Silica Fume Concrete: a Solution to Steel Reinforcement Corrosion in Concrete

by J.T. Wolsiefer, Sr.

Abstract: This paper discusses the utilization of silica fume concrete admixture to prevent reinforcing steel corrosion. The mechanism of steel corrosion in salt impregnated concrete is described, along with laboratory test data showing how ordinary concrete's corrosion prone characteristics are altered by the use of silica fume. The mineral admixture significantly lowers the concrete permeability to prevent chloride ingress to the reinforcing steel level, while simultaneously increasing the concrete's electrical resistance to corrosion currents. Test data from the FHWA 90-day Chloride Ponding Test indicates a 98% reduction in chloride penetration. AASHTO T277 Rapid Chloride Permeability test show a 10 times impermeability and 25 times resistivity improvement with the use of 12 percent silica fume. The Time-to Corrosion FHWA/NCHRP 244 Slab Test is a scaled down steel reinforced deck, from which macrocell corrosion current, AC resistance, half cell potential and chloride absorption is measured. Zero corrosion current was measured after NaCl was ponded in alternate soak/dry cycles for 48 weeks. The second phase test program evaluated the corrosion performance of full size concrete bridge sections, including beams, columns, piles and bridge deck panels. The test members were subjected to environments simulating salt water and deicing agents, for 370 days. Test results show that silica fume admixture prevents salt induced corrosion of steel rebar and tensioning strands.

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John Wolsiefer, Sr. is the president of Norcem Concrete Products, division of Scancem Industries, the Scandinavian Cement Industry. He is a member of ACI committees 363, High Strength Concrete and 234 Silica Fume Concrete. He is also a member of ASTM committees C09, Silica Fume Specification and F12.8 Protective Containment.

INTRODUCTION

Silica fume is a highly pozzolanic mineral admixture, which is being utilized increasingly to improve concrete durability, strength and as a portland cement replacement in the United States, Canada and the Scandinavian countries. As the wide spread use of this material is relatively new, this paper discuses general background on silica fume as a concrete admixture, and specifically the material's ability to lower chloride permeability and increase electrical resistivity in the prevention of steel reinforcement corrosion in concrete. The development of the mineral by-product, as a concrete admixture, started in the mid-seventies, when government environmental protection regulations enforced the collection of industrial flue gases, being dispersed into the atmosphere.

SILICA FUME PRODUCTION AND CHARACTERISTICS

Silica fume is a by-product of the ferro silicon and silicon metal industry. The material is amorphous silicon dioxide, which is generated in submerged electrical arc furnaces as a gas during the reduction of very pure quartz, with metallurgical coal. The gas vapor is condensed in bag house collectors as very fine spherical particles (0.1 to 0.3 microns), with a surface area of 220,000 to 300,000 cm^2/g. The silicon dioxide (SiO_2) content can vary from 70 to 96%, increasing in percentage, as the amount of silicon increases in the ferro silicon metal manufactured. Table 1, shows typical chemical compositions resulting from the production of various types of silicon alloys. Silica fumes used, in the United States, are usually at least 85% in SiO_2 content. Typical chemical and physical properties are shown in Table 2. World wide silica fume generation is estimated at 900,000 tons however, because the ferro silicon and silicon metal industry does not have recovery systems installed in all production facilities, the actual amount available is 400,000 tons. United States and Canadian combined silica fume production could be 130,000 tons, based on alloy furnace capacity, but because of present alloy market conditions, the amount of silica fume by-product available is 60,000 to 70,000 tons.

SILICA FUME PRODUCT FORMS

Silica fume is available in two basic product forms, that of dry powder and liquid slurry. Within these two general product forms, silica fume can be provided in dry bulk, dry "super sack" (1 ton), dry paper sack (50 lb.), liquid slurry bulk and liquid slurry drum. Dry silica fume, in its as collected uncompacted form, tends to be slightly dusty, prone to lumping, low in density (16 lbs/ft^3), difficult to move in cement handling equipment and uneconomical in transportation cost. Dry silica fume, is also available in compacted form which is a reversible agglomeration, that increases bulk density to typically 40 lbs/ft^3. Silica fume in this form is dustless, uniform, free of lumps, flows readily for material handling and is the most economical for transportation. Silica in compacted bulk form is normally transported in cement tankers (25 ton load size) for storage and batching in cement silos. Silica fume is also available in silica fume water slurries with an approximate 50% silica fume content by weight. Silica fume in this product form must be frost protected, and requires recirculation with agitation, along with pH control, to maintain material homogeneity. Silica fume slurry is utilized to facilitate dispensing systems, and reduce transportation cost over uncompacted material, but slurry is more complex to dispense, and less economical in transportation expense, than compacted silica fume.

SILICA FUME CHEMICAL AND POZZOLANIC REACTIONS

Silica fume, because of its high silica content, very fine particle size and extremely large surface area, is a highly effective pozzolanic material, that has a high pozzolanic activity index (210%) with portland cement. A comparison of the silica fume pozzolanic characteristics to that of fly ash is shown in Table 3. When utilized as a concrete admixture, silica fume combines with free lime during the hydration of cement in concrete, to form a new cementitious compound, calcium silicate hydrate (CSH). The resultant binder matrix is more chemically resistant, has a denser microscopic pore structure, and yields high strength, impermeable concrete. The extremely low chloride permeability and high electrical resistivity are key improvements in concrete characteristics, that combine to protect reinforcing steel and concrete from deterioration and corrosion caused by chemicals, deicing salts, sea water intrusion, road traffic, acid rain, and freeze and thaw cycles.

THE MECHANISM OF CORROSION IN STEEL REINFORCED CONCRETE AND SILICA FUME AS A SOLUTION

In the United States during the early 1970's, because of the increasing corrosion problems with steel reinforced concrete structures, there became a general awareness that corrosion resistance was deficient for a majority of our existing highway bridges, parking garages, and marine structures (1). This situation

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occurred because of the inadequate building code requirements, an initial lack of understanding of the mechanism of steel corrosion by structural design engineers, and a gross under estimation of the amount of impact of chloride ion being directed into concrete, from deicing salts, accelerating admixtures, and the marine environment. Historically reinforcing steel cover (1 to 2 in. - 25 to 51 mm) and maximum water-to-cement ratios (0.5), were insufficient when subjected to chloride ion levels that had been experienced in deteriorating concrete structures (1,2). Reports from the United States Federal Highway Administration (FHWA), indicate that over 4,000 bridges are in need of major or moderate restoration at a cost of $1,072,000,000 in 1983 dollars. In addition, they are projecting minor restoration repair of 29,000 bridges at an annual cost of $200,000,000. Finally, the FHWA expects the cost in 1996 for restoration and protection of bridges, on interstate systems alone to be 2.6 billion U.S. dollars (3). Obviously, the corrosion problem is a major technical and economic problem that requires solutions on many levels; that of protection of existing structures to stop further deterioration, rehabilitation of bridges to correct structural deficiencies, and the construction of new structures with adequate corrosion resistance. Today the engineering community has come to understand that the electro-chemical corrosion of embedded steel is caused by the existance of galvanic cells (4). These galvanic cells can exist along the steel (microcell) or between embedded steel layers (macrocell). An example of macrocell corrosion (Figure 1) is a concrete bridge deck where the top reinforcing steel mat performs as an anode and the bottom steel layer as a cathode. The anode steel deteriorates by losing electrons via conduction through connecting steel rebar and ties to the cathode steel, where the electrons are consumed by oxygen reduction. The corrosion cell circuit is completed by the diffusion of ions through moist concrete, which operates as an electolyte. To initiate steel corrosion, a chloride threshold level of 1.1 to 1.3 pounds per cubic yard (0.65 to 0.77 kg/m^3) must be exceeded, at the anode steel. The presence of chloride ions also disrupts the normal passivation, provided to steel by the alkalinity of the cement paste. Corrosion can be reduced or eliminated by one or a combination of the following: 1, reduction or elimination of chloride in the anode area 2, decreasing the oxygen available in the cathode area 3, increasing the electrical resistance of the concrete acting as the corrosion cell electrolyte. Steel-reinforced concrete marine structures, that are fully submerged, do not normally present problems because of the lack of oxygen available to the cathodic steel. However, there are large corrosion problems in the tidal and splash zone, due to the availability of oxygen and the constant wetting and drying action, which acts as a "chloride pump", increasing the chloride ion level. In the case of highway structures, increasing concrete cover over reinforcing steel and lowering the water-to-cement ratio to reduce permeability is of help, but not a total solution. Investigators have shown that merely lowering the water-to-cement ratio will not stop rebar corrosion. In addition, although increasing the concrete cover and using epoxy coated rebar may

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stop corrosion of a solid rebar, it is not a solution for pre or post stressed steel structures. The concrete cover must be at least 2 to 3 inches (51 to 76 mm), depending on the predicted amount of chloride passing into the structure from the environment (1,2,5). However, to maintain structural design efficiency, in terms of minimum clear cover and dead weight, and to protect pre-stressed or post-tensioned steel strands, silica fume concrete offers a solution. Extremely low permeability silica fume concrete decreases the amount of chloride at the anode steel, along with the reduction of moisture in the concrete. Silica fume also provides a concrete, with a high electrical resistivity, which eliminates corrosion current in the concrete electolyte. The protection will exist even in the event of cracking, which occurs in all concrete structures, because the high electrical resistivity will minimize microcell and macrocell corrosion current in the presence of chloride ion.

PERMEABILITY TEST PROGRAMS

There has been an evolution of test program development in the United States to measure concrete's ability to resist corro-sion induced by chloride ion. The first full scale corrosion studies, in the United States, are thought to be those investi-gations conducted in the early seventies, by the Federal Highway Administration (FHWA) (1). These Time-to-Corrosion studies were conducted on one-hunderd twenty four reinforced concrete slabs (20 square foot), in an outdoor exposure yard for a one year period. Concretes, prepared with various water-to-cement ratios, admixtures, curing procedures, surface treatments and different levels of concrete cover were ponded daily, with 3% sodium chloride solution. This program resulted in recommendations for lower water-to-cement ratios and greater concrete cover over reinforcing steel on bridge deck concrete (see Table 4 for program test data). However, a test procedure that could gener-ate data, in a short period of time, was required to evaluate various corrosion protection alternates. The first of these test methods to find widespread use was the Federal Highway Adminis-tration (FHWA) 90-Day Chloride Ponding Test, which measured chloride ion penetration into concrete. Flat slab concrete specimens are ponded with 3% NaCL solution for a period of 90 days, after which the total chloride is measured at two depths (0 to 1 inch) and (1 inch to 2 inch). Comparative test results for conventional portland cement concrete, latex concrete and silica fume concrete (20% by weight of cement) shows a reduction of 98.1% of the chloride penetration (Figure 2) by the silica fume concrete over that of the control (8). The National Cooper-ative Highway Research Program (NCHRP) developed the NCHRP Cube Test, which measured water absorption and chloride penetration, for 4-inch (100 mm) cube specimens under an air dry, chloride soak and air dry cycles. The first dry period is at 70°F (21°C) in a 50% relative humidity chamber for 34 days after which the cubes are soaked in 15% NaCl solution for 21 days, and then dried at 70°F (21°C) in the relative humidity chamber. Weight gain and

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absorbed chloride test data for a silica fume concrete, at a dosage rate of 20% by weight of cement, is compared to ordinary portland cement, latex, and epoxy modified concretes in Figures 3 and 4. The time period for these test procedures was too long and design engineers required a practical method of specifying and measuring the performances parameter of permeability. The use of the "Standard Method of Test for Rapid Determination of Chloride Permeability of Concrete", AASHTO Designation T277-83, (1986) is a standard test method that is fast, relatively inexpensive and becoming widely utilized by design engineers for performance specification of concrete structures in chloride environments. The test consists of monitoring the amount of electrical current passed through a 2-inch (5 cm) thick section of a 4-inch (10 cm) diameter cylinder or core. One end of the specimen is immersed in a three percent sodium chloride solution, while the other end is immersed in a 0.3 normal sodium hydroxide (NaOH) solution. The current in amperes, is measured in thirty minute increments over a period of six hours. A curve of current versus time is plotted and the area under the curve is calculated as the total charge passed coulombs. The data is then related to chloride permeability levels, established by comparative test data for various different concretes, such as; silica fume, latex, epoxy modified, and ordinary portland cement concrete. Typical classification of chloride permeabilities for these various concrete are shown in Table 5. Normal portland cement concrete with a low water-to-cement ratio (less 0.40) typically measures 1,500 to 2,000 coulombs of charge passed versus less than 100 coulombs for silica fume concrete with dosage rate of greater than 15%. Rapid Chloride Permeability tests can be performed on concrete field test cylinders at early age (2 to 3 days) after boiling as per the ASTM C684-81 "Standard Method of Making, Accelerated Curing and Test of Concrete Test Specimens". Other permeability test ages are 41 days laboratory water-cured specimens and the testing of field cores typically at 90 days and beyond. The permeability of all concrete, especially that of silica fume concrete depends on the curing method and the length of time utilized (6). The rate of permeability decrease with time, is proportional to the moisture available and cement hydration. As the ambient curing temperature has great influence on the rate of cement hydration, field cores taken in winter will not achieve low chloride permeability until adequately cured. Figure 5 shows Rapid Chloride Permeability decreasing as a function of the corresponding increase in a dry compacted silica fume admixture (dosage rate is addition, by weight of cement). Portland cement lightweight concrete is known to be more permeable than normal weight concrete, due to the high permeability caused by cement paste interface with porous aggregate. Silica fume improves significantly the permeability of lightweight concrete by an order of magnitude, from 3,667 coulombs for a portland cement concrete control to 227 coulombs for an air entrained silica fume concrete, with a dosage rate of 20% by weight of cement (Figure 6).

ELECTRICAL RESISTIVITY AND AC RESISTANCE

Electrical resistivity and AC resistance are a measure of concrete's ability to resist corrosion currents. These corrosion currents are encountered in steel reinforced concrete under chloride attack, in deicing and marine environments. Electrical resistivity (expressed in ohms-cm) has been measured in non standard laboratory tests, and can also be obtained from the AASHTO Standard T277-83, Rapid Chloride Permeability test. The resistivity values are calculated by determination of the cell constant of the test setup, and calibrations with the 4 pin platinum wire test method, and the use of solutions of known resistivity. Figure 7 shows electrical resistivity data, at 11% and 20% addition by weight of cement. The data indicate that silica fume concrete has high electrical resistance to the passage of corrosion current. The dry silica fume admixture, at the 20% dosage, generates a resistivity of 110,000 ohms-cm, as compared to 4,200 ohms-cm for the ordinary portland cement concrete control. Norwegian investigators measured electrical resistivity, by embedding an isolated steel plate in the middle of an insulated concrete cylinder (7). The test cylinder was immersed in water, with counter electrodes, and an AC bridge was employed to measure electrical resistivity. Figure 8 shows the resistivity data, for three concrete mixture proportions, each with 0, 10 and 20 percent silica fume addition by weight of cement. Good correlation, with the previous data generated by the AASHTO T277-83 method, is seen with a electrical resistivity of 127,000 ohms-cm for a comparable mixture (400 kg cement, 80 kg silica fume). Electrical resistivity, as a function of increasing percentage of silica fume admixture, is shown in Figure 9.

TIME-TO-CORROSION TEST PROGRAMS

Time-to-corrosion has been measured in the FHWA/NCHRP Southern Exposure Slab test, conducted under FHWA and Norcem funding. This laboratory test is a scaled down steel reinforced bridge deck, from which macrocell corrosion current, half cell potential, AC resistance, and chloride absorption is measured (Figure 10). Sodium chloride (15% solution) is ponded in alternate soak/dry cycles, for a period of 48 weeks. This test time, is said to simulate 10 to 20 years of high chloride exposure, when compared to chloride profiles taken from existing field structures (2). Figure 11 shows zero corrosion current measured between the top and bottom rebar for silica fume concrete slab specimens (20% by weight of cement). Correspondingly, a low w/c (0.32) AASHTO type portland cement concrete control mix started corrosion activity at 6 weeks and continued to a peak level of 200 micro amps. The AC resistance for a silica fume concrete sample increased from 5,000 ohms to 25,000 ohms at the test completion (Figure 12) wherein the corresponding concrete control was flat at 890 ohms. Chloride content, of the silica fume concrete, was measured at 96 ppm [one inch (2.54 cm) depth of concrete cover] which was only 2.1% of the amount (4,650 ppm) measured in the control concrete.

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Copper-copper sulfate half cell potentials, measured at the top reinforcing steel mat, shown in Figure 13, are well below ⁻50 millivolts peak decreasing to ⁻40 millivolts, at 48 weeks. These data are contrasted to the portland cement control, which exhibited half cell potentials over ⁻350 millivolts within 7 weeks, increasing to ⁻470 millivolts, at 48 weeks. Half cell potential of over ⁻350 millivolts are indicators of corrosion activity (95% probability) when oxygen and moisture are available at the cathode to complete the corrosion cell circuit. This NCHRP southern exposure test program had also been conducted by Kenneth C. Clear, Inc. and completed approximately 8 months prior to the Wiss, Janney & Elstner test program. There was excellent correlation of test performance between the two projects. A silica fume concrete (20% dosage by weight of cement) showed no corrosion current and higher than 25,000 ohms AC resistance after 48 weeks of accelerated chloride exposure (9). The data from these test programs, along with simultaneous corrosion current measurements, indicates that the silica fume concrete will not support macrocell corrosion activity. A second phase of this FHWA test program, "Protection Systems for New Prestressed and Substructures Concrete", evaluated the corrosion protection of full size concrete bridge sections, including steel reinforced beams and columns and precast, prestressed piles and bridge deck panels (10). The test specimens were fabricated with 1-inch (2.54 cm) of clear concrete cover over the solid rebar and prestressing steel strands. The test program evaluated many different solutions to the corrosion problem, such as; epoxy coated rebar, sealers, calcium nitrate additive and silica fume concrete against a AASHTO Building Code, portland cement concrete control. The test members were subjected to chloride environments, simulating salt water spray, splash and tidal variation, for marine structure applications. Deicing salts applied directly to decks, splashed against columns and flowing over beams from drains were simulated for bridge deck applicaitons. The chloride (15% NaCl) was constantly recycled in test figures for a period of 370 days, which was meant to approximate over 20 years chloride exposure. Measurement of macrocell corrosion current, instant off potentials, electrical resistance, and half-cell potentials were made on all structural members. During different cyclic test periods in the program, all AASHTO concrete controls showed signs of corrosion activity, while the silica fume concrete elements showed no measurable corrosion current. Chloride ion measurements at a 1-inch (2.54 cm) depth, as an average of five test conditions, stopped 94% of chloride ingress as compared to the AASHTO control concrete (Figure 14). The average silica fume concrete half-cell potentials were ⁻60 millivolts as compared to ⁻470 millivolts for the AASHTO controls, which is well below the ⁻350 millivolt corrosion voltage threshold level (Figure 15). Autopsy of AASHTO specimens showed evidence of corrosion by-products on the reinforcing steel and the silica fume specimen exhibited none. Measurements of silica fume concrete pH level (12.4), at the reinforcing bar level, showed that the concrete provided uninterrupted passivation of the steel. The concrete

proportions for this program, along with the strength results, are shown in Table 6. The silica fume concrete was high strength; 10,150 psi (70 Mpa) at 28 days, and 13,120 psi (90.4 Mpa) when cored at 322 days. The corresponding AASHTO concrete mixture strength was 5,840 psi (40.2 Mpa) at 28 days.

FIELD TEST DATA

In the last few years, there has been a steady growth, in the use of silica fume admixture, to improve the durability of automobile parking garages, marine terminals and bridge deck overlays. Some of the construction projects requiring protection against chloride induced corrosion, have been utilizing the AASHTO T277 Rapid Chloride Permeability test as an evaluation tool and performance specification. Test data correlation has been good, between the previously cited laboratory test programs and tests performed on actual field concrete specimens. Table 7 lists Rapid Chloride Permeability measurements for various recent construction projects. Most of the projects referenced required field cores and/or field cylinders to be taken for each individual silica fume concrete placement. The Rapid Chloride Permeability data is the average for all placements, which in some cases numbered 20 to 40 data points.

CONCLUSIONS

The extremely low chloride permeability and the very high electrical resistivity characteristics of silica fume concretes are extremely important factors in the prevention of micro and macro corrosion cells in steel reinforced concrete structures. In particular, these parameters are an important consideration, with respect to the concrete cracking that can occur on almost all structures. The extremely high electrical resistance of silica fume concrete precludes significant corrosion current along and between reinforcement, in the presence of chloride ion intrusion allowed by concrete cracking. All the test programs described in this paper have been carried out with 1-inch (2.54 cm) of clear silica fume concrete cover over solid rebar and pre-stressing steel. Thus, design engineers can utilize the admixture to maintain structural design efficiency in terms of clear cover and dead weight. In addition, the fact that these properties exist simultaneously with increased mechanical properties, such as high strength and abrasion resistance, give silica fume admixtures large potential to increase significantly the durability of concrete structures located in aggressive chloride environments.

ACKNOWLEDGEMENTS

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TABLE 1 - CHEMICAL COMPOSITION OF SILICA FUME
FROM DIFFERENT ALLOY TYPES (WT%)

Chemical Component	Silicon Metal	Ferro-Silicon Metal (75%)	Ferro-Silicon Metal (50%)
SiO_2	95	90.5	84
C	1.3	1.5	1.9
F_2O_3	0.3	1.6	2.4
Al_2O_3	0.7	0.9	2.5
Na_2O	0.3	0.6	0.7
K_2O	0.3	0.7	1.3
MgO	0.2	1.4	2.0
SO_3	0.8	0.9	1.1
CaO	0.3	0.5	0.8
LOI	1.5	1.6	3.3

TABLE 2 - SILICA FUME MILL CERTIFICATE

Chemical Analysis and Physical Properties		Typical Value
SiO_2		96%
C		1.3%
Fe_2O_3		0.1%
Al_2O_3		0.4%
Na_2O		0.1%
K_2O		0.1%
MgO		0.2%
SO_3		0.1%
Cl^-		0.1%
CaO		0.2%
Loss of Ignition		1.5%
Bulk Density	uncompacted	16 lb/Ft^3
	compacted	40 lb/Ft^3
Moisture Content		0.2%
Specific Surface		25 M^2/gram
Specific Gravity		2.1%

TABLE 3 - COMPARISON OF CHEMICAL AND PHYSICAL CHARACTERISTICS
SILICA FUME, FLY ASH AND CEMENT

	Silica Fume	Fly Ash	Cement
SiO_2 CONTENT %	85 to 97	35 to 48	20 to 25
SURFACE AREA cm^2/gm *1	200,000 to 240,000	3,500 to 5,000	3,500 to 4,500
POZZOLANIC ACTIVITY *2 INDEX CEMENT %	210	85 to 110	N/A *3
POZZOLANIC ACTIVITY INDEX LIME psi (Mpa)	1,660 (11.4)	800 to 1,000 (5.5 to 6.9)	N/A *3

*1 Silica Fume measured by BET method, Fly Ash and Cement measured by Blaine method

*2 As measured by ASTM C618-78

*3 Not applicable

TABLE 4 - EFFECT OF CONCRETE MIX DESIGN AND COVER OVER STEEL ON CHLORIDE MIGRATION

Description	No. slabs	No. cores	Core depth, inches (a)	Rebar level chloride content, lbs. Cl⁻/yd³ concrete Average	Range	No. of salt applications to coring
1. Water-cement ratio						
(CF = constant = 7.0)						
W/C = 0.40	2	10	1.0	0.70	0.06 to 1.71	336
	2	10	2.0	0.07	0.05 to 0.11	337
	2	10	3.0	0.07	0.05 to 0.09	337
	1	3	0.25	9.22	8.96 to 9.59	359
W/C = 0.50	2	10	1.0	3.57	1.51 to 6.09	334
	2	10	1.0	0.98	0.09 to 2.20	-348
	2	10	3.0	0.08	0.04 to 0.30	344
	1	3	0.25	12.72	9.54 to 16.96	341
W/C = 0.60	1	3	1.0	5.51	3.76 to 6.66	313
	1	3	2.0	4.28	2.66 to 6.19	354
	2	6	3.0	0.74	0.41 to 1.00	316
	1	3	0.25	14.71	11.61 to 18.27	313
2. Cement factor						
(W/C = constant = 0.50)						
CF = 6.0	2	6	1.0	3.54	0.92 to 5.36	333
CF = 7.0	2	10	1.0	3.57	1.51 to 6.09	334
CF = 8.0	2	6	1.0	4.49	1.74 to 7.87	330
3. Aggregate Proportions						
(W/C = 0.5, CF = 7.0)						
= 0.882	2	10	1.0	3.57	1.51 to 6.09	334
= 0.429	2	6	1.0	3.10	1.21 to 6.63	320

(a) The nominal core depth is given. For example, for a 1.0-inch core depth, the actual concrete analyzed wzs from a 3/4" to 1-1/4" depth.

Reprinted from FHWA-RD-73-32 Report, Time-to-Corrosion of Reinforced Steel in Concrete Slabs, Vol. 2, Table 9

TABLE 5 - CHLORIDE PERMEABILITY BASED ON CHARGE PASSED

Charge Passed (coulombs)	Chloride Permeability	Typical Of
4,000 (greater than)	High	High water cement ratio (0.6) conventional concrete
2,000 to 4,000	Moderate	Moderate water cement ratio (0.4 - 0.5) conventional concrete
1,000 to 2,000	Low	Low water cement ratio (0.4) conventional concrete
100 to 1,000	Very Low	latex modified concrete, silica fume concrete (5 to 15%) and internally sealed concrete
100 (less than)	Negligible	Polymer impregnated concrete polymer concrete and high silica fume percentage concrete (15 to 20%)

TABLE 6 - CONCRETE MIX DESIGNS

	SILICA FUME lbs/yd³ (kg/m³)		AASHTO lbs/yd³ (kg/m³)	
CEMENT	800	(472)	560	(330)
SAND	1,060	(625)	1,230	(725)
STONE	1,750	(1,032)	1,850	(1,091)
SILICA FUME (20% by weight of cement)	160	(94)	0	
AIR CONTENT (%)	6		6	
SLUMP (in.) (cm)	6	(15)	4	(10)
WATER	175	(103)	247	(146)
W/C	0.22		0.44	
W/C + P	0.18		N/A	
STRENGTHS (avg.)				
* 18 hour (heat cured precast) psi (Mpa)	7,200	(49.6)	3,250	(22.4)
* 28 day (heat/moist) psi (Mpa)	10,150	(70.2)	5,840	(40.2)
* 322 day (cores) psi (Mpa)	13,120	(90.4)	N/A	

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TABLE 7 - CHLORIDE PERMEABILITY PROJECT FIELD DATA

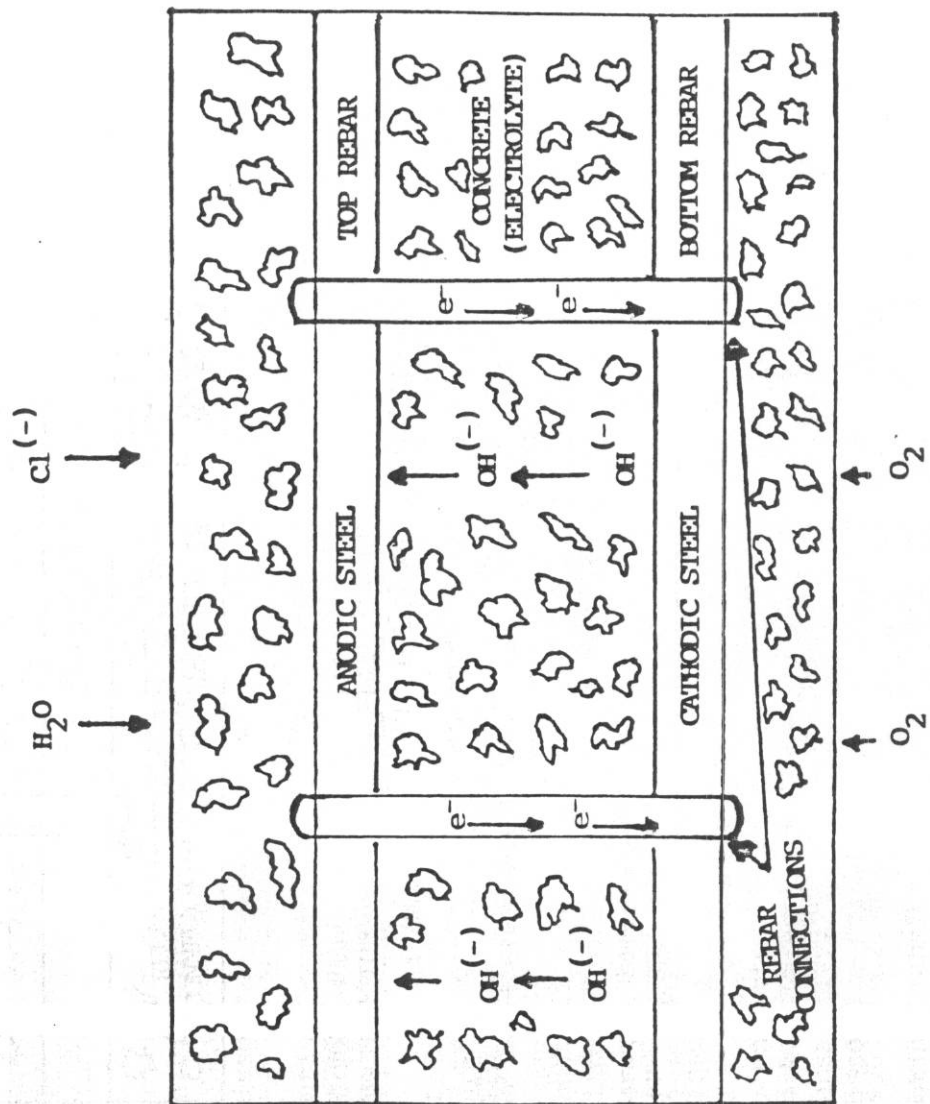| PROJECT NAME AND LOCATION	SILICA FUME % BY WEIGHT OF CEMENT	AVERAGE RAPID CHLORIDE PERMEABILITY (COULOMBS)
* St. Gregory Street Garage, Cincinnati, Ohio	8.5%	425
* Kansas City Int'l Airport Parking Garage, Terminal "A"; Kansas City, Missouri	11%	345
* Crown Center Parking Garage; Kansas City, Missouri	12%	323
* Marine Transfer Terminal; New York City	20%	185

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Fig. 1--Galvanic macrocell
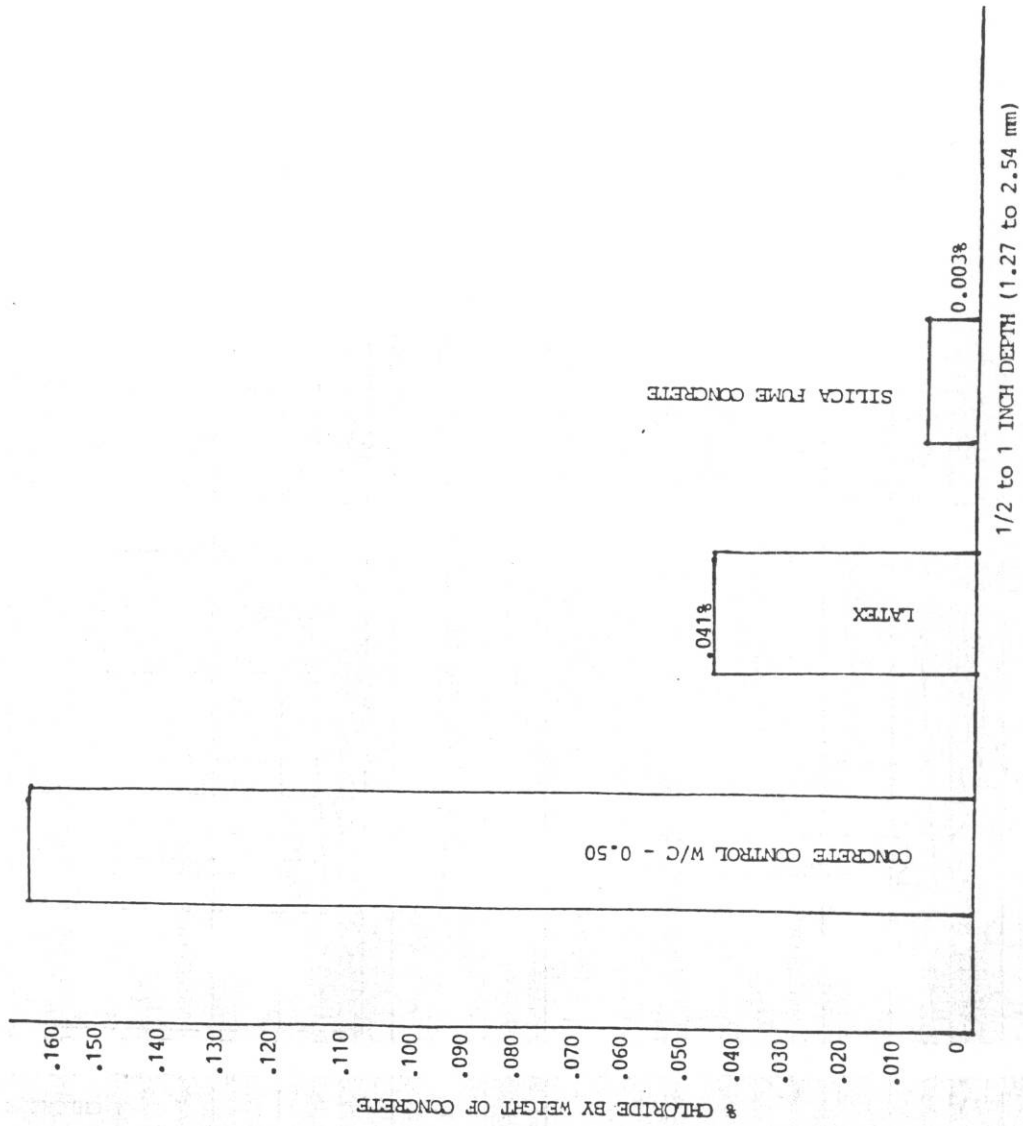
Fig. 2--Chloride permeability FHWA 90 day ponding test
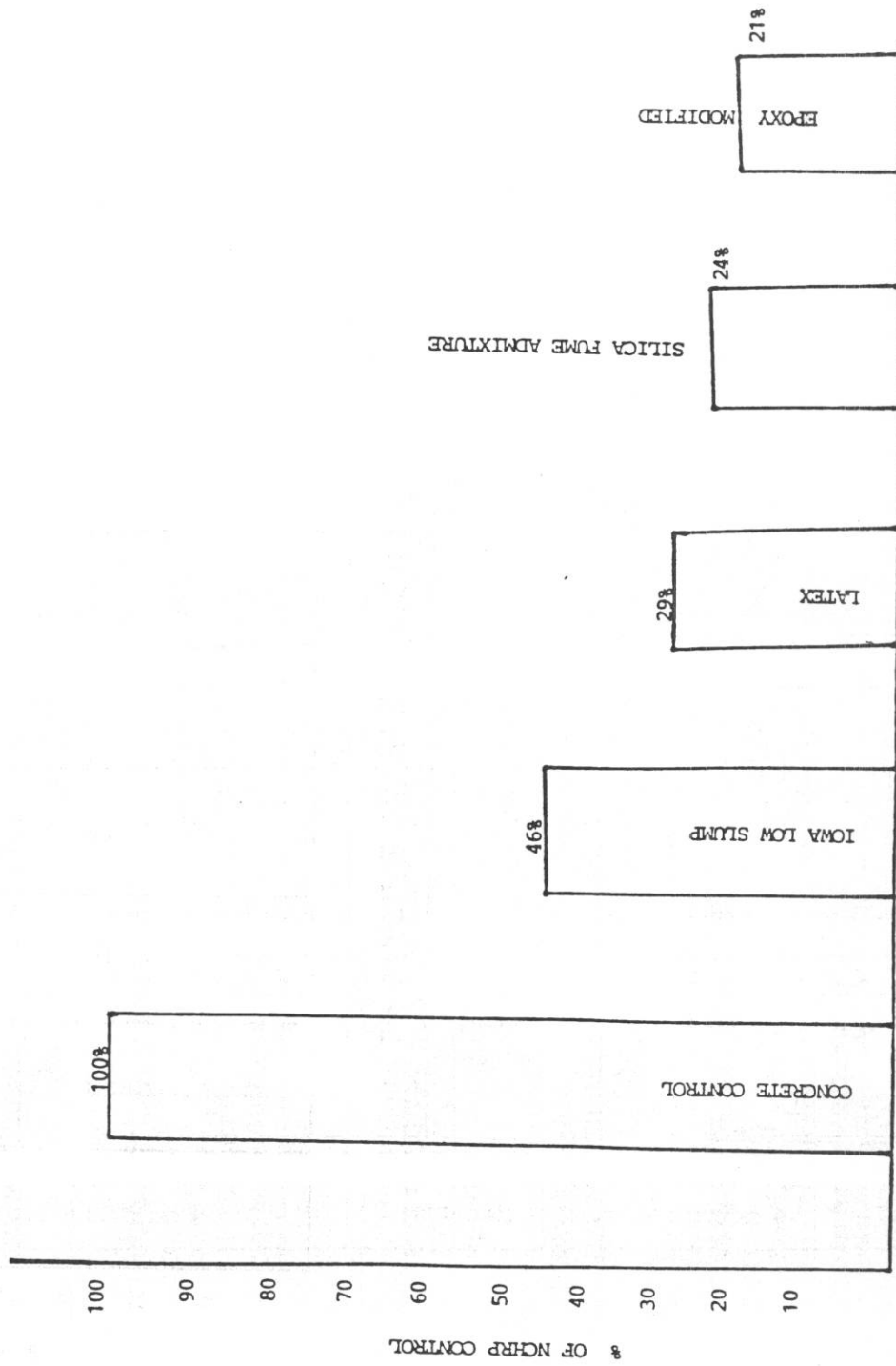
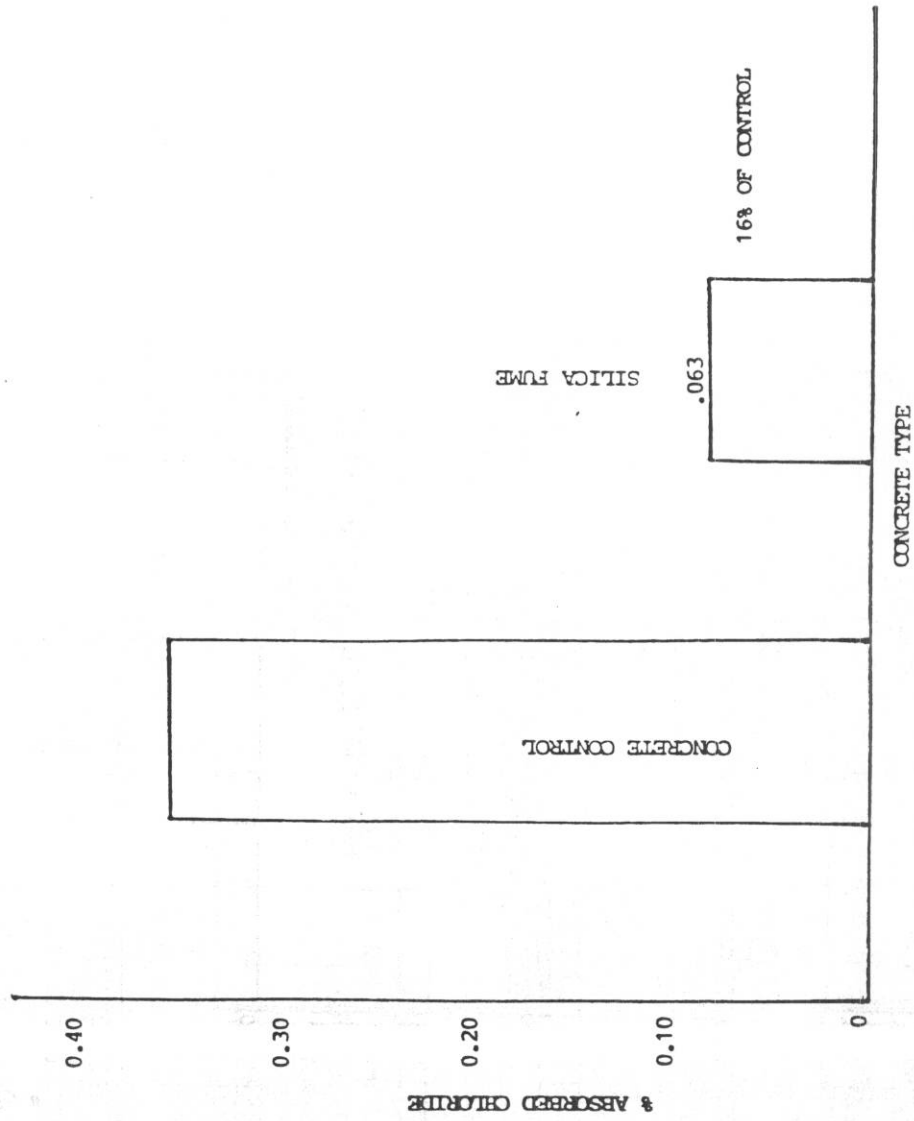Fig. 3--NCHRP 244, cube test weight gain (15% NaCl)

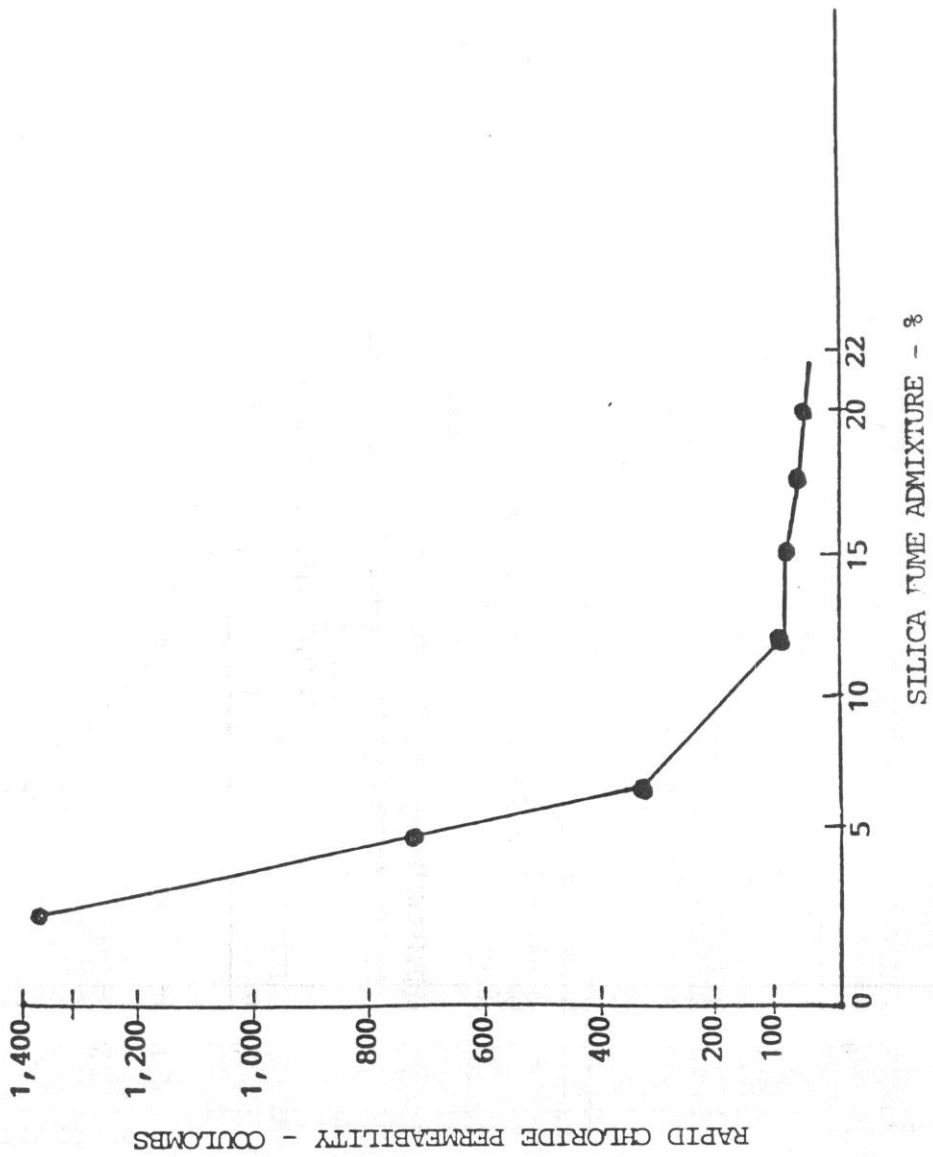Fig. 4--NCHRP 244, cube test % absorbed chloride

Fig. 5--Rapid chloride permeability versus silica fume admixture
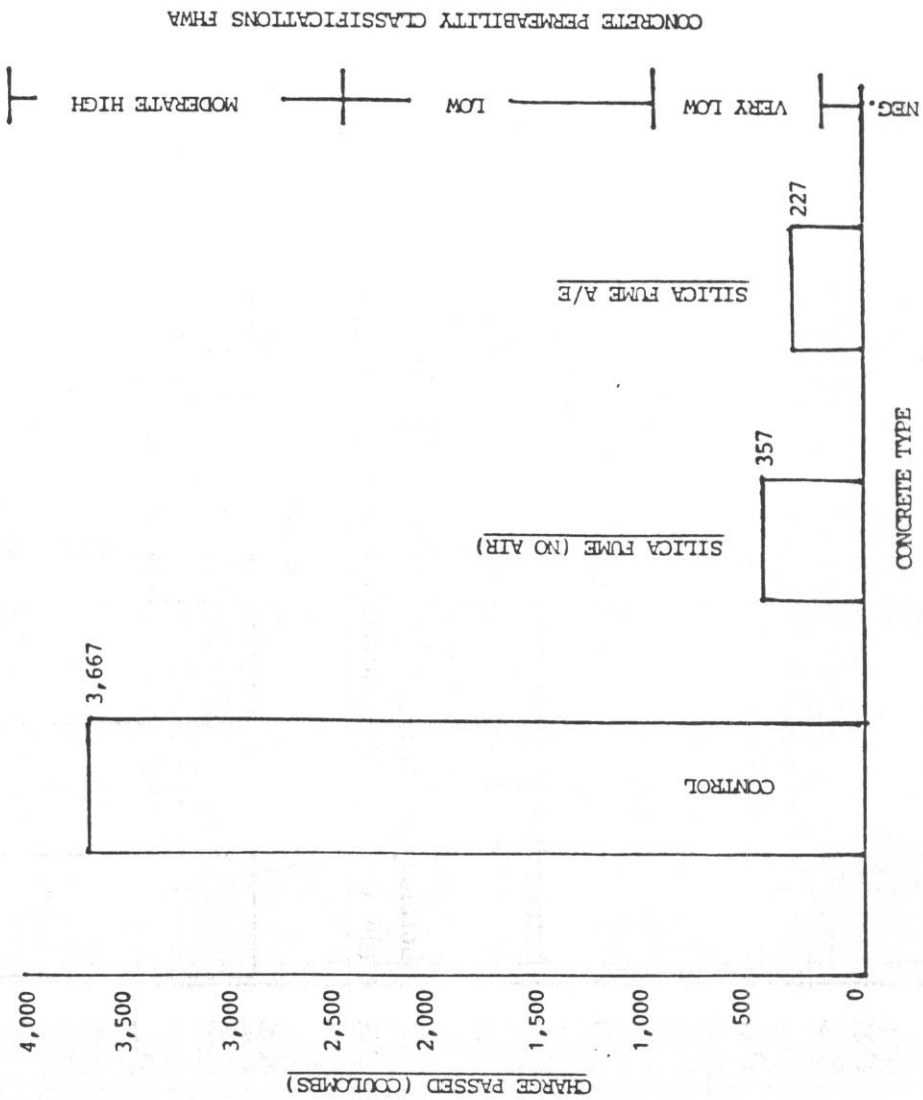percentage

Fig. 6--Lightweight concrete permeability FHWA rapid chloride permeability test
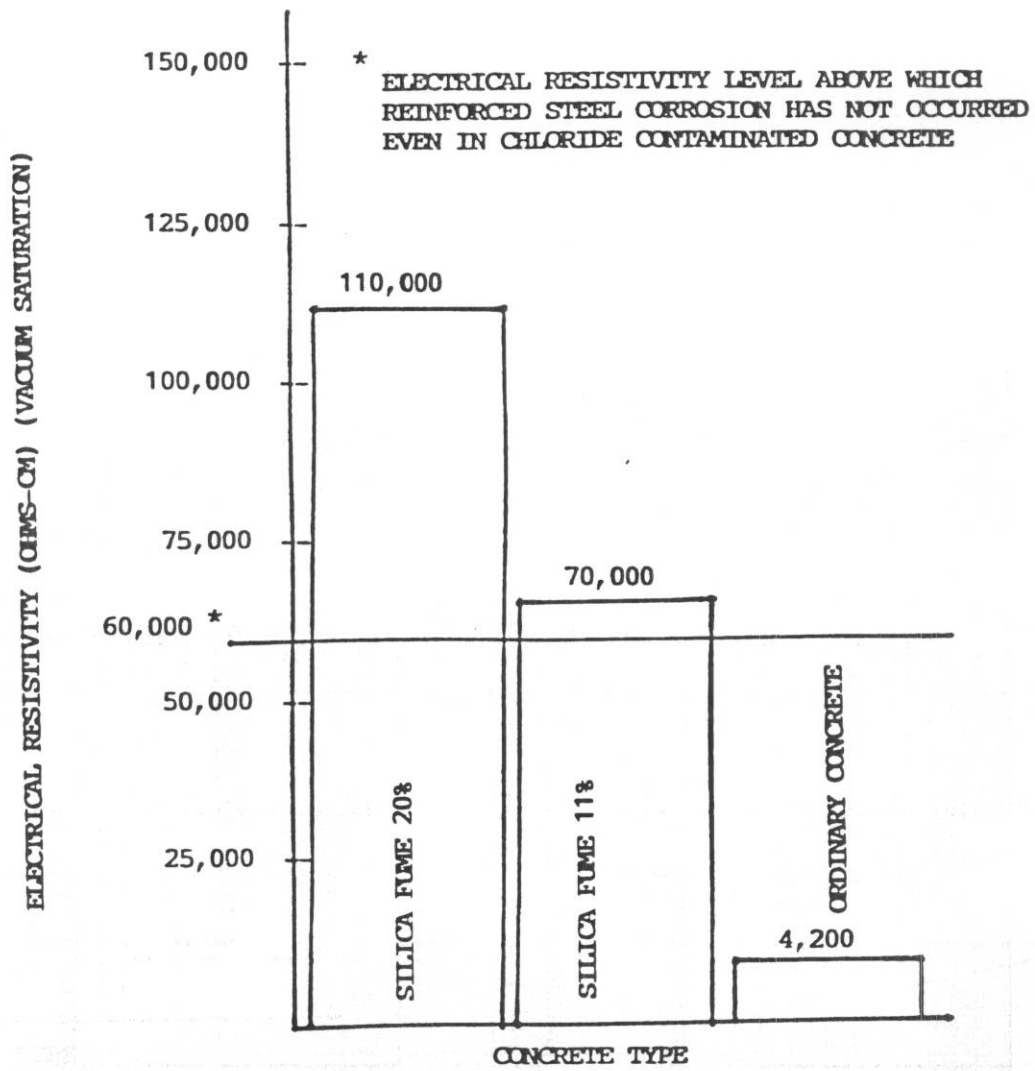
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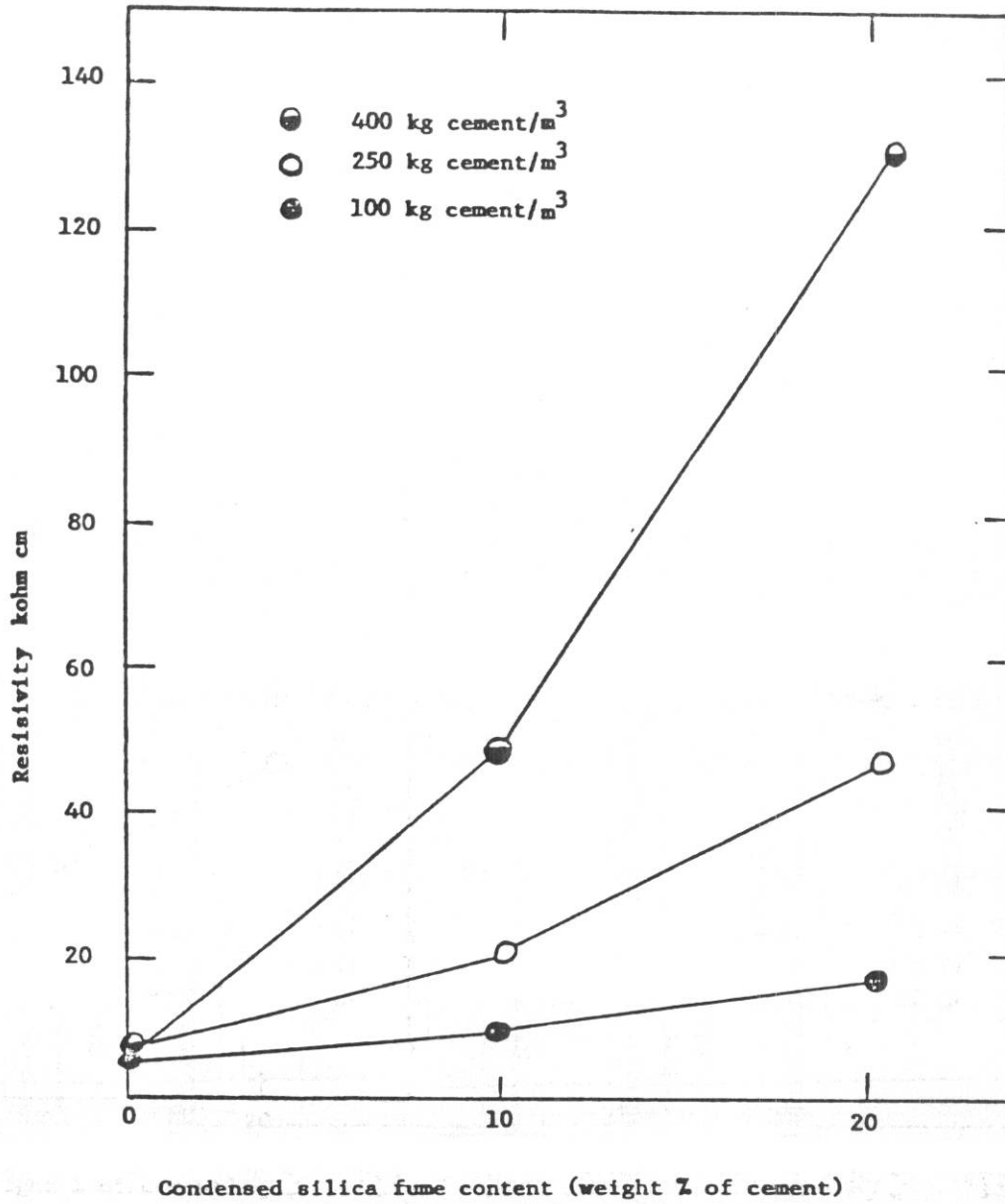Fig. 7--Concrete electrical resistivity

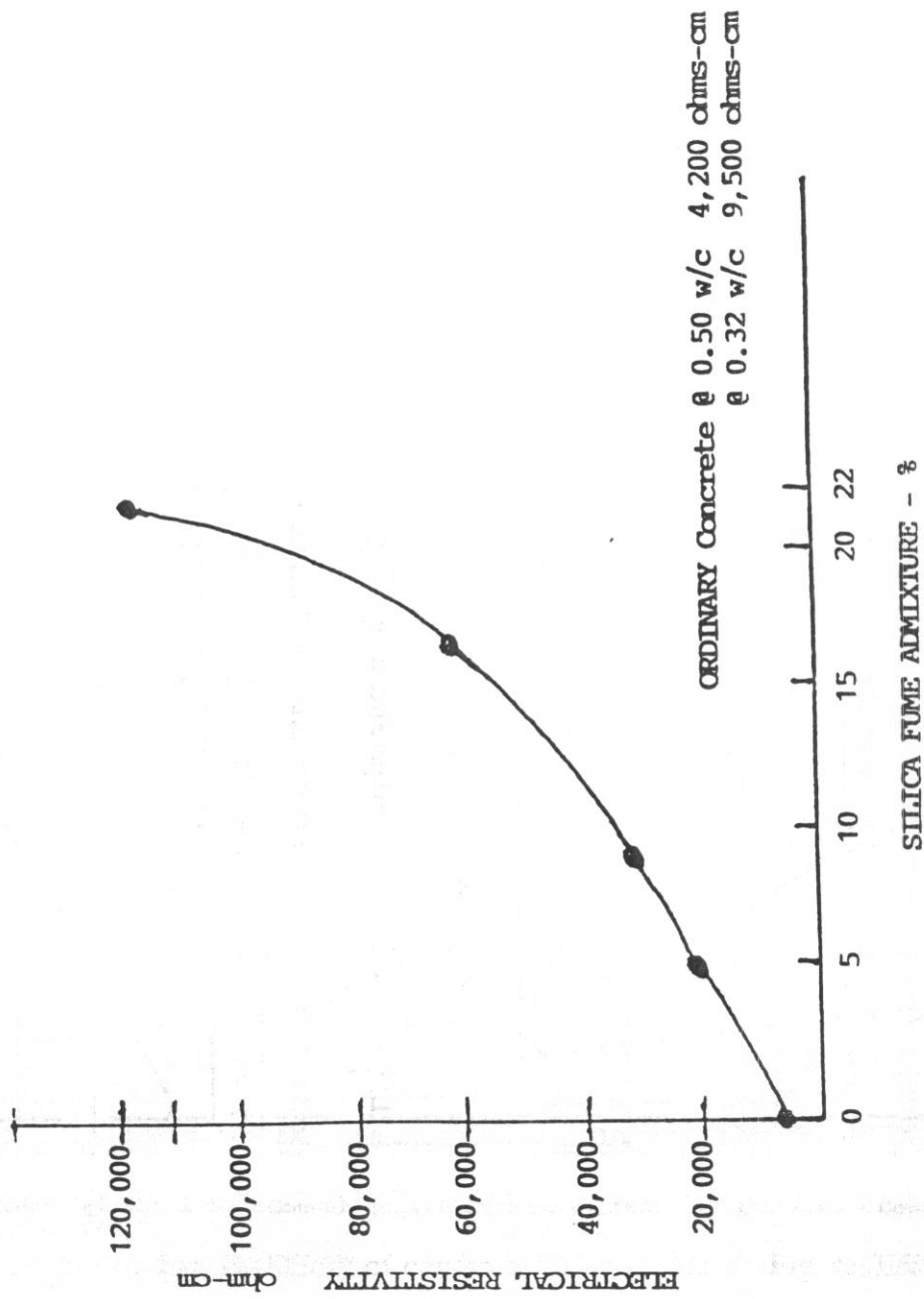Fig. 8--Effect of condensed silica fume on the resistivity of concrete

In the figure:
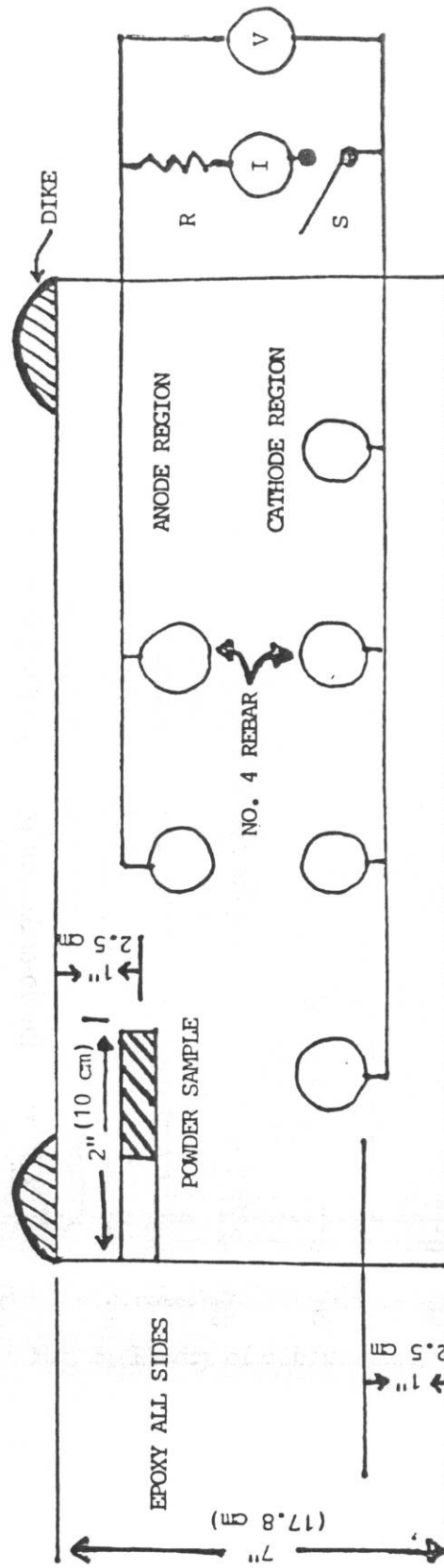- Y-axis: Resistivity kohm cm (0 to 140)
- X-axis: Condensed silica fume content (weight % of cement) (0, 10, 20)
- Legend:
  - 400 kg cement/m^3
  - 250 kg cement/m^3
  - 100 kg cement/m^3

Fig. 9--Electrical resistivity versus silica fume admixture percentage

ORDINARY Concrete @ 0.50 w/c   4,200 ohms-cm
              @ 0.32 w/c   9,500 ohms-cm

SILICA FUME ADMIXTURE - %

ELECTRICAL RESISTIVITY   ohm-cm

120,000
100,000
80,000
60,000
40,000
20,000

0   5   10   15   20 22

MEASUREMENTS: HALF CELL POTENTIALS COPPER SULPHATE
CORROSION CURRENT, AC RESISTANCE
CHLORIDE CONTENT BY CORES AT 44 WEEKS

DIKE

V

I

R

S

ANODE REGION

CATHODE REGION

NO. 4 REBAR

2" (10 cm)

POWDER SAMPLE

1"

2.5 cm

EPOXY ALL SIDES

1"

2.5 cm

7"

(17.8 cm)

PONDED 15% NaCl, 4 DAYS SOAK, 3 DAYS DRY
48 WEEKLY CYCLES EQUIVALENT TO 20 YEARS ACTUAL EXPOSURE

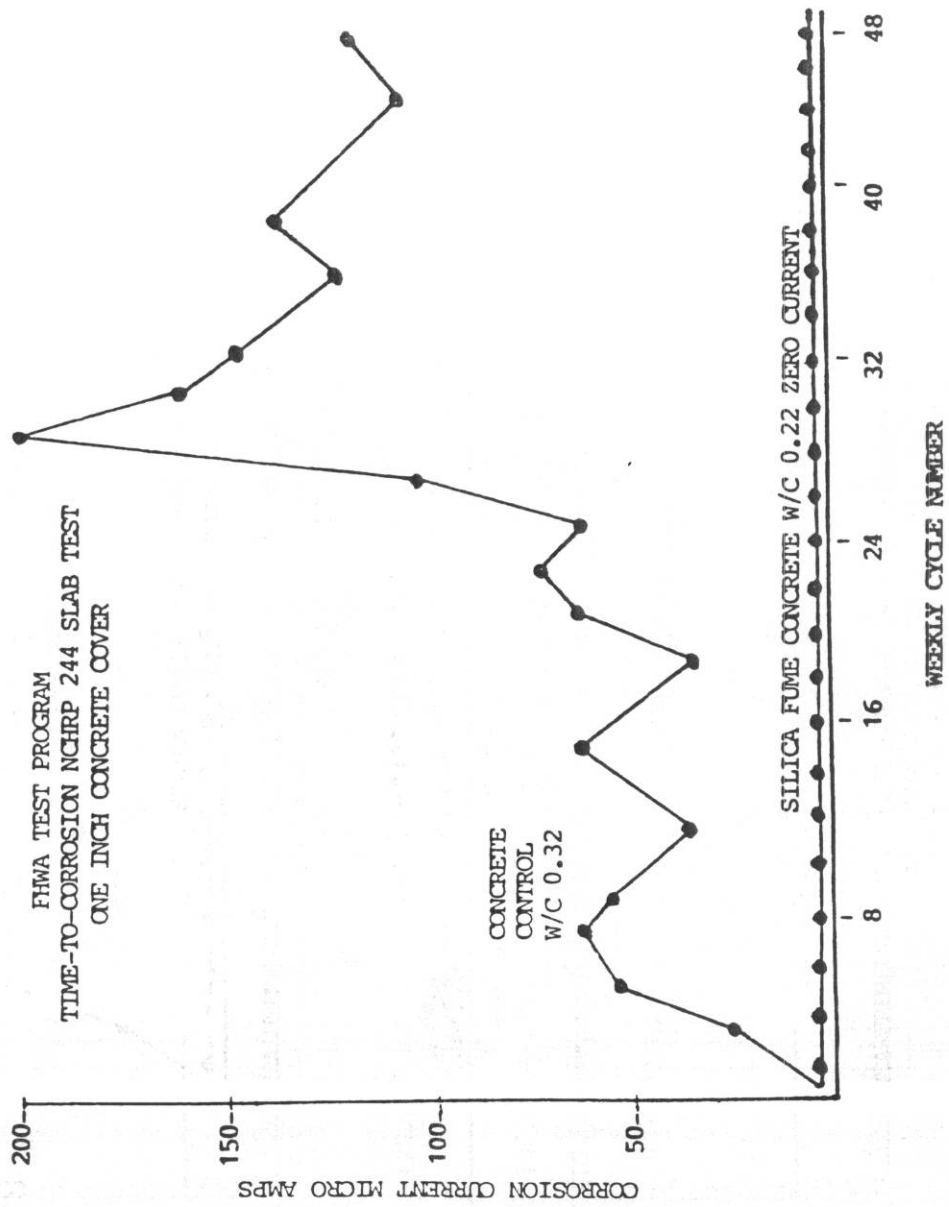Fig. 10--Time-to-corrosion NCHRP slab test southern exposure

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FHWA TEST PROGRAM
TIME-TO-CORROSION NCHRP 244 SLAB TEST
ONE INCH CONCRETE COVER

CONCRETE
CONTROL
W/C 0.32

SILICA FUME CONCRETE W/C 0.22 ZERO CURRENT

CORROSION CURRENT MICRO AMPS

WEEKLY CYCLE NUMBER

Fig. 11--Macrocell corrosion current versus time

TIME-TO-CORROSION NCHRP 244 SLAB TEST
FHWA TEST PROGRAM ONE INCH CONCRETE COVER

SILICA FUME CONCRETE W/C 0.22

CONCRETE CONTROL W/C 0.32

890 OHMS

AC RESISTANCE, OHMS

25,000
20,000
15,000
10,000
5,000
0

WEEKLY CYCLE NUMBER

0   8   16   24   32   40   46
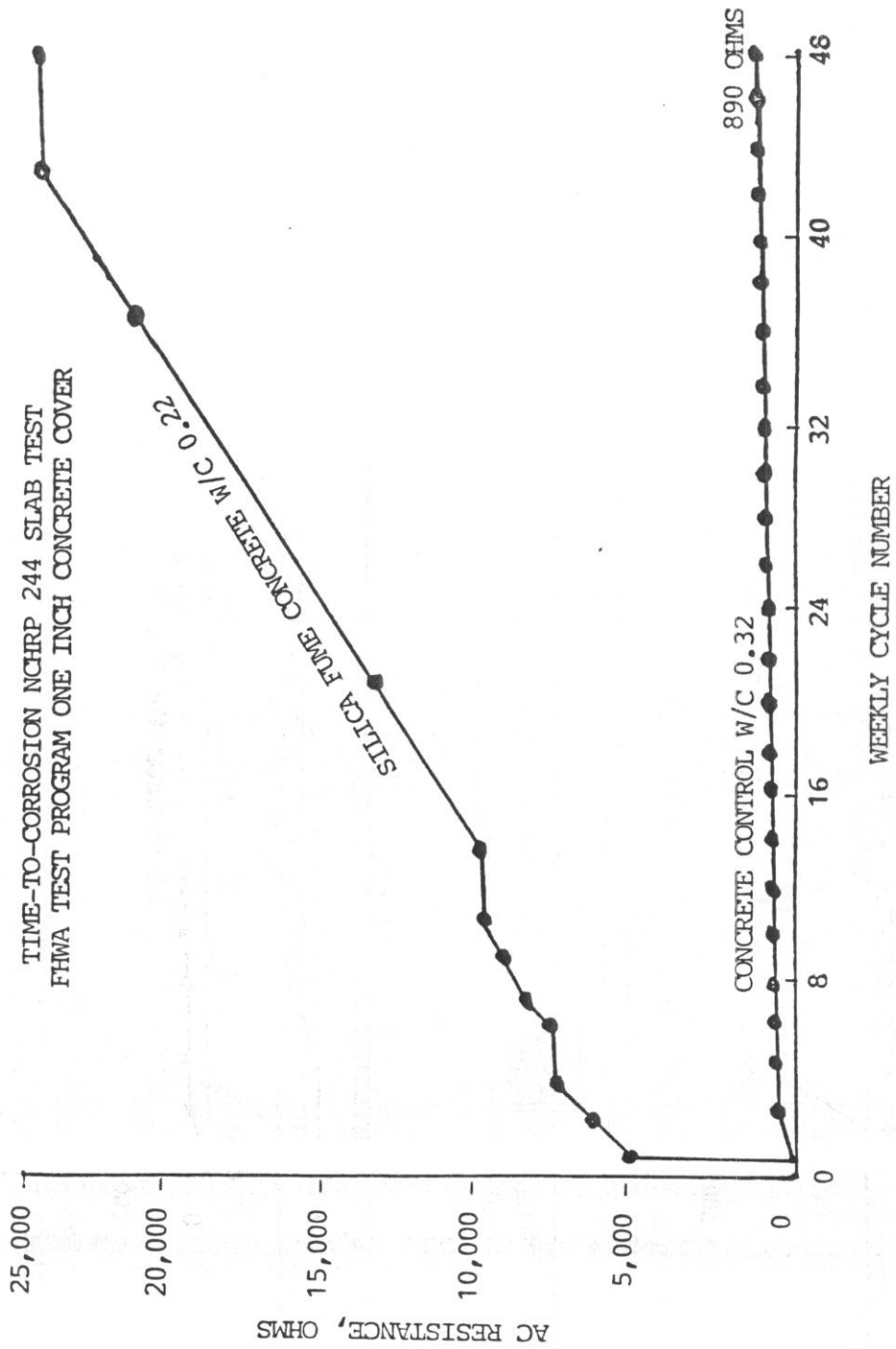
Fig. 12--AC resistance versus time to mat

TIME-TO-CORROSION – NCHRP 244 SLAB TEST
FHWA TEST PROGRAM ONE INCH CONCRETE COVER

NO. 1-1-32 A

CONTROL W/C 0.32

SILICA FUME W/C 0.22 NO. 28-2-32 B

WEEKLY CYCLE

AVERAGE POTENTIAL – mv CSE
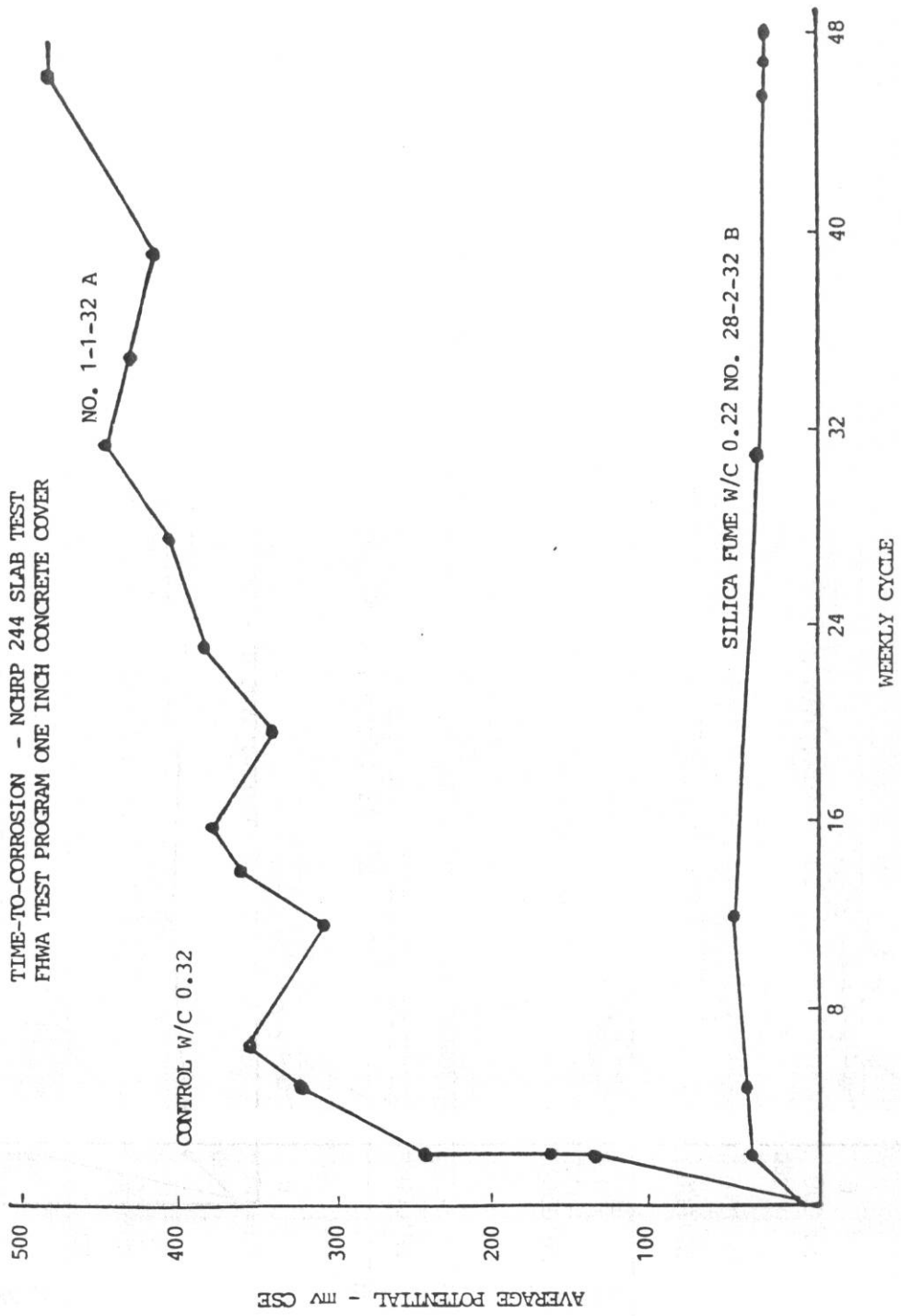
Fig. 13--Half cell potential top mat rebar

CHLORIDE ION CONTENT AT 1-INCH DEPTH (AS A PERCENTAGE OF TOTAL CONCRETE WEIGHT)

CHLORIDE ION CONTENT (BY % OF CONCRETE WEIGHT)

.200
.190
.180
.170
.160
.150
.140
.130
.120
.110
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010

.178%

AASHTO CONTROL

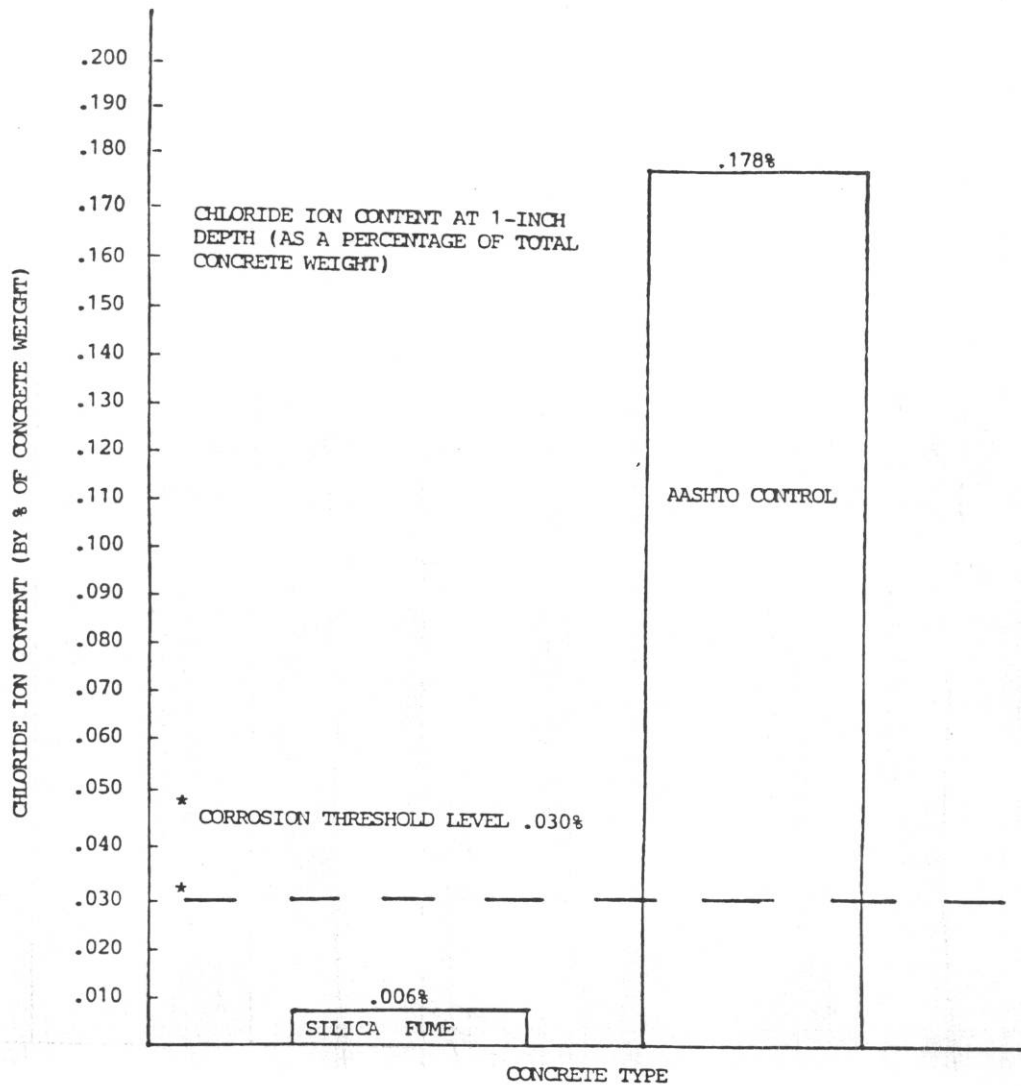* CORROSION THRESHOLD LEVEL .030%

*

.006%

SILICA FUME

CONCRETE TYPE
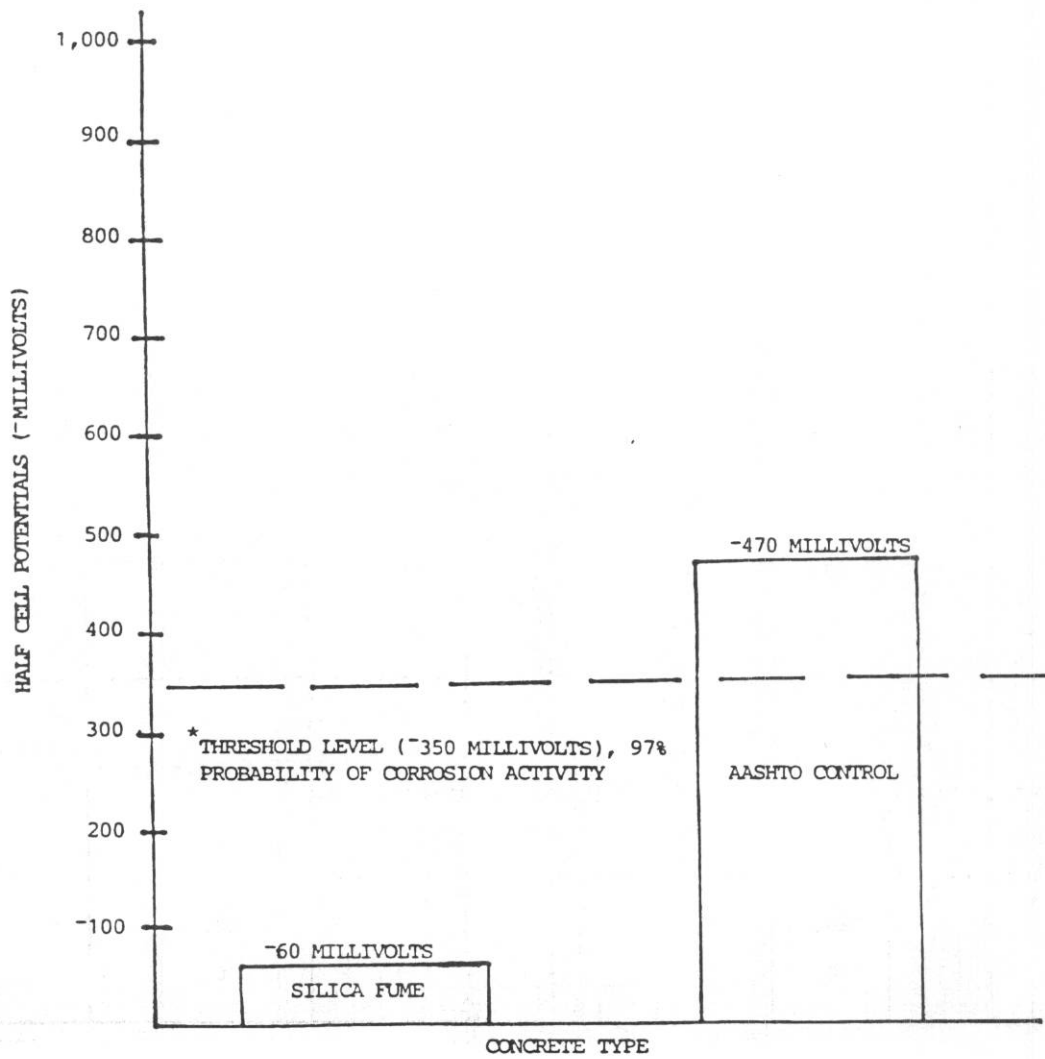
Fig. 14--Chloride ion penetration FHWA full scale bridge members

Fig. 15--Half cell potentials FHWA full scale bridge members