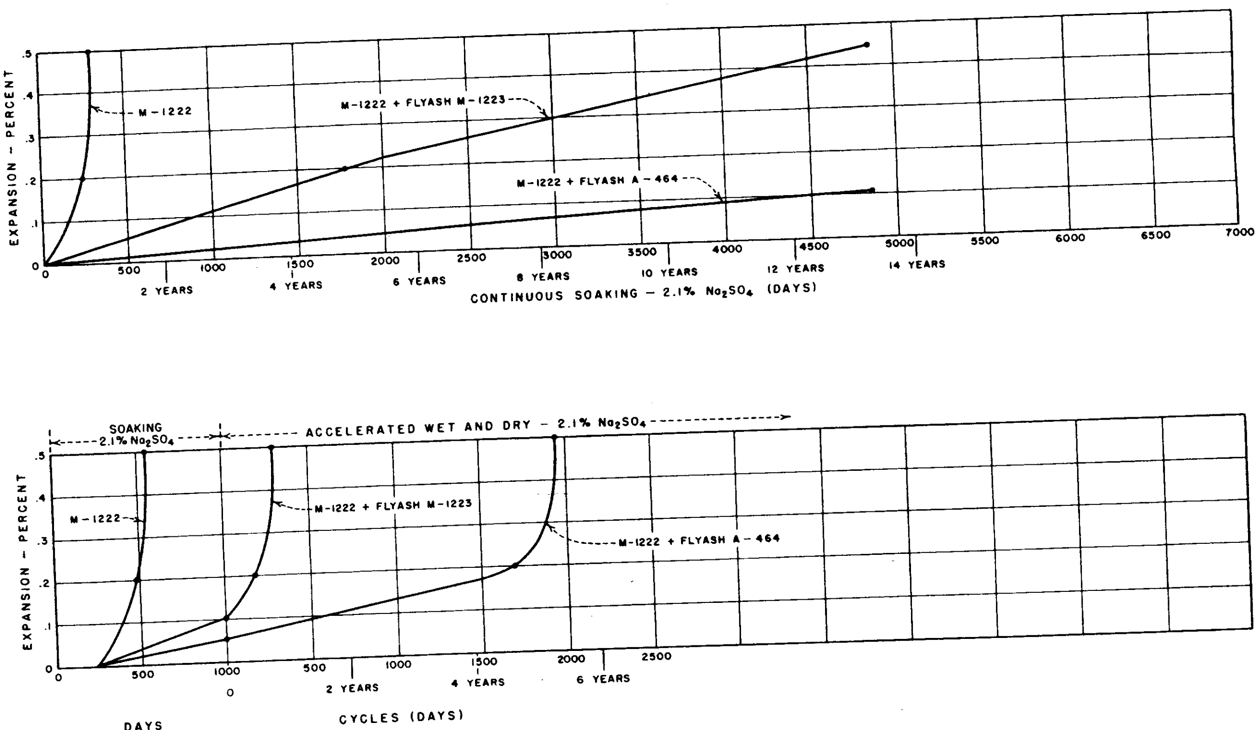

Figure 1.—Effect of fly ash on sulfate resistance of concrete containing Type I cement (M–1222), Series A.

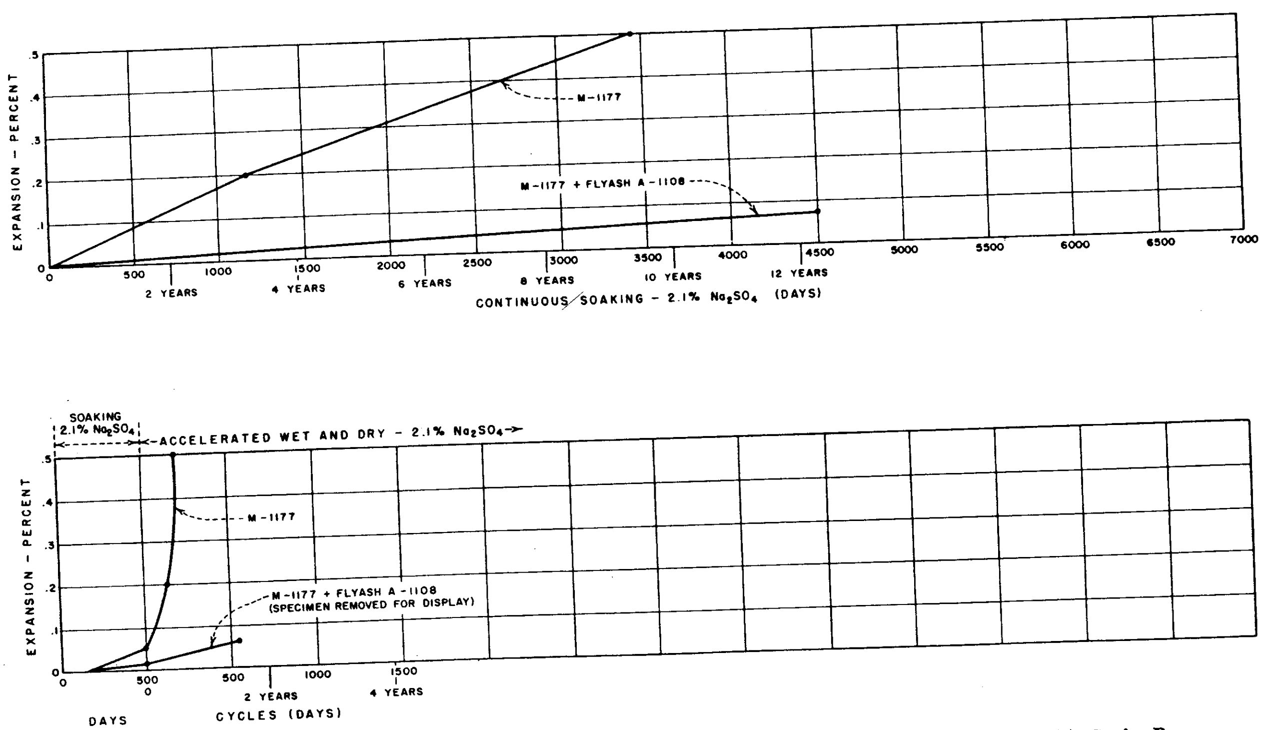

Figure 2.—Effect of fly ash on sulfate resistance of concrete containing Type I cement (M–1177), Series B.

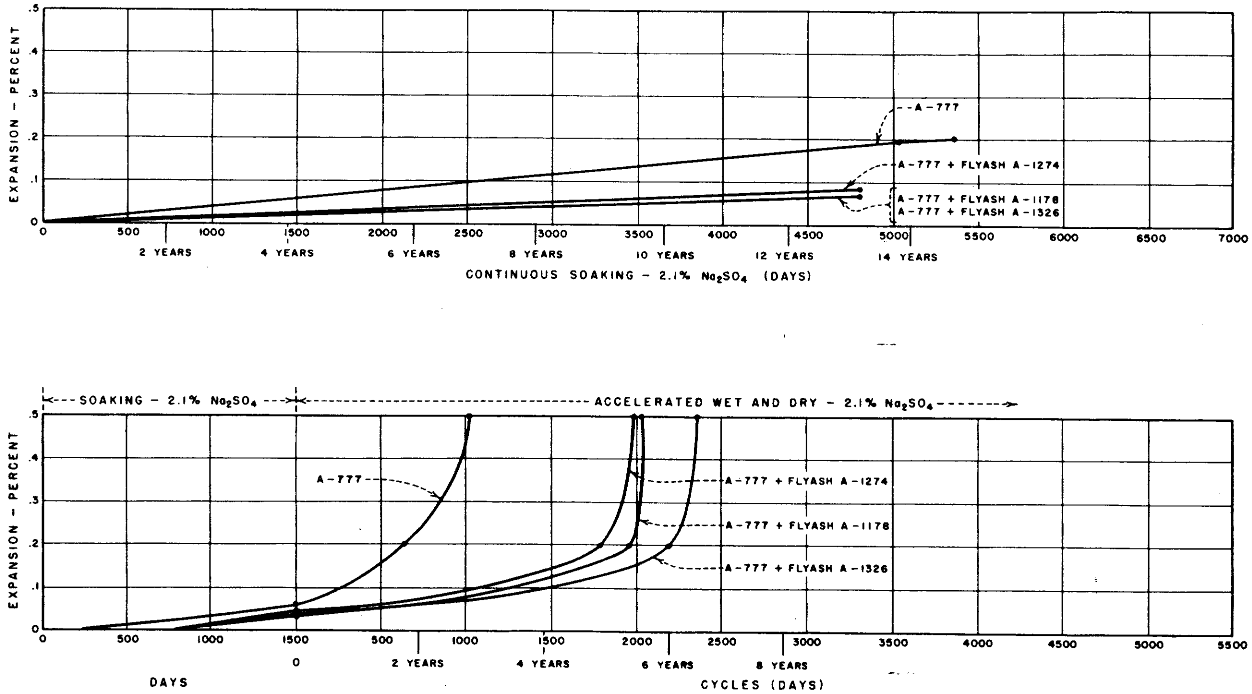

Figure 3.—Effect of fly ash on sulfate resistance of concrete containing Type II cement (A–777), Series C.

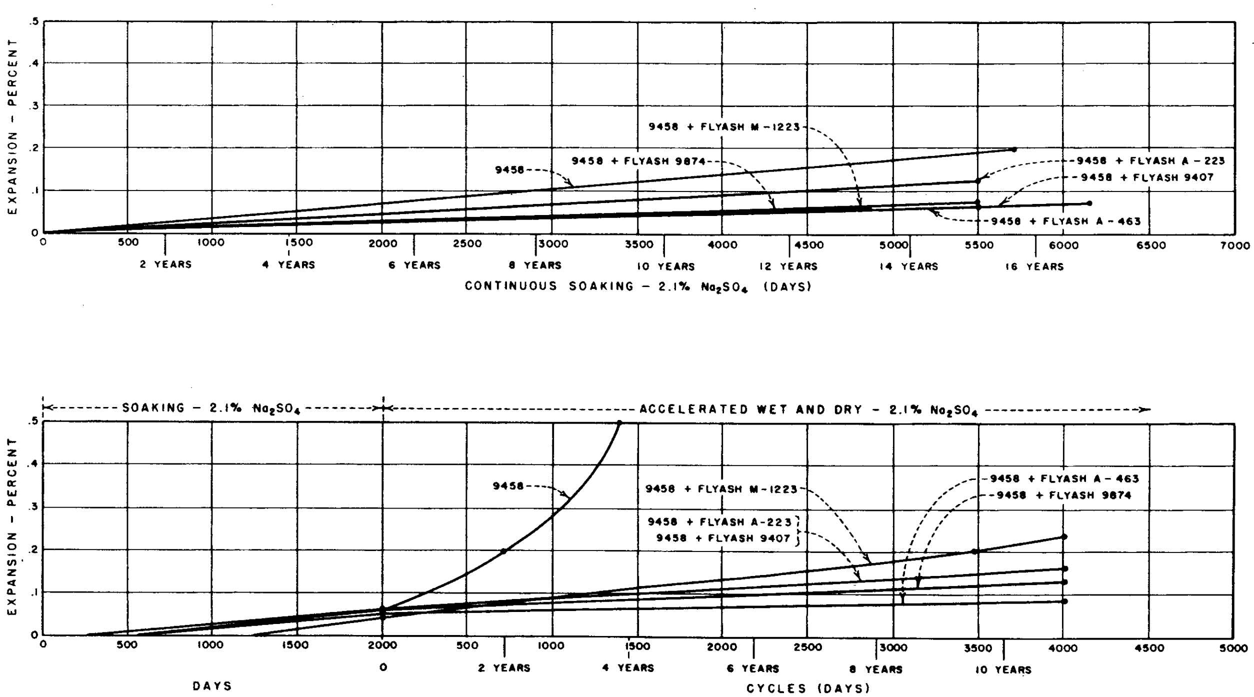

Figure 4.—Effect of fly ash on sulfate resistance of concrete containing Type II cement (9458), Series D.

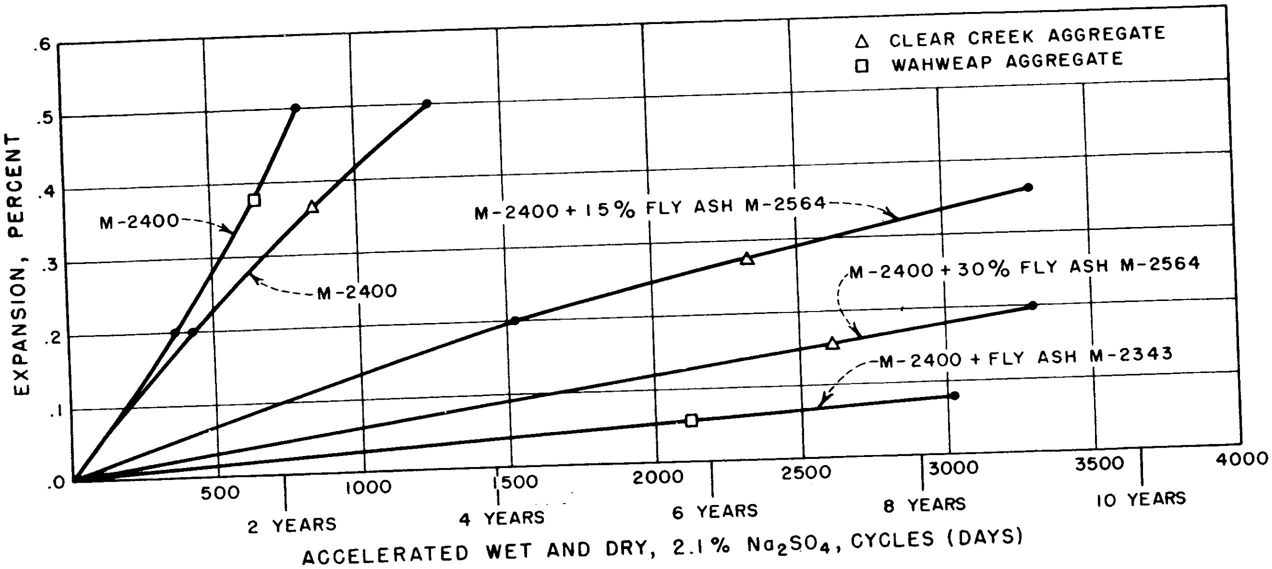

Figure 5.—Effect of fly ash on sulfate resistance of concrete containing Type II cement (M–2400), Series E.

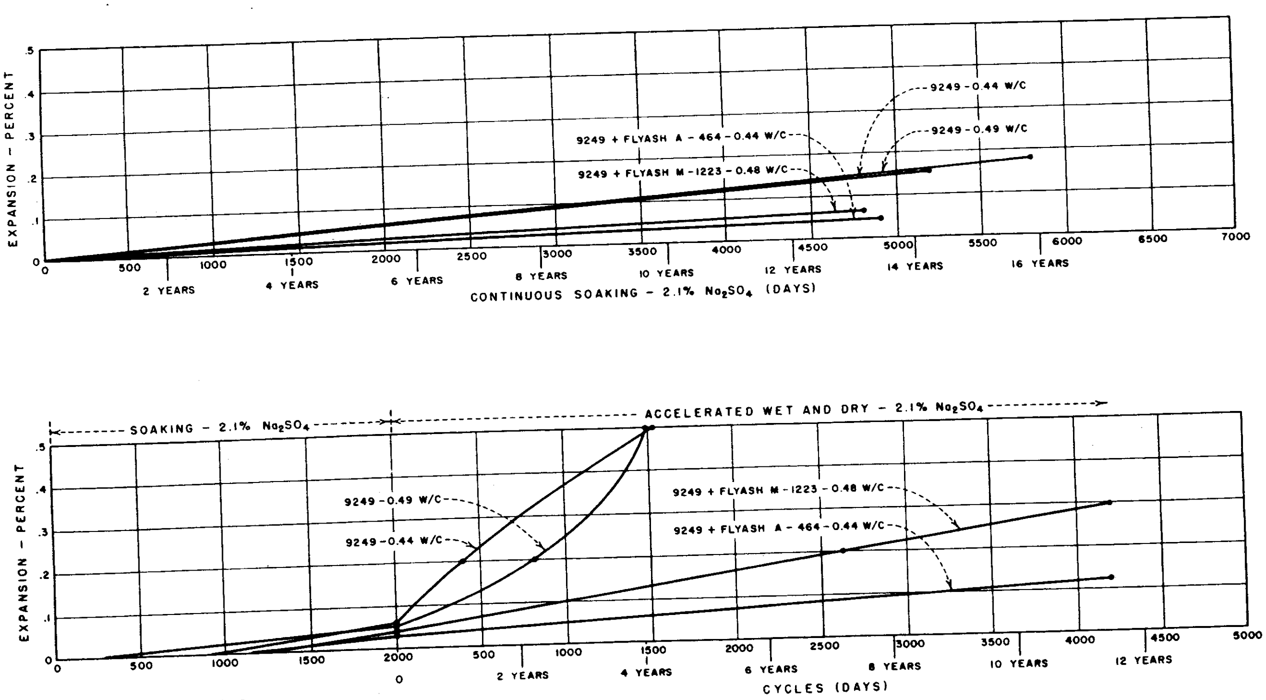

Figure 6.—Effect of fly ash on sulfate resistance of concrete containing Type V cement (9249), Series F.

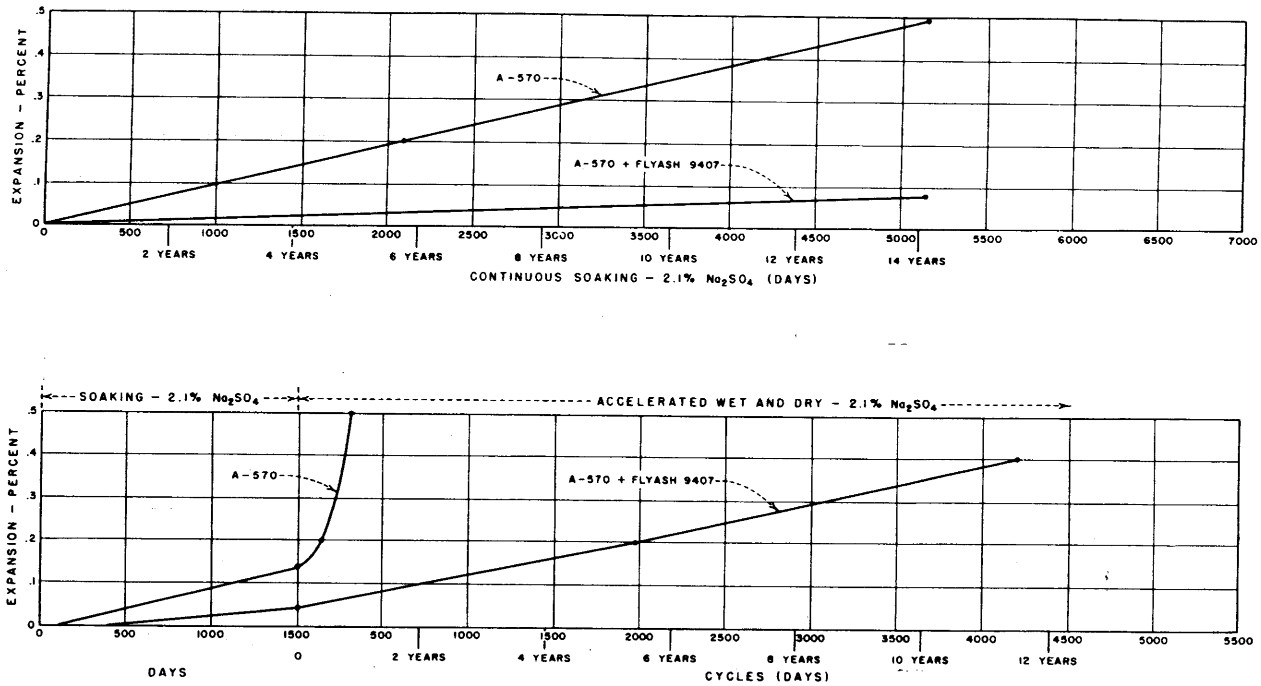

Figure 7.—**Effect of fly ash on sulfate resistance of concrete containing Type V cement (A–570), Series G.**

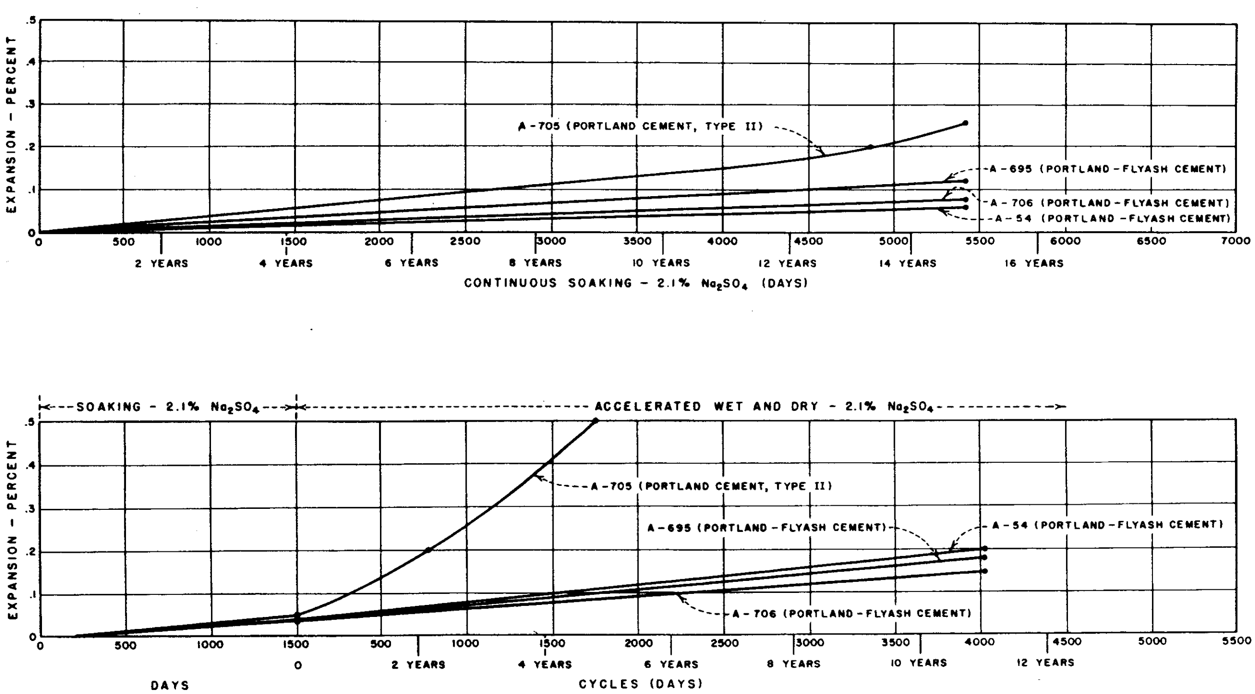

Figure 8.—**Effect of portland-fly ash cement on sulfate resistance of concrete, Series H.**

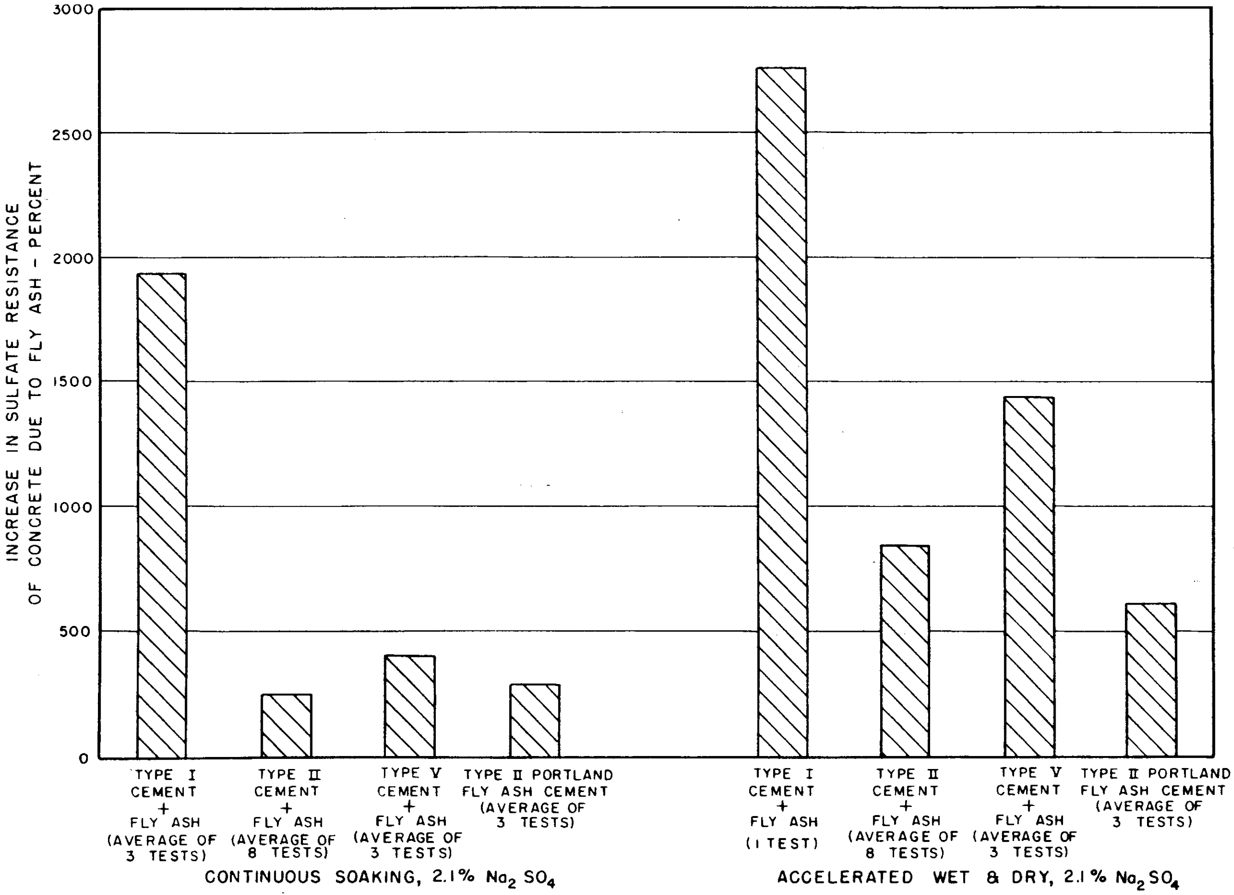

***Figure 9.*—Fly ash improves the resistance of concrete to sulfate attack.**

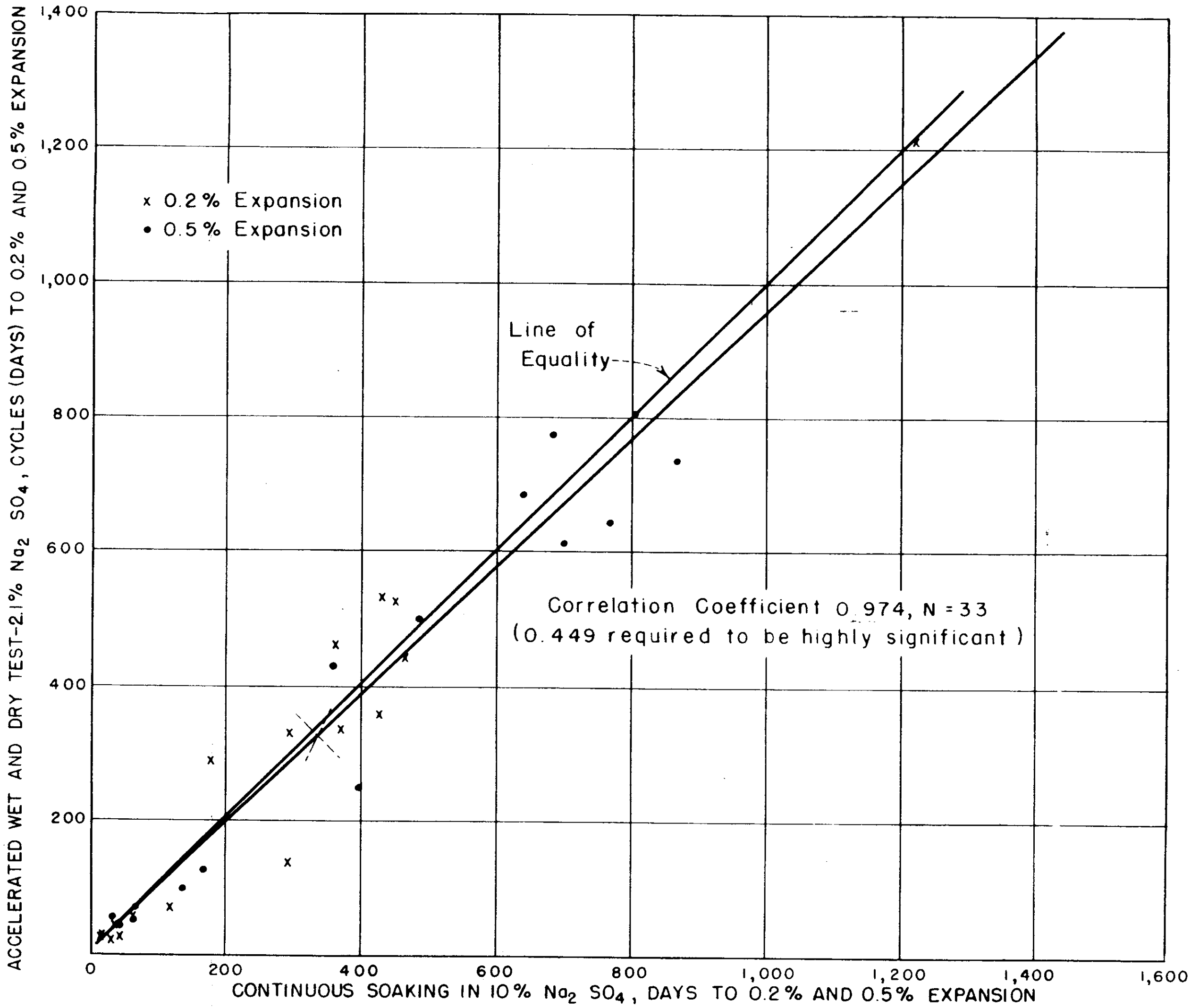

Figure 10.—**Correlation between rates of expansion in the accelerated sulfate test and in the 10-percent Na_2SO_4 soaking test shows the two tests to be approximately equal in severity.**

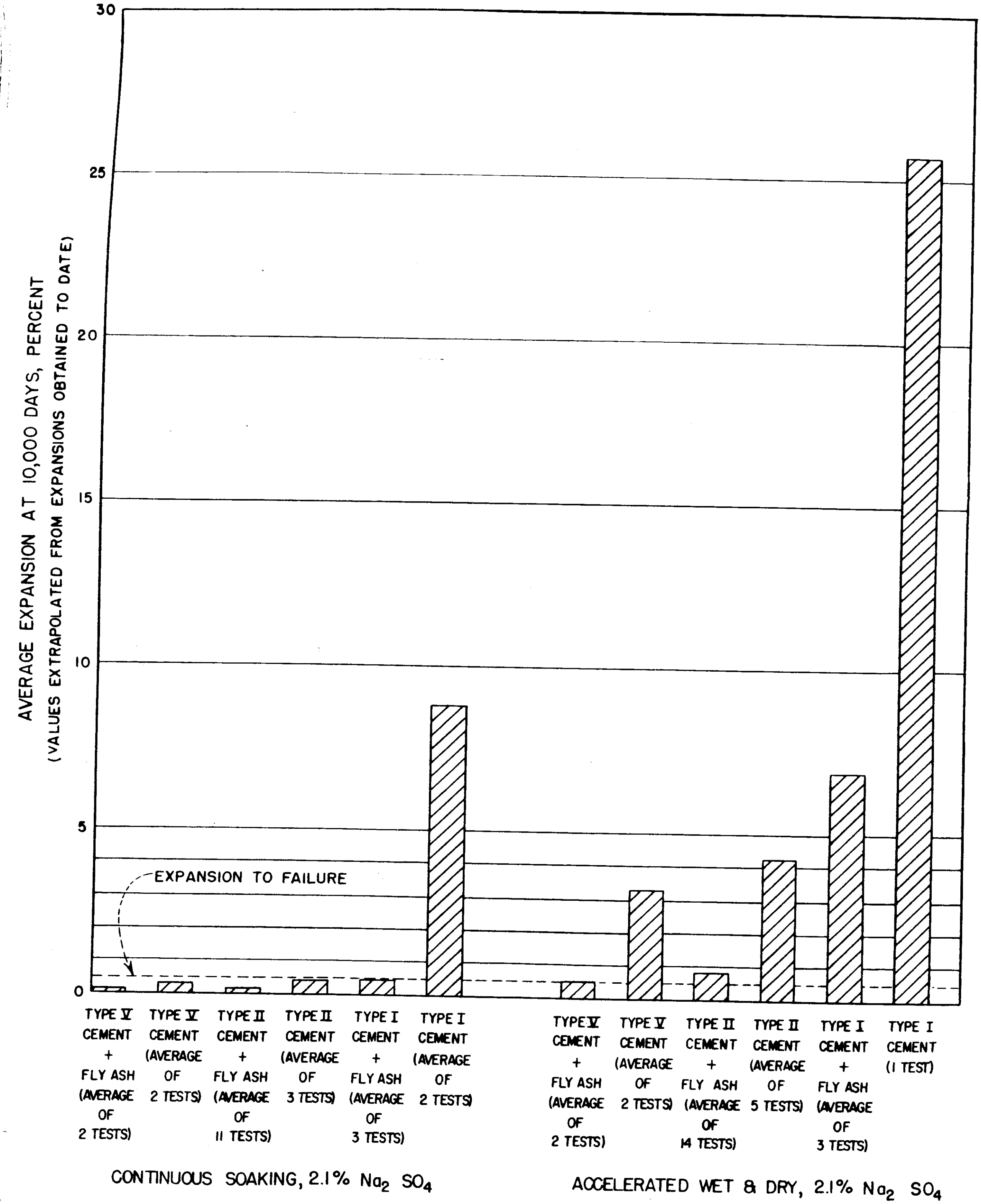

Figure 11.—Reduced expansion of concretes containing fly ash illustrates the improved sulfate resistance afforded by its use.

This study is based on the analysis of laboratory data obtained from sulfate resistance tests performed on 30 concrete mixes made from eight portland cements (Types I, II, and V), three portland fly ash cements, and 12 bituminous coal fly ashes. Concretes containing each of the eight cements without fly ash were used as control mixes. Test mixes contained partial replacement of cement with fly ash. Analysis of results indicates that all bituminous coal fly ashes tested significantly improved the resistance of concretes to sulfate attack, regardless of type of cement used. Effectiveness of fly ash in improving sulfate resistance of concrete increases as the severity of sulfate exposure is increased. A wide range of sulfate resistance properties may be obtained with each type of cement used, depending partially on the cement content and air content of concrete, in addition to the individual composition properties within each cement type and source.

DESCRIPTORS—*fly ash/*portland cement/concrete mixes/laboratory tests/research and development/durability/concrete testing/concrete/*concrete technology/expansion/mixes/*chemical stability/test specimens/concrete pipes/pozzolans/*sulfates/sodium sulfates/alkali soils/drain tiles.

U.S. GOVERNMENT PRINTING OFFICE : 1975—O-570-134