FINAL REPORT

ALTERNATIVES TO TYPE II CEMENT

by

H. Celik Ozyildirim
Research Engineer

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways & Transportation and the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

July 1978
VHTRC 79-R3

0504

CONCRETE RESEARCH ADVISORY COMMITTEE

MR. J. E. GALLOWAY, JR., Chairman, Assistant Materials Engineer, VDH&T

MR. T. R. BLACKBURN, District Materials Engineer, VDH&T

MR. B. W. BUTT, Assistant Construction Engineer, VDH&T

MR. C. L. CHAMBERS, Asst. Division Bridge Engineer, FHWA

MR. JOHN W. CHILES, Resident Engineer, VDH&T

MR. F. C. MCCORMICK, Professor of Civil Engineering, U. Va.

MR. K. H. MURRAY, Professor of Civil Engineering, Old Dominion Universi

MR. W. R. MUSTAIN, Assistant District Engineer, VDH&T

MR. H. H. NEWLON, JR., Associate Head, VH&TRC

MR. A. D. NEWMAN, District Materials Engineer, VDH&T

MR. R. W. SCHWARTZ, District Bridge Engineer, VDH&T

MR. J. F. J. VOLGYI, JR., Bridge Design Engineer, VDH&T

MR. R. P. WINGFIELD, Assistant Maintenance Engineer, VDH&T

PREFACE

This study was undertaken to investigate the possibility of using concrete mixtures made of Type IP cement and Type I cement with fly ash as alternatives to concretes containing Type II cement. A testing program was initiated and the early results were presented in an interim report (see Reference 16) with appropriate conclusions. In the early tests some of the concretes containing fly ash exhibited marginal resistance to freezing and thawing in salt solution in the form of weight loss through undesirable scaling. Therefore, further investigation was deemed necessary. Also, additional testing was performed to verify the initial results from the heat of hydration tests, which were based on one sample for each cement type tested. This final report describes the second testing program and presents the data on the initial test program not included in the interim report because of time limitations. It includes the conclusions from the interim report together with the overall conclusions.

00506

SUMMARY

Concrete mixtures incorporating fly ash were investigated as possible alternatives to mixtures utilizing Type II cements. The mixture characteristics considered were strength, resistance to freezing and thawing and sulfates, heat of hydration, and volume stability. Two testing programs were undertaken. In the first program control mixtures were prepared using Types I, II, and III cements and the experimental mixtures were made of Type IP cement and Type I cement with fly ash. An interim report presented in February 1977 gave the results of the initial tests for compressive and flexural strengths, resistance to rapid freezing and thawing, early volume change, time of set, and heat of hydration. Some of the specimens containing fly ash in the initial testing program exhibited marginal resistance to freezing and thawing in salt solution as manifested by weight loss, which indicates scaling. To investigate this finding further, a second testing program using Types II, IP, and Type I cement with fly ash was initiated. Also, additional mixtures were prepared using Types I, II, IP, and I with fly ash to test the level of heat of hydration. This final report presents the data on the initial testing program not included in the interim report and describes the second testing program. In general, the results indicate that concretes containing IP or Type I cement with fly ash can be an acceptable alternate to Type II; however, it should be recognized that more scaling in the presence of deicers may be expected.

FINAL REPORT

ALTERNATIVES TO TYPE II CEMENT

by

H. Celik Ozyildirim
Research Engineer

INTRODUCTION

The Virginia Department of Highways & Transportation requires the use of Type II cement in all of its structures and pavements. Type IP and Type III modified cements may be used in limited applications.[1]

The continued demand for Type II cement is attributed to its moderate sulfate resistance and heat of hydration. Both of these characteristics have been achieved in the past without additional cost as compared with ordinary Type I cements. In addition, the Type II cements used in Virginia have had a relatively low (less than 0.6%) alkali content, which has minimized or eliminated the possibility of deleterious chemical reactions between cement alkalies and aggregates. Unfortunately, it is anticipated that the demand for Type II cement will have to be met from a diminished supply brought about by environmental and energy conservation policies. Also, in the future a higher level of alkalies is expected in the cements as a result of recycling of kiln dust during production.

Cement production requires considerable energy. In the United States the amount of energy consumed in generating a unit of cement is higher than that required in some other industrialized nations such as Japan and Germany. It is necessary to remodel old plants or to build new ones to achieve efficiency and to meet pollution requirements.[2,3] However, the high costs involved make this task difficult. It is desirable that alternative materials be found and the amount of cement used be reduced. Substituting other cements for Type II or reducing the amount of it used in portland cement mixtures by incorporating additives or admixtures are possible solutions to the impending shortage. However, these alternatives should not be adopted if they result in a significant sacrifice of the qualities which make Type II cement so desirable.

Pozzolan is one material that can be used in portland cement mixtures to improve some of their properties.[4,5] It is a siliceous, or siliceous and aluminous, material that in a fine gradation state can combine with lime in the presence of water to form compounds possessing cementitious properties.[6] The pozzolan can be artificial, as in the form of fly ash, or natural, as in the form of volcanic glass, pumicite, opaline shales and cherts, and calcined diatomaceous earth. The use of a good pozzolan with a low carbon content in optimum amounts can improve workability and sulfate resistance, produce low heats of hydration and thermal shrinkage, reduce permeability, and inhibit the deleterious reactions between certain aggregates and alkalies in cements.(3,5,7,8) Conversely, if a pozzolan is of poor quality or is used excessively, it can reduce the rate of hardening and strength development, increase water demand and drying shrinkage, and lower the resistance to freezing and thawing.

Among the available pozzolans is fly ash, a waste product produced in abundant quantities in electric power plants that use pulverized coal as fuel. It consists of solid or hollow spherical particles of siliceous and aluminous glass, and, in small amounts, thin-walled, multifaceted polyhedrons with a high content of iron particles and irregularly shaped porous carbon.(5) Where fly ash is blended or interground with cements at the plant, the end products are marketed as Type IP cements. Such cements are covered by ASTM Specification C595-76. Fly ash can also be used as an admixture in the preparation of concrete mixtures, provided it meets ASTM Specification C618-77. Even though it has not been utilized widely as an admixture in concrete by the Virginia Department of Highways and Transportation, a considerable experimental effort was directed toward its evaluation in the 1950's by the Research Council.(9-14) At that time it was found that problems regarding the uniformity of the material severely limited its use in concrete. One other utilization of fly ash is in the manufacture of cement as a portion of the raw material.(15)

Ordinary cement blended or mixed with fly ash could provide the desirable properties provided by Type II cement and, in so doing, enable a flexibility in the choice of cementitious materials that would eliminate total dependence on one type of cement and reduce the amount of cement used in the mixture. As a result, considerable economic advantages in the building of highway structures could be gained.

OBJECTIVE AND SCOPE

The objective of this study was to evaluate two possible alternatives to Type II cement mixtures; namely, mixtures utilizing Type IP cements and Type I cement with fly ash. The evaluation was based on the study of the following properties of concrete:

1. Compressive strength at 28 days,
2. resistance to freezing and thawing,

3. sulfate resistance,
4. heat of hydration, and
5. volume stability (freshly mixed and hardened concrete).

Two testing programs were undertaken. In the initial program, control mixtures were made with Types I, II and III cements, and experimental mixtures were prepared utilizing Type IP, and Type I with fly ash. The mixtures were prepared to meet the Department's requirement for Class A3 and A4 concrete. A total of 416 cylinders, 96 prisms, 16 slabs, and 32 cylinder mortar specimens were fabricated from 48 batches of concrete. Also to obtain the fly ash content yielding the highest strength for a fixed cement content, 110 small cylinders were fabricated and tested from 22 batches of concrete. In the second testing program 13 batches of A3 concrete were prepared to obtain 39 large and 12 small cylinders and 36 prisms.

PROCEDURE

The initial testing program, described in the interim report,[16] provided data on the control mixtures made of Types I, II, and III cements and the experimental mixtures containing Type IP cement and Type I cement with both processed and unprocessed fly ash. The difference between the two types of fly ash is that the unprocessed ash is used as obtained from the burning of pulverized coal, while the processed ash is tested and treated to assure that it meets certain requirements and that the variability in the product is minimized. However, in this testing program both types of fly ash were found to be of good quality.

According to the criteria in Table 7 of the interim report, for satisfactory resistance to freezing and thawing at 300 cycles averages of three specimens should yield a weight loss less than 7.0%, relative dynamic modulus of elasticity larger than 60%, and surface rating less than 3.0. In the initial testing program, some concretes containing fly ash exhibited poor and borderline performance in weight loss that indicate a high level of scaling based on the acceptance criteria adopted by the Research Council. The specimens tested were cured in the moist room for 14 days and air dried for 7 days. In all the mixtures high relative dynamic modulus of elasticity values indicative of good internal structure were found. To investigate the high weight loss in some fly ash concretes, a second testing program using Types II, IP, and Type I cement with fly ash was initiated to test more specimens for resistance to accelerated freezing and thawing. Also, concrete mixtures utilizing cement types I, II, IP and I with fly ash, were prepared to determine the heat of hydration generated by experimental mixtures.

RESULTS OF INITIAL TESTING PROGRAM

The interim report gives the results of 7-, 14- and 28-day compressive strength tests, 7- and 28-day flexural strength tests, and the values for rapid freezing and thawing, early volume change, time of set, and heat of hydration. Given below are the results of 6-month tests for compressive and flexural strengths, and information obtained on sulfate resistance, drying shrinkage, and the scaling resistance of slabs, along with data from the petrographic examination of some of the specimens containing fly ash.

Long-Term Compressive Strength

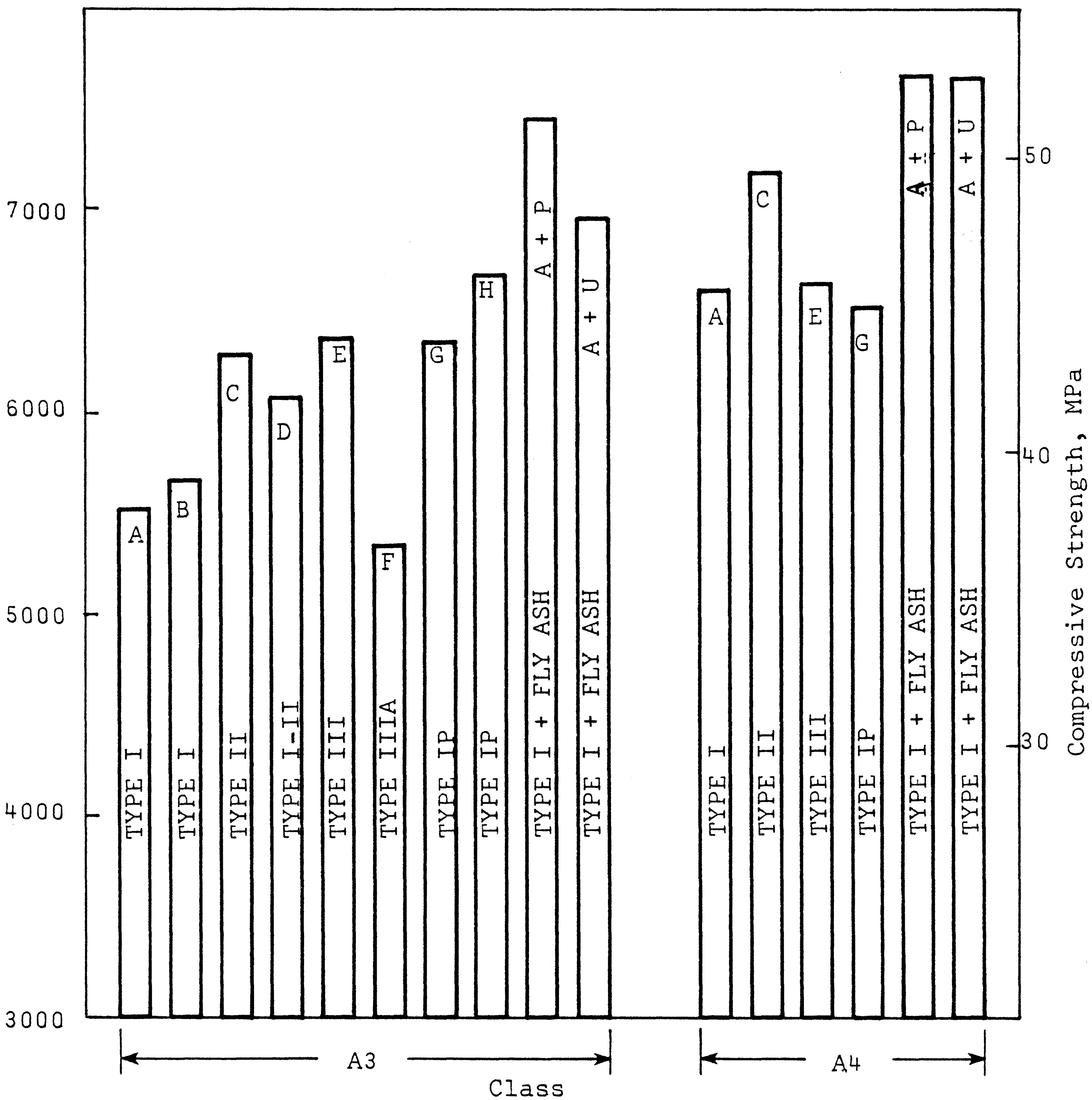
The compressive strengths of specimens containing cements with and without fly ash were determined in accordance with ASTM C39-72. The test results for both A3 and A4 concrete mixtures are shown in Figure 1 and Table 1 and are discussed below.

A3 Concrete

At 6-months, concretes containing Type I cement with fly ash and Type IP cement attained compressive strengths higher than those for mixtures made of Type I cements as shown in Figure 1 and Table 1. Concrete mixtures with Type II and Type I-II cements also exhibited values lower than that of Type I cement with fly ash and Type IP cement but higher than that of the Type I cement mixtures. The compressive strengths of samples using Type III A cement from source F were the lowest. However, mixtures with Type III cement from source E attained compressive strengths higher than those for Types I and II, Type IP cement from source G, and Type III A from source F. The concretes containing fly ash exhibited a high rate of strength gain from 28 days to 6 months, as shown by the ratio of 6-month to 28-day strengths in Table 1. Figure A-1 in the Appendix indicates the relationship between compressive strength and time for mixtures utilizing Type I cements with and without fly ash. The rate of increase in strength and the long-term strength levels of concrete containing fly ash are shown in that figure.

A4 Concrete

At 6 months the compressive strengths of concretes utilizing Type I cement from source A with processed and with unprocessed fly ash were considerably higher than those for the controls made of Types I, II and III cements. Mixtures containing Type IP cement from source G reached the lowest value. Concretes containing fly ash showed a higher rate of strength gain from 28 days to 6 months than did the controls, as is shown in Table 1. This is also indicated in Figure A-2 in the Appendix, which relates strength to age for mixtures utilizing Type I cement with and without fly ash.



P = Processed fly ash
U = Unprocessed fly ash

Figure 1. Compressive strength values at 6 months. (NOTE: Letters denote the sources which are included in Appendices A-5 and A-6.

Table 1

Compressive and Flexural Strength Data

Cement Type	Source	Class of Concrete	Compressive Strength 6 mo., psi	Compressive Strength Ratio of 6 mo. to 28 days	Flexural Strength 6 mo., psi	Flexural Strength Ratio of 6 mo. to 28 days	Ratio of Flex. to Comp. Str. at 6 mo.
I	A	A3	5520	1.20	705	1.04	0.13
I	B	A3	5660	1.15	790	1.05	0.14
II	C	A3	6270	1.16	840	1.06	0.13
I-II	D	A3	6070	1.23	810[a]	1.14	0.13
III	E	A3	6360	1.11	895	1.13	0.14
IIIA	F	A3	5320	1.20	710	1.10	0.13
IP	G	A3	6350	1.27	865	1.22	0.14
IP	H	A3	6680	1.23	935	1.36	0.14
I & Ash	A & P[b]	A3	7460	1.49	955	1.35	0.13
I & Ash	A & U[c]	A3	6950	1.44	770	1.15	0.11
I	A	A4	6600	1.21	925	1.26	0.14
II	C	A4	7190	1.20	860	1.10	0.12
III	E	A4	6630	1.17	850	1.04	0.13
IP	G	A4	6520	1.27	840	1.24	0.13
I & Ash	A & P	A4	7660[a]	1.48	955	1.33	0.12
I & Ash	A & U	A4	7650	1.47	965	1.18	0.13

(a) Average of 2 specimens (Rest average of 3 specimens)

(b) Processed fly ash

(c) Unprocessed fly ash

NOTE: 1 psi = 6.89 kPa; 1000 psi = 6.89 Mpa

Comparison of Compressive Strengths of A3 and A4 Concretes

The requirements of the Department's Class A3 (general use) and A4 (superstructure) concretes were given in Table 1 of the interim report. The A3 concretes have a minimum compressive strength requirement of 3,000 psi (20.7 MPa) at 28 days and the A4 mixtures must have a minimum of 4,000 psi (27.6 MPa). Table 2 summarizes the data for the A3 and A4 mixtures that incorporated the same cement type. At 28 days, all the samples far exceeded the A3 and A4 requirements for compressive strength. In the mixtures with Types I and II cements the difference in strengths between the A3 and A4 concretes at 28 days were 860 psi (5.9 MPa) and 610 psi (4.2 MPa), respectively, as shown in Table 2. These differences are smaller than the expected difference of 1,000 psi (6.9 MPa). In fact, in the A3 control mixtures the maximum allowable water was used, but in the A4 control mixtures 5% of the allowable water was withheld to keep the slump within specifications. However, at 6 months the differences between A3 and A4 concretes with Type I and Type II cements, as given in Table 2, were about as expected. The differences in compressive strengths at 28 days and 6 months in A3 and A4 concretes containing fly ash were low compared to the values for the Type I and II cement mixtures, which indicates that in rich mixtures the effect of fly ash is smaller than in lean mixtures. At 28 days, specimens made of Type III cement from source E and meeting Class A4 requirements unexpectedly exhibited slightly lower strengths than did their A3 counterparts. However, at 6 months the expected trend was observed, and, even though the difference was small, the A4 mixtures achieved higher strength than did the A3 concretes.

Table 2

Differences in Compressive Strengths Between A3 and A4 Concretes at 28 Days and 6 Months

Cement	Source	28-day Compressive Strength, psi			6-month Compressive Strength, psi		
		A3	A4	Δ = (A4-A3)	A3	A4	Δ = (A4-A3)
I	A	4,600	5,460	860	5,520	6,600	1,080
II	C	5,390	6,000	610	6,270	7,190	920
III	E	5,730	5,670	- 60	6,360	6,630	270
IP	G	5,000	5,130	130	6,350	6,520	170
I & Ash	A & P[(a)]	4,990	5,170	180	7,460	7,660	200
I & Ash	A & U[(b)]	4,830	5,200	370	6,950	7,650	700

(a) Processed fly ash

(b) Unprocessed fly ash

NOTE: 1 psi = 6.89 kPa; 1000 psi = 6.89 MPa

At 28 days, A3 and A4 concretes containing both processed and unprocessed fly ash exhibited comparable strength levels. At 6 months, A3 concretes utilizing unprocessed fly ash attained lower values than those mixtures containing processed fly ash. A4 concretes with both fly ashes exhibited strength levels that were equivalent. Therefore, the difference between A3 and A4 concretes at 6 months was considerably higher for concretes containing unprocessed fly ash than the processed one.

Long-Term Flexural Strength

To evaluate the flexural strength of the mixtures, three concrete prisms 3 x 4 x 16 in. (75 x 100 x 400 mm) were prepared for each cement type and tested in accordance with ASTM C78-75. The 6-month results are summarized in Table 1 and Figure 2, and are discussed below.

A3 Concrete

Concrete samples made of Type I cement from source A with processed fly ash and Type IP cement from source H attained the highest flexural strengths. Samples made of Type III cement from source E achieved the third highest strength level. The Type I cement mixtures with unprocessed fly ash exhibited lower strengths than Type II and Type I-II cement mixtures. Mixtures containing Type I cement from source A exhibited the lowest strength. In general, the strength gain from 28 days to 6 months was higher in concretes with fly ash than in the controls as shown in Table 1.

A4 Concrete

At 6 months concretes containing Type I cement with processed and with unprocessed fly ash attained the highest strength levels. They were followed by concretes with Type I cement from source A. The mixtures with Type IP cement from source G exhibited the lowest strength, but were satisfactory since they exceeded 15% of the design compressive strength which is recognized to be acceptable.

The ratios of flexural strengths to compressive strengths for all the samples at 6 months were calculated and are shown in Table 1 The results indicate a similarity between concretes with fly ash and those without it.

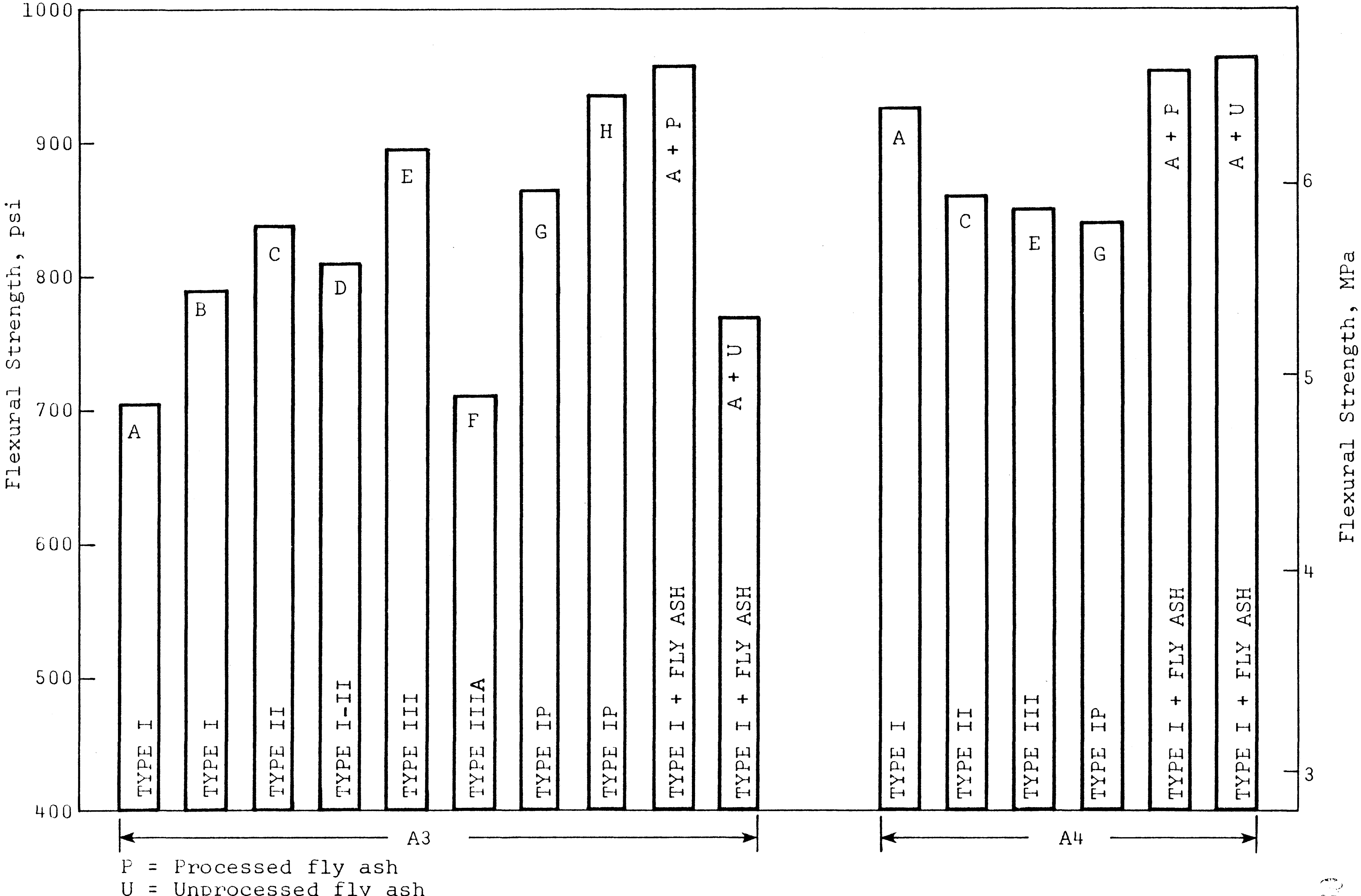


Figure 2. Flexural strength values at 6 months.

Sulfate Resistance

In the initial testing program, cylinders 3 x 6 in. (76 x 152 mm) with reference lugs at both ends were prepared to determine the sulfate resistance of concretes containing different types of cement, including the ones containing fly ash. The samples were immersed in a solution containing 5% sodium sulfate and 5% magnesium sulfate. Similar tests are described in the literature.(17,18) The specimens were moist cured for 28 days prior to placement in the sulfate tank. At intervals of 28 days, the weights and the lengths of specimens were measured over a period of 1 year. Before these measurements were taken, the samples were blown with compressed air to remove surface water and loose material. The results of the sulfate test at 1 year are summarized in Table 3 for the A3 and A4 concretes. The weight loss and length change undergone by the samples are shown in Figures 3 and 4, respectively. The criteria adopted for failure were a weight loss of 25.0% or a length change of 0.15%.(18)

A3 Concrete

The weight loss and length change for all the specimens were below the levels of failure adopted. Concretes made with Type IP cement from source G reached the highest weight loss at 9.56%. Mixtures with Type I cement from source A showed the second highest loss. Mixtures made of this cement with processed and with unprocessed fly ash gave lower values, which indicates that fly ash admixtures can improve the sulfate resistance of mixtures. Types II and I-II cements exhibited weight losses less than those of the mixtures with Type I cements but higher than those for mixtures with Type I cement and fly ash. Type III cement from source E achieved the lowest weight loss. Mixtures with Type IP cement from source H exhibited a weight loss between that reached by the mixtures with Type II and Type I-II cements. The third highest weight loss was shown by mixtures containing Type III A cement from source F.

In length change values, the mixtures with Type II cement yielded the third largest value, after those with Type I cement from source A and Type III A cement. Mixtures with Type I cement from source A reached a length change higher than those exhibited by the mixtures containing Type I cement with processed and with unprocessed fly ash, which indicates that fly ash can help to increase the sulfate resistance of mixtures as was the case with weight loss. The lowest length change was exhibited by mixtures utilizing Type III cement from source E. Type IP cement mixtures exhibited length changes smaller than those for mixtures with Types I and II cement.

Table 3

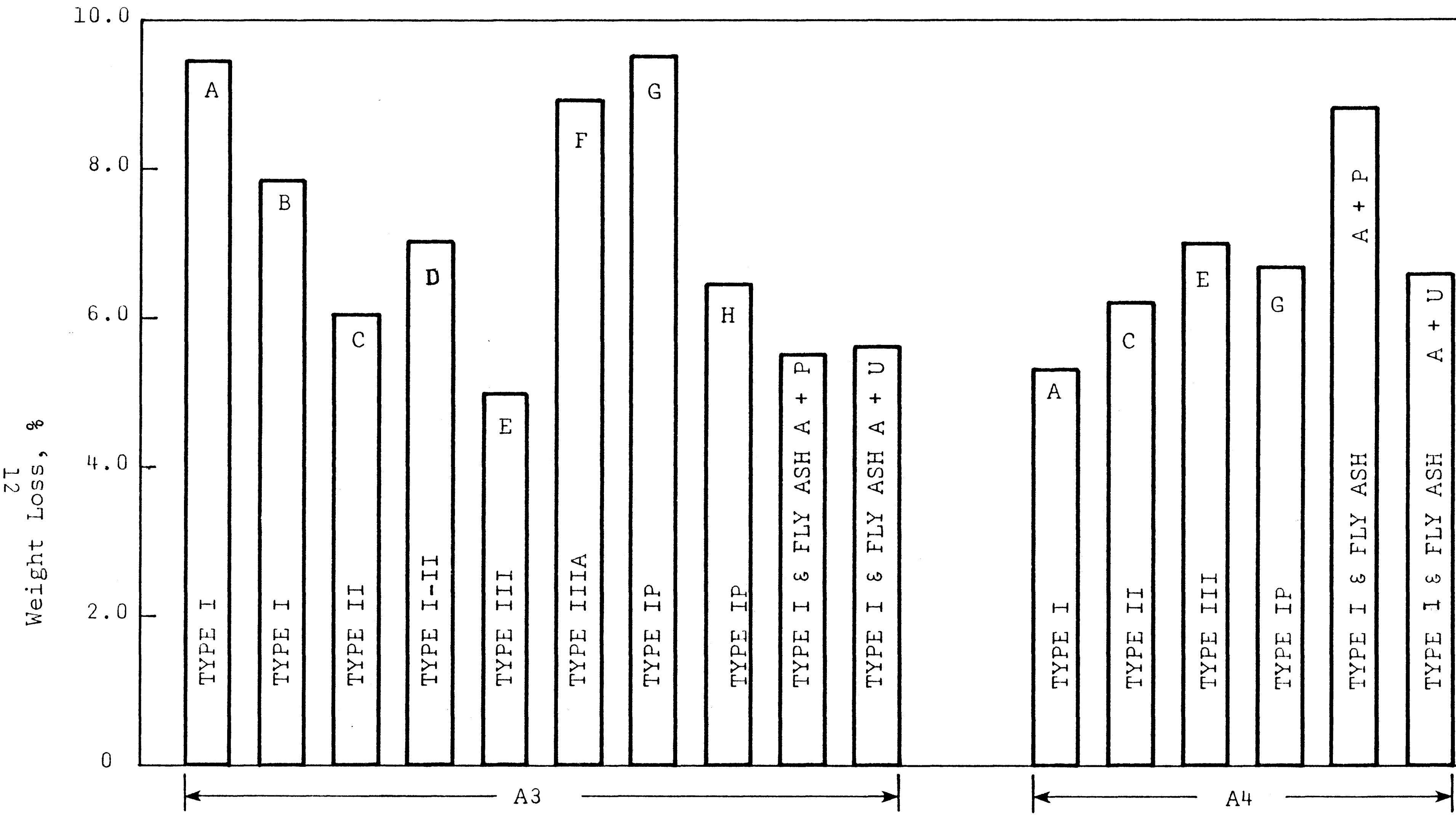
Weight Loss and Length Change at 1 Year

Cement Type	Source	Class of Concrete	Weight Loss, %	Length Change, %
I	A	A3	9.43	0.0308
I	B	A3	7.82	0.0224
II[(a)]	C	A3	6.10	0.0276
I-II	D	A3	7.02	0.0250
III	E	A3	4.98	0.0075
IIIA	F	A3	8.87	0.0278
IP	G	A3	9.56	0.0145
IP	H	A3	6.43	0.0210
I & Ash	A + P[(b)]	A3	5.56	0.0274
I & Ash	A + U[(c)]	A3	5.61	0.0145
I	A	A4	5.28	0.0167
II	C	A4	6.21	0.0075
III	E	A4	7.04	0.0115
IP	G	A4	6.65	0.0179
I & Ash	A + P	A4	8.79	0.0220
I & Ash	A + U	A4	6.57	0.0237

(a) Average of two specimens (Rest average of three specimens)

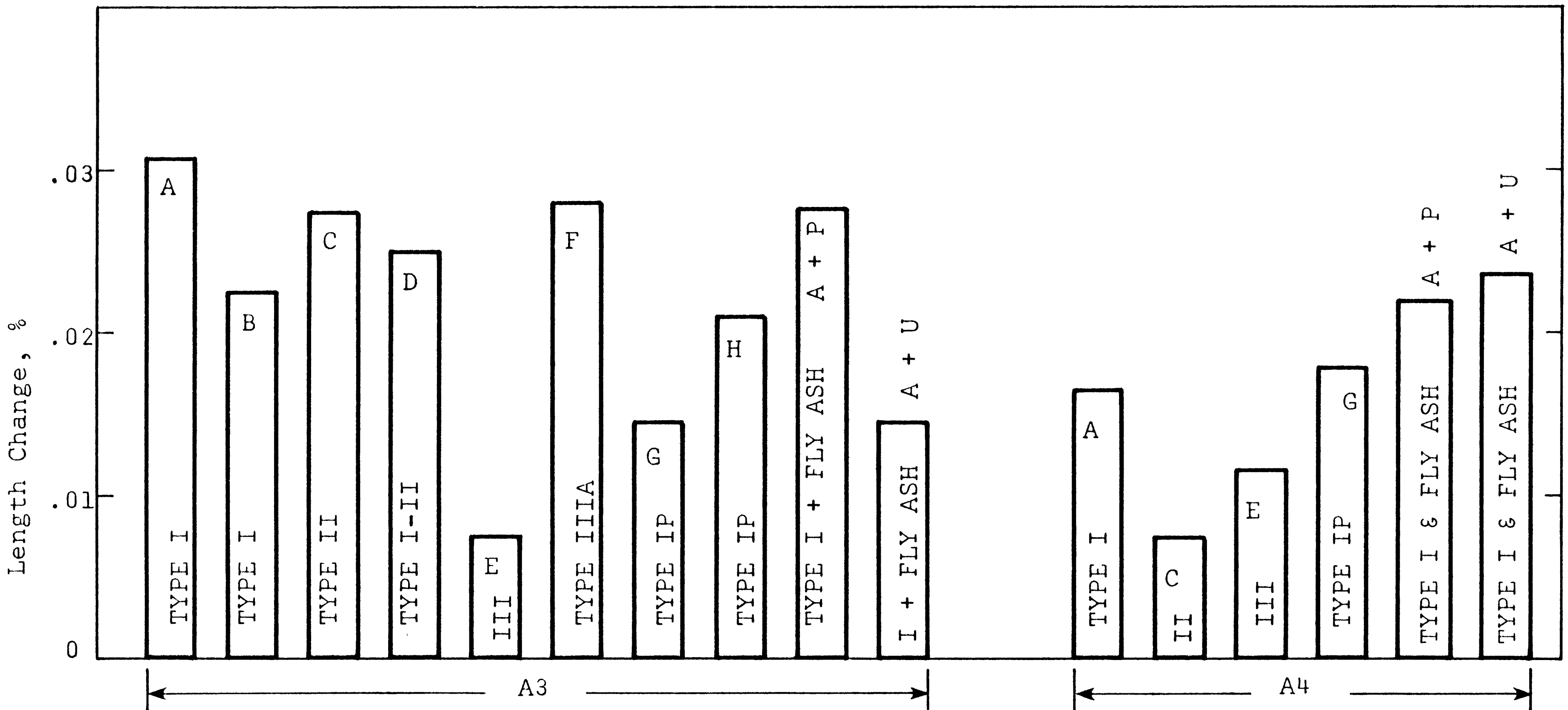
(b) Processed fly ash

(c) Unprocessed fly ash



P = Processed fly ash
U = Unprocessed fly ash

Figure 3. Weight loss of specimens subjected to sulfate solution at 1 year.



P = Processed fly ash
U = Unprocessed fly ash

Figure 4. Length change of specimens subjected to sulfate solution at 1 year.

A4 Concrete

All the A4 mixtures exhibited satisfactory performance in the sulfate environment. The highest weight loss was 8.79% in mixtures with Type I cement with processed fly ash. Contrary to the results obtained in A3 mixtures, Type I cement mixtures exhibited the lowest weight loss. The Type II cement mixtures exhibited a weight loss slightly lower than that attained by the mixtures with Type IP cement and Type I cement with unprocessed fly ash.

The lowest length change value was exhibited by Type II cement mixtures and the next lowest by the Type III mixtures. The Type I cement mixtures yielded a value lower than those exhibited by the mixtures with Type I cement and processed fly ash, Type I and unprocessed fly ash, and Type IP.

Discussion on Sulfate Resistance

In A3 concretes, there was a beneficial effect of fly ash on sulfate resistance. The improved resistance of concrete containing good quality fly ash has been reported by other researchers, as well.[19,20] However, in A4 concretes such a beneficial effect was not evident in the samples tested, but all the concretes showed satisfactory performance. It is possible that an experimental error could have caused the Type I cement A4 mixtures to exhibit lower weight loss and length change than their fly ash counterparts, or it may be that in dense, high strength concretes such as A4 mixtures the improvement in sulfate resistance from the use of fly ash is not apparent as in leaner A3 mixtures; all the A4 mixtures had a very low weight loss and length change. As did all others, the mixtures with Type I cement exhibited satisfactory resistance; however, that from source A had a C_3A content of 8.8% and that from source B gave a 6.0% value. These are low C_3A contents. Cook presents data which show that 11 out of 152 specimens exposed to warm sea water (a sulfate environment) failed the sulfate resistance test. Eight of the 11 failed specimens contained cements with C_3A contents exceeding 12.0%.[21] Also, Verbeck has shown that concretes made with cements with C_3A contents of 11.2% or less have performed satisfactorily through 25 years of exposure in warm sea water.[22] The satisfactory results and the difficulties in differentiating between cement types for all mixtures in the present study can be attributed to low C_3A contents in relation to the marginal values given by Cook and Verbeck.

Drying Shrinkage

To determine the volume change from drying shrinkage of hardened concrete samples with and without fly ash, test specimens 3 x 3 x 11 in. (75 x 75 x 275 mm) with studs at both ends were prepared. During most of the time the data were collected regularly; however, towards the end of the test program all the data on drying shrinkage were lost and further measurements were discontinued.

Some researchers have indicated that concrete containing fly ash generally will exhibit less shrinkage upon drying than will concrete without fly ash.[23,24]

Scaling Resistance

In the initial testing program, to determine the scaling resistance of concrete surfaces exposed to deicing chemicals, slabs 12 x 12 x 13 in. (300 x 300 x 75 mm) made of concretes with different types of cement were prepared and placed in an outdoor exposure area and subjected to cycles of freezing and thawing in the presence of 2% NaCl. (In the laboratory rapid freezing and thawing tests 2% NaCl was also used). In each cycle a measured volume of water was poured on the slab and left to freeze. Then NaCl was placed on the slab. The salt solution caused thawing and then was allowed to freeze. After thawing again occurred the cycle was complete. The surface was flushed clean and another cycle was started. The slabs were subjected to 45 cycles in 2 years and were rated visually using the scale shown in Table 4. The results are given in Table 5. After 45 cycles of freezing and thawing the A3 mixtures containing Type I cement from source A and Type III A cement from source F showed no scaling. The mixtures with Type I cement from source B, Type II cement from source C, and Type III cement from source E exhibited very slight scaling. Slight to moderate scaling was observed for mixtures with Type I-II cement from source D and Type IP cement. The mixtures containing Type I cement with processed and with unprocessed fly ash showed moderate scaling.

The A4 concretes with Types I and III cement exhibited no scaling. Those with cement Types II, IP, and I cements with processed fly ash showed slight to moderate scaling. Moderate scaling was observed in mixtures made of Type I cement with unprocessed fly ash. In general, a slightly higher scaling was observed on specimens containing fly ash than on the control mixtures. This finding agrees with the rapid freezing and thawing test results in the presence of 2% NaCl. The higher scaling of concretes containing portland-pozzolan cements in the presence of deicers was also observed by other researchers.[25] However, results which show equal performance have been reported when concretes containing 564 lb. (256 kg) cement were compared to the mixtures using 493 lb. (224 kg) cement and 100 lb. (45 kg) of low carbon fly ash.[26]

Table 4

Rating System Used to Evaluate Scaling

Rating	Condition of Surface
0	No scaling
1	Very slight scaling
2	Slight to moderate scaling
3	Moderate scaling
4	Heavy scaling

Table 5

Surface Rating of Slabs

Cement Type	Source	Class	Rating
I	A	A3	0
I	B	A3	1
II	C	A3	1
I-II	D	A3	2
III	E	A3	1
IIIA	F	A3	0
IP	G	A3	2
IP	H	A3	2
I & Ash	A & P[a]	A3	3
I & Ash	A & U[b]	A3	3
I	A	A4	0
II	C	A4	2
III	E	A4	0
IP	G	A4	2
I & Ash	A & P	A4	2
I & Ash	A & U	A4	3

(a) Processed fly ash

(b) Unprocessed fly ash

Petrographic Examination

Some of the samples exhibiting marginal performance in the initial freezing and thawing tests were subjected to petrographic examination. Four samples that showed excessive scaling in the freezing and thawing test were cut and lapped. The air contents, specific surfaces, and spacing factors were determined using the linear traverse method in accordance with ASTM 457 and they are given in Table 6. Mixtures with Type IP cement from source G exhibited a spacing factor of 0.0055 in. (0.140 mm), which should provide satisfactory resistance to freezing and thawing. The rest had values above the accepted limit of 0.008 in. (0.200 mm), which would indicate poor resistance.(27)

The freezing and thawing samples had already lost the surface mortar. Therefore, other specimens made from the same batch for drying shrinkage tests were cut and lapped for examination. Also the air content, specific surface, and spacing factor of these drying shrinkage samples were determined and are summarized in Table 6. All the spacing factors for these specimens were below the 0.008 in. (0.200 mm) value that would indicate satisfactory resistance, and these values were also much lower than the ones originally obtained on specimens that had been subjected to freezing and thawing. It is possible that small bubbles in specimens that have undergone freezing and thawing cannot be detected because of damage incurred to the bubbles during testing and preparation. The damage could result from a weakening of the matrix during cycles of freezing and thawing. Furthermore, the high specific surfaces of 1,016 in.$^{-1}$ (40 mm^{-1}) and above and the low spacing factors obtained from the drying shrinkage specimens raised questions, because in a recent study a variety of mixtures, including the ones with high air contents, exhibited much lower specific surfaces ranging from 503 in.$^{-1}$ (19.8 mm^{-1}) to 831 in.$^{-1}$ (32.7 mm^{-1}).(28) Therefore, a closer examination of these lapped specimens containing fly ash at high magnifications up to 400 x was made. In addition, fluorescent dye impregnated, ultrathin sections were prepared and investigated — under the microscope. The results show that hollow fly ash particles resemble air bubbles in appearance. It is difficult and sometimes impossible to differentiate them from air bubbles. The shell of the hollow fly ash particles is often very thin and can exhibit a variety of colors ranging from gray or buff to glass-clear within the same batch. Some of these colors blend well with the matrix and could not be detected as fly ash at the magnifications used in linear traverse. Some are brownish or have brown spots and are easier to detect, but still close scrutiny is required to differentiate them from air bubbles. Figure 5 shows a polished surface and an etched surface. The hollow fly ash particles are the size of small air bubbles; therefore, even though their contribution to total air content may be small, their effect on the specific surface and spacing factor values can be considerable. In the photographs, some of the larger fly ash particles exhibit a shiny appearance; however, when viewed through the microscope, and because of the lighting and the speed at which the specimen moves during linear traverse, they are still difficult to identify. It is impossible to categorize many of the smaller cenospheres. Due to the difficulty encountered in determining the air void structure of hardened concrete containing fly ash, a further linear traverse analysis on samples with fly ash was not attempted.

Table 6

Air Content and Specific Surface of Samples Prepared From Same Batch but Subjected to Freezing and Thawing, and Drying Shrinkage
(Each value represents one specimen.)

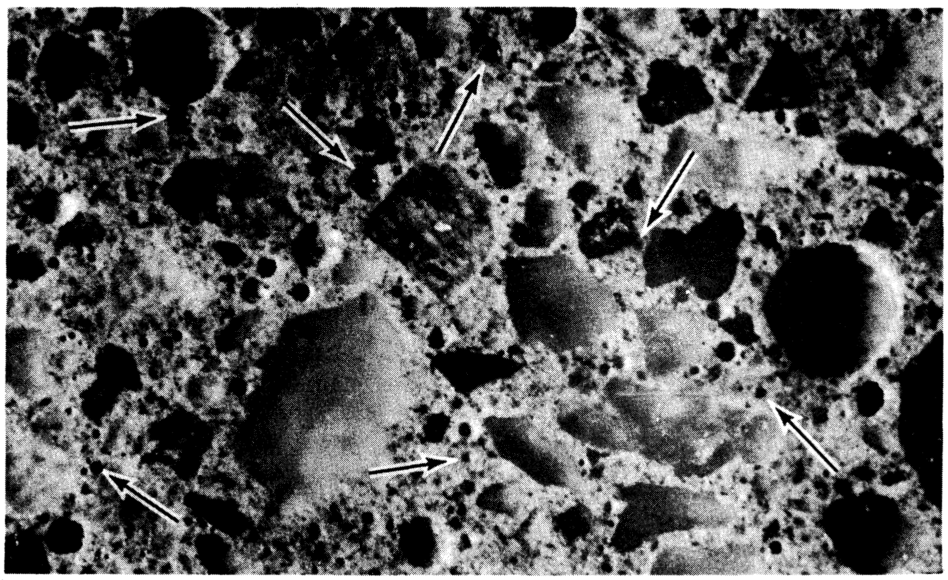
Cement Type	Source	Class	Fresh Conc.	Hardened Concrete					
				Freeze-Thaw Samples			Drying Shrinkage Samples		
			Air, %	Air, %	Specific Surface, in.$^{-1}$	Spacing Factor, in.$^{-1}$	Air, %	Specific Surface, in.$^{-1}$	Spacing Factor, in.$^{-1}$
IP	G	A3	7.3	5.7	857	0.0055	6.8	1,123	0.0039
IP	H	A3	4.9	2.6	459	0.0147	4.5	1,016	0.0052
I & Ash	A & P[a]	A3	5.7	4.7	517	0.0100	4.3	1,018	0.0053
I & Ash	A & U[b]	A4	5.1	3.9	689	0.0082	3.0	1,432	0.0044

(a) Processed fly ash

(b) Unprocessed fly ash

NOTE: 1 in. = 25.4 mm.

The surfaces of the drying shrinkage specimens were also studied under the microscope. There were cracks perpendicular to the surface and extending to an average depth of 0.12 in. (3 mm). The sample made of Type IP cement from source H exhibited the most severe cracking and that with Type I cement containing unprocessed fly ash showed the least. Another observation made on the concrete containing Type I cement with processed and with unprocessed fly ash was the absence of layer of carbonation at the surface. Also the surfaces exhibited a dark area about 0.01 in. (0.25 mm) deep, which may have resulted from a porous surface absorbing oil during preparation of the specimen. The control specimens had a dense surfac layer exhibiting carbonation. Type IP cement mixtures also showed carbonation at the surface but it may not have been as dense as that observed in the controls, because some of them showed more scaling than the controls. It would be desirable to study the surface carbonation of concretes with fly ash further in an attempt to understand their durability.



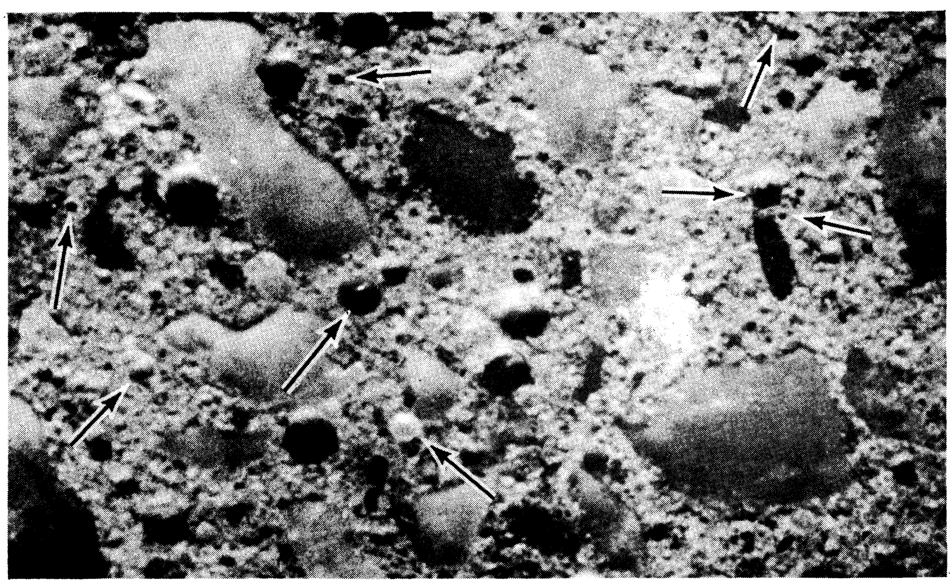


Figure 5. At top, polished surface (24x); bottom, etched surface (45x). Fly ash particles are indicated by arrows; remaining voids are assumed to be air bubbles.

SECOND TESTING PROGRAM

An additional testing program was pursued to determine the causes of borderline resistance to accelerated freezing and thawing experienced with some test specimens utilizing fly ash. Also, additional testing was performed to verify the initial results on the heat of hydration tests that had been based on one sample for each cement type. There is a considerable interest in the use of fly ash to lower the rate of heat liberated during hydration, especially in massive structures such as abutments and retaining walls.

The materials and the mixture proportions used and the results from the tests on resistance to freezing and thawing, and heat of hydration, obtained in the second testing program are discussed below.

Materials and Mix Proportions

The coarse aggregate used was a locally available granite gneis with a specific gravity of 2.78 and a dry rodded unit weight of 103. lb./ft.^{3} (1.7 g/cm^3). The fine aggregate was a quartz sand with a specific gravity of 2.62 and a fineness modulus of 2.8. Type II ceme was used to prepare control mixtures, and the experimental mixtures were made of Type IP and Type I containing fly ash. The results of chemical and physical analyses of the cements are given in Appendix Table A-1 and that of the fly ash in Table A-2.

In the initial testing program the volume of coarse aggregate per unit volume of concrete was found from Table 5.3.6 of ACI 211.1-74, which is based on the fineness modulus of sand. The volumes of cement, water, air and fly ash were either specified or found by trial mixtures. Then the volume of sand was calculated. When fly ash is used as a partial replacement for cement, usually a higher amount of fly ash by weight is added than the cement removed to achieve equivalent 28-day strengths of control mixtures. For example in the initial testing program, the control A3 mixtures had a cement content of 588 lb./yd.^{3} (349 kg/m^3). The concretes containing fly ash as an admixture had a cement content of 470 lb./yd.^{3} (279.0 kg/m^3 and a fly ash content of 140 lb./yd.^{3} (83.0 kg/m^3). Even though a reduction in the amount of sand is made to accommodate extra fly ash in the mixture, a large amount of fines is introduced into the mixture. To compensate for this situation in the second mixing program, a reduction in the ratio of fine aggregate to total aggregate was used for mixtures utilizing fly ash. This adjustment resulted in the use of higher amounts of coarse aggregate and lower amounts of sand in the mixtures with fly ash compared to the control mixtures, and led to improved workability and finishing characteristics. Table 7 gives the proportions of ingredients used. In the testing program the cement content in the control mixtures was 588 lb./yd.^{3} (349 kg/m^3) and that in the concretes with fly ash was 506 lb./yd.^{3} (300 kg/m^3) of cement and 125 lb./yd.^{3} (74 kg/m^3) of fly ash were used. Thus a smaller portion of cement, 14%, was replaced compared to the 20% in the initial testing program to achieve improved strength and durability.

Table 7

Mix Proportions Used in Second Testing Program

Type	Cement, lb./yd.^{3}	Fly Ash, lb./yd.^{3}	Water, lb./yd.^{3}	C.A., lb./yd.^{3}	F.A., lb./yd.^{3}	F.A./(F.A. + C.A.) % by volume	AEA Dosage as a Ratio of Control
II	588	-	270	1,869	1,192	0.40	1
IP	588	-	270	1,924	1,112	0.38	4
I & Ash	506	125	270	1,922	1,063	0.37	2.4

NOTE: 1 lb. = 454 gm; 1 lb./yd.^{3} = 0.59 kg/m^3

The mixtures were proportioned to meet the A3 (general use) requirements of the Virginia Department of Highways and Transportation. For air entrainment, a commercially available neutralized vinsol resin was used. To fulfill the air content requirements, it was necessary to increase the dosage of air entraining agent in the IP mixtures to four times that for the control and in Type I with fly ash to increase it 2.4 times to achieve comparable air contents as shown in Table 7. The necessity for increasing the admixture dosage was due mainly to the carbon particles in fly ash, which adsorb chemical admixtures.[29]

Freezing and Thawing

For each type of cement (Type II control and Type IP and Type I with fly ash) three batches of concrete were prepared and samples for rapid freezing and thawing and compression tests were fabricated. The mixture temperature, air content, slump, and unit weight of mixtures utilizing the different cements are shown in Table 8. From each batch four 3 x 4 x 16 in. (75 x 100 x 400 mm) prisms and three 6 x 12 in. (150 x 300 mm) cylinders were cast. At the Research Council, the freezing and thawing test generally is performed in accordance with ASTM C666 (Procedure A), except that specimens are air dried for 1 week after 2 weeks of moist curing and during testing a 2% solution of NaCl is used rather than water. In the initial testing program the above procedure was followed. In the second testing schedule, specimens were tested in both water and in the 2% NaCl solution. Also, it was planned to test specimens after a longer curing period of 2 months in addition to the 2 weeks of moist curing and 1 week of air drying. Concrete cylinders were prepared for testing at the same time the prisms were subjected to rapid freezing and thawing and also at 28 days. However, due to the breakdown of the freeze-thaw equipment, specimens were not tested for the early stage and only after 2 months of moist curing could the second set of specimens be subjected to testing. The rapid freezing and thawing data at 300 cycles on weight loss, relative dynamic modulus, and surface rating on specimens tested in water and also in 2% NaCl are shown in Tables 9 and 10. The 28-day and 2-month compressive strengths are depicted in Table 11. The results indicate that at 28 days mixtures incorporating fly ash can attain compressive strength equivalent to that of control mixtures with considerable savings in cement. In the mixtures made of Type I cement with fly ash the amount of cement reduced was 14% compared to the control. At 2 months, both the type IP and Type I with fly ash exhibited higher strengths than the control. The freezing and thawing results show that specimens tested in the 2% NaCl solution underwent a higher weight loss and gave a larger surface rating than did the specimens tested in water. In general, the concretes containing fly ash exhibited slightly higher scaling than the controls in both water and 2% NaCl. However, in the second testing program, the difference in scaling between the control and the fly ash mixtures was not as high as that obtained in the initial testing program. This result could be due to the redesign of the mixtures to replace less cement and reduce the ratio of the fine aggregate to total aggregate. The acceptance criterion at the Research Council is based on 300 cycles. The specimens moist cured for 2 weeks and air dried for 1 week should exhibit a weight loss of less than 7%, a relative dynamic modulus higher than 60%, and a surface rating of less than 3.0. The specimens tested were cured longer but were not air dried. In all the specimens the weight loss was less than 7% and the relative dynamic modulus was larger than 60%; they all were considered to perform satisfactorily. The high surface ratings obtained by visual examination were not substantiated by the values for weight loss, which represent a more objective determination.

Table 8

Air Content, Slump, and Unit Weight of Mixtures Prepared for Rapid Freezing and Thawing Tests

Cement Type	Mixture Temp., °F	Air, %	Slump, in.	Unit Weight, $lb./ft.^3$
II	70	6.6	3.4	146.0
IP	70	6.6	2.9	144.2
I & Ash	69	6.1	3.4	145.5

NOTE: 1 $lb./ft.^3$ = 16.0 kg/m^3

Table 9

Rapid Freezing and Thawing Data at 300 Cycles of Specimens Moist Cured for 2 Months and Tested in Water (Average of 3 Specimens)

Cement Type	Weight Loss, %		Rel.Dyn.Mod., %		Surface Rating	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
II	1.0	0.6	87	1	1.8	0.2
IP	2.2	0.6	85	6	2.1	0.2
I + Ash	1.3	0.4	68	15	1.8	0.3

Table 10

Rapid Freezing and Thawing Data at 300 Cycles of Specimens
Moist Cured for 2 Months and Tested in 2% NaCl Solution
(Average of 3 Specimens)

Cement Type	Weight Loss, %		Rel.Dyn.Mod., %		Surface Rating	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. De
II	5.1	2.1	82	1	3.1	0.2
IP	5.5	1.9	84	3	3.4	0.6
I & Ash	6.3	2.0	80	5	3.6	0.4

Table 11

Compressive Strength of Moist Cured Specimens
at Different Ages
(Average of 3 Specimens)

Cement Type	Compressive Strength			
	28-Day	Std. Dev.	2-Month	Std. Dev.
II	5,195	70	5,710	59
IP	5,115	141	5,995	220
I & Ash	5,380	88	6,150	236

NOTE: 1 psi = 6.89 kPa; 1,000 psi = 6.89 MPa

Heat of Hydration

During the initial testing program, an evaluation of the temperature levels reached during hydration of the different types of cements with and without fly ash was made through an adaptation of Method CRD-C 38-73 of the Corps of Engineers, Method of Test for Temperature Rise in Concrete. Cylinders 6 x 12 in. (150 x 300 mm) were placed in well-insulated autogenous curing containers that gave simulated adiabatic conditions. The temperature rise was recorded for a period of 2 days through a 20 gauge copper-constantan thermocouple inserted in the center of the cylinder at a 6 in. (150 mm) depth. In general, the results based on 1 sample for each cement type indicated that in specimens where a certain amount of cement is replaced by fly ash slightly lower maximum temperatures are attained. Types II and I-II convertible cements had yielded lower maximum temperatures than those of Types I and IP and Type I with fly ash. Subsequently, three batches of concrete were prepared using Types I, II, and IP cements, and one additional batch utilizing Type I cement with fly ash. The mixture proportions are given in Table 7. Mixtures utilizing Types I and II cements had the same proportions. From each batch three 6 x 12 in. (150 x 300 mm) cylinders were fabricated and placed in autogenous curing containers. Also three 3 x 6 in. (75 x 150 mm) cylinders were cast to determine the 28-day compressive strengths. The mixture temperature, the maximum temperatures attained, slump, air content of the fresh concrete, and 28-day compressive strengths of small cylinders are given in Table 12.

Table 12

Maximum Temperatures in Autogenously Cured Specimens and the Temperature, Slump, Air Content and Compressive Strength of the Mixtures

Cement Type	Mix. Temp., °F	Max. Temp.,(a) °F	Slump, in.	Air Content, %	28-Day(b) Comp. Strength psi
I	73	126	3.1	5.8	5,470
II	74	121	3.3	6.7	5,080
IP	70	114	2.7	5.8	5,010
I & Ash	71	119	3.9	6.2	5,140

(a) Average of 3 specimens

(b) Average of three 3 x 6 in. (75 x 150 mm) cylinders

NOTE: $t^{o}_{C} = (t^{o}_{F} - 32)/1.8$; 1 in. = 25 mm; 1 psi = 6.89 kPa;

1000 psi = 6.89 MPa.

The results indicate that replacement of a portion of cement by fly ash yielded a lower level of heat of hydration. The Type I cement mixtures attained a maximum temperature of 126°F (52°C). When 14% of this cement was removed and fly ash added, the maximum temperature level was lowered to 119°F (48°C). The difference corresponds approximately to the amount of cement removed from the mixture, since at early ages only slight pozzolanic activity could take place. It is stated in the literature that fly ash produces about 50% as much heat as the cement it replaces.[23,30] Therefore, a lowering of the maximum temperature is expected when fly ash replaces a portion of cement. But in fly ash mixtures where only a small amount of cement is removed, and also the fly ash added is in excess of the cement removed, the beneficial effect of lowering temperatures might be minimal, depending on the amounts involved.

The results given in Table 12 also show that mixtures made of Type II cement attained lower temperatures than mixtures with Type I cement, but higher than those using Type I cement with fly ash. The comparative performances of the Type I cement mixtures with fly ash and the Type II cement mixtures will depend on the chemical and physical composition of the cements and on the amount of cement removed from the mixtures, so cannot be generalized. The same reasoning would hold for Type IP cement mixtures. Here, Type IP cement exhibited the lowest temperature at 114°F (46°C). The compressive strengths of all the 3 x 6 in. (75 x 150 mm) samples were satisfactory and above 5,000 psi (34.5 MPa) as shown in Table 12.

CONCLUSIONS OF THE INTERIM REPORT

The conclusions presented in the interim report were as follows:

1. Average 28-day flexural and compressive strengths of A3 mixtures incorporating fly ash at an optimum level were comparable to those of corresponding control Types I and II cement concretes. These strengths were lower but still satisfactory in A4 mixtures.

2. Average 28-day flexural and compressive strengths attained by concretes with IP cement and those containing fly ash were lower than the ones for the concretes with Type III cement from source E. Mixtures with Type IIIA cement from source F gave the lowest values among all the concretes.

3. Resistance to freezing and thawing in the presence of 2% NaCl caused more scaling on the specimens containing fly ash and IP cements than on the samples without fly ash. Specimens with lower water-cement ratios provided better scaling resistance.

4. Addition of fly ash to Type I cement mixtures lowered the maximum heat attained in autogenously cured specimens compared to corresponding control concretes since a lesser amount of cement was used. In A4 mixtures, higher maximum temperatures and a faster rate of temperature increase were observed as compared to the A3 mixtures.

5. Early shrinkage in mixtures incorporating fly ash was comparable to that for mixtures without fly ash. Mixtures with high cement contents in general yielded high early shrinkage.

6. Concretes made with Type IP and Type I cements and incorporating fly ash exhibited setting rates comparable to those of the control mixtures. It has been reported that fly ash possibly slows the setting time of cement;[5] however, such behavior cannot be concluded from this study.

7. Mixtures made with Type I cement and incorporating fly ash and those with Type IP cement required larger amounts of air entraining agent than did the control mixtures to attain the required range of air contents.

8. Type I mixtures utilizing fly ash and representing A3 concrete had slightly less water demand than did their control counterparts. However, in A4 mixtures the reverse was true. Type IP cement concrete required the same amount of water as did the control mixtures for A3 concretes but needed slightly more water in A4 mixtures than did the control mixtures.

OVERALL CONCLUSIONS

The final conclusions based on the initial and the second laboratory investigations are as follows:

1. Mixtures incorporating fly ash can attain 28-day strengths comparable to those for straight mixtures. However, it may be necessary to add fly ash in amounts greater than the amount of cement replaced and to limit the amount of cement replaced. Such mixtures could exhibit long-term strengths in excess of those of straight mixtures. The optimum amount of fly ash needed for strength can be determined by trial batching. However, limitations on the amount of cement replaced may also be necessary to ensure adequate resistance to scaling.

2. A3 mixtures, being less rich than A4 mixtures, benefit more than A4 mixtures from the addition of fly ash.

3. The addition of fly ash in excess of the cement replaced can result in poor finishing characteristics. This condition was improved when fly ash mixtures were redesigned and the ratio of fine aggregate to total aggregate was reduced.

4. Concretes containing fly ash would achieve satisfactory resistance to freezing and thawing as Type II mixtures have exhibited over the years, provided the desirable void structure is maintained. However, in concretes containing fly ash somewhat more scaling, especially in the presence of deicers, can be expected, as was observed in the laboratory specimens.

5. Mixtures made with Type I cement with fly ash and those with Type IP cement required larger amounts of air entraining agent than did the control mixtures to attain the required range of air contents. In the mixtures for the second testing program, the dosage of air entraining agent in the Type IP cement mixtures was four times that in the control mixtures, and in the Type I cement with fly ash mixtures it was 2.4 times that in the control, as shown in Table 7.

6. The specimens containing fly ash were subjected to petrographic examination to determine the void structure. However, satisfactory results could not be obtained because of the difficulty in distinguishing hollow fly ash particles from air voids.

7. In the limited samples tested, the fly ash additions improved the sulfate resistance of A3 concretes. In the richer A4 mixtures such behavior was not observed, but in all cases the sulfate resistance of the mixtures was satisfactory.

8. The addition of fly ash to Type I cement mixtures lowered the maximum heat attained in autogenously cured specimens compared to corresponding control mixtures since a lesser amount of cement was used. Type II cement mixtures liberated heat less than did the Type I cement mixtures. The comparison of heat liberated by Type I with fly ash and IP to Type II mixtures depends on the amounts and the chemical and physical composition of the cements and fly ash, and equal performance can be achieved.

9. The early volume change in mixtures incorporating fly ash was comparable to that for mixtures without fly ash.

10. The concretes made with Type IP and Type I cements incorporating fly ash exhibited setting rates comparable to those of the control mixtures. It has been reported that fly ash possibly slows the setting time;(5) however, such behavior cannot be concluded from this study.

RECOMMENDATIONS

The following recommendations are presented as a result of this study.

1. Caution should be exercised in quality control, especially in the attainment of air entrainment of fly ash concretes. Variations in the fineness, carbon content, and moisture content of fly ash could lead to undesirable mixtures.

2. In massive concreting operations, additions of fly ash on an equal volume basis rather than on the basis employed in this study would help to lower the maximum temperature, but equivalent strength would be achieved at a later age. In such cases, the amounts of cement replaced and fly ash added should be optimized and the 28-day strength requirements may need to be waived to a later date such as 56 or 90 days.

ACKNOWLEDGEMENTS

The study was performed under the general direction of Jack H. Dillard, state highway research engineer, and was financed from HPR funds. Sincere appreciation is expressed to Howard H. Newlon for his generous assistance. The author extends his appreciation to Hollis Walker for the petrographic examinations. Special thanks are given to Clyde Giannini, Lewis Woodson, John Stulting, Bobby Marshall, Allen Baker, Paul Hughes, Arlene Fewell, Mike Burton and Preston Hubble for their valuable help in this study. Also, sincere appreciation is given to Harry Craft for his generous contribution.

REFERENCES

1. Road and Bridge Specifications, Virginia Department of Highways and Transportation, January 1978.

2. Federal Energy Administration, Conservation Paper 26, Washington, D. C.

3. Price, W. H., "Pozzolans — A Review", ACI Journal, May 1975.

4. "The Efficient Use of Cement", Concrete Construction, Illinois, June 1974.

5. Abdun-Nur, E. A., "Fly Ash in Concrete", HRB Bulletin 284, Highway Research Board, Washington, D. C., 1961.

6. ACI Manual of Concrete Practice, Part I, ACI, Detroit, Michigan, 1974.

7. PFA Utilization, Central Electricity Generating Board, Printed by Gibbons of Wolverhampton, 1972.

8. Higginson, E. C., "Mineral Admixtures", from Concrete and Concrete Making Materials, STP 169-A, ASTM, Philadelphia, Pa., April 1966.

9. Alexander, G. W., Progress Report No. 1, "The Use of Fly Ash in Concrete", Virginia Council of Highway Investigation and Research, Charlottesville, Virginia, December 1954.

10. Melville, P. L., Progress Report No. 2, "The Use of Fly Ash in Concrete", Virginia Council of Highway Investigation and Research, Charlottesville, Virginia, February 1955.

11. Romero, I., Progress Report No. 3, "The Use of Fly Ash in Concrete", Virginia Council of Highway Investigation and Research, Charlottesville, Virginia, December 1955.

12. Romero, I., and T. H. Forrer, Progress Report No. 4, "The Use of Fly Ash in Concrete", Virginia Council of Highway Investigation and Research, Charlottesville, Virginia, January 1956.

13. Forrer, T. H., Progress Report No. 5, "The Use of Fly Ash in Concrete", Virginia Council of Highway Investigation and Research, Charlottesville, Virginia, December 1956.

14. ____________, Progress Report No. 6, "The Use of Fly Ash in Concrete", Virginia Council of Highway Investigation and Research, Charlottesville, Virginia, February 1958.

15. Mielenz, R. C., "Specifications and Methods of Using Fly Ash in Portland Cement Concrete", Bureau of Mines Information Circular 8640, Third International Ash Utilization Symposium, U. S. Government Printing Office, Washington, D. C., 1974.

16. Ozyildirim, H. C., "Alternatives to Type II Cement, Part I — Preliminary Laboratory Studies", VHTRC 77-R38, Virginia Highway and Transportation Research Council, Charlottesville, Virginia, February 1977.

17. McGhee, K. H., and H. E. Brown, "An Investigation of the Durability of Steam Cured Concrete", Virginia Highway and Transporta-tion Research Council, Charlottesville, Virginia, May 1969.

18. Polivka, M., and E. H. Brown, "Influence of Various Factors on Sulfate Resistance of Concretes Containing Pozzolan", ASTM Proceedings, Vol. 58, p. 1977, 1958.

19. Dikeou, J. T., "Fly Ash Increases Resistance of Concrete to Sulfate Attack", Research Report No. 23, A Water Resources Technical Publication, United States Department of the Interior 1970.

20. Kalousek, G. L., L. C. Porter, and E. M. Harboe, "Past, Present and Potential Developments of Sulfate-Resisting Concrete", Journal of Testing and Evaluation, Vol. 4, No. 5, September 197(

21. Cook. H. K., "Experimental Exposure of Concrete to Natural Weathering in Maine Locations", ASTM Proceedings, American Soci-ety for Testing Materials, Vol. 52, 1952, pp. 1169.

22. Verbeck, G. J., "Field and Laboratory Studies of the Sulfate Resistance of Concrete", Research Bulletin 227, Portland Cement Association, Skokie, Illinois.

23. Timms, A. G., and W. E. Grieb, "Use of Fly Ash in Concrete", ASTM Proceedings, Vol. 56, American Society for Testing Materia: Philadelphia, Pennsylvania, p. 1139, 1956.

24. Blanks, R. F., "Fly Ash as a Pozzolan", Journal of the American Concrete Institute, May 1950.

25. Perenchio, W. F., and P. Klieger, "Further Laboratory Studies o: Portland-Pozzolan Cements", PCA Research & Development Bulletin RD 041.01 T, 1976.

26. Timms, A. G., and W. E. Grieb, "Use of Fly Ash in Concrete", Public Roads, Vol. 29, No. 6, February 1957.

27. Mielenz, R. C., V. E. Wolkodoff, J. E. Backstrom, and R. W. Burrows, "Origin, Evolution, and Effects of the Air Void System in Concrete, Part 4 — The Air Void System in Job Concrete", ACI Journal, October 1958.

28. Ozyildirim, H. C., "Distribution of Voids in Field Concrete", VHTRC 78-R35, Virginia Highway and Transportation Research Council, Charlottesville, Virginia, February 1978.

29. Brown, P. W., R. L. Berger, J. R. Clifton, and G. Frohnsdorff, "Limitations to Fly Ash Use in Blended Cements", Merc/SP-76/4, Fourth International Ash Utilization Symposium, Energy Research & Development Administration, Morgantown, West Virginia, 1976.

30. ACI Committee 207, "Mass Concrete for Dams and Other Massive Structures", ACI Manual of Concrete Practice, Part I, 1976.

0546

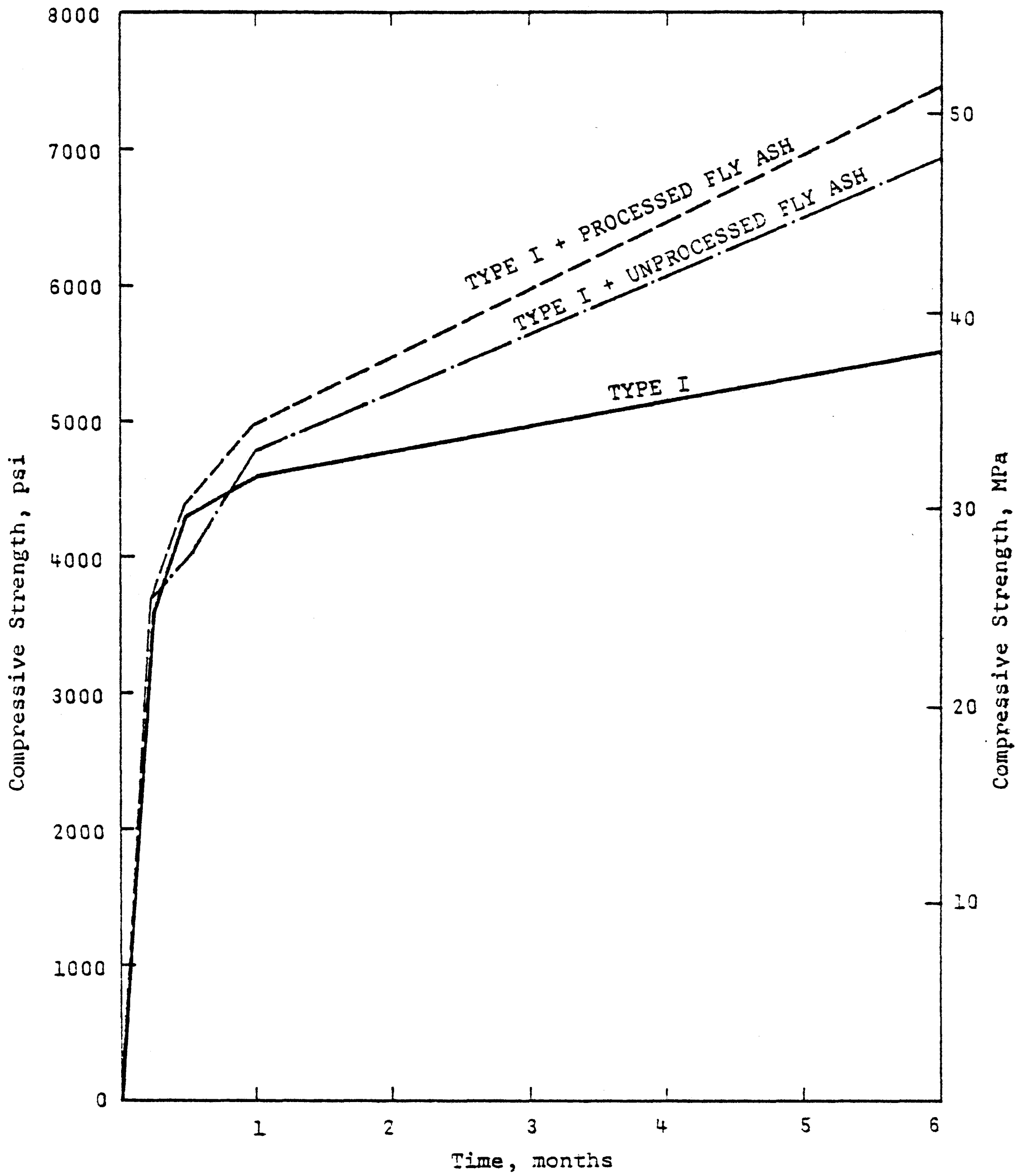


Figure A-1. Strength-age relationship of A3 concrete mixtures.

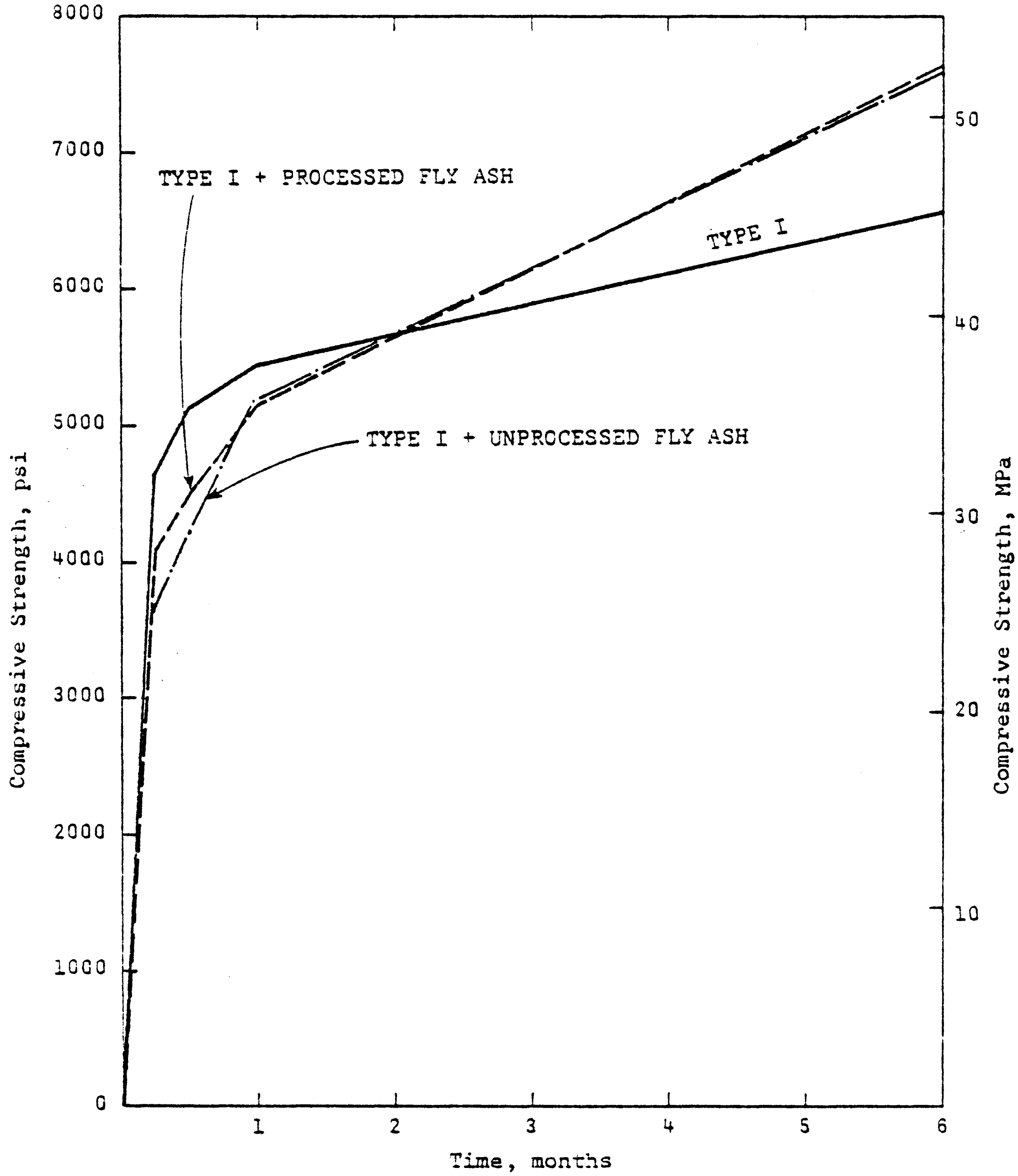


Figure A-2. Strength-age relationships of A4 concretes.

Table A-1

Chemical and Physical Analyses of Cements Used in Second Testing Program

Properties	Cement Type		
	I	II	IP
Chemical (%):			
SiO_2	20.8	21.3	
Al_2O_3	4.9	4.4	
Fe_2O_3	2.4	4.3	
CaO	64.1	63.7	
MgO	3.5	3.0	1.1
SO_3	2.8	2.7	2.8
Total Alkalies	0.88		
C_3S	58.5	54.0	
C_2S	15.5	20.3	
C_3A	8.9	4.0	
Physical:			
Fineness (Blaine)	3634	3646	4887
Soundness (%)			
Time of Set			
Vicat			
Initial (min.)	120	165	
Gilmore			
Initial (hr:min)	2:30	3:15	2:40
Final (hr:min)	4:30	5:00	5:15
Compressive Str. (psi)			
1 day	2550	2167	
3 day	4217	3083	3260
7 day	5083		4450
Air Content	7.8	10.0	

Table A-2

Analysis of Fly Ash Used in Second Testing Program

Chemical Analysis	Analysis	ASTM C-618-77 Specifications
SiO_2	53.20	-----
Al_2O_3	31.18	-----
Fe_2O_3	6.79	-----
Sum of SiO_2, Al_2O_3, and Fe_2O_3	91.17	70.0 minimum
MgO	1.04	-----
SO_3	0.30	5.0 maximum
Moisture Content	0.30	3.0 maximum
Loss on Ignition	2.68	12.0 maximum
Available Alkalies as Na_2O	0.60	*1.5 maximum *Only when required by the purchaser.
Physical Analysis		
Fineness: Amount Retained on 325 sieve, percent	18.63	34 maximum
Increase of Drying Shrinkage @ 28 days, percent	0.01	+0.03 maximum
Water Requirement, percent control	93	105 maximum
Autoclave Expansion, percent	0.01	0.8 maximum
Pozzolanic Activity: with Portland Cement, 28 days	87	75 minimum %
with Lime at 7 days	842	800 minimum psi
Specific Gravity	2.29	

NOTE: 1 psi = 6.89 kPa

TABLE A-3

Chemical and Physical Analyses of Cements Used

Properties	Cement Source								
emical: (%)	A	C	E	B	D	F*		H	G
SiO_2	21.1	22.8	20.6	21.2	21.5	21.4			
Al_2O_3	4.9	4.0	4.8	4.2	4.4	4.4			
Fe_2O_3	2.5	3.6	2.4	3.3	3.3	3.1			
CaO	63.7	63.6	63.4						
MgO	3.5	3.0	3.3	4.3	3.6	3.6		2.8	1.1
SO_3	2.6	2.6	3.3	2.7	2.7	2.8		1.6	2.6
tal Alkalies	0.73	0.60	0.75	0.65	0.71		0.67	0.68	0.63
C_3S	55.0	46.2	56.5	54	49	53			
C_2S	19.0	30.5	16.5						
C_3A	8.8	4.5	8.7	6	6	7			
ysical:									
ieness (Blaine)	3470	3615	4695	3570	3630	5180	5135	3750	4522
indness (%)	0.11	0.11	0.05	0.13	0.08	0.08	0.05	0.03	
ne of Set: Vicat									
tial (min) Gillmore	175	145	155				120	120	
tial (hr: min)				1:50	1:55	2:05			2:35
ial (hr: min)				5:05	5:00	5:05			4:45
mpressive Strength (psi)**									
1-day	1895	1040	2575			2480	1805		
3-day	3165	2950	4385	3100	3250	3620	2655	3100	3410
7-day	4025	3750	4900	4000	4050		3075	3580	4610
Content (%)	10.2	10.1	11.2			19.4	17.0	5.9	4.6
nent Type	I	II	III	I	I-II	IIIA	IIIA	IP	IP

* Values in the first column for cement source F were furnished by the manufacturer and those in the second column were determined by the Department

* 1 psi = 6.89 kPa   1000 psi = 6.89 MPa

TABLE A- 4

Analyses of Processed and Unprocessed Fly Ash

Properties	Processed Fly Ash	Unprocessed Fly Ash
SiO_2	55.50	53.38
Al_2O_3	30.11	28.58
Fe_2O_3	6.07	5.95
SO_3	0.18	0.18
MgO	0.33	0.56
CaO	1.12	5.88
T_iO_2	1.10	0.60
Moisture	0.20	0.40
Loss on Ignition	3.38	2.45
% Retained on 325 mesh sieve	12.26	14.24
Specific Gravity	2.23	2.21