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16. Abstract

This study was conducted to determine whether significant improvements could be achieved in the resistance to the penetration by chloride ions of concretes with fly ash or slag by the addition of silica fume with either Type II or Type III cement and whether early strengths of concretes with fly ash or slag could be improved by the addition of silica fume. The chloride permeability was estimated by means of AASHTO Test Method T 277.

The results show that lower permeability is attained by the addition of silica fume in amounts equal to 5 percent of the cementitious material in both fly ash and slag concretes. There were significant differences between results for specimens moist cured 1 day and 14 days, but with specimens made with Type III cement, even the 1-day moist curing provided low chloride permeability.

Silica fume also increased the strength of similar concretes to some degree, but generally, this increase was not large. Except for those specimens containing slag, 1-day strengths higher than 3000 psi are obtainable with a water-to-cementitious-material ratio (w/c) of 0.40 with all of the concretes tested with Type III cement as well as control concretes with Type II cement. Concretes with slag and silica fume reached compressive strengths of 3000 psi in a little more than 2 days.

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SI CONVERSION FACTORS

To Convert From	To	Multiply By
Length:		
in	cm	2.54
in	m	0.025 4
ft	m	0.304 8
yd	m	0.914 4
mi	km	1 . 609 344
Area:		
in^2	cm^2	6.451 600 E+00
ft^2	m^2	9.290 304 E-02
yd^2	m^2	8.361 274 E-01
mi^2	Hectares	2.589 988 E+02
acre (a)	Hectares	4.046 856 E-01
Volume:		
oz	m^3	2.957 353 E-05
pt	m^3	4.731 765 E-04
qt	m^3	9.463 529 E-04
gal	m^3	3.785 412 E-03
in^3	m^3	1.638 706 E-05
ft^3	m^3	2.831 685 E-02
yd^3	m^3	7.645 549 E-01
Volume per Unit Time:	NOTE: $1m^3$ = 1,000 L	
ft^3/min	m^3/sec	4.719 474 E-04
ft^3/s	m^3/sec	2.831 685 E-02
in^3/min	m^3/sec	2.731 177 E-07
yd^3/min	m^3/sec	1.274 258 E-02
gal/min	m^3/sec	6.309 020 E-05
Mass:		
oz	kg	2.834 952 E-02
dwt	kg	1.555 174 E-03
lb	kg	4.535 924 E-01
ton (2000 lb)	kg	9.071 847 E+02
Mass per Unit Volume:		
lb/yd^2	kg/m^2	4.394 185 E+01
lb/in^3	kg/m^3	2.767 990 E+04
lb/ft^3	kg/m^3	1.601 846 E+01
lb/yd^3	kg/m^3	5.932 764 E-01
Velocity: (Includes Speed)		
ft/s	m/s	3.048 000 E-01
mi/h	m/s	4.470 400 E-01
knot	m/s	5.144 444 E-01
mi/h	km/h	1.609 344 E+00
Force Per Unit Area:		
lbf/in^2 or psi	Pa	6.894 757 E+03
lbf/ft^2	Pa	4.788 026 E+01
Viscosity:		
cS_t	m^2/s	1.000 000 E-06
P	Pa·s	1.000 000 E-01

Temperature: (°F-32) ^{5}/9 = °C

FINAL REPORT

USE OF SUPPLEMENTAL CEMENTITIOUS MATERIALS FOR OPTIMUM RESISTANCE OF CONCRETE TO CHLORIDE PENETRATION

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(A Cooperative Organization Sponsored Jointly by the Virginia Department of Transportation and the University of Virginia)

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

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ABSTRACT

This study was conducted to determine whether significant improvements could be achieved in the resistance to the penetration by chloride ions of concretes with fly ash or slag by the addition of silica fume with either Type II or Type III cement and whether early strengths of concretes with fly ash or slag could be improved by the addition of silica fume. The chloride permeability was estimated by means of AASHTO Test Method T 277.

The results show that lower permeability is attained by the addition of silica fume in amounts equal to 5 percent of the cementitious material in both fly ash and slag concretes. There were significant differences between results for specimens moist cured 1 day and 14 days, but with specimens made with Type III cement, even the 1-day moist curing provided low chloride permeability.

Silica fume also increased the strength of similar concretes to some degree, but generally, this increase was not large. Except for those specimens containing slag, 1-day strengths higher than 3000 psi are obtainable with a water-to-cementitious-material ratio of 0.40 with all of the concretes tested with Type III cement as well as control concretes with Type II cement. Concretes with slag and silica fume reached compressive strengths of 3000 psi in a little more than 2 days.

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INTRODUCTION

For satisfactory long-term durability, it is necessary that concretes used in roadways and other highway structures be highly resistant to the penetration of water, chloride solutions, or other corrosive fluids. A recent study at the Virginia Transportation Research Council has shown that good resistance to the penetration of chloride ions (termed low chloride permeability in this report) can be achieved at relatively early ages by adding slag or silica fume as a supplemental cementitious material to concretes with a low ratio of water-to-cementitious material (w/c) [1]. The addition of fly ash resulted in concretes with adequate strength, but there was little or no reduction in their chloride permeability compared to the control concretes. Although the results indicated that concretes containing slag have considerably lower chloride permeability than the controls, they had low strength at 24 hours. Thus, early (next day) traffic over these concretes would not be feasible.

This study was conducted to determine whether improvements could be made in the early strength and resistance to chloride penetration of concretes containing fly ash or slag by combining them with silica fume and/or using a high early strength cement (Type III) instead of a Type II cement.

MATERIALS AND METHODS

Nine concretes with the different material combinations shown in Table 1 were made in duplicate. Type II and Type III cements were used. The analysis of these cements is given in Table A-1 of the appendix. Table A-2 of the appendix shows the chemical and physical analyses of the fly ash, slag, and silica fume. From each batch of concrete, 4-in by 8-in cylinders were made to be tested for compressive strengths at 1, 2, 7, 28, and 90 days and for chloride permeability at 28 and 90 days. Also, three beams measuring 3-in by 3-in by 11 1/4-in from each batch were prepared for flexural strength tests.

Control concretes were prepared using 658 lb/yd^3 portland cement. Experimental concretes were prepared using the combinations of cementitious material shown in Table 1. The total amount of cementitious material was 658 lb/yd^3, and the w/c was 0.40 for all batches. The mass of each ingredient used in each concrete batch is given in Table A-3.

Table 1

Percentage of Cementitious Material by Mass

Batch	Cement Type	Identification	Cement	Fly Ash	Slag	Silica Fume
1	II		100			
2	II	20F - 5SF[1]	75	20		5
3	II	45S - 5SF	50		45	5
4	III		100			
5	III	20F - 5SF	75	20		5
6	III	45S - 5SF	50		45	5
7	III	25F	75	25		
8	III	50S	50		50	
9	III	5SF	95			5

[1] Numbers indicate the percentage of the supplemental material by mass in the total cementitious material. The balance is portland cement of the type indicated. F = fly ash; S = slag; SF = silica fume.

The nominal maximum size of coarse aggregate was 1/2 in. Concretes were tested at the freshly mixed stage for air content (ASTM C 231), slump (ASTM C 143), and unit weight (ASTM C 138). At the hardened stage, compressive strength (AASHTO T 22 using neoprene caps), flexural strength (ASTM C 78), and chloride permeability were determined.

The chloride permeability of different specimens from the same batch of concrete cured in two different ways was determined at 28 and 90 days. In the first curing procedure (cure 1), specimens were moist cured for 1 day and then air dried until tested. In the second curing procedure (cure 2), specimens were moist cured for 14 days and then air dried until tested. After the moist curing, the top 2 in of the cylinders were cut off for use as the test specimens. The sides of the specimens were then coated with an epoxy resin and set on a plastic sheet to prevent moisture loss from the sides and the bottom. The chloride permeability was determined using AASHTO Method T 277, which is based on the electrical conductance of the specimens under the conditions of the test. Table 2 shows chloride permeability ratings based on the coulombs passing through specimens in the 6-hour test period.

Table 2

Chloride Permeability

Charged Passed, coulombs	Chloride Permeability
>4,000	High
2,000-4,000	Moderate
1,000-2,000	Low
100-1,000	Very low
<100	Negligible

RESULTS

Test results for the freshly mixed concretes are given in Table A-4, and all of the data developed for the hardened concretes are shown in Tables A-5 through A-8.

The average values for compressive strength for the indicated ages and for the flexural strength at 28 days are given in Table 3. Chloride permeability values are summarized in Table 4. Each value shown is the average of two measurements. Figure 1 summarizes the 1-day and 28-day strengths for specimens made with the various combinations and Type III cement. Figure 2 shows the relative chloride permeability at 28 days for the specimens with Type III cement.

DISCUSSION

The low w/c and the 1/2-in nominal maximum size for the coarse aggregate was chosen for the tests because the primary interest in evaluating such concretes is for their potential for use in the relatively thin overlays used on concrete bridge decks. For such use, a major consideration is whether or not satisfactory resistance to chloride ion penetration and strengths sufficient to carry traffic are attained at early ages. For this study, a value of 3,000 psi in one day was assumed to indicate satisfactory early strength. The chloride permeability is considered satisfactorily low when a coulomb value less than 2,000 is attained (AASHTO T 277). This value is the upper limit of the low permeability range (see Table 2).

Table 3

Strengths of Concretes[a]

Identification[b]	Compressive Stength, psi 1 day	2 days	7 days	28 days	90 days	Flexural Strength[c] (psi)
Specimens with Type II Cement						
Control	3,190	3,960	5,420	7,030	7,660	720
20F - 5SF	2,550	3,090	4,450	6,570	7,720	673
45S - 5SF	980	1,650	3,570	7,260	8,720	657
Specimens with Type III Cement						
Control	4,740	5,470	6,420	7,820	8,260	824
5SF	4,480	5,120	6,620	8,140	9,110	765
25F	3,190	3,740	4,860	6,120	7,520	680
20F-5SF	3,320	3,890	5,320	7,210	8,160	688
50S	1,450	2,430	5,640	7,960	8,450	826
45S-5SF	2,040	2.880	5,700	8,160	9,060	766

[a] All concretes have a w/c of 0.40. Each value is the average of two measurements.

[b] Numbers are the percentage (by mass) of the supplemental ingredients in the total cementitious material; the balance is portland cement of the type indicated. F = fly ash; SF = silica fume; S = slag.

[c] At 28 days.

Table 4

Chloride Permeability of Concretes[a]

Identification[b]	28-day Tests Cure 1[c] Coulombs	28-day Tests Cure 2[d] Coulombs	90-day Tests Cure 1 Coulomb	90-day Tests Cure 2 Coulomb
Specimens with Type II Cement				
Control	7,710(H)[e]	4,970(H)	7,400(H)	6,120(H)
20F-5SF	3,130(M)	2,340(M)	4,010(H)	1,960(L)
45S-5SF	3,050(M)	2,670(M)	2,320(M)	1,370(L)
Specimens with Type III Cement				
Control	5,650(H)	3,660(M)	6,200(H)	3,970(M)
5SF	2,240(M)	1,060(L)	1,210(L)	720(VL)
25F	8,990(H)	4,800(H)	7,270(H)	3,340(M)
20F-5SF	1,460(L)	1,150(L)	1,400(L)	540(VL)
50S	2,340(M)	1,670(L)	2,250(M)	1,480(L)
45S-5SF	640(VL)	720(VL)	800(VL)	410(VL)

[a] All concretes have a w/c of 0.40. Each value is the average of two measurements.

[b] Numbers are the percentage (by mass) of the supplemental ingredients in the total cementitious material. The balance is portland cement of the type indicated. F = fly ash; SF = silica fume; S = slag.

[c] Cure 1 - Moist cure 1 day and air dried until tested.

[d] Cure 2 - Moist cure 14 days and air dried until tested.

[e] Parentheses indicate rating assigned in accordance with AASHTO T 277. H = high; M = moderate; L = low; VL = very low.

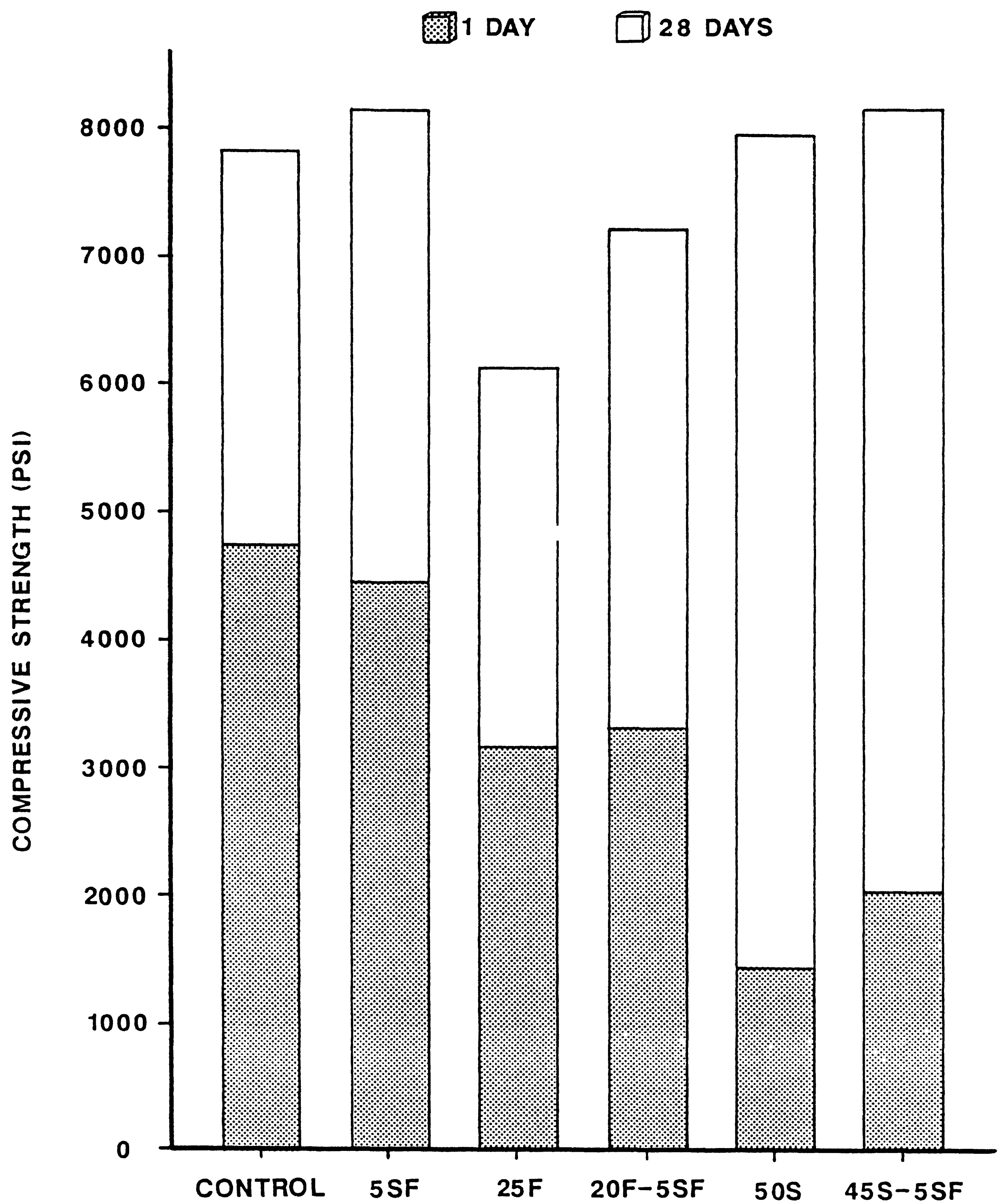

Figure 1. Compressive strength of concretes with Type III cement, psi.

Compressive Strength

The strengths at different ages given in Table 3 show several trends of interest. With either cement, the control specimens had 1-day strengths greater than 3,000 psi. However, as expected, the use of Type III cement resulted in 1-day strengths about 50 percent higher.

Concretes made with Type II cement and either fly ash and silica fume or slag and silica fume did not reach 3,000 psi in 1 day. However, when Type III cement was used, all of the combinations containing fly ash that were tested had 1-day strengths greater than 3,000 psi. Concretes with Type III cement and slag or slag and silica fume required slightly more than 2 days to reach 3,000 psi. However, specimens containing 45 percent slag and 5 percent silica fume had about 40 percent greater strength in 1 day than those containing 50 percent slag. Strength values at 7 days for the slag specimens exceeded the normally specified 28-day strength for bridge deck concrete, thus indicating the usefulness of slag combinations if very early opening to traffic is not a consideration.

The 28-day and 90-day strengths of all the concretes exceeded 6,000 psi, thus indicating adequate strengths in all cases. Concretes containing the same combinations of supplemental materials made with Type III cement had higher strengths than those with Type II cement. These high strengths result for the most part from the low w/c of 0.40 used for all specimens.

Flexural Strengths

The results of the flexural-strength tests at 28 days (summarized in Table 3) show that satisfactory modulus of rupture values exceeding 650 psi were achieved in all the specimens when tested using the third-point loading. Values obtained with Type III cement were higher than those with Type II cement for the same variable.

Chloride Permeability

Table 4 shows significant differences in chloride permeability depending on the type of cement, the type of supplemental cementitious material, and the curing procedure used. Concretes containing Type II cement and combinations of fly ash and silica fume or slag and silica fume were rated as having moderate chloride permeability at 28 days. Specimens containing Type II cement which were moist cured for 14 days (cure 2) generally had lower coulomb values than those moist cured for 1 day (cure 1), but the permeability ratings remained the same.

The effects of silica fume combinations with specimens made with Type III cement are illustrated in Figure 2. The effect of better moist curing is also demonstrated. The control concretes cured for 1 day had high chloride permeability as did the specimens containing 25

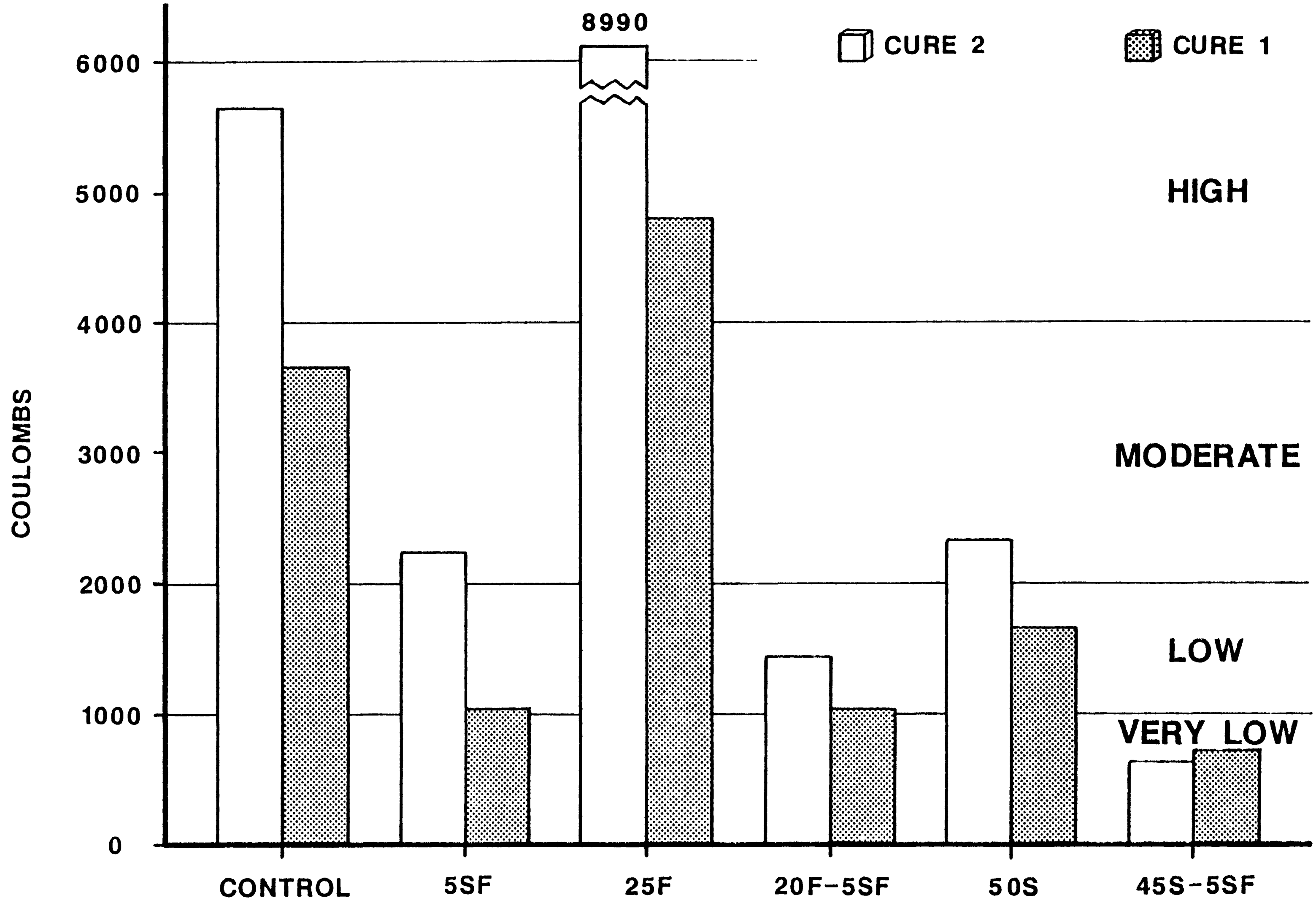

Figure 2. Chloride permeabiity of concretes with Type III cement at 28 days.

percent fly ash cured at 1 day and at 14 days. However, all other specimens had moderate or lower chloride permeability. The reduction in the chloride permeability of the specimens containing fly ash and silica fume is of particular significance. Specimens containing 25 percent fly ash had high chloride permeability, but those containing 20 percent fly ash and 5 percent silica fume had low chloride permeability. This is an indication that the use of combinations of fly ash and silica fume would provide concrete with both high strength and low chloride permeability. Such concrete should also be economical in areas where fly ash is available at low shipping costs.

Specimens made with slag but no silica fume had moderate chloride permeability (values were at the lower end of the moderate range) after 1 day of moist curing. When moist cured for 14 days, specimens of the same composition had low permeability. Specimens with a combination of 45 percent slag and 5 percent silica fume showed a further reduction in chloride permeability. Values well within the very low permeability range were attained using either curing procedure. In most cases, fewer coulombs passed through the specimens tested at 90 days than those tested at 28 days. The exceptions are attributed to the initial differences in the specimens used for the tests. The lower chloride permeability achieved using Type III cement compared to Type II probably results from the small particle size of Type III, which accelerates hydration and provides more lime for the early reaction of the pozzolans.

CONCLUSIONS

The low percentage of silica fume (5 percent of the total cementitious material) used in the specimens in this study did not appreciably alter the early strength development of concrete containing fly ash made with either Type II or Type III cement. However, 1-day strengths higher than 3,000 psi are obtainable with a w/c of 0.40 for all the concretes with Type III cement except for specimens containing slag. Specimens containing combinations of both slag and silica fume had improved 1-day strengths, but the development of 3,000 psi compressive strength required slightly more than 2 days. Concretes with Type III cement had higher strengths than concretes of similar composition with Type II cement.

AASHTO Test Method T 277, which is based on electrical conductance, indicates that a significant reduction in chloride permeability is attained in all concretes tested when 5 percent silica fume is made a part of the total cementitious material. Generally, the improvement is greater when Type III cement is used rather than Type II. The importance of properly curing all concretes is demonstrated by these results. Specimens that were cured for 14 days under standard moist conditions had lower chloride permeability than similar specimens cured only 1 day. However, 1-day moist curing did provide low chloride permeability when silica fume and Type III cements were used in conjunction with fly ash or slag.

RECOMMENDATIONS

Further studies should be conducted with different combinations of fly ash, slag, silica fume, and different cement types with the objective of defining the optimum combinations of cementitious materials for adequate field performance and maximum economy.

ACKNOWLEDGEMENTS

Special thanks are expressed to Mike Burton and Leroy Wilson for the preparation and testing of the concrete specimens. Appreciation is extended to Roger Howe for the editing and to Arlene Fewell for the typing of the paper.

REFERENCE

1. Ozyildirim, C. and W. J. Halstead, "Resistance to Chloride Ion Penetration of Concretes Containing Fly Ash, Silica Fume, or Slag." VTRC 88-R11 Virginia Transportation Research Council, Charlottesville, VA, February 1988.

APPENDIX

Table A-1

Chemical and Physical Analyses of Cements

Chemical, %	Type II	Type III
SiO_2	21.0	20.7
Al_2O_3	4.8	5.1
Fe_2O_3	3.8	2.2
CaO	62.7	62.7
MgO	3.1	3.3
SO_3	2.7	3.9
Total Alkalies	0.74	0.72
C_3S	50	49
C_3A	6	10
Physical		
Fineness (Blaine)	3,833	5,275

Chemical and Physical Analyses of Fly Ash, Slag, and Silica Fume

Chemical, %	Fly Ash (F)	Slag (S)	Silica Fume (SF)
SiO_2	54.5	36.0	93.2
Al_2O_3	30.4	10.8	0.1
Fe_2O_3	3.2	0.7	0.3
CaO	0.7	42.7	1.0
MgO	N.D.[a]	8.9	0.2
SO_3	0.2	1.2	0.1
Total alkalies	0.82	0.32	0.18
Loss on ignition	2.16	1.89	1.80
Physical			
Fineness			
% ret on No. 325 sieve	14.2	1.1	N.D.
Specific Gravity	2.22	2.93	2.27

[a] N.D. = Not determined.

Table A-3

Mixture Proportions for Cubic Yard of Concrete, lb/yd^3

Identification	Cement[a]	Fly Ash	Slag	Silica Fume	Fine Aggregate[b]
Control	658	---	---	---	1,432
25F	494	164	---	---	1,377
50S	329	---	329	---	1,413
5SF	625	---	---	33	1,422
20F - 5SF	494	132	---	33	1,377
45S - 5SF	329	---	296	33	1,404

---

[a] Type III cement used for all combinations. Additional specimens for control, 20F-5SF, and 45S-53F were made with Type II cement.

[b] The amount of fine aggregate was adjusted to provide an equal volume of mortar in all specimens. The amount of coarse aggregate was 1,506 lb/yd^3 and the water was 263 lb/yd^3.

Table A-4

Characteristics of Concrete

Identification[a]	Slump, in.	Air %	Unit Weight, lb/ft^3
Type II Cement (C_2)			
Control	5.0	7.5	142.8
	5.0	6.7	142.8
20F-5SF	5.0	7.4	139.6
	3.5	8.4	137.6
45F-5SF	7.0	8.6	138.0
	6.0	8.9	136.4
Type III Cement (C_3)			
Control	6.7	6.5	143.6
	5.5	5.6	144.4
5SF	5.0	6.6	142.4
	5.5	7.5	140.4
25F	8.0	6.8	141.6
	6.0	6.2	141.6
20F-5SF	7.0	6.0	141.6
	7.7	8.0	138.8
50S	7.8	5.7	142.0
	6.2	7.1	140.8
45S-5SF	7.5	7.7	140.4
	6.7	9.0	136.8

[a] Numbers are the percentgage (by mass) of the supplemental ingredients in the total cementitious materials. The balance is portland cement of the type indicated. F = Fly ash; SF = silica fume; S = slag.

Table A-5

Strengths of Concretes with Type II Cement

Identification[a]	Compressive Strength, psi					Flexural Strength
	1 day	2 days	7 days	28 days	90 days	28 days
Control	3,190	3,820	5,300	6,970	7,370	640
	3,180	4,090	5,540	7,090	7,960	806
Avg.	3,190	3,960	5,420	7,030	7,660	720
20F-5SF	2,370	3,000	4,350	6,580	7,710	678
	2,720	3,170	4,540	6,560	7,730	668
Avg.	2,550	3,090	4,450	6,570	7,720	673
45S-5SF	1,110	1,870	4,350	8,270	9,400	680
	840	1,420	2,790	6,250	8,040	635
Avg.	980	1,650	3,570	7,260	8,720	657

[a] Numbers are the percentage (by mass) of the supplemental ingredients in the total cementitious material. The balance is portland cement of the type indicated. F = fly ash; SF = silica fume; S = slag.

Table A-6

Strengths of Concretes with Type III Cement

Identification[a]	Compressive Strength, psi 1 day	2 days	7 days	28 days	90 days	Flexural Strength 28 days
Control	4,780	5,560	6,340	7,610	7,760	808
	4,690	5,380	6,510	8,040	8,770	839
Avg.	4,740	5,470	6,420	7,820	8,260	824
5SF	4,500	5,050	6,810	8,260	9,200	750
	4,460	5,200	6,420	8,010	9,020	778
Avg.	4,480	5,120	6,620	8,140	9,110	765
25F	3,150	3,720	4,800	6,060	7,640	686
	3,230	3,770	4,930	6,190	7,390	675
Avg.	3,190	3,740	4,860	6,120	7,520	680
20F-5SF	3,190	3,800	5,360	7,320	8,270	707
	3,460	3,980	5,290	7,100	8,060	668
Avg.	3,320	3,890	5,320	7,210	8,160	688
50S	1,360	2,360	6,050	8,270	8,500	821
	1,540	2,500	5,240	7,640	8,400	830
Avg.	1,450	2,430	5,640	7,960	8,450	826
45S-5SF	2,170	3,100	6,520	8,920	9,500	811
	1,900	2,660	4,880	7,410	8,610	720
Avg.	2,040	2,880	5,700	8,160	9,060	766

[a] Numbers are the percentages (by mass) of the supplemental ingredients in the total cementitious materials. The balance is portland cement of the type indicated. F = fly ash; SF = silica fume; S = slag.

Table A-7

Charge Passed through Concretes with Type II Cement

Identification[a]	Coulombs 28 Day Tests Cure 1[b]	Coulombs 28 Day Tests Cure 2[c]	Coulombs 90 Day Tests Cure 1[b]	Coulombs 90 Day Tests Cure 2[c]
Control	9,100	5,540	7,290	7,700
	6,330	4,390	7,510	4,540
Avg.	7,710	4,970	7,400	6,120
20F-5SF	3,510	2,470	4,050	1,080
	2,750	2,200	3,980	2,830
Avg.	3,130	2,340	4,010	1,960
45S-5SF	2,280	1,660	1,770	1,100
	3,820	3,590	2,980	1,650
Avg.	3,050	2,670	2,320	1,370

[a] Numbers are the percentages (by mass) of the supplemental cementitious material. The balance is portland cement of the type indicated. F = fly ash; SF = silica fume; S = slag.

[b] Cure 1 - Moist cure 1 day - air dried until tested

[c] Cure 2 - Moist cure 14 days - air dried until tested. (AASHTO T 277 procedure)

Table A-8

Charge Passed through Concretes with Type III Cement

	Coulombs Passed			
	28 Day Tests		90 Day Tests	
Identification[a]	Cure 1[b]	Cure 2[c]	Cure 1[b]	Cure 2[c]
Control	6,180	3,970	6,210	4,330
	5,130	3,350	6,200	3,610
Avg.	5,650	3,660	6,200	3,970
5SF	3,240	1,010	1,280	700
	1,230	1,110	1,150	740
Avg.	2,240	1,060	1,210	720
25F	8,760	4,940	6,600	3,670
	9,220	4,650	7,930	3,010
Avg.	8,990	4,800	7,270	3,340
20F-5SF	1,520	1,220	1,400	500
	1,200	1,080	1,400	580
Avg.	1,460	1,150	1,400	540
50S	3,060	1,820	2,180	1,460
	1,630	1,530	2,320	1,490
Avg.	2,340	1,670	2,250	1,480
45S-5SF	610	690	720	430
	670	760	890	400
Avg.	640	720	800	410

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[a] Numbers are the percentages (by mass) of the supplemental ingredients in the total cementitious material. The balance is portland cement of the type specified. F = fly ash; SF = silica fume; S = slag.

[b] Cure 1 - Moist cured 1 day and air dried until tested.

[c] Cure 2 - Moist cured 14 days and air dried until tested. (AASHTO T 277 procedure)