Resistance to Chloride Ion Penetration of Concretes Containing Fly Ash, Silica Fume, or Slag

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Synopsis: 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 proportions 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 chloride 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.

Keywords: blast furnace slag; chlorides; compressive strength; concretes; fly ash; permeability; pozzolans; silica fume

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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 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.

The study summarized in this paper was conducted to assess the potential usefulness of several supplemental cementitious materials for increasing the resistance of hydraulic-cement concretes to penetration of chloride ions. 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 latex-modified concrete was included in the study for comparison.

The amounts of each supplemental cementitious material used were 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. Also, specimens were prepared from control concretes and 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). The material combinations, mixture proportions, and characteristics of the materials are given in the Appendix.

TESTS CONDUCTED AND MIXTURE PROPORTIONS

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 at 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 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 in service 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 contents determined using AASHTO T 260.

Compressive strength was determined at 1, 7, 28, 90, and 365 days. Specimens were prepared and tested in accordance with AASHTO 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

The slump, air content, and unit weight of the freshly mixed concretes are summarized in Table A-3 of the Appendix. 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.

The results of the tests made on the hardened concretes 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

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 permeability zone 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 the 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.

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. The 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.

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 developer 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 2 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 are summarized in the following sections.

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 vs 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 materials, 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 the Appendix 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.

Results at 28 days, summarized in Table 5, 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. 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 the chloride permeability as indicated by the rapid permeability test. 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 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, 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 larger Q values when cured at 40°F(4°C). Strength values for concretes containing slag were higher for the concretes cured at 73°F(23°C) and 100°F(38°C) (those with Type III cement exhibited higher values) and lower for those cured at 40°F(4°C).

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 which 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.

SUMMARY OF RESULTS AND CONCLUSIONS

1. Concretes with different w/c and prepared with 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 in coulombs 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 material 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.

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APPENDIX A — TESTS CONDUCTED AND MIXTURE PROPORTIONS

TABLE A-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 - Latex

[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 A-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	206	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] Latex modifier - 206 lb (98 lb solids, 108 lb water).

TABLE A-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 A-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 A-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 A-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

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

TABLE 1--RESULTS OF CHLORIDE PERMEABILITY TESTS AT VARIOUS AGES AND DIFFERENT WATER/CEMENT RATIOS

ID[a]	w/c = 0.35[b]			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[c]	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[d]	3,730	8,080	5,810	4,800
C1F-15	--	--	--	3,330	2,010	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[e]	--	--	--	3,000	1,370[f]	352	--	--	--
C1L	--	--	--	2,290	1,410	439	--	--	--

(a) See Table A-1 for Code

(b) Water to cementitious material ratio

(c) Q = Coulombs, current passed through specimens in 6 h

(d) value at 76 days

(e) 0.37 w/c

(f) value at 104 days

TABLE 2--RELATION OF CHLORIDE CONTENT TO RESULTS OF RAPID PERMEABILITY TEST CHLORIDE CONTENT, LB/YD3 (a)

Identification	1/4"-3/4" Depth 1	1/4"-3/4" Depth 2	1/4"-3/4" Depth Avg.	3/4"- 1 1/4" Depth 1	3/4"- 1 1/4" Depth 2	3/4"- 1 1/4" Depth Avg.	Avg.(b) Total	Q, Coulombs 28 Day	Q, Coulombs 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.

TABLE 3--STRENGTHS OF CONCRETES PREPARED WITH VARIOUS SUPPLEMENTAL CEMENTITIOUS MATERIAL

		Compressive Strengths, psi at:				
ID[a]	w/c[b]	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.

(a) See Table A-1 for Code

(b) Water to cement + admixture ratio by mass

(c) C2 are type II cement concretes, C1 are type I.

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

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

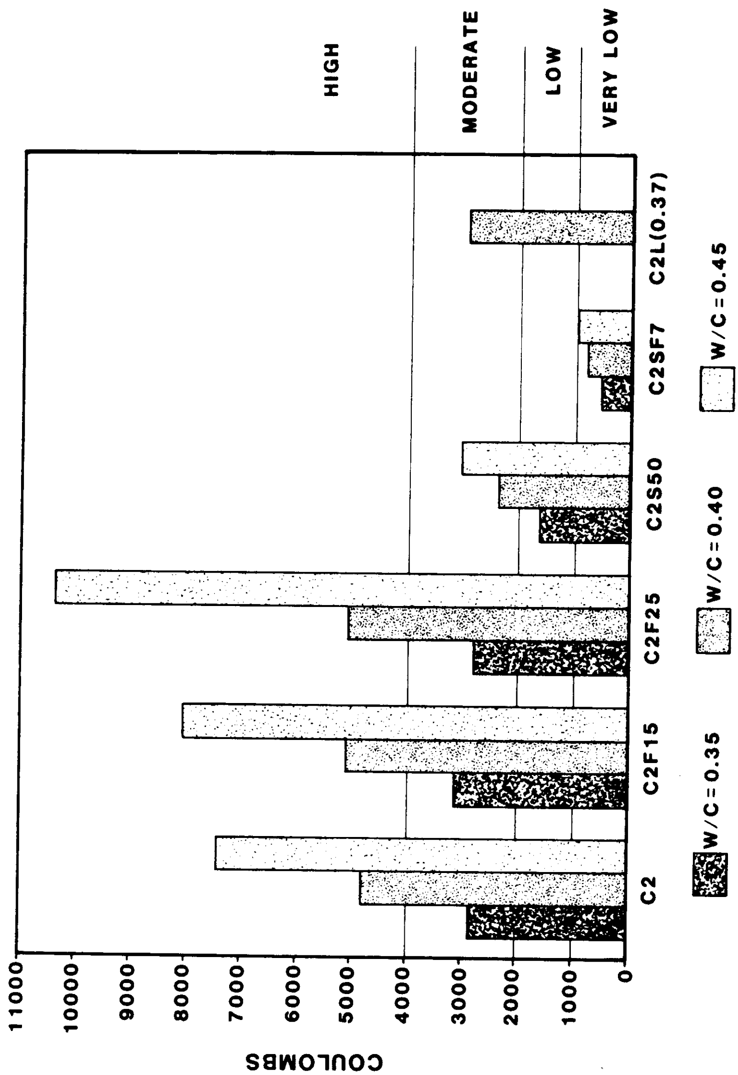

Fig. 1--Results of 28-day chloride permeability test

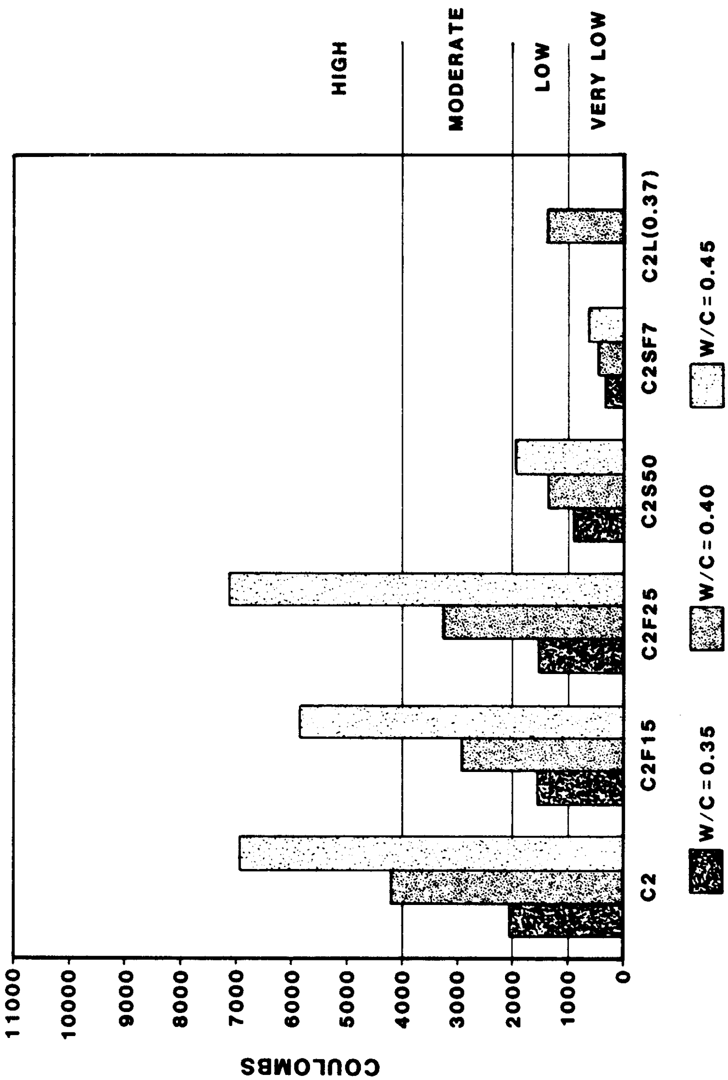

Fig. 2--Results of 90-day chloride permeability test

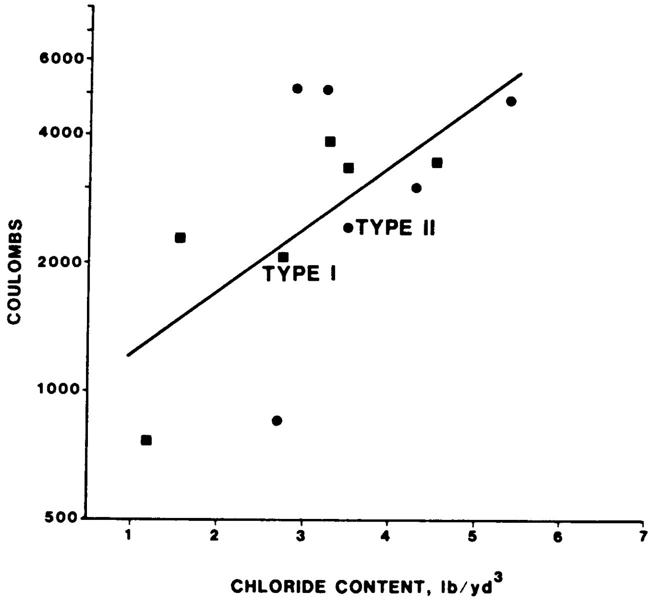

Fig. 3--Relation of Q at 28 days to total chloride absorbed (¼ to 1¼ in.) after 90 days (1 lb/yd^3 = 0.59 kg/m^3, 1 in. = 25.4 mm)

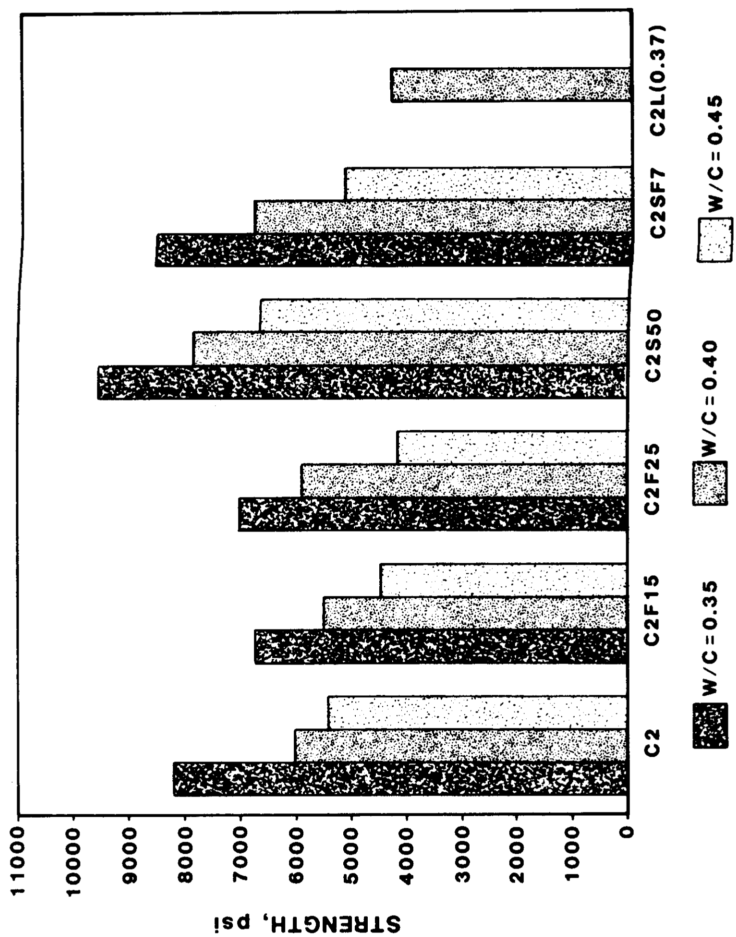

Fig. 4--28-day strengths (1 psi = 6.895 kPa)

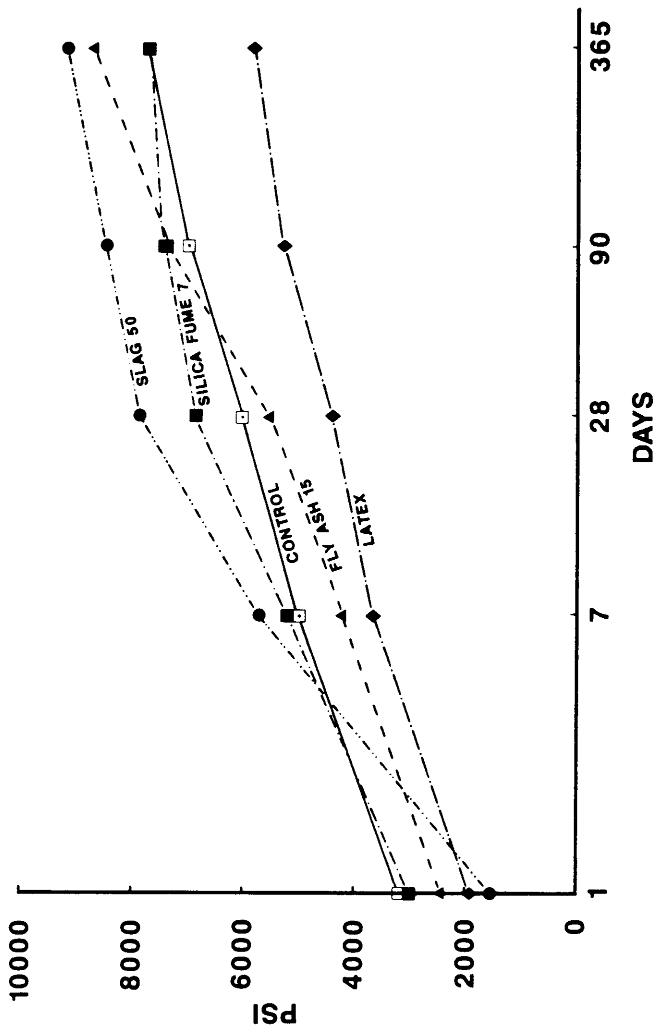

Fig. 5--Compressive strength versus age for concretes with Type II cement at 0.40 w/c (1 psi = 6.895 kPa)