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16. Abstract

Concretes with equal water/cement ratios and equal paste volumes of various combinations of cement, fly ash, and silica fume were tested to establish parameters for strength and chloride permeability. Comparative specimens with Type II and Type III cement were tested. The effects of temperature and moisture availability during curing were also evaluated. In general, the laboratory tests showed that, when adequate curing in the 73°F to 100°F temperature range is provided, concretes with satisfactory early and 28-day strengths and good resistance to chloride ion penetration can be obtained with either type of cement and various combinations of fly ash and silica fume. The cementitious material can be in the range of 30 to 35 percent fly ash and 5 percent silica fume, based on the weight of the cementitious material. Similar specimens cured at 43°F generally did not develop an adequate early strength, and the chloride permeability was high. Combinations of the pozzolans with Type III cement yielded higher strengths and a lower chloride permeability than did similar combinations with Type II cement.

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FINAL REPORT

OPTIMUM MIXTURE PROPORTIONS FOR CONCRETES CONTAINING FLY ASH AND SILICA FUME

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

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ABSTRACT

Portland cement concretes and concretes with various combinations of cement, fly ash, and silica fume were tested to establish parameters for strength and chloride permeability. Comparative specimens with Type II and Type III cement were tested. The effects of temperature and the availability of moisture during curing were also determined. Specimens were compared on the basis of equal water-to-cementitious-material ratios and equal paste volumes.

In general, the laboratory tests showed that, when adequate curing in the temperature range of 73°F to 100°F is provided, concretes with satisfactory early and 28-day strengths and good resistance to chloride ion penetration can be obtained with either type of cement and various combinations of fly ash and silica fume. The cementitious material can be composed of 30 to 35 percent fly ash and 5 percent silica fume based on weight. Similar specimens cured at 43°F generally did not develop an adequate early strength, and the chloride permeability was high. Combinations of the pozzolans with Type III cement yielded a higher strength and a lower chloride permeability than did similar combinations with Type II cement.

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FINAL REPORT

OPTIMUM MIXTURE PROPORTIONS FOR CONCRETES CONTAINING FLY ASH AND SILICA FUME

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INTRODUCTION

Previous studies at the Virginia Transportation Research Council demonstrated that silica fume added in relatively small amounts to fly ash concrete significantly improves the early resistance of the concrete to penetration by chloride ions (chloride permeability) when tested in acordance with AASHTO T277.[1,2] The type and source of the cement, the characteristics of the fly ash and the silica fume, and the amount of each constituent affected the results of these studies. Thus, the optimum combinations to achieve minimum chloride permeability vary with the materials being used. Ideally, the minimum and maximum performance criteria for such concretes should be defined and appropriate evaluation procedures should be established for judging compliance with such criteria. The specific proportioning of concrete to be furnished to the Virginia Department of Transportation would then be left to the concrete supplier.

OBJECTIVE

The objective of this study was to determine the general amounts of fly ash and silica fume that would be expected to yield concrete with adequate early and 28-day strengths and low chloride permeability. The effects of different curing procedures, temperatures, and water/cement plus pozzolan ratios [w/(c + p) ratio] were determined as well as the cost-effectiveness of such a concrete for normal or special uses.

METHODS AND MATERIALS

The study was conducted in two parts. One series of tests was conducted to define, to the extent possible, the practicable range of acceptable combinations using maximum amounts of fly ash and minimum amounts of silica fume that would yield concretes of adequately high strength and low chloride permeability for highway construction when placed and cured at different ambient temperatures. Based on the findings of the first series of tests, a second series was conducted to determine further the effects of different temperatures and curing procedures on the combinations considered to be within the range for adequate performance.

Test Series 1

In test series 1, ten batches of concrete were prepared in the laboratory. In five of the batches, Type II cement was used, and in the remaining five, Type III cement was used. One of the five batches was a control batch that contained only portland cement. The remaining batches included experimental mixtures that had combinations of portland cement, fly ash, and silica fume at different percentages by weight, as shown in Table 1.

The fine aggregate used was siliceous sand, and the coarse aggregate was crushed granite gneiss with a nominal maximum size of 1 in. The chemical and physical analyses of the cements, fly ash, and silica fume are given in Tables A-1 and A-2 of Appendix A. The cement content in the control mixture was 635 lb/yd^3. In the experimental mixtures, the volume of the paste was kept equal to that of the control mixture; thus the weight of the cementitious material varied in the batches, as did the weight of water. A w/(c + p) ratio of 0.44 was needed to achieve the desired slump in the control mixture with Type II cement. This w/(c + p) ratio was then used in all subsequent batches for the first test series. Comparative specimens of paste volumes in the experimental concretes equal to the paste volume in the control specimen ensured that the differences in concrete behavior would relate primarily to the differences in the properties of the cementitious materials. The proportions of each ingredient by weight are given in Table A-3 of Appendix A.

From each batch, 18 cylinders measuring 4 by 8 in. for tests on compressive strength and 12 cylinders measuring 4 by 4 in. for rapid chloride permeability tests were fabricated at 73°F. These cylinders were divided into three sets for curing at 43°F, 73°F, and 100°F, respectively. Each set had 6 cylinders for compressive strength tests at 1, 7, and 28 days (2 cylinders for each measurement) and 4

Table 1
Combinations of Cementitious Material for Test Series 1 (% by Weight)

Batch[a]	Cement	Fly Ash	Silica Fume
1, 1A	100	—	—
2, 2A	65	32	3
3, 3A	65	26	9
4, 4A	55	40	5
5, 5A	55	35	10

[a]Batches 1–5 contained Type II cement; 1A–5A contained Type III cement.

cylinders for permeability tests at 28 days following two different curing procedures. The top 2 in. of these cylinders were cut off and used as the permeability test specimens. One-day moist curing was used in one procedure, and 14-day moist curing in the other.

Test Series 2

Test series 2 was conducted on concretes using the combinations of materials shown in Table 2. This series also included tests with both Type II and Type III cement. All materials for this series were from the same sources as those used in the first series. Tests were made at two w/(c + p) ratios: 0.40 and 0.45. The weight of each ingredient is given in Table A-4 of Appendix A.

Test cylinders (4 by 8 in.) were molded from each of these batches. Compressive strength tests were made at 1, 7, and 28 days using standard curing conditions (in a moist room at 73°F until tested). Five different curing and storage conditions were used for the cylinders to be tested for chloride permeability at 28 days in accordance with AASHTO T277. The conditions used were as follows:

1. *Moist cured 1 day at 73°F.* Specimens were stored in ambient laboratory conditions for the remaining 27 days before the test.
2. *Moist cured 1 day at 100°F.* Specimens were stored in ambient laboratory conditions the remaining 27 days before the test.
3. *Moist cured 14 days at 73°F.* Specimens were stored in ambient laboratory conditions the remaining 14 days before the test.
4. *Moist cured 1 day at 100°F plus 13 days at 73°F.* Specimens were stored in ambient laboratory conditions the remaining 14 days before the test.
5. *Moist cured 3 days at 100°F plus 11 days at 73°F.* Specimens were stored in ambient laboratory conditions the remaining 14 days before the test.

Table 2
Combinations of Cementitious Material for Test Series 2 (% by Weight)

Batch	w/(c + p) Ratio	Cement	Fly Ash	Silica Fume
6, 6A	0.40	60	35	5
7, 7A	0.45	60	35	5
8, 8A	0.40	65	30	5
9, 9A	0.45	65	30	5

[a]Batches 6–9 contained Type II cement; 6A–9A contained Type III cement.

RESULTS

The results of the compressive strength tests for the first series are given in Table A-5 (Appendix A). These are depicted in Figures 1 and 2. The results of the permeability tests are given in Table A-6 (Appendix A) and are depicted in Figures 3 and 4. For convenience and ease of comparison, the results for the charge passing through the specimen (coulomb values) in the test are rounded to the nearest 10. The relationship of chloride permeability and coulomb values as established in accordance with AASHTO T277 is shown in Table A-7 (Appendix A).

Table A-8 (Appendix A) gives the strength results obtained in test series 2. These are depicted in Figures 5 and 6. Table A-9 (Appendix A) shows the coulomb values for these concretes, which are depicted in Figures 7 and 8.

DISCUSSION

Test Series 1

The strength results depicted in Figures 1 and 2 show that:

1. At 1 day, when cured at 43°F, all concretes with Type II cement had a low compressive strength. The control specimens exhibited the highest strength, averaging 600 psi. Concretes with Type III cement, in general, had only marginally higher strengths. When cured at 73°F and 100°F, the 1-day compressive strengths were significantly higher than those at 43°F. They ranged from 1,100 psi to 3,240 psi when Type II cement was used and from 1,440 psi to 3,740 psi when Type III cement was used. The control specimens exhibited the highest strengths.

2. At 7 and 28 days, the control specimens had higher strengths when cured at 73°F than when cured at 100°F, but differences were small and insignificant from a practical standpoint. In contrast, concretes with pozzolans had a higher strength as the curing temperature increased, with concretes with Type III cements having a higher strength than those with Type II cement.

3. At 7 and 28 days, the control specimens of both types of cement, when cured at 43°F and 73°F, had a higher compressive strength than concretes with pozzolans. However, when cured at 100°F, concretes with pozzolans had a higher strength than the controls in most cases.

4. At 28 days, the minimum design strength of 4,500 psi was achieved in all the concretes when cured at 73°F and 100°F except the control specimen

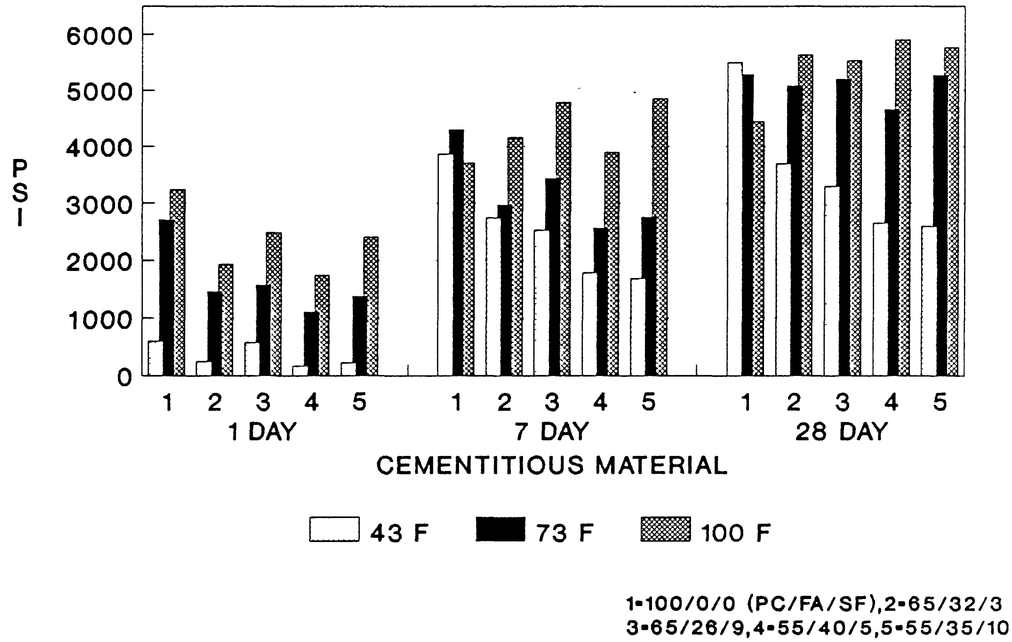

Figure 1. Compressive strengths of specimens made with Type II cement and various combinations of fly ash and silica fume at different curing temperatures and ages.

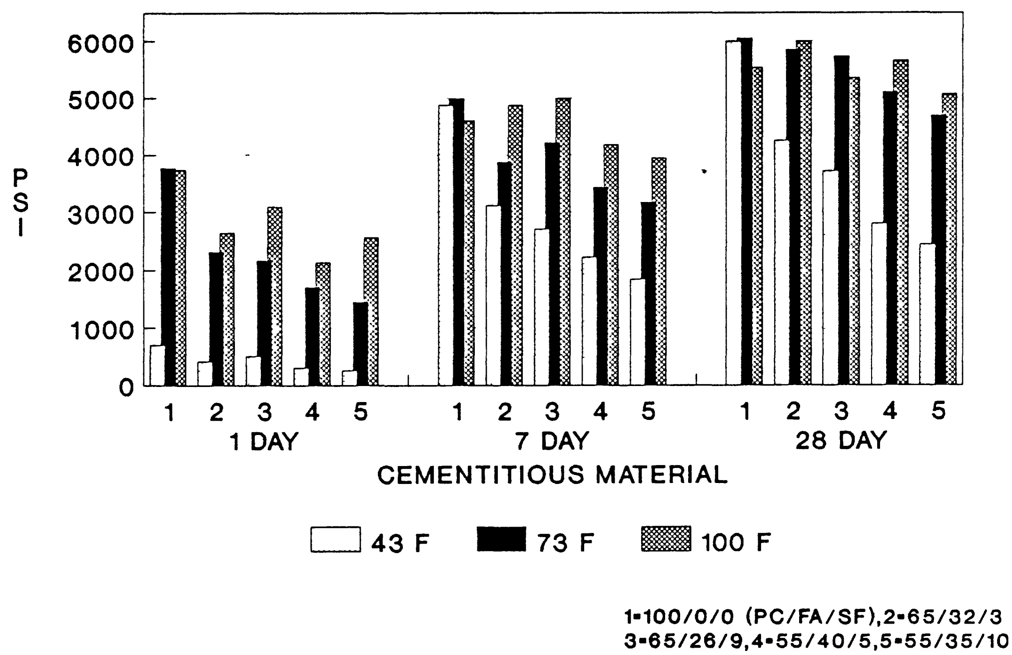

Figure 2. Compressive strengths of specimens made with Type III cement and various combinations of fly ash and silica fume at different curing temperatures and ages.

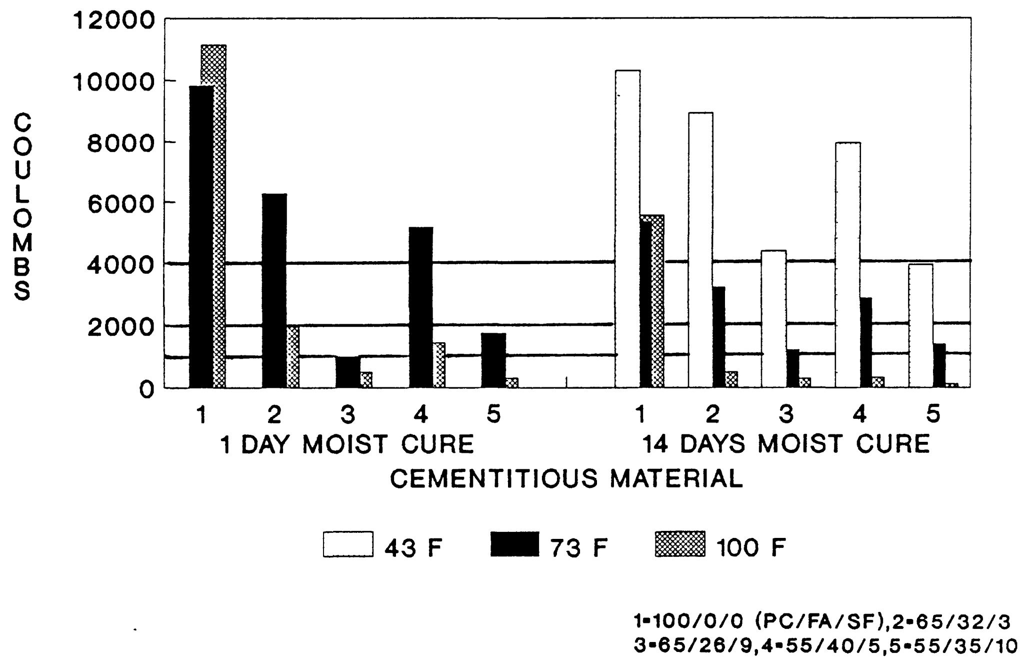

Figure 3. Chloride permeability of specimens cured at different temperatures for test series 1 using Type II cement.

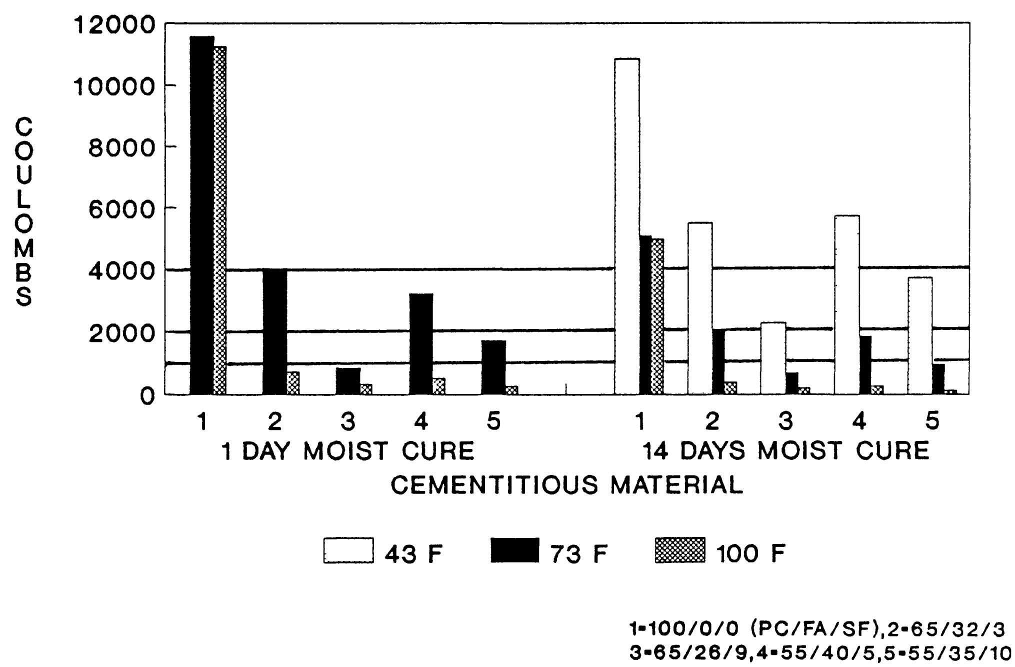

Figure 4. Chloride permeability of specimens cured at different temperatures for test series 1 using Type III cement.

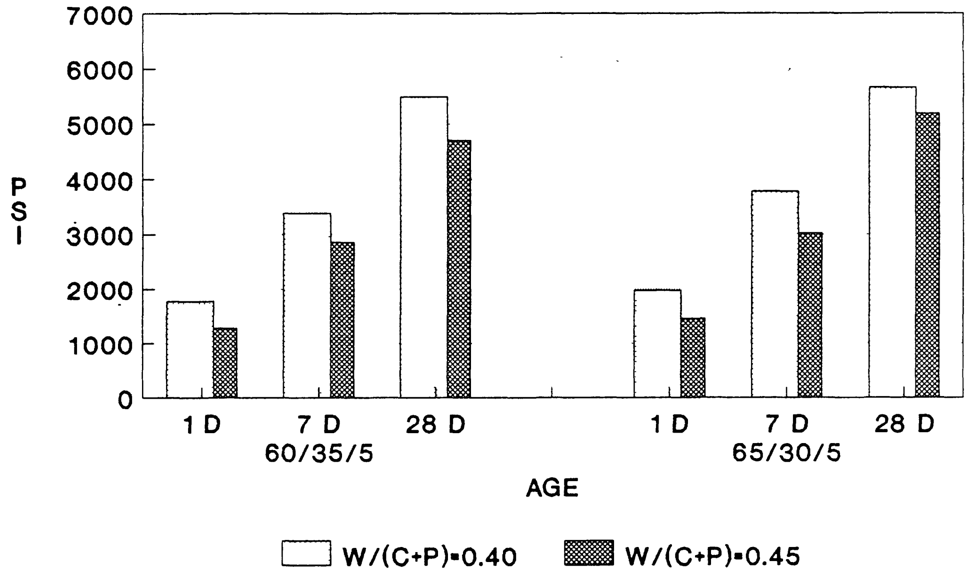

Figure 5. Compressive strengths of concretes at different ages and w/(c + p) ratios for test series 2 using Type II cement.

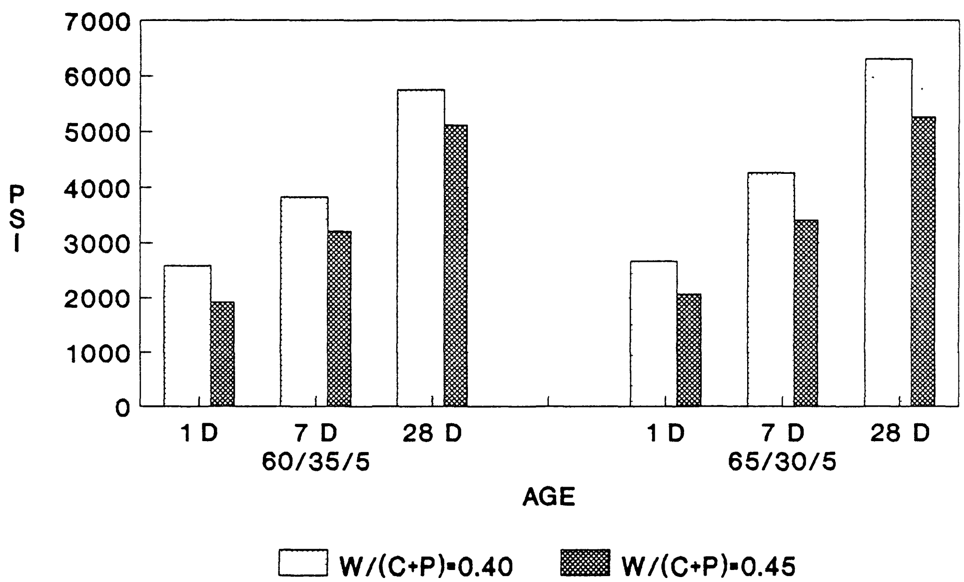

Figure 6. Compressive strengths of concrete at different ages and w/(c + p) ratios for test series 2 using Type III cement.

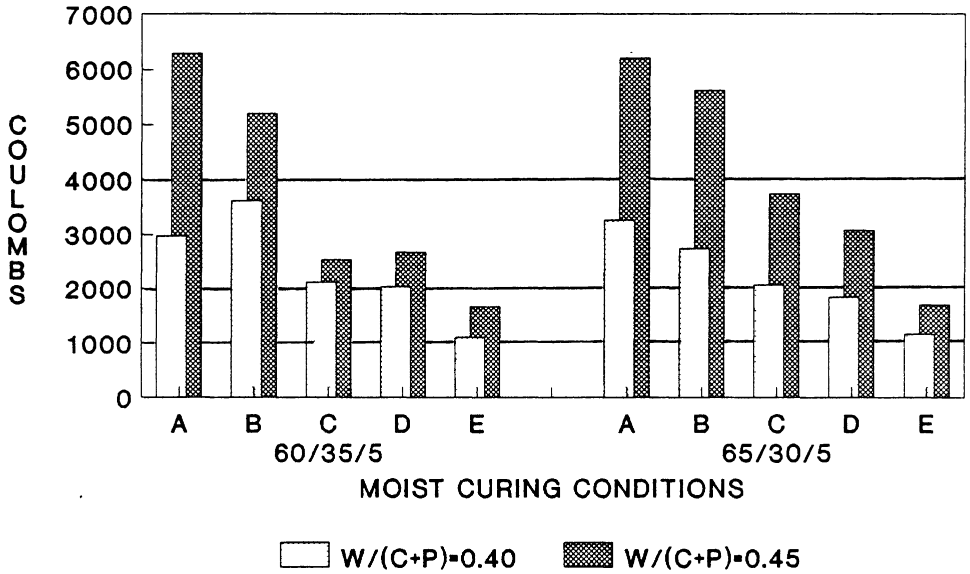

Figure 7. Chloride permeability of concretes at different w/(c + p) ratios and curing conditions using Type II cement.

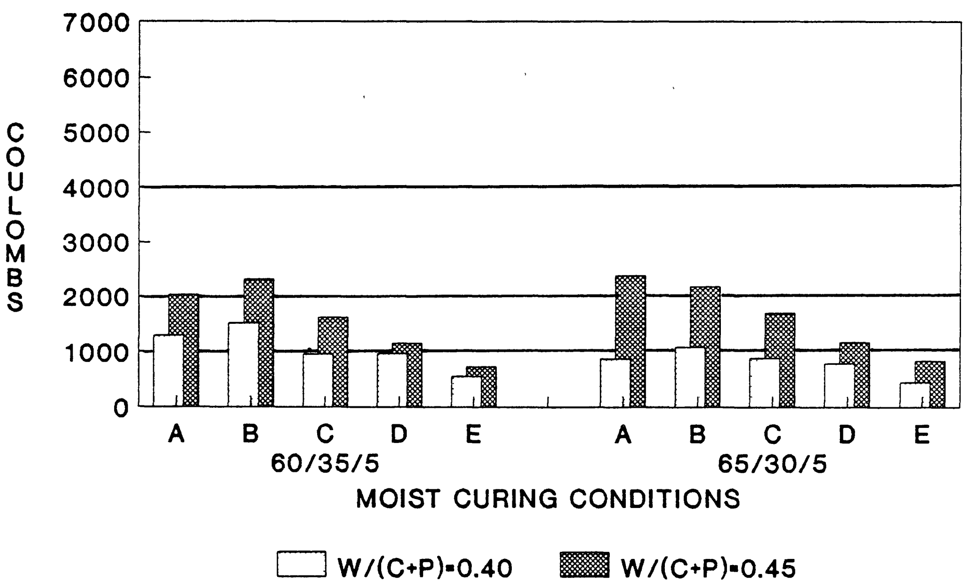

Figure 8. Chloride permeability of concretes at different w/(c + p) ratios using Type III cement.

with Type II cement. The strength for this concrete was 4,440 psi when cured at 100°F. At 43°F, only the control specimens had a strength in excess of 4,500 psi at 28 days.

These results demonstrate the positive effect of increased curing temperatures on the behavior of concretes containing pozzolans. However, the adverse effect of cold temperatures on the strength development of concretes with pozzolan requires attention. Placement of these concretes at a low temperature should be avoided or precautions should be taken to maintain an adequate curing temperature. Additional tests are needed to determine if the strength of specimens cured at 43°F will ultimately develop to an acceptable level when the specimens are exposed to a higher temperature in the presence of adequate moisture.

Figures 3 and 4 demonstrate several important trends with respect to chloride permeability:

1. In all cases, concretes with pozzolan had a lower coulomb value than the control concretes made with only portland cement.
2. Moist curing for 14 days greatly reduced the coulomb value in all cases.
3. Concretes made with Type III cement had a lower coulomb value than similar concretes with Type II cement when cured in the same manner and at the same temperature.
4. Increasing the curing temperature greatly decreased the coulomb value in specimens containing pozzolan.
5. A relatively low percentage of silica fume made a significant difference in the reduction in the coulomb value. When moist cured at 100°F for either 1 or 14 days, all specimens with a pozzolan and Type III cement had a coulomb value less than 1,000, indicating very low permeability. Specimens with Type II cement had a very low chloride permeability when cured at 100°F except for combinations with silica fume additions of 3 and 5 percent when moist cured for only 1 day. In these cases, the chloride permeability would be classed as low.
6. The coulomb value for specimens cured only 1 day at 43°F was not determined. Specimens moist cured for 2 weeks at this temperature generally had a coulomb value in the high permeability range. The exceptions were the specimens with a high percentage of silica fume that had a coulomb value in the moderate range.

Test Series 2

The results of test series 1 generally showed the significant effects of temperature and curing with pozzolanic specimens, especially with respect to the chloride permeability for specimens containing silica fume. However, since all of these specimens were made with the same w/(c + p) ratio, there were no indications of the relative effects of this parameter. It was also recognized that curing conditions in the field might deviate significantly from conditions in the two curing procedures used in test series 1. Accordingly, test series 2 was conducted. Fly ash contents of 30 and 35 percent by weight of cementitious material were used. These percentages were deemed to approach the maximum considered to be feasible for a suitable early strength of the concretes. Similarly, the percentage of silica fume was kept at 5 percent, which was believed to be the lowest practicable level for good results with respect to lowering the chloride permeability. One set of specimens was made with a w/(c + p) ratio of 0.40 to approximate conditions likely to be used for bridge deck overlays, and a w/(c + p) ratio of 0.45 was chosen to approximate that which would likely be used for new pavement or bridge deck concrete.

The strengths reported in Table A-8 and depicted in Figures 5 and 6 showed that, at 28 days, all concrete values with both types of cement and w/(c + p) ratios, had a compressive strength in excess of the desired strength of 4,500 psi. The effects of a higher w/(c + p) ratio, as well as the differences between the strength development for specimens containing Type II cement and those containing Type III cement, are also demonstrated by these data. For similar compositions and w/(c + p) ratios, specimens with Type III cement had a higher strength at all ages than those with Type II cement. The difference at 1 day was the largest, and the difference decreased for the 14- and 28-day tests. The effect of changing the cement/fly ash ratio from 65/30 to 60/35 with the amount of silica fume remaining constant at 5 percent was relatively small in most cases.

The chloride permeabilities obtained under the various curing and storing conditions were the more significant results in this series of tests. As shown in Table A-9 and Figures 7 and 8, the w/(c + p) ratio, the manner of curing and storing specimens before testing, and the cement type all had significant effects on the chloride permeability.

Curing conditions with only 1 day of moist curing at 73°F and 100°F, respectively, are considered to be representative of poor curing in the field. As shown in Figure 7, specimens with Type II cement would be in the high range for all specimens with a w/(c + p) ratio of 0.45 for these conditions (*A* and *B*) and specimens with a w/(c + p) ratio of 0.40 would be in the moderate range. Better curing, as indicated by extended conditions of moist curing, resulted in specimens having low or moderate chloride permeability in all cases.

Better results were obtained with Type III cements, as shown in Figure 8. For similar curing conditions, all specimens made with Type III cements had a lower coulomb value than comparable specimens with Type II cement. All specimens with Type III cement and a w/(c + p) ratio of 0.40 had a coulomb value in the very low range except those with limited 1-day moist curing, which generally had a low chloride permeability. Concretes with a w/(c + p) ratio of 0.45 were in the low range or had a coulomb value only slightly in excess of the limit between the low and moderate range. The 14-day moist curing with 1 or 3 days curing (*D* and *E*) at 100°F resulted in the lowest chloride permeability, and the specimens with Type III cement subjected to this curing had a very low permeability for both w/(c + p) ratios.

The importance of good curing procedures is demonstrated by these results. The significant positive effect with both types of cement after 3 days of moist curing at 100°F indicates that measures to retain the early heat of hydration in the concrete would be worthwhile. Tests on concretes cured in the field under different environmental conditions are needed in order to define optimum field procedures.

Costs

Costs of cement, fly ash, and silica fume vary depending on location and, for silica fume, on the amount and mode of purchasing. However, general estimates of typical costs in 1989 were $60 per ton for portland cement, $20 per ton for fly ash, and $400 to $900 per ton for silica fume, depending on whether it was purchased in bulk or as small amounts of prepared products. On this basis, the costs of cementitious materials in a cubic yard of concrete such as that to be used on bridge decks in Virginia can be estimated in order to provide a general comparison of relative costs. The assumptions and calculations used for these estimates are given in Appendix B. It is shown that the relative cost for the cementitious material used for the indicated combinations would be

- *portland cement only:* $19.00
- *65 cement/30 fly ash/5 silica fume:* $19.50–$27.00
- *60 cement/35 fly ash/5 silica fume:* $18.90–$26.30.

Thus, although handling and storage costs for the pozzolans, as well as the probable need for additional admixtures, would further increase the cost of the pozzolanic concrete, such concretes would be competitive in price and the advantage of lower permeability should make them cost-effective. Such concretes would cost significantly less than the latex-modified concretes now often used for bridge deck overlays. For pavement concretes, where there is a possibility of an alkali-silica reaction in the aggregate, such concretes might possibly provide better durability from the standpoints of both better protection against the alkali-silica reaction and the lower permeability that offers a reduced danger of corrosion of the reinforcing bars caused by chloride penetration.

CONCLUSIONS

On the basis of the results obtained in this study, the following conclusions can be drawn:

1. Adding a small amount of silica fume to fly ash concretes significantly reduces the chloride permeability of the concrete.

2. For concretes with a combination of fly ash and silica fume, both a higher curing temperature and a longer duration of moist conditions reduce the chloride permeability, other conditions being the same.

3. When Type III cement is used with fly ash and silica fume, concrete with a lower chloride permeability is attained than when similar concretes are made with Type II cements.

4. Although different combinations of materials are likely to develop quantitatively different characteristics, these tests show that concrete with a low or a very low chloride permeability can be attained when 30 to 35 percent of the cementitious material is fly ash, 5 percent is silica fume, and the balance is Type III cement. The 28-day strength of such concretes would meet the usual requirement for bridge deck concrete.

5. It is expected that properly proportioned concretes containing fly ash and silica fume would be cost-effective and have good durability when used in locations such as pavements or bridge decks where deicing salts are likely to be applied. Field tests are needed to determine the optimum curing conditions and temperatures for concretes containing such pozzolans.

6. A secondary advantage is that the pozzolanic concretes are less energy intensive than normal portland cement concretes, and they use industrial byproducts, thus conserving resources.

RECOMMENDATION

Field tests on the combinations of fly ash and silica fume should be conducted (1) to verify the results of this laboratory work and (2) to establish the effects of placement and environmental temperature on the properties of these concretes.

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APPENDIX A

Table A-1
Chemical and Physical Analyses of Cements

Property	Type II	Type III
Chemical (%)		
SiO_2	20.8	20.5
Al_2O_3	4.7	5.2
Fe_2O_3	3.8	2.2
CaO	63.6	63.0
MgO	2.9	3.2
SO_3	2.6	4.0
Total alkalies	0.68	0.72
C_3S	56	51
C_3A	6	10
Physical		
Fineness (Blaine)	3,857	5,514
1-day compressive strength (psi)	2,478	3,863

Table A-2
Chemical and Physical Analyses of Fly Ash and Silica Fume

Property	Fly Ash	Silica Fume
Chemical (%)		
SiO_2	56.7	93.2
Al_2O_3	32.9	0.1
Fe_2O_3	3.1	0.3
CaO	0.6	1.0
MgO	0.7	0.2
SO_3	0.05	0.1
Total alkalies	0.37	0.18
Loss on ignition	2.3	1.80
Physical		
Fineness (% retained on No. 325 sieve)	23.0	ND[a]
Specific gravity	2.28	2.27

[a]Not determined.

Table A-3
Mixture Proportions for Test Series 1 (lb/yd^3)

Batch[a]	w/(c + p) Ratio	Cement	Fly Ash	Silica Fume
1, 1A	0.44	635	—	—
2, 2A	0.44	391	192	18
3, 3A	0.44	391	156	54
4, 4A	0.44	325	237	30
5, 5A	0.44	326	207	60

[a]Batches 1–5, Type II cement; 1A–5A, Type III cement. The amount of coarse aggregate was 1,869 lb/yd^3 and of fine aggregate was 1,108 lb/yd^3.

Table A-4
Mixture Proportions for Test Series 2 (lb/yd^2)

Batch	w/(c + p) Ratio	Cement	Fly Ash	Silica Fume	Fine Aggregate[b]
6, 6A	0.40	356	208	30	1,043
7, 7A	0.45	359	209	31	960
8, 8A	0.40	389	179	31	1,043
9, 9A	0.45	389	179	31	960

[a]Batches 6–9, Type II cement; 6A–9A, Type III cement. The amount of coarse aggregate was 1,869 lb/yd^3.

Table A-5
Compressive Strength Data for Test Series 1

Combination of Cementitious Material[a]	Compressive Strength When Cured at:					
	43°F		73°F		100°F	
	Type II Cement	Type III Cement	Type II Cement	Type III Cement	Type II Cement	Type III Cement
			1-Day Strengths			
100/0/0	600	700	2,710	3,780	3,240	3,740
65/32/3	240	410	1,460	2,310	1,930	2,640
65/26/9	570	500	1,570	2,170	2,490	3,100
55/40/5	170	300	1,100	1,710	1,740	2,140
55/35/10	220	260	1,380	1,440	2,410	2,560
			7-Day Strengths			
100/0/0	3,860	4,870	4,290	4,980	3,710	4,600
65/32/3	2,750	3,120	2,970	3,880	4,160	4,870
65/26/9	2,530	2,710	3,440	4,220	4,780	4,980
55/40/5	1,780	2,220	2,560	3,440	3,900	4,180
55/35/10	1,680	1,840	2,760	3,180	4,850	3,940
			28-Day Strengths			
100/0/0	5,490	5,990	5,280	6,050	4,440	5,530
65/32/3	3,690	4,250	5,080	5,850	5,630	5,990
65/26/9	3,300	3,720	5,200	5,730	5,530	5,350
55/40/5	2,650	2,800	4,660	5,100	5,900	5,650
55/35/10	2,600	2,440	5,270	4,690	5,770	5,070

[a]Cement/fly ash/silica fume by weight percentage of the total cementiitous material.

Table A-6
Chloride Permeability Data for Test Series 1

Combination of Cementitious Material[a]	Coulomb Value of Specimens Cured for:				
	1 Day at		14 Days at		
	73°F	100°F	43°F	73°F	100°F
			Type II Cements		
100/0/0 Control	9,820	11,150	10,300	5,340	5,560
65/32/3	6,270	1,970	8,940	3,240	500
65/26/9	990	490	4,410	1,200	280
55/40/5	5,180	1,440	7,950	2,880	320
55/35/10	1,740	310	3,970	1,390	110
			Type III Cements		
100/0/0 Control	11,580	11,240	10,850	5,080	4,980
65/32/3	4,040	730	5,510	2,080	390
65/26/9	840	330	2,300	680	210
55/40/5	3,240	510	5,730	1,860	260
55/35/10	1,720	270	3,740	950	120

[a]Cement/fly ash/silica fume by weight percentage of total cementitious material.

Table A-7
Chloride Permeabilities Based on Charge Passed

Charge Passed (Coulomb Value)	Chloride Permeability
> 4,000	High
2,000 –4,000	Moderate
1,000– 2,000	Low
100 –< 1,000	Very low
<100	Negligible

Table A-8
Compressive Strength Data for Test Series 2

Combination of Cementitious Material[a]	w/(c + p) ratio	Compressive Strengths					
		1 Day		7 Days		28 Days	
		Type II Cement	Type III Cement	Type II Cement	Type III Cement	Type II Cement	Type III Cement
60/35/5	.40	1,780	2,580	3,380	3,830	5,490	5,750
60/35/5	.45	1,280	1,920	2,850	3,200	4,710	5,110
65/30/5	.40	1,980	2,670	3,780	4,260	5,650	6,300
65/30/5	.45	1,460	2,070	3,020	3,400	5,190	5,260

[a]Cement/fly ash/silica fume by weight percentage of total cementitious material.

Table A-9
Chloride Permeability Data Second Test Series 2

Combination of Cementitious Material[a]	w/(c + p) Ratio	Coulomb Value for 5 Curing and Storing Conditions[b]				
		A	B	C	D	E
		Specimens with Type II Cement				
60/35/5	.40	2,970	3,620	2,110	2,030	1,110
	.45	6,290	5,200	2,530	2,670	1,670
65/30/5	.40	3,260	2,740	2,070	1,850	1,170
	.45	6,210	5,620	3,740	3,080	1,710
		Specimens with Type III Cement				
60/35/5	.40	1,300	1,520	950	970	560
	.45	2,030	2,320	1,620	1,160	730
65/30/5	.40	870	1,080	880	790	450
	.45	2,380	2,180	1,710	1,180	840

[a]Cement/fly ash/silica fume by weight percentage of total cementitious material.
[b]Length of cure in moist environment and the temperature for each set of conditions are:
A = 1 day at 73°F
B = 1 day at 100°F
C = 14 days at 73°F
D = 1 day at 100°F; 13 days at 73°F
E = 3 days at 100°F; 11 days at 73°F.
After curing as stated, all specimens were stored in ambient laboratory conditions until tested at 28 days.

APPENDIX B

Estimates of Relative Costs of Concretes

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Comparison of cost of cement for 1 yd^3 of concrete containing 635 lb of cement with 1 yd^3 of concrete containing equal paste volumes of combinations of portland cement, fly ash, and silica fume as indicated:

Assumptions:

- Cost per pound of cement = $ .03
  - fly ash = .01
  - bulk silica fume = .20
  - packaged silica fume = .45
- Increased yield for pozzolanic concretes is 6%. (Volumes of fly ash and silica fume are greater than equal weights of portland cement.)

Computations:

1. Concrete with portland cement only:

635 x .03	=	$19.05

2. Concrete with 65% portland cement, 30% fly ash, and 5% silica fume:

Cement	= (635 x .65 x .03)	=	$12.38
Fly ash	= (635 x .30 x .01)	=	1.91
Bulk silica fume	= (635 x .05 x .20)	=	6.35
Packaged silica fume	= (635 x .05 x .45)	=	14.29

Total cost for 1.06/yd^3 of concrete:

Low (bulk silica fume)	=	$20.64
High (packaged silica fume)	=	28.58

Rounded cost estimates for 1 yd^3 are $19.50 to $27.00.

3. Concrete with 60% portland cement, 35% fly ash, and 5% silica fume:

Cement	= (635 x .60 x .03)	=	$11.43
Fly ash	= (635 x .35 x .01)	=	2.22
Bulk silica fume	= (635 x .05 x .20)	=	6.35
Packaged silica fume	= (635 x .05 x .45)	=	14.29

Total cost for 1.06 yd^3 of concrete:

Low (bulk silica fume)	=	$20.00
High (packaged silica fume)	=	27.92

Rounded cost estimates for 1 yd^3 are $18.90 to $26.30.

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