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16. Abstract

The effects of two pozzolanic admixtures, fly ash and silica fume, and a ground-granulated blast furnace slag on the chloride ion intrusion of concretes prepared with low water-to-cementitious material ratios (w/c) (0.35 to 0.45) were investigated.

Results of the rapid permeability test (AASHTO T 277) showed that the resistance of concrete to the penetration of chloride ions increases significantly as the w/c is decreased for the same proportion of solid ingredients. Usually, concretes with pozzolans or slag exhibited higher resistance to chloride ion penetration than the control concretes containing portland cement as the cementitious material. Results of the 90-day ponding test (similar to AASHTO T 259), which was conducted with 0.40 w/c concretes only, indicated minimal choride content at depths below 3/4 in (19 mm) for all the test concretes. Strength values for all concretes made with the pozzolans and slag at 90 days were in excess of 5,000 psi (34.5 MPa), which is satisfactory.

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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 (s)	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	
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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
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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:		
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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)		
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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

RESISTANCE TO CHLORIDE ION PENETRATION OF CONCRETES CONTAINING FLY ASH, SILICA FUME, OR SLAG

by

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and

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Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia
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In Cooperation with the U.S. Department of Transportation
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ABSTRACT

The effects of two pozzolanic admixtures, fly ash and silica fume, and a ground-granulated blast furnace slag on the chloride ion intrusion of concretes prepared with low water-to-cementitious material ratios (w/c) (0.35 to 0.45) were investigated. Each of these supplemental cementitious materials was used with a Type I and Type II cement. A Type III cement was also used to determine possible differences in behavior between this cement and Type II when cured at a range of temperature from 40°F to 100°F.

The resistance of these concretes to chloride ion penetration was determined using the rapid permeability test (AASHTO T 277) and the 90-day ponding test similar to AASHTO T 259. Results of the rapid permeability test show that the resistance of concrete to the penetration of chloride ions increases significantly as the w/c is decreased for the same proportion of solid ingredients. Usually, concretes with pozzolans or slag exhibited higher resistance to chloride ion penetration than the control concretes containing portland cement as the cementitious material. Results of the 90-day ponding test, which was conducted with 0.40 w/c concretes only, indicated minimal choride content at depths below 3/4 in (19 mm) for all the test concretes. A precise correlation of the rapid test for chloride permeability (AASHTO T 277) and the 90-day ponding test with salt solution was not attained, but a general relationship was shown.

Strength values for all concretes made with the pozzolans and slag at 90 days were in excess of 5,000 psi (34.5 MPa), which is satisfactory. For the same type and amount of supplemental cementitious material, strength increased as the resistance to chloride ion penetration increased; but when concretes made with different materials were compared, there was no specific relationship between strength and the results of the rapid test for resistance to chloride ion penetration.

FINAL REPORT

RESISTANCE TO CHLORIDE ION PENETRATION OF CONCRETES CONTAINING FLY ASH, SILICA FUME, OR SLAG

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INTRODUCTION

Significant damage to concrete results from the intrusion of corrosive solutions; for example, dissolved chlorides corrode reinforcing steel and cause spalling. Any treatment that effectively blocks the penetration of these solutions will eliminate or greatly reduce this damage and lead to increased durability with the consequent economic benefits.

Considerable research has been conducted on this problem, including the evaluation of special coatings, pore blocking admixtures, and special concretes applied as overlays in the thickness range of 1-1/4 to 2 in (32 to 50 mm)(1,2). The overlay concretes include water-reducing admixtures and usually have a water to cementitious material ratio (w/c) of 0.40 or lower. One successful system for overlays at a minimum thickness of 1-1/4 in (32 mm) has been latex-modified concrete (LMC). In addition to the added cost of materials for such overlays, special expertise and equipment are needed for field applications; consequently, such concretes are considerably more expensive than commercially prepared ready-mixed concretes.

Previous studies at the Virginia Transportation Research Council have demonstrated the potential usefulness of a number of supplemental cementitious materials for improving the properties of hydraulic cement concretes. The objectives of these studies generally have been to measure the extent to which each supplemental material can be substituted for a portion of the portland cement without detrimental effects on the strength and durability of the concrete. Improved resistance to chloride ion penetration has been an important but secondary consideration in most of the studies. An exception is the study on the use of silica fume, where the objective was to determine the feasibility of using various amounts of silica fume to produce concretes with low permeability to chloride ion comparable to those of LMC.

Because all of these admixtures can be mixed utilizing ready-mix plants and normal placement procedures, production costs are lower compared to specialized systems; therefore, this study was undertaken to obtain data on relative strength development and resistance to chloride ion penetration when the recommended amount of each supplemental material was used under similar conditions. Such data would permit comparisons of the relative economy and efficiency of fly ash, silica fume, and slag.

SCOPE AND OBJECTIVES

The test program was designed to determine the effects of different admixtures in minimizing chloride ion permeability and to establish the relationship between chloride ion permeability and variations in the water cement ratio.

As a guide for determining the type and amount of various admixtures to be used in the study, a literature review was conducted. A summary of the findings with respect to the admixtures used in this study is provided as Appendix A.

The materials evaluated were a fly ash conforming to ASTM Specification C-618 (Class F), a silica fume, and ground-granulated-iron blast furnace slag. A LMC was included in the study for comparison.

The specific objectives of the study were:

1. to evaluate the effectiveness of various mineral admixtures in producing concrete of low permeability,
2. to estimate the relative cost of concretes made with the chemical and major by-product admixtures for essentially equal levels of permeability, and
3. to determine the time required for concretes made with different admixtures to reach the desired level of low permeability.

TESTS CONDUCTED AND MIXTURE PROPORTIONS

The amount of each supplemental cementitious material was based on the amount recommended by promoters of the various materials or by previous laboratory studies at the Council:

1. 15% of the cement by mass was replaced with 1.2 times that mass by a Class F fly ash
2. 25% of the cement by mass was replaced with 1.2 times that mass by a Class F fly ash

3. 50% of the cement by mass was replaced with slag

4. 7% of the cement by mass was replaced with silica fume.

Each combination of materials with C2, a Type II cement, was tested at w/c of 0.35, 0.40, and 0.45. Combinations with C1, a Type I cement, were tested at a w/c of 0.40. Specimens were prepared using concretes with 15% fly ash, 50% slag, and 7% silica fume with Type II (C2) and Type III cements at 0.40 w/c to investigate the effect of curing temperatures of 40° (4°C), 73°F (23°C), and 100°F (38°C). Also, specimens were made from two control concretes using Type II and Type III cements. The material combinations, mixture proportions, and characteristics of the materials are given in Appendix B.

The concretes were mixed and specimens prepared in accordance with ASTM C 192. They all contained an air-entraining and a water-reducing admixture. The air-entraining admixture was a neutralized vinsol resin added in amounts adequate to give the desired air content, and the water-reducing admixture was an aqueous solution of complex organic compounds added at the recommended dosage. A high-range water-reducing admixture (HRWR) was used to achieve workable concretes at w/c of 0.35 and 0.40; it was an aqueous solution of a modified naphthalene sulfonate. At a w/c of 0.35, it was necessary to add HRWR in amounts approximately double the dosage recommended by the manufacturer. At the 0.40 w/c, the amounts of HRWR added were within the manufacturer's recommended dosages. At a w/c of 0.45, HRWR was added only to the concretes containing silica fume. It was needed in this case to aid in the dispersion of the very fine silica fume particles and to increase the workability of the concretes. The air content of the freshly mixed concrete was measured by the pressure method (ASTM C 231). Slump was measured by ASTM C 143, and unit weight was determined by ASTM C 138.

The hardened concretes were tested for resistance to chloride ion penetration and compressive strength using 4 in by 8 in (100 by 200 mm) cylinders. The resistance to chloride ion penetration was determined using AASHTO T 277 ("Rapid Determination of the Chloride Permeability of Concrete"). This test is based on a relationship between the electrical conductance and the resistance to chloride ion penetration. The cylinders used for the test were moist cured for 2 weeks, after which the top 2 in (50 mm) was cut off and used as the test specimen. The sides of the specimens were coated with an epoxy resin to prevent lateral moisture loss, and they were set on a plastic sheet and kept in the ambient laboratory conditions until the time of the test. This procedure is believed to partially simulate the continued curing of concrete where only the top surface is exposed to the atmosphere. Each reported test value is an average of the results from two cylinders.

The resistance of concretes to chloride penetration was also evaluated by tests on two cylinders from each batch at a w/c of 0.40 using a ponding test similar to AASHTO T 259 ("Resistance of Concrete to Chloride Ion Penetration"). Cylinders measuring 4 in by 8 in were moist cured for 2 weeks and air dried for an additional 2 weeks. Then they were ponded with 3% NaCl for 90 days. Afterward, they were drilled with a 2-in diameter bit to obtain samples for a determination of chloride content at two depths: 1/4 to 3/4 in (6 to 19 mm) and 3/4 to 1 1/4 in (19 to 32 mm). Samples were pulverized and the chloride ion content determined using AASHTO Method T 260.

Compressive strength was determined at 1, 7, 28, 90, and 365 days. Specimens were prepared and tested in accordance with AASHTO Method T 22 using neoprene pads in steel-end caps for capping. Each reported test value is an average of the results from three cylinders.

Samples prepared using Type II and Type III cements to study the effect of curing temperature were tested for permeability (AASHTO T 277) and strength at 28 days.

TEST RESULTS AT THE FRESH STAGE

The slump, air content, and unit weight of the test concretes are summarized in Table B-3 of Appendix B. The results indicate that air-entrained concretes with satisfactory workability can be obtained with the use of air-entraining and either regular or regular and high-range water-reducing admixtures, depending on the w/c.

TEST RESULTS AT THE HARDENED STAGE

The results of the tests made for this study were generally consistent with the results reported by others (3,4,5,6). However, the quantitative evaluation of the effect of different variables will be useful as a basis for the selection of combinations of available cementitious materials that will provide good resistance to chloride ion penetration of concrete at economical cost.

Chloride Ion Penetration

Electrical Conductance Test

Table 1 shows the results of the tests for electrical conductance as determined by AASHTO Method T 277. This test measures the quantity of electricity, expressed as coulombs, that passes through the test specimens in six hours. This quantity is designated as Q for the purposes of this report. In accordance with AASHTO T 277, the test results are used to rate the concretes with respect to chloride permeability as follows:

Coulombs		Permeability
>4,000	-	high
2000 - 4000	-	moderate
1000 - 2000	-	low
100 - 1000	-	very low
<100	-	negligible

TABLE 1

Results of Chloride Permeability Tests at Various Ages and Different Water/Cementitious Ratios

ID[a]	w/c = 0.35			w/c = 0.40			w/c = 0.45		
	28-days	90-days	365-days	28-days	90-days	365-days	28-days	90-days	365-days
	Q	Q	Q	Q	Q	Q	Q	Q	Q
C2	2,890	2,020	2,330	4,830	4,210	3,660	7,460	6,910	4,770
C1	2,850	1,940	2,260	3,860	3,590	4,800	5,290	5,430	5,450
C2F-15	3,190	1,540	1,900	5,110	2,960[b]	3,730	8,080	5,810	4,800
C1F-15	--	--	--	3,330	2,010[b]	2,870	--	--	--
C2F-25	2,820	1,540	1,780	5,110	3,220	3,440	10,420	7,110	5,260
C1F-25	--	--	--	3,430	1,890	1,920	--	--	--
C2S-50	1,650	900	1,350	2,410	1,330	2,160	3,100	1,950	3,290
C1S-50	--	--	--	2,050	1,600	2,350	--	--	--
C2SF-7	570	340	168	850	460	300	1,020	620	730
C1SF-7	--	--	--	760	490	390	--	--	--
C2L[c]	--	--	--	3,000	1,370[d]	352	--	--	--
C1L	--	--	--	2,290	1,410	439	--	--	--

(a) See Table B-1 for Code

(b) value at 76 days

(c) 0.37 w/c

(d) value at 104 days

Figures 1 and 2 show the values of Q at 28 and 90 days for concrete made with the Type II cement (C2). The w/c significantly affected the test results in all cases: the value of Q decreased as the w/c decreased. At 28 days, the Q values for the controls and the concretes containing fly ash were in the moderate or high permeability zone in all cases. The concretes containing slag had Q values in the moderate zone (AASHTO T 277) with a w/c of 0.40 and 0.45, and in the low zone with a w/c of 0.35. At a 0.45 w/c, the Q values for slag concretes were slightly higher and with 0.35 and 0.40 w/c they were lower than the LMC (with a w/c of 0.37). The most significant effect on the chloride permeability test results was shown by the concretes containing silica fume. With silica fume, the values of Q at 28 days were below 1,000 coulombs except for one at 1,020. At 28 days, the Q values for the LMC regularly used as overlay material over bridge decks were in the moderate permeability range.

At 90 days, controls and concretes with fly ash exhibited Q values that decreased significantly as the w/c decreased. The results for the LMC and concretes containing slag were generally within the low range for all w/c. The results for the concretes containing silica fume were all substantially less than 1,000 coulombs, indicating a very low permeability to chloride ion.

The trends with respect to the effects of w/c at 28 and 90 days were also shown by the tests on the 365-day specimens.

A comparison of results on 28-day specimens and 90-day specimens indicate that for most concretes the resistance to chloride ion intrusion increases during that period. With the exception of concrete made with Type I cement with a 0.45 w/c, all the Q values for 90-day specimens were lower than the Q value for the corresponding 28-day specimens, and in most cases the difference was significant. Changes for those concretes containing pozzolans or slag were proportionately greater than the changes for the controls. Q values measured on 365-day specimens are inconclusive as to whether further changes occur after 90 days. In a majority of the cases, the Q value for the 365-day specimens was greater than that recorded for the corresponding 90-day specimens. However, the chloride ion permeability classification in accordance with AASHTO T 277 remained unchanged in most cases. A notable exception is the LMC made with both cements. The Q values at 365 days for these concretes were in the very low range.

While there are some indications of differences between concretes made with Type I cement and Type II cement, such differences are not great. This indicates the relatively small effect of the cement type in these experiments. The effect, if any, is that at 28 days, concretes made with Type I cements have lower Q values than concretes made with Type II cements. At later ages, differences caused by the cement type have diminished.

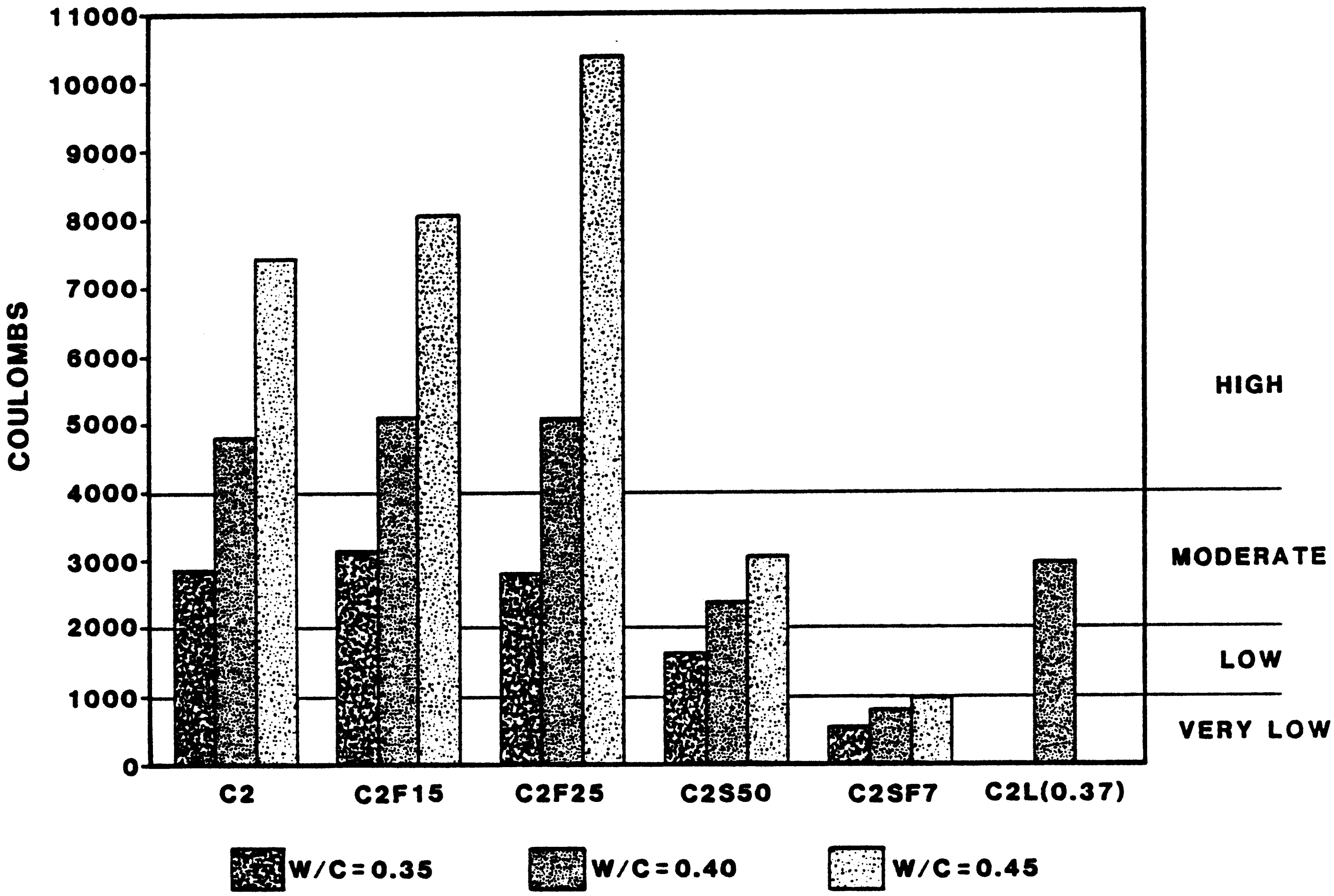

Figure 1. Results of 28-day chloride permeability test.

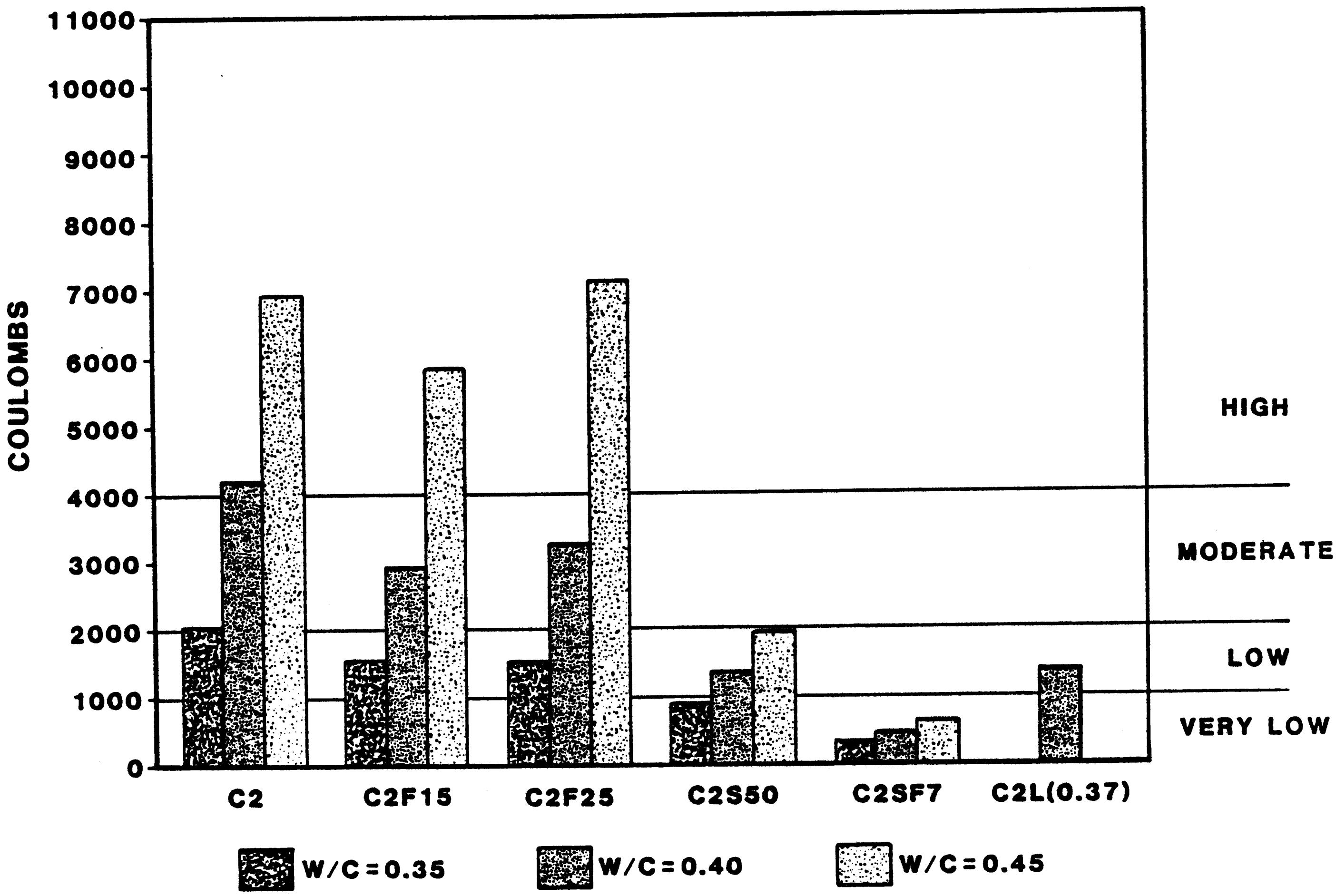

Figure 2. Results of 90-day chloride permeability tests.

90-Day Ponding Tests

Table 2 summarizes the results of the tests for resistance of concrete with a w/c of 0.40 to chloride ion penetration using the 90-day ponding test. The results indicate that at a depth of 1/4 to 3/4 in (6 to 19 mm), all of the concretes except the one with silica fume and C1 had chloride content above 1.32 lb/yd^3 (0.78 kg/m^3), which is the threshold value for corrosion of the reinforcing steel reported by FHWA (7). The value for LMC with C1 was close to the threshold value. The concretes with Type I cement exhibited lower chloride content than those with Type II cement, except for the fly-ash concretes. Concretes with supplemental cementitious materials as well as LMC had a lower chloride content than the controls. Concretes with SF had the least amount of chloride penetration. At the lower depth of 3/4 to 1-1/4 in (10 to 32 mm) all the concretes had significantly lower values than the corrosion threshold value; the highest average value of any pair of two samples was 0.38 lb/yd^3 (0.22 kg/m^3). Thus, it appears that all the concretes with a low w/c in this study would have significant resistance to chloride ion penetration under actual service conditions. However, these results do not provide a measure of the length of service that may be expected from the concretes.

TABLE 2

Relation of Chloride Content to Results of Rapid Permeability Test

Chloride Content, lb/yd^3 [(a)]

	1/4"-3/4" Depth			3/4"- 1 1/4" Depth			Avg.[(b)]	Q, Coulombs	
Identification	1	2	Avg.	1	2	Avg.	Total	28 Day	90 Day
C2	6.15	3.89	5.02	0.58	0.18	0.38	5.40	4,830	4,210
C2FA-15	2.87	2.52	2.70	0.13	0.29	0.21	2.91	5,110	2,960
C2FA-25	3.37	2.75	3.07	0.14	0.29	0.21	3.28	5,110	3,220
C2S-50	2.36	4.28	3.33	0.04	0.29	0.17	3.50	2,410	1,330
C2SF-7	3.21	1.59	2.40	0.26	0.35	0.31	2.71	850	460
C2L	4.81	3.35	4.08	0.29	0.12	0.21	4.29	3,000	1,370
C1	3.95	2.09	3.02	0.30	0.23	0.26	3.28	3,860	3,590
C1FA-15	3.61	2.98	3.30	0.25	0.16	0.21	3.51	3,330	2,010
C1FA-25	4.96	3.39	4.18	0.26	0.46	0.36	4.54	3,430	1,890
C1S-50	1.27	3.84	2.56	0.07	0.35	0.21	2.77	2,050	1,610
C1SF7	0.85	1.19	1.02	0.17	--	0.17	1.19	760	490
C1L	1.74	1.06	1.40	0.19	0.10	0.15	1.55	2,290	1,410

1 lb/yd^3 = 0.59 kg/m^3, 1 in = 25.4 mm

(a) Corrected for average base line chloride of 0.13 lb/yd^3.

(b) Sum of average for both levels.

Relation of Rapid Permeability Test to 90-Day Ponding Test

The rapid chloride permeability test was developed by the Construction Technology Laboratories of the Portland Cement Association on a contract for the Federal Highway Administration(8). The development work showed a generally good correlation with the 90-day ponding test for chloride intrusion; but a large standard error for the test led the developers to conclude that the test was best utilized to rank concretes in order of expected permeability rather than to predict 90-day ponding results. It is also apparent that the condition of the test specimens and the characteristics of the materials being tested make it difficult to establish a relationship between the results of the 90-day ponding test and those from the rapid permeability test. Consequently, the extent to which differences in the Q values can be considered a measure of the differences in chloride permeability of the concrete under actual service conditions is uncertain.

Table 2 gives the Q value as an average of two specimens obtained for the same batch of concrete after the specimens had been aged for 28 and 90 days. The same table also gives the individual chloride content after the ponding test. There were large differences in the total salt found in the duplicate specimens. These differences make it impossible to establish a quantitative relationship between the Q values obtained in the rapid permeability test and the results of the ponding test.

When the sum of the average of chlorides absorbed at 1/4 to 3/4 in (6 to 19 mm) and 3/4 to 1-1/4 in (19 to 32 mm) are plotted against the Q values for the 28-day specimens on a logarithmic scale as shown in Figure 3, considerable scatter of the points is evident. Much of this may be caused by the poor precision of both the ponding test and the rapid permeability test. The line of best fit shows a correlation coefficient of 0.625 and indicates a general relationship of lower salt content with lower values of Q. A similar relationship was obtained at 90 days with a correlation coefficient of 0.577.

Strength Development

Table 3 provides the test results for compressive strengths at various ages for each combination of materials. The results are depicted in Figure 4, in which bar graphs of the strengths at 0.35, 0.40, and 0.45 w/c are shown for each combination of materials using Type II cement at 28 days. Figure 5 shows the pattern of strength development with age for the various materials. The plotted results are those for a w/c of 0.40, but the relationships are essentially the same at the other w/c tested. As noted in Figure 5, the patterns vary depending on the supplemental cementitious material used.

The results of the strength tests are summarized in the following sections.

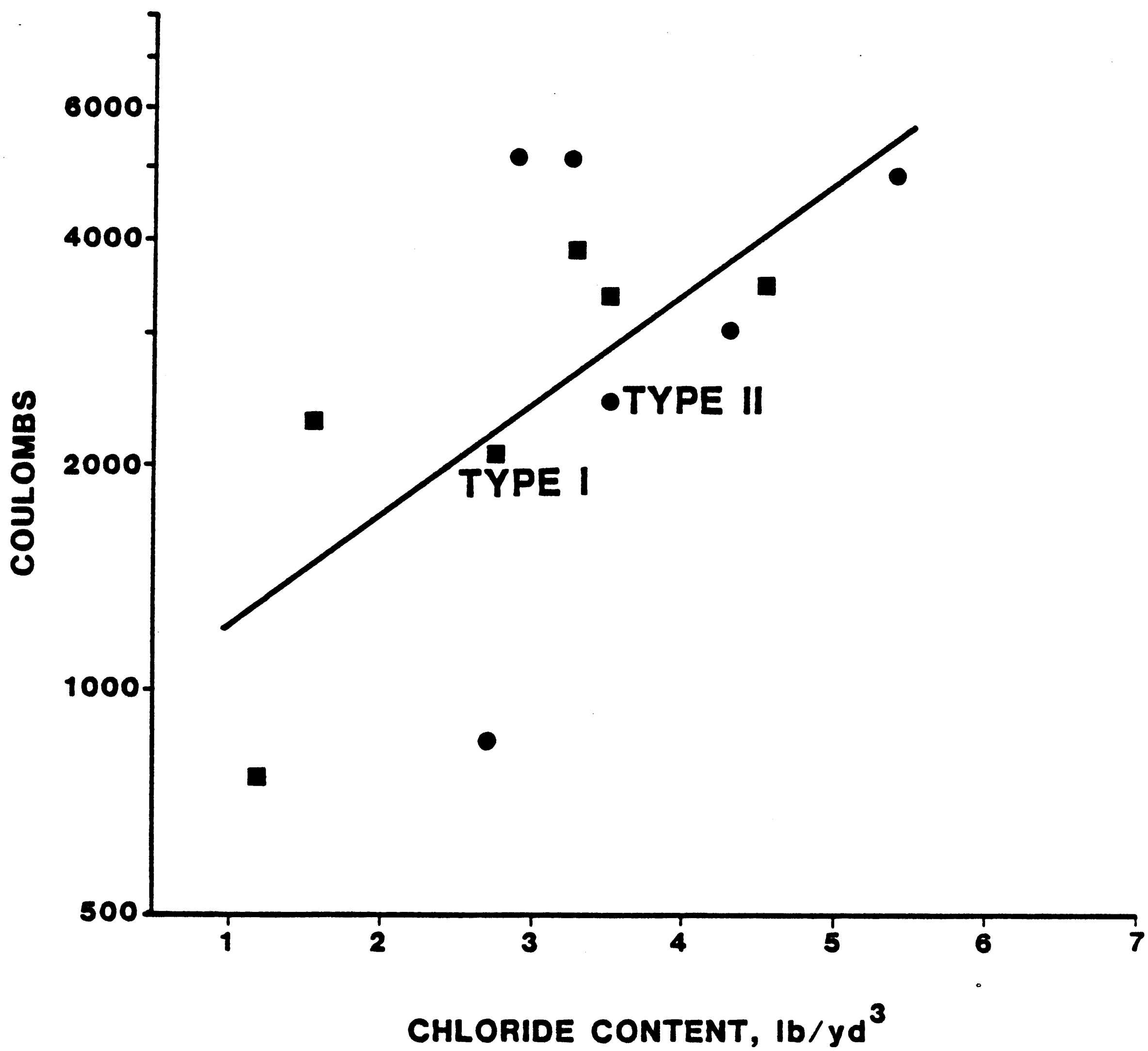

Figure 3. Relation of Q at 28 days to total chloride absorbed (1/4 to to 1 1/4 in) after 90 days.

(1 lb/yd^3 = 0.59 kg/m^3, 1 in = 25.4 mm)

TABLE 3

Strengths of Concretes Prepared with Various Supplemental Cementitious Material

ID	w/c	Compressive Strengths, psi at: 1-Day	7-Days	28-Days	90-Days	365-Days
C2	0.35	4,890	6,860	8,180	8,870	10,220
	0.40	3,170	4,960	6,010	6,950	7,700
	0.45	1,880	4,170	5,400	6,170	6,840
C2F-15	0.35	2,930	5,160	6,730	8,380	9,900
	0.40	2,440	4,200	5,490	7,310	8,650
	0.45	1,530	3,250	4,450	6,080	7,440
C2F-25	0.35	3,200	5,250	7,010	9,230	10,870
	0.40	1,960	4,150	5,840	8,010	8,950
	0.45	1,320	2,830	4,150	5,750	6,620
C2S-50	0.35	1,540	7,580	9,540	10,370	11,130
	0.40	1,540	5,700	7,830	8,440	9,160
	0.45	890	4,540	6,670	7,500	8,060
C2SF-7	0.35	3,900	6,650	8,600	9,200	9,780
	0.40	3,030	5,200	6,850	7,410	7,690
	0.45	2,350	3,930	5,260	5,860	6,120
C2-L	0.37	1,900	3,630	4,380	5,240	5,800
C1	0.35	4,600	6,470	7,810	8,920	9,550
	0.40	3,800	5,590	6,490	7,610	8,250
	0.45	2,830	4,480	5,340	6,140	6,600
C1F-15	0.40	2,850	4,440	5,520	7,030	7,790
C1F-25	0.40	2,820	4,390	5,890	7,560	8,290
C1S-50	0.40	1,750	5,980	7,580	8,200	8,440
C1SF-7	0.40	3,480	5,460	6,500	7,130	7,170
C1-L	0.37	2,560	3,510	4,390	5,150	5,660

1 psi = 6.895 kPa.

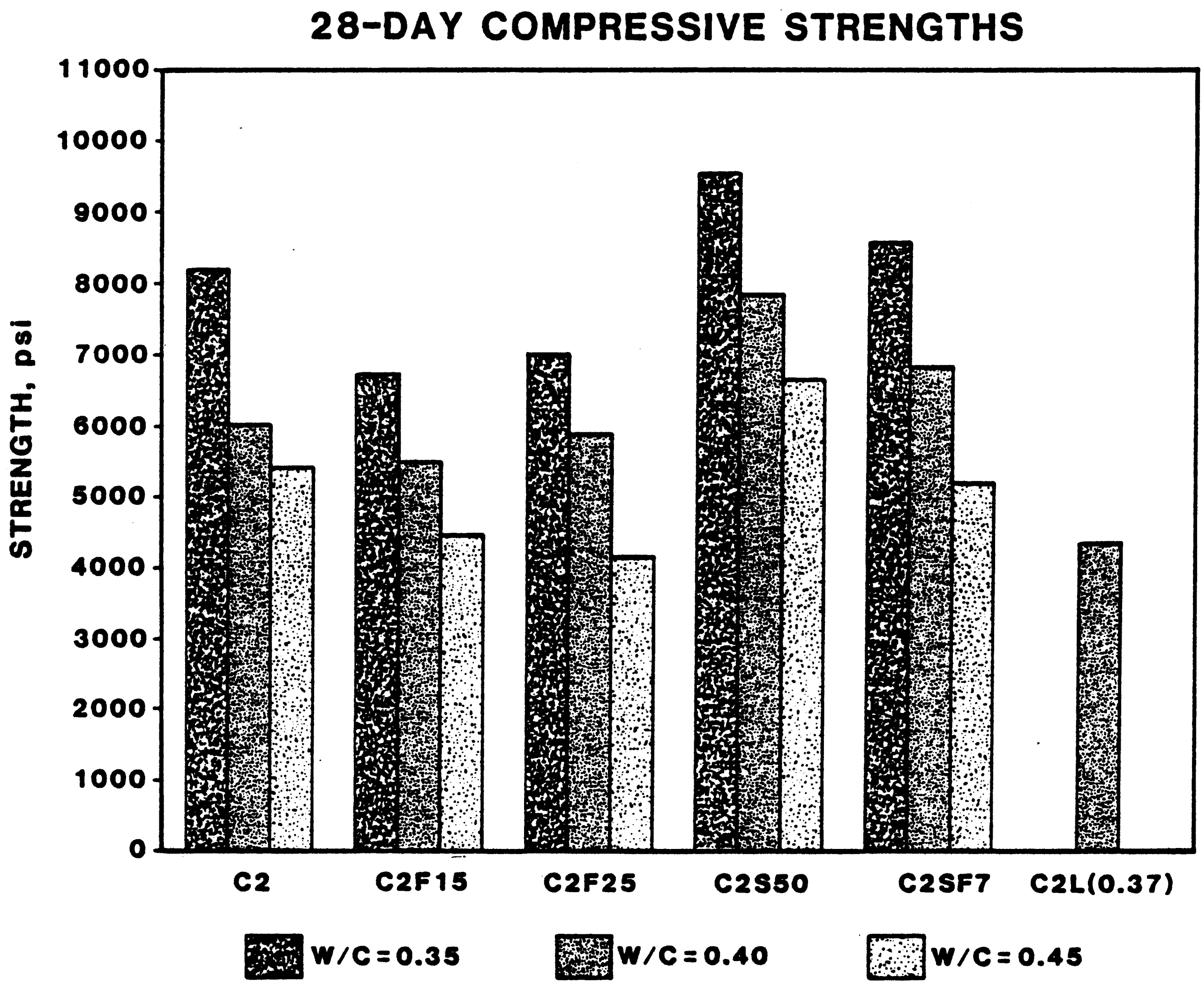

Figure 4. 28-day strengths (1 psi = 6.895 kPa).

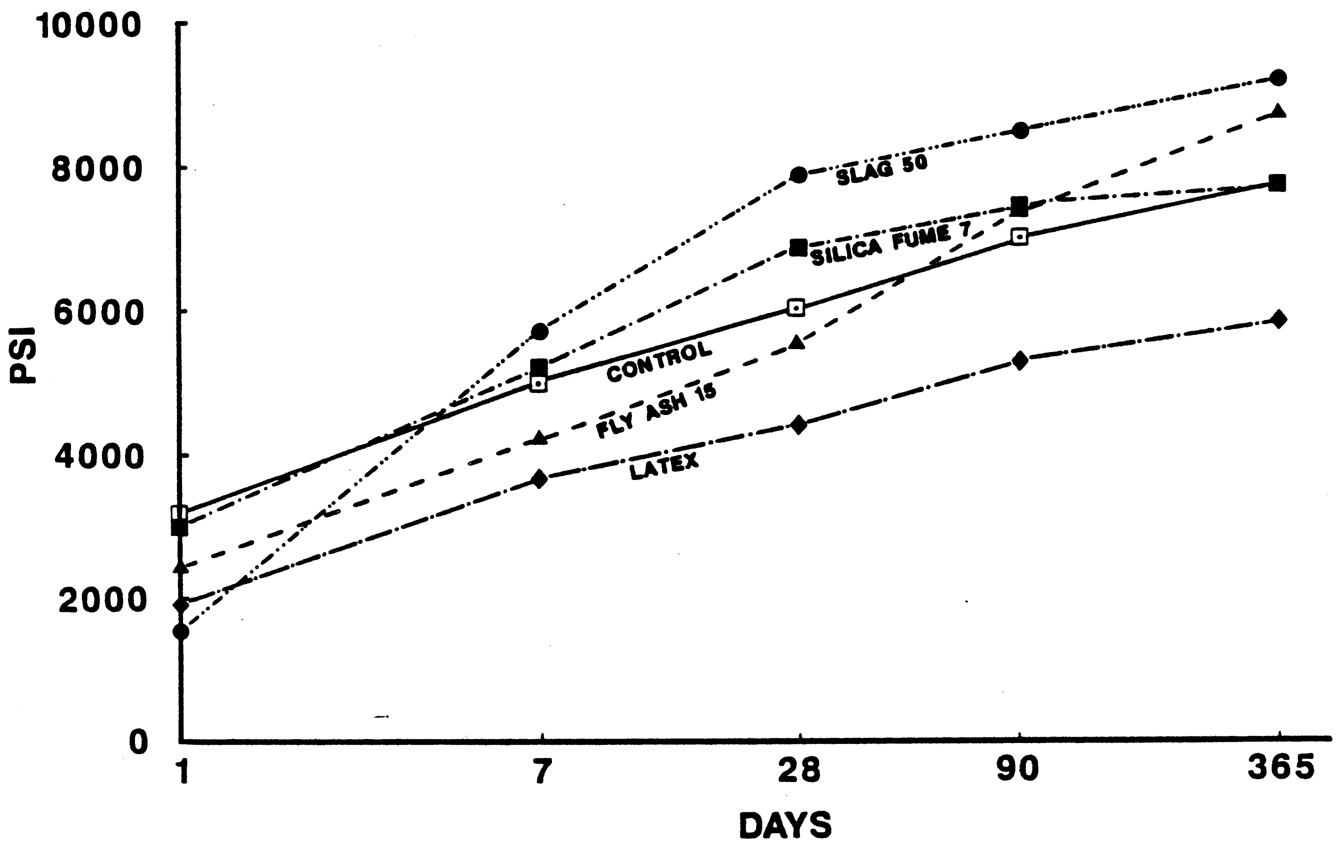

Figure 5. Compressive strength vs age for concretes with Type II cement at 0.40 w/c (1 psi - 6.895 kPa).

Effect of w/c

In all cases an increase in strength is attained by reducing the w/c for a given proportion of solid ingredients. It should be noted that workable concretes with the lower w/c were obtained only through use of high-range water-reducing admixtures under laboratory conditions. Ratios as low as 0.35 may not be practicable for field concretes using locally available materials. However, these results indicate that the lowest practicable w/c ratio should be used in conjunction with all the supplemental cementitious material tested and that potentially lower strengths for concretes containing pozzolanic admixtures such as fly ash can be counteracted with relatively minor reductions of the w/c.

Concretes Containing Fly Ash

Results for concretes containing fly ash are as would be expected from previous research (9). In each case the strengths at early ages were lower than the controls. Generally, the strengths of the fly ash concretes increased at a slightly greater rate than the controls, and the rate of increase accelerated during the 28 to 90 day period. At 90 and 365 days, the fly ash concretes generally had strengths comparable to or significantly greater than the controls.

The same general trends were indicated by both the 15 and 25% replacement series. The lowest values were those for the 25% replacement specimens at the 0.45 w/c. They were 4,150 psi (28.6 MPa) at 28 days, 5,750 psi (39.6 MPa) at 90 days, and 6,620 psi (45.6 MPa) at 365 days, indicating satisfactory strength for bridge-deck concrete. This implies that the greater economy of replacing a larger proportion of the cement could be utilized with only minor adjustment in specifications and construction practices, and this would result in concretes with equal or higher strengths at later ages.

Concretes Containing Slag

The results show that an activation period is needed for strength development by the hydration of the slag components. One-day strengths are very low; they are approximately one half of the value of the control. But at seven days the slag concretes were stronger than the controls. There were further significant increases up to 28 days. After 28 days the slag concrete and control increased in strength at approximately the same rate.

Concretes Containing Silica Fume

The concretes containing silica fume developed strengths at approximately the same rate and amount as the control. Some differences are apparent for the different w/c, but this may be experimental error. The general indications are that the pozzolanic reactions with silica fume occur rapidly (10). Long-term increases such as those observed for fly ash concretes, should not be expected, especially for the small percentages of silica fume used in this study.

Latex-Modified Concretes

The strength development curves for the LMC are essentially parallel to those for the controls, but consistently lower. These concretes were prepared at a w/c of 0.37, the value normally used for bridge deck overlays using this material.

Type I versus Type II Cement

In general, control concretes with Type II cement had lower strengths than those with Type I cement at early ages and about equal strengths at 28 and 90 days. For each supplemental cementitious material, similar trends were observed indicating relatively minor effects of the cement characteristics at later ages.

Relation of Strength to Chloride Permeability

For the same type and amount of supplemental cementitious material, Q values decrease as strength increases, indicating an inverse relationship between chloride permeability (AASHTO T 277) and strength. However, there is no specific relation between the Q values and strength per se. For example, concretes containing silica fume had significantly lower Q values, indicating lower permeabilities than concretes containing slag; but their strengths were significantly lower.

Effects of Curing Temperature on Chloride Permeability and Strength

All of the specimens tested thus far in this study were cured under standard conditions in a moist room or air dried at 73°F (23°C). However, since it is known that moisture and temperature affect the rate of hydration or pozzolanic reactions, it was of interest to obtain some indication of the potential effects of curing temperatures on the results of the chloride permeability test and strength. It was also of interest to determine if Type II cements reacted significantly differently from Type III, especially with respect to the resistance to penetration of chloride ions as evaluated by the electrical conductance tests. Accordingly, additional specimens were made at a w/c of 0.40.

Control concretes and concretes containing 15% fly ash, 50% slag, and 7% silica fume with the same proportions given in Appendix B were prepared. For each variable, two batches of concrete, one with Type II and the other with Type III cement, were prepared. The concretes were tested at the fresh stage, and the characteristics are summarized in Table 4. Test specimens were prepared for chloride permeability and strength at room temperature, and within half an hour, they were placed in different curing environments at 40°F (4°C), 73°F (23°C), and 100°F (38°C) without removal of the molds. Molds were removed the following day, and the specimens were returned to different temperature environments. Cylinders for the rapid chloride permeability test were kept moist for 2 weeks and air dried for 2 weeks. Those for the strength test were moist cured until the time of test.

TABLE 4

Characteristics of Freshly Mixed Concrete
(w/c = 0.40)

Variable	Cement Type	Slump, in	Air, %	Unit Weight, lb/ft^3
Control	II	6.0	5.7	145.2
F-15	II	5.7	6.2	142.4
S-50	II	4.5	7.0	142.0
SF-7	II	3.5	7.5	139.2
Control	III	5.5	8.2	139.6
F-15	III	5.8	8.5	140.0
S-50	III	3.8	8.5	140.4
SF-7	III	5.0	8.9	138.8

1 in = 25.4 mm, 1 lb/ft^3 = 16.02 kg/m^3

Results at 28 days indicate that control concretes with either cement had comparable Q values when cured at 73°F (23°C) and 100°F (38°C); but concretes cured at 40°F (4°C) had significantly higher Q values except in one case (slag - Type II cement), which may be experimental error (see Table 5). Strengths were comparable or significantly higher for the concretes containing Type III cement. With either cement the highest strengths were obtained when cured at 73°F (23°C) and the lowest when cured at 100°F (38°C). Of particular interest is the behavior of the concretes with fly ash with respect to chloride permeability. With either cement, the Q values of the specimens decreased significantly as the curing temperature increased. Specimens cured at 100°F (38°C) had Q values indicative of chloride permeabilities in or very close to the very low range. The results for specimens cured at 73°F (23°C) indicated high chloride permeabilities, and those for specimens cured at 40°F (4°C) indicated even higher permeabilities. Fly ash concretes with Type II cement had the lowest strength when cured at 40°F (4°C) and the highest strength when cured at 100°F (38°C). With Type III cement, fly ash specimens cured at 73°F (23°C) developed the highest strength.

The Q values for concretes containing slag cured at 73°F (23°C) and 100°F (38°C) indicated comparable chloride permeabilities. For specimens cured at 40°F (4°C), the Q values for concretes with Type II cement were the same as those for specimens cured at 73°F (23°C) and 100°F (38°C), but specimens containing Type III cement had significantly higher Q values when cured at 40°F (4°C). Strength values for concretes containing slag with either cement were highest when cured at 73°F (23°C) and lowest when cured at 40°F (4°C).

TABLE 5

Effect of Curing Temperature on Chloride Permeability and Strength

Curing Temp. °F	Permeability, coulomb		Strength, psi	
	Type II	Type III	Type II	Type III
Controls				
40	8,240	8,580	6,340	6,610
73	4,260	4,200	6,580	7,260
100	4,300	3,640	5,460	5,410
15% Fly Ash				
40	9,240	11,080	4,560	5,170
73	6,210	4,970	5,260	5,770
100	920	1,110	5,940	5,230
50% Slag				
40	1,390	4,280	5,340	5,220
73	1,040	1,360	7,030	7,760
100	1,370	1,130	5,980	7,130
7% Silica Fume				
40	2,600	6,920	5,010	6,270
73	1,020	1,090	6,130	7,220
100	1,010	580	4,760	6,740

1 psi = 6.895 kPa, $t^{o}_{C} = (t^{o}_{F} - 32)/1.8$

The results for concretes with silica fume indicated the lowest permeability of 580 coulombs when combined with Type III cement and cured at 100°F (38°C). The Q values for concretes made with either cement and cured at 73°F (23°C) were approximately 1,000 coulombs, indicating a low chloride permeability. This was also true for those containing Type II cement cured at 100°F (38°C). Significantly higher Q values were obtained for concretes containing either cement when cured at 40°F (4°C). The highest strengths for concretes containing SF were obtained when specimens were cured at 73°F (23°C) for either cement.

In general, the test results indicate that the chloride permeabilities were comparable in concretes with Type II and Type III cements, except that considerable differences were obtained for slag and silica fume concretes at 40°F (4°C). Both of these had higher Q values with Type III cement (this needs further investigation). Strengths were comparable or significantly higher for the concretes containing Type III cement.

Economic Considerations

The material costs per cubic yard of concrete for the fly ash and slag would be in the range of 85% to 90% of the cost of A4 concrete using only portland cement. The cost of silica fume concrete would be slightly higher than regular A4. The small differences in material costs are relatively unimportant since a number of other cost factors enter into consideration of the cost of a thin overlay on a bridge deck(11). Sprinkel showed that on the basis of several alternative assumptions the relative cost per square yard of a LMC overlay would be only 1.06 to 1.31 times the cost of an overlay with normal A4 concrete, even though the material and special equipment costs were five times greater. The cost factors of the combinations of materials used in this study are much more favorable; thus costs are likely to be lower.

However, the degree to which they are cost effective will depend on the relative placement costs and performance over an extended time. This can only be determined by experimental installations.

SUMMARY OF RESULTS AND CONCLUSIONS

1. Concretes with different w/c and different supplemental cementitious materials varied in their resistance to chloride permeability (using AASHTO Test Method T 277). For each combination of materials, a reduction in the Q value occurred as the w/c was decreased. Concretes with pozzolans, slag, or latex had lower Q values than the controls. Q values decreased as the age of the specimens increased from 28 to 90 days. The 365-day results were inconclusive as to whether changes in permeabilities occurred after 90 days.

2. Concretes with fly ash and slag had lower early strengths but generally higher ultimate strengths than the controls. For concretes containing silica fume, strengths were about the same or slightly higher at all ages. In all cases, a lower w/c resulted in higher strengths for concretes containing the same proportion of solid ingredients.

3. Strengths of all the concretes at 90 days were in excess of 5,000 psi (34.5 MPa) and thus are satisfactory. In some concretes, early strengths were low. For the same type and amount of supplemental cementitious material, strength increased as Q values decreased. However, when concretes with different composition are considered, there is no specific relationship between strength and the results of the rapid test for chloride permeability (AASHTO T 277). Concretes with essentially equal strength but containing different supplemental cementitious material had significantly different Q values. For example, the test results indicated that concretes with pozzolans or slag having strengths similar to the controls generally had lower Q values.

4. Results of the 90-day ponding test on concretes with w/c of 0.40 and containing different supplemental cementitious materials indicate differences in the chloride content at a depth of 1/4 to 3/4 in (6 to 19 mm). Concretes with pozzolans, slag, or latex had less chloride intrusion than the controls, but all the values were above the threshold value of 1.32 lb/yd^3 (0.78 kg/m^3) except for one batch of silica fume concrete. At the deeper depth of 3/4 to 1 1/4 in (19 to 32 mm), the chloride intrusion for all the concretes was very low. The highest value was in a control concrete that had an average chloride content of 0.38 lb/yd^3 (0.22 kg/m^3). It appears likely that all the low w/c concretes in this study (0.40 or less) would have significant resistance to chloride ion penetration under actual service conditions. However, these values do not provide a measure of the length of service that may be expected from them.

5. When control, slag, and silica-fume concretes with Type II and Type III cements were cured at 73°F (23°C) and 100°F (38°C), there was little difference in the chloride permeabilities for the same concrete at each temperature. For concretes cured at 40°F (4°C), the chloride permeabilities were generally higher. However, fly ash concretes made

with either cement showed a very significant reduction in Q values as the curing temperature increased. When the fly ash concrete was cured at 40°F (4°C) or 73°F (23°C), chloride permeabilities were in the high range, but when they were cured at 100°F (38°C), they were in or very close to the very low range. In general, the strengths of all concretes were highest when cured at 73°F (23°C). Concretes with Type III cement had strengths comparable to or significantly higher than those with Type II cement.

RECOMMENDATIONS

It is recommended that experimental field installations of thin overlays using concrete containing silica fume be made and its performance monitored to establish evidence of increased durability and cost effectiveness. Follow-up laboratory research should also be conducted to determine if combinations of silica fume and fly ash or silica fume and slag used with either Type II or Type III cement will provide optimum concrete characteristics with respect to both strength and resistance to chloride ion penetration.

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APPENDIX A

BEHAVIOR OF CONCRETES CONTAINING FLY ASH, SILICA FUME, OR SLAG
-- LITERATURE REVIEW --

It has been stated that "given any combination of cement and aggregate, it is generally observed that the less permeable the concrete, the greater will be its resistance to aggresive solutions and pure water" (1)*. Accordingly, the ability of a pozzolanic admixture or slag to improve the resistance of concrete to sulfate and chloride attack depends to a considerable extent on its ability to reduce the permeability of concrete or, more correctly, to increase its resistance to penetration by the chloride ion. Increased strength is also generally expected in materials exhibiting lower permeability, but there is evidence that different relationships exist between strength and chloride ion permeability for different materials.

The following sections summarize the general concepts derived from published literature for the supplemental materials used in this study -- class F fly ash, slag, and silica fume.

Fly Ash (Class F)

The fly ash used in this study was from a bituminous coal and is classified by ASTM and AASHTO specifications as class F. It is a pozzolan by definition and has no self-hardening properties. The summary presented does not necessarily apply to class C fly ashes.

Increased strengths at later ages of fly ash concrete compared to similar concrete without fly ash have been demonstrated by numerous studies. Such increases are generally attributed to pozzolanic reactions occurring between the calcium hydroxide released in the initial hydration of the cement constituents and the fly ash. These are said to reduce permeability and thereby increase the resistance to chloride or other ion penetration by filling or partially filling the pores of the concrete. The summary by Berry and Malhotra reviewed data developed by Davis in 1954 for concrete pipe (1). These show that at 28 days the relative permeability of concretes with 30% of the cement replaced with each of two fly ashes were 2.2 and 3.2, respectively, compared to the control concretes at the same age. At 6 months the situation was reversed. Although the permeability of the control concrete had decreased to a relative value of 0.26 compared to the 28-day value, both fly ash concretes had relative values of 0.05 (the control concrete at 28 days equals 1). Similar trends were reported with concretes in which 60% of the cement was replaced with fly ash, except the relative values at 28 days were considerably higher being (14.1 and 18.8, respectively, for the two fly ashes). The 6-month relative values were 0.02 and 0.07. These tests were made on 6 x 6

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* Numbers refer to references listed at the end of the Appendix.

in cylinders at ratios of water to cement and fly ash from 0.65 to 0.75, but the manner of determining the permeability was not provided. Berry and Malhotra also summarized the work of Kanitakis, who used an "initial absorption test" to compare concretes with and without a low-calcium fly ash. Tests at 7, 17, 28, and 56 days showed significant decreases with time in the initial surface absorption with accompanying increases in compressive strength. In these test concretes, 50 kg of cement per cubic yard were replaced with 100 kg of fly ash with some change in fine and coarse aggregate per cubic yard. Kanitakis concluded from this work that at early ages fly ash concrete behaves as a lean-mix concrete and is thus permeable. At later ages, permeability is reduced as the pozzolanic action proceeds. Other work discussed is consistent with the view that a transformation of large pores to fine pores occurs as a consequence of the pozzolanic reaction between portland cement paste and fly ash, thus substantially reducing permeability in the cementitious systems.

Blast Furnace Slag

Ground granulated iron blast-furnace slag (generaly referred to simply as slag in this report) is a cementitious material that does not depend on the pozzolanic reaction for strength development. It has been used as a major ingredient of blended cements for a number of years, and such cements generally have performed well in concretes for a number of purposes. More recently, the use of slag as a separate ingredient at the concrete mixer has been promoted. This approach provides greater flexibility in the proportioning of concrete mixtures, and it is claimed that use of the slag as a partial replacement (40% to 60%) can improve the quality of the concrete without increasing the cost.

A Virginia Transportation Research Council (VTRC) study showed that concretes in which up to 65% of the cement was replaced by slag were generally satisfactory (2). The slag used in the present study is from the same source as that identified in the cited report as S1. Initial and final setting times of slag concretes in this study were one to two hours longer than the control concretes without slag. Seven-day strengths of slag concrete were about 80% of the strength of the equivalent control, but equal or higher strengths were usually obtained at 28 days or longer. There were some small discrepancies with the lower activity slag and high rates of replacement. All freeze-thaw durability factors were satisfactory. On the basis of this study, it was recommended that the activity index of the slag used be 100 or greater and that the maximum replacement by weight of the portland cement be 50%.

The low permeability of slag concretes to chloride ions as measured by the electrical conductance test was also demonstrated in the VTRC report(2). The reduction in Q for specimens with 50% replacement and a w/c of 0.48 ranged from 38% to 48% and was 33% for the only combination tested at 65% replacement.

Unpublished results of rapid chloride permeability tests conducted at the Federal Highway Administration research facility showed that at a given w/c and sample age, Q decreased with increasing percentages of slag replacement for cement. It was also shown that at a given w/c ratio and slag replacement, Q values decreased significantly with sample age for all the samples. The Q values after one year generally were on the order of one-third of the initial value measured at 16 days. All specimens containing slag had Q values of less than 2,160 at one year, thus indicating a low permeability to chloride ions.

In other FHWA tests made for the Georgia DOT at a w/c of 0.49, the average Q values decreased from 8,856 to 2,261 as slag replacement increased from 0% to 70%. At a w/c of 0.41, Q decreased from 5,083 to 1,471, that is from a high to a low chloride ion permeability. For equal slag percentages, Q values decreased by 15% to 43% as w/c decreased from 0.49 to 0.41.

When a Type I cement replaced Type III cement in the specimens at the 50% replacement rate, a 22% reduction in Q values was attained. Similarly, reducing the w/c from 0.41 to 0.38 in a 50/50 mixture resulted in a 21% reduction in the Q values.

It was also noted that specimens moist cured for 7 days under standard conditions gave considerably lower Q values than did specimens using similar slags cured at elevated temperatures to simulate 2-day steam curing.

Silica Fume

Silica fume is a by-product of the manufacture of silicon and ferrosilicon alloys. It constitutes the particles condensed from the gases emitted from the furnaces used in the manufacturing process. This product is also referred to as condensed silica fume or microsilica. The particles are very fine spheres with a surface area of the order of 20,000 m^2/kg. Most particles are smaller than 1μ -- about 1/100 of that of a cement particle. Chemically, the product is mostly amorphous silicon dioxide (SiO_2) and thus is a pozzolan that because of its extreme fineness, reacts relatively rapidly with calcium hydroxide (lime) in solution.

The SiO_2 content of such by-products vary considerably (65% to 98%), depending on the metal being manufactured. Generally, materials suitable for use in concrete will have SiO_2 content greater than 85%.

Some initial investigations of the effects of silica fume in concrete were conducted in the 1950s and 1960s, and because of the increased volume of the product being collected, studies were accelerated in the 1970s. Much of this early work occurred in Europe, with Norway taking the major role. Interest in North America was triggered by publications by Malhotra and Carette (4) and the first international symposium on the use of fly ash, silica fume, slag, and other mineral byproducts in concrete held in Montebello, Canada in August 1983. The proceedings of this symposium are published as SP79 by the American Concrete Institute.

Volume II of this publication contains a number of papers concerning the properties of concretes containing silica fume (3,5,6,7,8). Collectively these papers provide a good account of the role of silica fume in concrete.

Research at the Virginia Transportation Research Council as well as other sources has shown that significant decreases in concrete permeability with accompanying increases in strength are attained by the use of silica fume (3,4). It is also shown that some negative effects may be encountered that could eliminate potential advantages from use of silica fume if proper precautions are not taken (4). Because of its extreme fineness, increased plastic shrinkage can occur as well as long-term shrinkage. Silica fume should not be used without a water reducer, preferably of the type classed as high range. When silica fume is used, good concreting and quality control practices must be followed. Proper curing is extremely important. Jahren states that the single most important factor that ensures good quality concrete with silica fume is a low w/c. He recommends that the w/c should never be greater than 0.5 (5).

Sellevold and Radjy showed that the water demand increases with microsilica content when no water reducing agent is used (6). However, this deficiency can be overcome by the use of water reducers. They also state that at 20°C the main pozzolanic contribution of silica fume to strength occurs between 3 and 28 days. The shape of the curve for the 28-day strength versus the w/c for a fixed microsilica content is the same as that for the reference concrete, but it shifts to a higher level. These authors also state that microsilica is both a highly reactive pozzolan and a very efficient filler. The microsilica reduces both the amount and continuity of capillary pores in cement pastes much beyond that which results from using inert fillers. This ability to alter the pore structure of the cement paste is believed to be the reason microsilica has such a profound effect on the properties of hardened concrete.

Work reported by Gjorv illustrates the effectiveness of silica fume in reducing the permeability of concrete, especially with low cement content (6). With higher cement content, the normal increase in density from the additional cement lessens the effect of the silica fume. Measurements with a mercury porosimeter show that even small additions of silica fume affect the pore-size distribution. The amount of capillary voids is substantially reduced whereas the amount of smaller voids (below 400°A) is increased. To eliminate or significantly reduce damage from reactive aggregates, Iceland makes use of concretes to which silica fume amounting to 7.5% of the weight of cement has been added.

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APPENDIX B

TESTS CONDUCTED AND MIXTURE PROPORTIONS

TABLE B-1

Material Combinations and Batch Parameters

Identification	Cementitious Material[a]	Percent Cement Replaced	Water-Cementitious Ratio[b] 0.45	0.40	0.35
C2 (Control)	C2	0	x	x	x
C1 (Control)	C1	0	x	x	x
C2F-15	F + C2	15[c]	x	x	x
C1F-15	F + C1	15[c]		x	
C2F-25	F + C2	25[c]	x	x	x
C1F-25	F + C1	25[c]		x	
C2S-50	S + C2	50	x	x	x
C1S-50	S + C1	50		x	
C2SF-7	SF + C2	7	x	x	x
C1SF-7	SF + C1	7		x	
C2L	L + C2			x[d]	
C1L	L + C1			x[d]	

[a] C2 - Type II cement -- alkalies, 0.50%
C1 - Type I cement -- alkalies, 0.78%
F - Class F fly ash with good performance record
S - Ground iron blast furnace slag with good performance record
SF - Silica fume
L - Styrene butadiene latex emulsion

[b] ratio of water to cement plus supplemental cementitious ingredient w/c.

[c] The mass of fly ash added was 1.2 times the mass of cement replaced.

[d] Water-cement ratio = 0.37.

TABLE B-2

Mixture Proportions for Cubic Yard of Concrete

Identification	W/C	Cement (lb)	Mineral Admixture (lb)	F.A.(lb)	C.A.(lb)
C2	0.35	658	--	1,540	1,505
C2	0.40	658	--	1,455	1,505
C2	0.45	658	--	1,371	1,505
C2F-15	0.35	559	119	1,484	1,505
C2F-15	0.40	559	119	1,398	1,505
C2F-15	0.45	559	119	1,314	1,505
C2F-25	0.35	494	197	1,446	1,505
C2F-25	0.40	494	197	1,361	1,505
C2F-25	0.45	494	197	1,277	1,505
C2S-50	0.35	329	329	1,521	1,505
C2S-50	0.40	329	329	1,435	1,505
C2S-50	0.45	329	329	1,351	1,505
C2SF-7	0.35	612	46	1,527	1,505
C2SF-7	0.40	612	46	1,442	1,505
C2SF-7	0.45	612	46	1,358	1,505
C2L	0.37	658	a	1,572	1,234
C1	0.35	658	--	1,540	1,505
C1	0.40	658	--	1,455	1,505
C1	0.45	658	--	1,371	1,505
C1F-15	0.40	559	119	1,398	1,505
C1F-25	0.40	494	197	1,361	1,505
C1S-50	0.40	329	329	1,435	1,505
C1SF-7	0.40	612	46	1,442	1,505
C1L	0.37	658	a	1,572	1,234

1 lb = 454 g.

[a] Styrene butadiene latex emulsion - 206 lb (98 lb solids, 108 lb water).

TABLE B-3

Characteristics of Freshly Mixed Concrete

Identification	w/c	Slump, in	Air, %	Unit Weight, lb/ft^3
C2	0.35	2.3	5.1	147.6
	0.40	5.4	8.0	139.6
	0.45	1.4	5.9	144.4
C2F-15	0.35	3.8	8.0	139.6
	0.40	3.3	6.2	140.8
	0.45	3.4	6.0	140.8
C2F-25	0.35	6.7	5.0	145.6
	0.40	3.7	5.8	142.8
	0.45	3.6	6.8	139.6
C2S-50	0.35	3.8	6.0	144.4
	0.40	2.5	5.5	144.0
	0.45	1.8	6.6	140.8
C2SF-7	0.35	4.3	7.5	141.6
	0.40	3.3	7.5	140.4
	0.45	2.7	8.8	137.1
C2-L	0.37	6.3	3.5	143.6
C1	0.35	2.0	5.7	146.0
	0.40	2.3	5.4	145.2
	0.45	1.7	6.4	142.4
C1F-15	0.40	3.2	7.5	140.4
C1F-25	0.40	2.7	5.4	143.6
C1S-50	0.40	2.3	5.3	144.4
C1SF-7	0.40	2.5	8.0	140.4
C1-L	0.37	4.6	3.6	144.0

1 in = 25.4 mm, 1 lb/ft^3 = 16.02 kg/m^3.

TABLE B-4

Chemical and Physical Analyses of Cements

Chemical, %	Type II (C2)	Type I (C1)	Type III
SiO_2	21.2	20.6	20.3
Al_2O_3	3.7	5.7	5.5
Fe_2O_3	2.0	2.2	2.2
CaO	62.9	63.3	62.7
MgO	3.5	3.5	3.5
SO_3	3.0	2.9	3.7
Total alkalies, as Na_2O	0.50	0.78	0.71
C_3S	58.6	51	51
C_3A	6.5	11	11
Physical			
Fineness (Blaine)	3,677	3,725	5,285

TABLE B-5

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	87.2
Al_2O_3	30.4	10.8	0.3
Fe_2O_3	3.2	0.7	2.3
CaO	0.7	42.7	1.2
MgO	N.D.[(a)]	8.9	0.8
SO_3	0.2	1.2	0.3
Total alkalies	0.82	0.32	0.56
Loss on ignition	2.16	1.89	3.80
Physical			
Fineness			
% ret on No. 325 sieve	14.2	1.1	N.D.
Surface area, air permeability, cm^2/g	N.D.	5,250	N.D.

[a] N.D. = Not determined

TABLE B-6

Aggregate Characteristics

Coarse Aggregate -- crushed granite gneiss	
Maximum size	1/2 in
Specific gravity	2.78
Unit weight	103.3 lb/ft^3
Fine Aggregate -- siliceous sand	
Fineness modulus	2.90
Specific gravity	2.59

1 in = 25.4 mm, 1 lb/ft^3 = 16.02 kg/m^3.