Aspects of Concrete Strength and Durability

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Research is under way to study the strength and durability of concrete in Florida. Results of the first phase of this research are presented. Twenty-two concrete mixtures were prepared and tested for compressive strength, water permeability, chloride permeability (AASHTO T277), and corrosion resistance. Four groups of concrete mixtures that covered a wide range of materials and mixture proportions were included. Water/cementitious ratios used were 0.45, 0.38, and 0.33, corresponding to cementitious contents of 564, 658, and 752 lbs/yd^3, respectively. Different combinations of fly ash and silica fume were used. Fly ash content ranged between 10 and 50 percent by weight of the total cementitious material. Silica fume was included in proportions between 5 and 15 percent. Effects of fly ash and silica fume on strength and permeability of concrete and on corrosion of steel in concrete are discussed. Correlation is established between results of the Florida water permeability test and results of the AASHTO T277 chloride permeability test. It is also shown that concrete mixtures with equal compressive strengths do not necessarily produce equal levels of permeability, especially when fly ash and silica fume are included in the mixture. This lack of correlation continues until the strength reaches about 8,000 psi. At and beyond 8,000 psi, a well-defined trend is observed. With increased concrete strength, the permeability becomes consistently low to very low according to both AASHTO T277 and water permeability classifications. Findings from this phase of the research affirm the need to develop specifications for concrete durability based on requirements for both compressive strength and permeability of concrete.

Quality and performance of concrete have traditionally been assessed by its compressive strength. However, in marine structures, problems associated with poor durability, such as corrosion of the reinforcement, are by far more prevalent than problems related to strength. Thus when structures in aggressive environments (such as sea water) are considered, emphasis is placed not only on achieving a concrete with optimum strength but also, and more important, on ensuring a highly durable concrete. In these situations testing for and evaluating concrete durability become equally, if not more, important as testing for strength. Durability is better evaluated from permeability and strength tests than from a strength test alone. Resistance to freezing and thawing is another indication of durability. However a freeze-thaw test of concrete was not considered in this study because Florida is not concerned with freezing temperatures.

In most specifications, permeability has not been established as a requirement for concrete durability. Material specifications address the durability aspect by requiring a low water/cement ratio (w/c) and the use of pozzolanic materials and admixtures. Low w/c and the use of such pozzolanic materials as fly ash, blast-furnace slag, and silica fume are design parameters that can contribute to improved strength and long-term performance of concrete.

It is generally assumed that achieving a specified target strength in concrete would also imply a given level of durability. The problem is how to accurately evaluate and ensure an acceptable level of durability in a given mixture when its compressive strength has met the specified strength requirement. Durability is greatly influenced by concrete permeability. Many mixtures, designed with widely different materials and mixture proportions, can produce concretes with equal strength but different permeability levels. Concrete that meets only the strength requirement may fail to develop the expected durability if the permeability is high. Against this background, the Florida Department of Transportation (FDOT) has embarked on a major research effort to study strength and durability of concrete. The overall objective of this research is to develop an advanced understanding of the relationship between concrete durability and strength. The goal is to develop specifications for testing and classifying durability of concrete using test data related to aggressiveness of the environments.

Findings from the first phase of this extensive research program are presented in this paper. Work discussed here was limited to one source of Florida limestone aggregate. Different proportions of cement, fly ash, and silica fume were used in the concrete mixtures. Results of the compressive strength, permeability, and corrosion tests are correlated to assess the durability of different concrete mixtures. A water permeability classification for concrete is developed based on correlation between results of the water permeability test, developed in Florida (*1*), and of the rapid chloride permeability test (AASHTO T277).

EXPERIMENTAL PROGRAM

Materials

Type II cement was used throughout this phase of the investigation. The chemical and physical properties of the cement are shown in Tables 1 and 2, respectively. Class F fly ash and silica fume in slurry form were used primarily as partial replacements for the cement. However, in two mixtures, silica fume and fly ash were added to the cement content. The chemical composition and physical properties of fly ash are presented in Tables 1 and 2.

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TABLE 1 CHEMICAL COMPOSITION

Constituent Percent	Type II Cement	Class F Fly Ash
Calcium Oxide (CaO)	63.23	4.71
Silicon Dioxide (SiO_2)	20.21	
Aluminum Oxide (Al_2O_3)	5.53	86.53
Ferric Oxide (Fe_2O_3)	4.32	
Magnesium Oxide (MgO)	0.62	
Sulfur Trioxide (SO_3)	2.67	1.24
Loss on Ignition	1.69	2.88
Insoluble Residue	0.33	
Alkalis (Na_2O + $0.658K_2O$)	0.48	
Tricalcium Silicate (C_3S)	52.84	
Dicalcium Silicate (C_2S)	18.07	
Tricalcium Aluminate (C_3A)	7.34	
Tetracalcium Aluminoferrite (C_4AF)	13.16	

TABLE 2 PHYSICAL TESTS RESULTS

Test	Type II Cement	Fly Ash
Fineness -		
Blaine, m^2/kg	383	
Retained on Mesh 325, %		23.63
Soundness	0.02	0.01
Pozzolanic Activity Index @ 28 Days		84.90
Specific Gravity	3.15	2.47
Gillmore Setting Time -		
Initial Set, Minutes	120	
Final Set, Minutes	245	
Compressive Strength, psi -		
1 Day	2038	
3 Day	3188	
7 Day	4319	

1 psi = 0.0069 MPa

The coarse aggregate was crushed limestone, and the fine aggregate was silica sand. Both aggregates were obtained from sources in Florida. Table 3 presents the physical properties and gradation of the aggregates.

Mixture Proportions

Table 4 presents the concrete ingredients for the 22 mixtures batched during this study. Four primary groups are included.

TABLE 3 PROPERTIES AND GRADATION OF AGGREGATE

Property	Coarse Aggregate	Fine Aggregate
Specific Gravity, Dry	2.32	2.61
Specific Gravity, SSD	2.45	2.63
Absorption, %	5.3	0.7
Unit Weight lb/cu.ft	88	----
Fineness Modulus	7.13	2.43

Gradation	Sieve	% Passing	Sieve	% Passing
	1 in	100	3/8 in.	100
	3/4 in	96	#4	99
	1/2 in	62	#8	98
	3/8 in	23	#16	85
	#4	3	#30	54
	#8	3	#50	19
			#100	2

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

Mixtures in Group A were basically designed with water cementitious ratio (w/ct) of 0.45, and cementitious content of 564 lb/yd^3. The fly ash content in this group was between 10 and 30 percent by weight of the cementitious material. Group B mixtures had w/ct of 0.38, and a cementitious content of 658 lb/yd^3. The fly ash content was similar in percentages to those in Group A. Group C included 6 mixtures. Each mixture was designed with 0.33 w/ct and contained 752 lbs/yd^3 of the cementitious material. In this group, the percent fly ash in the cementitious material ranged between 10 and 50.

In Group D mixtures, the cementitious material included both silica fume and fly ash. The silica fume was in slurry and, according to the supplier, contained an unspecified ASTM Type G high-range water-reducer (HRWR). The basic design for mixtures D1 through D6 was similar to the control mixture (C1) with respect to w/ct and the total weight of the cementitious material. The difference was the use of silica fume as part of the cementitious content. Mixtures D1, D2, and D3 used silica fume, respectively, at 5, 10, and 15 percents by weight of the total cementitious material. Mixtures D4 to D6 included 20 percent fly ash with 5, 10, and 15 percent silica fume.

The last two mixtures in this group were different from the rest. In mixtures D7 and D8, the fly ash and silica fume were additions to the cement content. This increased the total weight of the cementitious materials in a cubic yard of concrete from 752 lb to 826 lb for D7, and to 977 lb for D8. The water content was held constant at 248 lb/yd^3, similar to the water content in Group C and mixtures D1 through D6. However, because fly ash and silica fume were in addition to the cement the w/ct was reduced to 0.30 for D7 and 0.25 for D8.

It should be noted that the weight of the coarse aggregate was kept constant at 1,682 lb/yd^3 for all mixtures in this study, allowing fluctuation to occur in weight of the fine aggregate only. Also, the coarse aggregate stockpile was kept in "wet" condition up to the time of batching, using a sprinkler system operating intermittently. This was in accordance with the standard operating procedure of FDOT to account for the high absorption of the coarse aggregate (see Table 3). Adjustment to the batch weights were subsequently made based on the moisture content of the wet aggregate.

Chemical admixtures were used in all mixtures. Water reducing and retarding admixture, meeting ASTM requirements (ASTM C494) as Type D, was used in every mixture at a constant rate of 7.5 fl oz/100 lb of cement. HRWR, classified as ASTM C494 Type F, was used in some mixtures to supplement the Type D in achieving the target slump of 2 to 4 in. Rates of HRWR were between 1 and 5 fl oz/100 lb of cement. It should be noted that no air-entraining admixture was used in any of the mixtures. The size of each concrete batch was 14 ft^3. The materials were batched and mixed in a 24 ft^3 size pan mixer.

Properties of Plastic Concrete

Tests performed on plastic concrete included slump, air content (volumetric method), and unit weight. Two operators performed these test simultaneously, each using a different set of equipment for each test. Averages of the two test results for each property are presented in Table 4. A slight increase

TABLE 4 MIXTURE PROPORTIONS PER ONE CUBIC YARD OF CONCRETE

Mix name	Water To Cementitious ratio (W/CT)	Cementitious Material (lb) Cement	Fly Ash	Silica Fume	Aggregate Fine (lb)	Mix Water (lb)	Plastic properties Slump (in)	Air (%)	Unit Wt. lb/ft³
A1	0.45	564 (100)	--	--	1398	254	2.1	3.7	141.7
A2		508 (90)	56 (10)	--	1387		3.4	3.0	141.8
A3		451 (80)	113 (20)	--	1375		3.3	2.2	142.1
A4		395 (70)	169 (30)	--	1362		3.8	2.9	142.5
B1	0.38	658 (100)	--	--	1329	250	2.3	3.0	142.7
B2		592 (90)	66 (10)	--	1316		2.6	3.1	143.2
B3		526 (80)	132 (20)	--	1300		2.6	3.0	141.7
B4		461 (70)	197 (30)	--	1287		4.5	2.8	140.8
C1	0.33	752 (100)	--	--	1257	248	4.0	3.2	141.4
C2		677 (90)	75 (10)	--	1242		2.4	2.4	143.7
C3		602 (80)	150 (20)	--	1226		3.6	2.1	143.1
C4		526 (70)	226 (30)	--	1208		2.5	2.1	144.7
C5		451 (60)	301 (40)	--	1193		1.9	2.0	142.7
C6		376 (50)	376 (50)	--	1177		2.5	2.1	142.6
D1	0.33	714 (95)	--	38 (5)	1246	248	2.5	2.7	143.6
D2		677 (90)	--	75 (10)	1232		3.5	2.2	144.5
D3		639 (85)	--	113 (15)	1221		7.5	1.8	145.2
D4		564 (75)	150 (20)	38 (5)	1213		3.4	2.2	143.4
D5		527 (70)	150 (20)	75 (10)	1200		3.6	2.2	144.7
D6		489 (65)	150 (20)	113 (15)	1188		4.0	2.2	144.1
D7	0.30	752	--	75	1170	248	3.3	1.9	144.7
D8	0.25	752	150	75	1013	248	3.3	2.3	144.6

Note: Number in parentheses is percent ratio of total cementitious material

can be observed in unit weights of Group D mixtures. This increase is probably a result of concrete densification caused by silica fume in the mixture.

Specimen Preparation and Curing

Three 6- × 12-in. concrete cylinders were prepared for each compression test. Two 4- × 8-in. cylinders were cast for each water permeability test, one of which was also used in the rapid chloride permeability test. Three 4- × 5¾-in. cylinders were prepared for each corrosion test. Each cylinder had a ½-in.-diameter reinforcing bar embedded along its central axis.

The molds were filled with two layers of concrete; each layer was consolidated using a vibrating table. Vibrating time was approximately 45 sec. After 24 hr, the molds were removed, and the specimens were placed in lime-saturated water for curing. Water curing continued until the time of testing.

TESTS AND RESULTS

Compressive Strength

Testing for compressive strength was performed according to ASTM C39. Three concrete cylinders were tested at ages 3, 7, 28, and 91 days. Neoprene pads in steel controllers were used for capping ends of the tested specimen. Compressive strength at each age was determined by averaging strength results from the three tested specimens. Test results of the compressive strengths for concrete at ages 3, 7, 28, and 91 days are presented in Table 5. Each compressive strength at 3, 7, and 91 days was also presented as a percent ratio of the 28-day strength of the same mixture. The overall average strength gains, with respect to the 28-day strength, for all mixtures at 3, 7, and 91 days were 71, 84, and 111 percent, respectively.

In Table 6 each strength value is presented as a percent ratio of the 28-day strength of Mixture C1. This manipulation

TABLE 5 COMPRESSIVE STRENGTH OF CONCRETE

Mix Name	Compressive Strength (psi) Age - Days: 3	7	28	91
A1	4380 (75)	5210 (89)	5860	6210 (106)
A2	4010 (73)	4540 (82)	5520	6240 (113)
A3	3590 (67)	4360 (81)	5370	6340 (118)
A4	3300 (64)	4290 (83)	5170	6150 (119)
B1	4350 (73)	5430 (91)	6000	6680 (112)
B2	4720 (74)	5620 (88)	6400	7070 (111)
B3	4600 (71)	5550 (85)	6500	7470 (115)
B4	4050 (70)	4770 (82)	5810	6950 (120)
C1	5350 (81)	6140 (93)	6570	7140 (109)
C2	5310 (80)	5670 (85)	6670	7410 (111)
C3	5060 (81)	5640 (90)	6250	7430 (119)
C4	4550 (72)	5360 (85)	6300	7590 (121)
C5	3830 (62)	4710 (76)	6170	6920 (112)
C6	3470 (59)	4320 (73)	5920	6700 (113)
D1	6140 (75)	7130 (87)	8180	8450 (103)
D2	6220 (73)	7580 (90)	8470	8510 (101)
D3	5600 (65)	6030 (70)	8650	9150 (106)
D4	5310 (69)	6550 (85)	7720	8100 (105)
D5	5270 (67)	6550 (83)	7870	8500 (108)
D6	4960 (62)	6740 (84)	8040	8660 (108)
D7	6850 (80)	7628 (89)	8580	8990 (105)
D8	6170 (72)	7414 (86)	8580	8880 (104)

Note: Numbers in parentheses are ratios of the 28-day strength.

1 psi = 0.0069 MPa

TABLE 6 COMPRESSIVE STRENGTH AS PERCENT OF THE 28-DAY STRENGTH OF MIXTURE C1

Mix Name	% of C1-28 Day Compressive Strength			
	3 Day	7 Day	28 Day	91 Day
A1	67	79	89	94
A2	61	69	84	95
A3	55	66	82	96
A4	50	65	79	94
B1	66	83	91	102
B2	72	86	97	108
B3	70	84	99	114
B4	62	73	88	106
C1	81	93	100	109
C2	81	86	101	113
C3	77	86	95	113
C4	69	82	96	116
C5	58	72	94	105
C6	53	66	90	102
D1	93	108	124	129
D2	95	115	129	130
D3	85	92	132	139
D4	81	100	117	123
D5	80	100	120	129
D6	76	103	122	132
D7	104	116	131	137
D8	94	113	131	135

TABLE 7 RESULTS OF WATER PERMEABILITY, RAPID CHLORIDE PERMEABILITY (AASHTO T277), AND CORROSION TESTS

Mix	28 Day		91 Day		Corrosion,
Name	K-H2O in/s (E-12)	K-Cl Coulombs	K-H2O in/s (E-12)	K-Cl Coulombs	Days To Failure
A1	8.88	6913	7.18	5712	15
A2	8.92	4971	8.69	4788	7
A3	3.64	4262	3.68	3279	11
A4	4.30	3606	3.96	1963	10
B1	6.76	5575	6.18	6943	17
B2	4.61	5524	4.77	2725	18
B3	4.83	3684	3.79	2343	25
B4	3.17	2561	2.32	1696	22
C1	4.98	5709	4.30	5999	30
C2	4.95	4860	4.21	3244	22
C3	4.24	3965	3.12	2496	35
C4	2.31	3188	2.36	971	40
C5	2.62	2458	2.35	1017	68
C6	2.30	1887	2.16	931	38
D1	1.30	1170	1.12	1238	90
D2	1.37	510	1.40	691	100
D3	1.41	668	1.13	369	120
D4	1.09	869	1.10	1053	48
D5	1.00	680	1.43	466	95
D6	1.53	319	1.22	212	120
D7	2.29	427	2.15	695	120
D8	1.02	444	1.02	446	120

Note : Test was terminated at 120 days for D3,D6,D7,& D8
K-H2O = Water permeability, K-Cl = Chloride permeability
in/s = 0.0254 m/s

of the data allows more direct comparison between strengths at various ages, within and among different groups.

Permeability

Concrete permeability was determined using two test methods. The first was the rapid chloride permeability test (AASHTO T277). This is an indirect test for permeability. It is based on chloride diffusion into a 4- × 2-in. slice of a concrete cylinder or core. A potential of 60 V is applied across the concrete specimen. The total charge (determined in coulombs) that passes through the specimen during a 6-hr period is used as the indicator of concrete permeability.

The second method was the water permeability test, which was developed at the University of Florida. The procedure for water permeability test is described elsewhere (*1*). In this test water under 100 psi pressure is forced into a 2-in.-thick specimen cut from a 4- × 8-in. cylinder or core. The amount of water flowing into the specimen is plotted against time. The average rate of flow into the specimen is obtained from the segment of the curve where flow rate is constant. Darcy's formula is then applied to determine the water permeability of concrete. Table 7 presents the permeability test results for different concrete mixtures at 28 and 91 days. The water permeability values are averages of two specimens, whereas the chloride permeability values represent single test results.

Corrosion

Resistance to corrosion was determined from Florida's Impressed Current test (*2*). The following is a summary of this test procedure. Three 4- × 5¾-in. concrete cylinders are prepared, with a 12-in.-long and ½-in.-diameter reinforcing bar embedded along the longitudinal axis at 1¾ in. from the cylinder bottom. The specimens are demolded after 24 hr, and then moist cured for 28 days. This is followed by additional 28 days of conditioning in a 5 percent NaCl solution. The test begins with the specimens partially submerged in a 5 percent NaCl solution and connected to a constant voltage rectifier. Direct current is passed from the rectifier to the specimen rebar, through the surrounding concrete and the chloride solution, into the ½-in.-diameter reinforcing bar (cathode) in the tank, and back to the rectifier. The rectifier is adjusted to maintain a 6-V direct current. The current, in milliamperes, that passes through each specimen is monitored daily. Testing continues until the specimen fails. Failure time is defined as the time when a large increase in current is measured. This is normally followed by staining and cracking of the concrete.

Average resistance to corrosion (in days) for the different concrete mixtures is presented in Table 7. The test was terminated for specimens that had not failed after 120 days to make space in the tank for new specimens.

DISCUSSION OF TEST RESULTS

Effect of Fly Ash

The rate of strength development at early ages is lower for concrete with fly ash than for similar concrete without fly ash (Table 5). Greater reduction in strength gain can be observed in mixtures with fly ash content of 40 percent (C5) and 50 percent (C6). Delay in the hydration process of fly ash at early ages is responsible for the slower growth in strength.

However, the early reduction in compressive strength is later recovered with the gradual increase in the rate of hydration of the cementitious material. At 91 days, the strength gain with respect to the 28-day strength is slightly higher for mixtures with fly ash, except for concrete with 40 and 50 percent fly ash content.

The percent difference in compressive strengths of concrete with and without fly ash can be determined from Table 6. At 3, 7, and 28 days, the strength of concrete without fly ash is greater than that of concrete with fly ash (except for Group B). For example, the difference at 3 days between C1 and C6 is 28 percent. However, this trend is reversed at 91 days. Concrete mixtures C2, C3, and C4 show strength 4 to 7 percent higher than that of C1. For mixtures C5 and C6, with 40 and 50 percent fly ash respectively, the strengths at 91 days were still 4 to 7 percent lower than the control mixture (C1). When all results of this study are considered, one can conclude that the substitution of fly ash for cement does not cause significant change in concrete strength at 28 and 91 days.

Fly ash can cause significant reduction in concrete permeability. Evidence of substantial reduction in permeability is shown in Table 7 and in Figure 1. The water permeability at 91 days was reduced by as much as 50 percent in some mixtures. As an example, with respect to Mixture C1, the reduction at 91 days in water permeability was 27 percent for Mixture C3 (with 20 percent fly ash), and 50 percent for Mixture C6 (with 50 percent fly ash).

In spite of some inconsistencies in the corrosion data, a general trend indicates good improvement in the corrosion resistance of concrete with fly ash. The most obvious improvement in corrosion resistance was observed in the fly ash concrete in Group C, as shown in Table 7. Lower w/ct and the use of higher fly ash contents contributed to lower permeability and better corrosion resistance. Results of this study show that the benefits to concrete durability from use of fly ash in concrete outweigh the slight reduction in strength.

Effect of Silica Fume

Concrete mixtures with silica fume (Group D) showed significant improvement in compressive strength, impermeability, and corrosion resistance over similar mixtures with no silica fume. The 28-day compressive strength of silica fume mixtures (D1, D2, and D3) was between 24 and 32 percent higher than that of Mixture C1 (with no silica fume), as shown in Table 6. In fact, the 3-day compressive strength of D2 (10 percent silica fume) reached 95 percent of the 28-day strength of Mixture C1. In mixtures D4, D5, and D6, 20 percent fly ash was also included in the cementitious material of the mixture. The fly ash did slow down the rate of strength development at 3 days by an average of 12 percent. However, after 7 days, the compressive strength increased by 20 percent, reaching a strength equivalent to the 28-day strength of Mixture C1. This shows that fly ash can be used with silica fume in concrete mixtures without causing significant reduction in early strength. In fact, the fly ash may actually provide advantages to silica fume concrete mixtures in terms of lower cost and lower heat of hydration.

In mixtures D7 and D8, silica fume and a combination of silica fume and fly ash were used as additions to the cement content. The 28-day strength for D7 and D8 was slightly higher than the strength of D2 and D5. However, this strength increase over mixtures with fly ash and silica fume as replacements is not considered significant enough to warrant the use of silica fume and fly ash as additions to a concrete mixture with a high cement content. Benefits from slight increase in strength may be outweighed by increase in the cost of concrete.

Improved durability is an important advantage of using silica fume in concrete. This widely acknowledged fact is clearly demonstrated by the results of permeability tests and corrosion tests of the mixtures in Group D, as shown in Table 7.

Figure 2 is a graphical representation of the water permeability test results of Group D mixtures. From Figure 2 it can be observed that silica fume decreases the 91-day concrete permeability by as much as 75 percent. This substantial reduction is almost identical in silica fume contents of 5, 10, and 15 percent.

Figure 2 and Table 7 highlight an important fact about the role of fly ash in silica fume concrete. It is clear that the use of fly ash in the mixture does not seem to further reduce the permeability of silica fume concrete. This can be realized

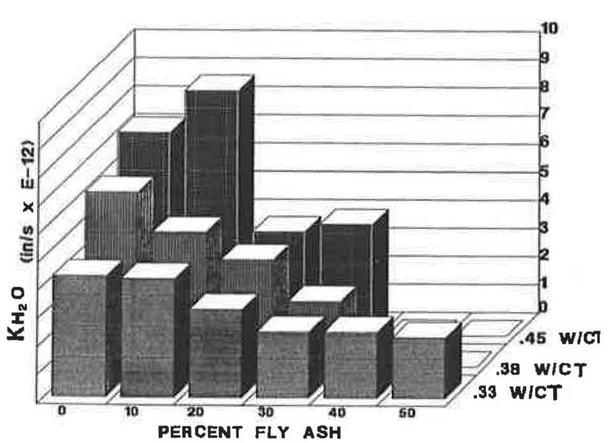

FIGURE 1 Effect of fly ash on water permeability of concrete at 91 days.

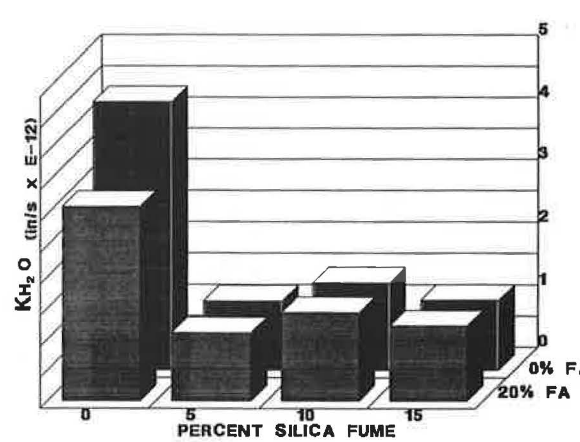

FIGURE 2 Effect of silica fume on water permeability of concrete at 91 days (FA = fly ash).

when comparing mixtures D4, D5, and D6 with D1, D2, and D3.

Silica fume also causes substantial increase in the corrosion resistance of concrete. This improvement in corrosion resistance correlates well with the significant drop in permeability, as shown in Table 7 and Figure 3. The silica fume/fly ash concrete mixtures in Group D showed remarkable resistance to corrosion compared with mixtures C1 (with only cement) and in C3 (with cement and fly ash). Tests on some Group D specimens had to be terminated after 120 days because no sign of corrosion was detected.

Correlation of Water and Chloride Permeability Tests

The AASHTO T277 rapid chloride permeability test is the only permeability test currently recognized in national specifications. An attempt was made to correlate results of the water permeability test developed in Florida with results of the chloride permeability test. Figure 4 shows the correlation between results of the two tests. By means of statistical regression analysis, a linear relation was established between the two tests. The equation is as follows:

$$K_{(H_2O)} = 9.02 \times 10^{-13} + 9.47 \times 10^{-16} K_{(Cl)}$$

R-square = 0.77

where $K_{(H_2O)}$ is water permeability and $K_{(Cl)}$ is chloride permeability. This simple relation can be used to correlate the results of the two permeability tests.

AASHTO T277 identifies 5 chloride permeability classifications and establishes criteria for these classifications based on charge passed through the specimen, as shown in Table 8. In this study, similar criteria based on water permeability were also established for the AASHTO classifications, as shown in the last column of Table 8. The water permeability criteria were derived from the correlation established between water and chloride permeabilities, as shown in Figure 4. Table 8 can now be used to determine permeability classification for a given concrete mixture based on results of either one of the two tests. This classification can be used to directly assess the

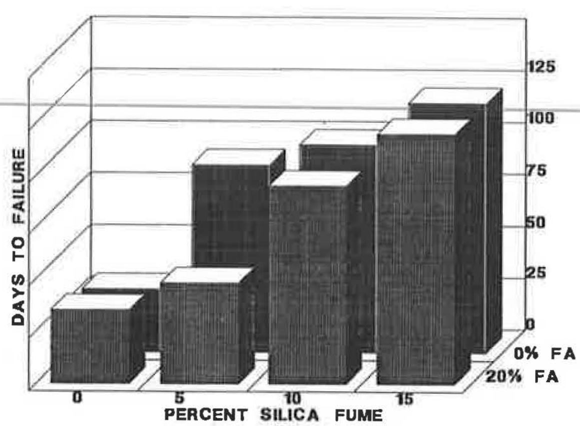

FIGURE 3 Time to corrosion (days) for concrete mixtures with silica fume (FA = fly ash).

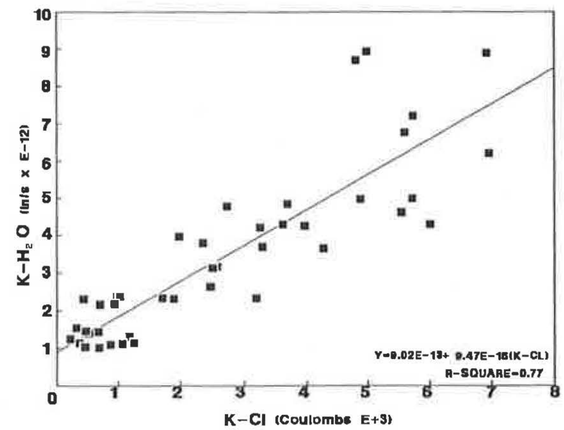

FIGURE 4 Relationship between water and chloride permeability test results.

durability of laboratory-produced concrete mixtures. Future work will be focused on developing criteria for permeability classification for field-produced concrete mixtures and for in-service structures.

Permeability and Compressive Strength

Water permeability values are plotted against the corresponding compressive strengths in Figure 5. Different classifications of water permeability are also plotted on the same figure. Compressive strength values are between 5,200 and 9,000 psi. Water permeability values are between 1.0×10^{-12} and 9×10^{-12} in./sec. The data points in Figure 5 represent all the mixtures including those with fly ash and silica fume.

It is clear from Figure 5 that concrete mixtures producing a given strength do not necessarily fall in the same permeability classification. There does not appear to be a clear correlation between strength and permeability. Lack of correlation is most obvious for concrete mixtures with compressive strengths between 5,000 and 7,500. Within this strength range, a concrete with low strength can have a lower permeability than that of a higher-strength concrete. This situation prevails until the compressive strength approaches 8,000 psi. At 8,000 psi and beyond, the permeability of concrete becomes low and remains within the low classification. A similar trend can also be observed in the relationship between chloride permeability and compressive strength, as shown in Figure 6.

TABLE 8 CLASSIFICATION OF CONCRETE PERMEABILITY

Permeability Classification, AASHTO T-277	Criteria	
	Chloride Permeability, Coulombs	Water Permeability, in/s x 10^{-12}
Negligible	< 100	------
Very Low	100 - 1000	< 1.0
Low	1000 - 2000	1.0 - 2.5
Moderate	2000 - 4000	2.5 - 4.5
High	> 4000	> 4.5

1 in/s = 0.0254 m/s

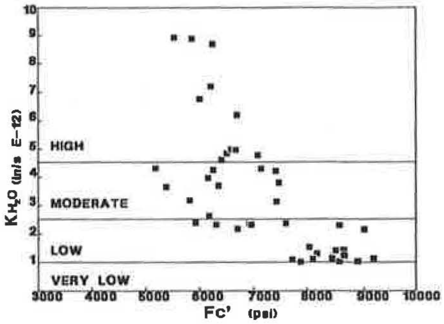

FIGURE 5 Correlation between water permeability and compressive strength.

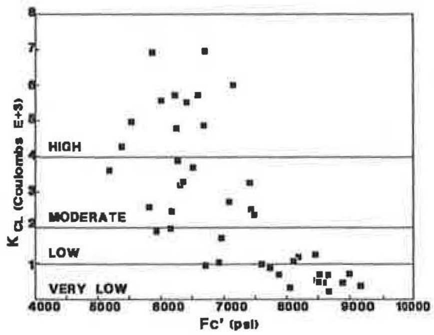

FIGURE 6 Correlation between chloride permeability and compressive strength.

In view of the poor correlation between strength and permeability, and the fact that permeability is an important indicator of durability, durability specifications should be developed for concrete to include requirements for both strength and permeability. These requirements can then be applied to improve the durability in concrete mixtures and ensure better-performing concrete structures.

CONCLUSIONS

Based on test results from this study the following conclusions are drawn:

1. Fly ash in concrete is effective in reducing permeability and improving corrosion resistance of concrete. Concrete with 20 to 30 percent fly ash shows the best overall results with respect to strength, permeability, and corrosion resistance.
2. Silica fume in concrete increases the compressive strength by up to 30 percent and lowers concrete permeability by as much as 70 percent.
3. High-performance concrete with respect to strength and durability can be produced from mixtures with w/c ratios at or below 0.35, and having at least 650 lb of cementitious material, including 20 to 30 percent fly ash and 5 to 10 percent silica fume.
4. A useful relationship is established between results of water permeability and the AASHTO T277 rapid chloride permeability tests for laboratory-produced concrete.
5. Concrete mixtures with similar compressive strength do not necessarily have similar level of permeability.
6. Durability specifications should be developed for concrete used in aggressive environments. These specifications should be based on requirements for both strength and permeability to ensure better performing and longer lasting concrete structures.

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