DURABILIDAD A LARGO PLAZO DEL CONCRETO ESTRUCTURAL CON MICROSILICA, CONCRETO LANZADO, MORTERO DE AGREGADO FINO, LOSA PARA CUBIERTAS Y PARCHES

por

John Wolsiefer y Ken Clear

Sinopsis: La microsílica previene la corrosión del acero de refuerzo en el concreto mediante la disminución de la permeabilidad al ion cloro y el aumento de la resistividad eléctrica. Los programas de ensaye de campo a largo plazo fueron llevados a cabo para concreto estructural, concreto lanzado, mortero de agregado fino, losa para cubiertas y parches de concreto. Los resultados de los ensayes muestran que el concreto con microsílica, concretos lanzados y morteros de agregado finos exhibían un aumento en la resistencia, muy baja permeabilidad, muy alta resistividad eléctrica, excelente resistencia a la adhesión y durabilidad al congelamiento y descongelamiento. Los parámetros positivos de durabilidad aumentan con el tiempo, dando como resultado un concreto extremadamente durable en ambientes agresivos con ion cloro.

Palabras clave: Durabilidad, microsílica, rápida permeabilidad al ion cloro, resistividad eléctrica, concreto estructural, concreto ligero, concreto lanzado, mortero de agregado fino, parchado del concréto, cubiertas de concreto.

LONG TERM DURABILITY OF SILICA FUME STRUCTURAL CONCRETE, SHOTCRETE, GROUT, SLAB OVERLAYS AND PATCHES

by

John Wolsiefer and Ken Clear

Synopsis: Silica fume prevents reinforcing steel corrosion in concrete by decreasing chloride permeability and increasing electrical resistency. Long term field test programs were conducted for structural concrete, shotcrete, grout, slab overlays and concrete patches. The test results show that silica fume concrete, shotcretes, and grouts exhibits increased strength, very low permeability very high electrical resistivity, excellent bond strength and freeze/thaw durability. The positive durability parameters increases with time, giving an extremely durable concrete in aggressive chloride environments.

Keywords: Durability, silica fume, rapid chloride permeability, electrical resistivity, structural concrete, lightweight concrete, shotcrete, grout, concrete patching, concrete overlays.

JOHN WOLSIEFER, SR. is President of Norcem Concrete Products, a silica fume manufacturer. He has 19 years experience, including past CEO positions, in consulting, ready mix and construction. He has a B.S. Applied Physics, a M.S. Management Engineering, and is a member of ACI, ASTM, and committees: ACI 363, High Strength; ACI 234, Silica Fume; and ASTM F12.8, Protective Containment Structures. He has given numerous presentations, authored papers on silica fume, and made a significant contribution to the development of silica fume concrete technology.

KENNETH C. CLEAR obtained a B.S. and M.S. in Civil Engineering at Pennsylvania State University. He spent 11 years heavily involved in the Federal Highway Administration's programs aimed at the elimination of premature bridge deck deterioration and his "Time-to-Corrosion" research efforts provided valuable information on the effect of concrete mix design, construction techniques and special treatments on salt penetration into concrete and subsequent corrosion of the reinforcing steel. Mr. Clear is a member of ASTM, NACE, ASCE, TRB, an ACI Fellow and received the 1987 Corrosion Award at the Mather International Conference on Concrete Durability.

INTRODUCTION

Since the mid 70's, silica fume has been used in the United States as a means of enhancing the durability of concretes and grouts. The initial uses were in the chemical industry, where increased resistance to acid was required. Beginning in about 1980, the authors began to consider silica fume (dry, uncompacted, in concert with superplasticizer) as a means of significantly decreasing the chloride permeability of concrete and increasing its electrical resistivity. The need for improved concrete properties, is related to corrosion of the reinforcement, as a result of exposure to deicing salt or marine environments. Conventional concretes and grouts exhibit relatively high permeability and low resistivity. The chloride, once present at the reinforcing level at a concentration of about 1.3 lbs/cy (0.77 kg/m³) or 0.035% by weight of concrete, destroys the passive film on the steel and acts as a catalyst, in a cancerous process, which results in concrete cracking, delamination (undersurface fractures at the level of the steel) and spalling. In some structures, the metal loss caused by corrosion can be significant and lead to structural performance problems. Many millions of dollars have been expended in the last two decades to rehabilitate existing bridge and parking decks and to provide protective systems for new structures. This paper summarizes our findings in select laboratory, outdoor exposure and field efforts in the last 13 years.

Initial Laboratory Test Programs

In the early 1980's, the authors initiated laboratory test programs to evaluate the potential of silica fume concrete to prevent chloride induced reinforcing steel corrosion in concrete. One of the first tests performed was that of the Federal Highway Administration (FHWA) 90 day chloride ponding test, which measured chloride ion penetration by ponding 3% NaCl onto concrete. This work showed that silica fume concrete mixes (20% by weight of cement) could reduce chloride penetration, by 98% compared to the control.' Another early test was the National Cooperative Highway Research Program (NCHRP) cube test, which measured water absorption and chloride penetration, under air dry, chloride soak cycles. The test data showed that silica fume mixes (20% by weight of cement) reduced the percent absorbed chloride to 16% of the control.' The time period to conduct these test procedures proved too long and AASHTO T277-83, "The Standard Method of Test for Rapid Determination of Chloride Permeability of Concrete" was then adopted to measure the performance potential, of silica fume concrete. Briefly, the test involves (1) trimming a 4-inch diameter core or cylinder to a 2-inch length, (2) vacuum saturation and overnight soak, (3) the sealing of the core in a permeability cell, with electrodes and specific solutions on each side, and (4) the application of 60 volts DC for 6 hours. The coulombs (amp-sec) of total charge passed is determined and has been correlated with chloride permeability. The lower the charge passed the lower the permeability. Resistivity, another important material property, which affects corrosion rate, can also be estimated, in this test, by measuring the AC resistance between the two electrodes prior to test start and converting to resistivity, using an experimentally defined cell constant. The resistivity, when measured in this way at 70°F is referred to as the wet resistivity because of the vacuum saturation and soak. Conventional concrete typically yields a charge passed in excess of 2000 coulombs and a wet resistivity less than 10,000 ohm-cm. The relatively high permeability allows chloride, from the environment, to readily penetrate, and the relatively low resistivity allows corrosion to continue (in the presence of oxygen) at a high rate. Thus, for maximum corrosion control, a concrete should exhibit very low permeability, but very high resistivity.

Initial Field Test Program:

During this time period, the primary use of silica fume in the United States, was the protection of concrete from chemical attack. The concrete deterioration was two fold, (1) cement paste failure due to acid and (2) reinforcing steel corrosion and concrete delamination due to salt penetration. As a silica fume admixture (dry silica fume and super at 20% by weight of cement) was performing well, in the chemical environment, an existing project with four years of service, was chosen for concrete field evaluation. Cores were extracted from a bulk storage fertilizer warehouse floor, (prilled ammonium nitrate fertilizer with a pH of 5.8 and a concentration of about 98 percent). The warehouse silica fume field concrete had a water/cement + silica fume (W/C + S) ratio of 0.35, 550 pounds of portland cement per cubic yard (325 kg/m³) and 110 pounds (0.65 kg/m³) of silica fume per cubic yard. The concrete was air-entrained and had a placement slump of 5 to 7 inches (127 to 178 mm). The RPT tests, performed in 1983, yielded results varying from 154 to 333 coulombs and averaging 226 coulombs. The wet concrete resistivities ranged from 52,000 to 107,000 ohm-cm. This resistivity range is the area, in which, most agree that corrosion problems will be minimal. Thus, this and other field testing confirmed that the dry silica fume/superplasticizer combination, that was performing well in the chemical environment, had the potential to provide a field concrete of very low permeability and high resistivity, suitable for concrete in chloride environments.

Long Term Structural Concrete Test Program:

A laboratory and outdoor exposure test program was initiated in 1982 to study the characteristics of silica fume concrete and continues today. Task 1 of the program involved the fabrication and testing of specimens using the two high strength silica fume concrete mix designs shown below:

SF Mix 1: W/C+S = 0.28
750 lbs cement/cy (441 kg/m³)
150 lbs silica fume admixture (88.5 kg/m³)

SF Mix 2: W/C+S = 0.22
1000 lbs. cement/cy (590 kg/m³)
200 lbs. silica fume admixture (118 kg/m³)

Normal weight aggregates were used in this part of the program. A conventional concrete (W/C = 0.50 and 615 lbs cement/cy [363 kg/m³]) was included for comparison. The average moist cured concrete compressive strengths were:

Concrete	Compressive Strength, psi (Mpa)		
	7 Day	28 Day	90 Day
Conventional	2,944 (20.3)	4,257 (29.4)	5,911 (40.7)
SF Mix 1	7,162 (40.4)	11,110 (76.6)	12,449 (85.9)
SF Mix 2	8,912 (61.5)	13,240 (91.3)	14,282 (98.5)

Concrete slabs were cast from each mix and cured in a fog room. Rapid permeability tests were run on portions of the cores from two slabs representing each mix (6 cores per variable) between 60 and 90 days of age. Average results ere as follows:

Concrete	Charged Passed coulombs	Wet Resistivity ohm-cm
Conventional	6,480	6,850
SF Mix 1	55	372,000
SF Mix 2	43	417,000

The silica fume structural concretes exhibited negligible permeabilities and extremely high resistivities, even when water saturated. At these levels of permeability and resistivity, it is doubtful that corrosion could be a problem in the long term. To confirm

this, concrete slabs with two mats of reinforcing steel (1-inch [25.4 mm] cover) and the above concrete mix designs were cast, cured and subjected to 24 weeks of NCHRP 244 southern exposure testing (Figure 1). Each weekly cycle consists of 4 days of ponding with 15 percent sodium chloride solution at 70°F, and three days unponded at 100°F. Figure 2 shows the macrocell corrosion current densities measured during this test series. Corrosion of the reinforcing steel in the conventional concrete was initiated after only 4 weekly cycles, but no corrosion occurred on the steel in any of the slabs containing silica fume. After the 23 weekly cycles, the resistivity (70°F) of the concrete between the two rebar mats in each slab was determined. The average values for each variable were:

Concrete	Mat to Mat Resistivity, ohm-cm
Conventional	19,500
SF Mix 1	440,000
SF Mix 2	673,000

These data show that the silica fume concretes exhibited resistivities which were much more higher (22 to 34 times higher), than that of the conventional concrete. All these resistivities are higher than those given above in the case of the rapid permeability tests (RPTs). Such occurs because the RPT test resistivity is a wet resistivity, whereas, the concrete in the test slabs is not saturated with water. Chloride analyses results after the 24 southern exposure cycles are shown in Figure 3. The conventional concrete underwent significant chloride penetration, whereas, the silica fume concretes did not. The conventional concrete slab testing was discontinued because rust staining and concrete cracking had begun. Autopsy showed severe corrosion of the top mat reinforcing. No rust staining, cracking, corrosive half cell potentials or macrocell current was present on any of the silica fume concrete specimens. Because of the good performance, the silica fume concrete slabs were subjected to another 24 weekly cycles of southern exposure. During these additional cycles, no corrosion occurred on any of the silica fume concrete slabs (see Figure 2). The slabs were then transferred to above ground racks at the KCC INC. outdoor exposure facility, in Virginia, where they have been subject to natural weathering, including freezing and thawing for about 8 years. No surface scaling, cracking, rust staining or other deterioration has occurred. Corrosion performance has been monitored using half cell potentials (ASTM C876), macrocell corrosion measurements and mat to mat resistance measurements. Also, in 1992, cores were extracted from one slab representing each variable and analyzed for chloride, permeability and resistivity. The resistivity of the SF Mix 1 concrete slabs has averaged 613,000 ohm-cm during outdoor exposure, and that for the SF Mix 2 slabs has averaged 1,050,000 ohm-cm. No significant decreases in resistivity with time have occurred on any of the silica fume concrete slabs; indicating that no deterioration of the corrosion resisting properties has occurred during the 8+ years of exposure. All half cell potentials have been more positive than -200 mV CSE, indicating a very high probability of no steel corrosion. Mat to mat macrocell corrosion currents have been zeroon all slabs throughout the eight years of outdoor exposure. Examination of the reinforcing steel extracted from the cores and the concrete traces showed conclusively that no corrosion had occurred. Chloride analyses in March 1992, indicated that very little chloride had penetrated the concretes (about 1.3 lbs/cy [0.77 kg/m³] or 0.035% by weight of concrete, is required to induce corrosion), as follows:

Sampling Depth, inches (mm)	Chloride, % by Weight of Concrete SF Mix 1	SF Mix 2
1/16 (1.6) to 0.5 (12.7)	0.0051	0.0032
0.5 (12.7) to 1 (25.4)	0.0017	0.0013
1 (25.4) to 1.5 (38.1)	0.0005	0.0008

Obviously, very, very little chloride penetrated these silica fume concretes during the 48 weeks of southern exposure (ponding 4 days of each week with 15 percent NaCl solution); and what little did penetrate, did not migrate deeply into the concrete during the subsequent 8 years of outdoor exposure. Carbonation depths are less than 1/16-inch and the material remains high pH throughout its thickness. Comparing these results to those in Figure 2 for the conventional concrete, after only 24 weeks of southern exposure, highlights the great superiority of the silica fume concretes. The results of the rapid permeability tests on cores from the slabs (9 years of age) were as follows:

Concrete	Charge Passed coulombs	Wet Resistivity ohm-cm
SF Mix 1	48	374,000
SF Mix 2	3	1,539,000

These values represent the lowest permeabilities and the highest wet resistivities of any concrete containing portland cement studied in the KCC INC laboratories in 10 years. Obviously, there has been no deterioration of these concretes, as a result of this test program. The slab surfaces show no signs of freeze-thaw deterioration or cracking. The reinforcing steel extracted from cores showed no corrosion.

In 1986, silica fume concrete test specimens were prepared with a varying silica fume admixture dosage that was increased in discrete steps (zero to 22% by weight of cement). After 42 days of moist laboratory cure, rapid chloride permeability and wet resistivity measurements were conducted. The resultant data showed that the rapid chloride permeability decreased, while the wet electrical resistivity increased, when the silica fume admixture dosage was increased. These tests were rerun April 1992, on previously untested 2-inch (50.8 mm) slices from the same specimens, after 7 years outdoor exposure, in the KCC INC test yard. The specimens had been exposed to hundreds of freeze-thaw, wetting and drying, and heating and cooling cycles during their outdoor exposure. the rapid chloride permeabilities (RCP) and wet resistivities are presented below:

Silica Fume dosage %	RCP coulombs 1986	RCP coulombs 1992	Wet Resistivity ohm-cm 1986	Wet Resistivity ohm-cm 1992
12	100	40	197,400	449,400
15	97	36	205,800	483,000
22	50	13	352,800	1,554,000

The specimens showed no evidence of cracking or freeze-thaw damage. The data presented shows that the rapid chloride permeability has decreased in the range of 26 to 40%, while the resistivity has increased 2.3 to 4.4 times. This improvement in concrete quality is dramatic, considering the small specimen size and the large number of freeze-thaw cycles experienced yearly, in this Virginia test yard location. The field data certainly reinforces previous test results reported for freeze-thaw durability (according to ASTM C666, procedure A), at higher silica fume admixture dosages (20%)[3].

Task 2 of the program involved the use of silica fume in lightweight concrete. In 1983, three lightweight concrete mixes were studied, each with 1000 lbs of portland cement per cubic yard (590 kg/m³) and superplasticizer. Slump was maintained in the range of 4 to 6 inches (102 to 152 mm) and the maximum lightweight aggregate size was 3/4 inch (19 mm). LtWt Mix 1 was the non-air entrained lightweight structural concrete control. SF LtWt Mix 2 had 20 percent silica fume admixture (by weight of cement), and SF LtWt Mix 3 had 30 percent silica fume admixture (by weight of cement) and air-entrainment. The 90 day compressive strengths, rapid permeabilities and resistivities are presented below:

Concrete	Comp. Str, psi (Mpa)	Charge Passed, coulombs	Resistivity, ohm-cm
LtWt, non-AE	9,230 (63.7)	3,667	5,850
SF LtWt, AE	9,071 (62.6)	357	54,100
SF LtWT, non-AE	10,880 (75.0)	277	41,400

These data indicate that the addition of 20 percent dry silica fume by weight of cement will result in a lightweight structural concrete of much lower permeability and much higher resistivity. Another lightweight aggregate concrete study was performed in 1986 using a shrinkage compensating cement and dry silica fume. Trial mixes were made with lightweight aggregate, superplasticizer and 0, 10 and 20 percent silica fume by weight of cement (658 pcy [388 kg/m³] of shrinkage compensating cement). Slumps ranged from 5 to 8 inches (127 to 203 mm) and all concretes were air entrained. The properties of these concretes (strengths at 60 days, other properties are 42 days of age) are summarized below:

Concrete	Comp. Str, psi (Mpa)	Charge Passed, coulombs	Wet Resistivity ohm-cm
LtWt, KC-AE	5,490 (37.8)	3,780	7,500
10% SF LtWt, KC-AE	7,480 (51.6)	542	33,600
20% SF LtWT, KC-AE	7,878 (54.5)	364	58,800

These data show that both 10 and 20 percent silica fume additions by weight of cement greatly improve both the permeability and the resistivity properties of a shrinkage compensating cement and lightweight aggregate concrete.

Project Field Testing:

Task 3 of the structural concrete test program involved quality control monitoring and outdoor exposure of concrete cylinders cast on field projects in which dry silica fume and superplasticizer were incorporated in parking deck concretes and marine loading docks throughout the United States. Approximately 15 projects were monitored over a five year period. Select examples are presented below.

A marine transfer terminal in New York was reconstructed in late 1986, using silica fume concrete. This project encompassed the encapsulation and repair of pile caps underwater, by tremie method, overlay of a ramp roadway and tipping platform subjected to truck traffic and the construction of a new ramp bridge with piles, beams and full depth roadway. The silica fume concrete mix design had a 750 lb/yd³ (441 kg/m³) cement factor with a silica fume admixture weighing 165 lbs/yd³ (90 kg/m³). The compressive strength averaged 11,430 (78.8 Mpa) psi at 56 days with 6% air entrainment. The 42 day charge passed on field cylinders cast in February 198 (laboratory moist cure) averaged 183 coulombs and the wet resistivity averaged 77,175 ohm-cm. Other portions of these specimens were boil cured to provide an indication of the long term permeability, of this concrete, after additional curing time. The average charge passed was 56 coulombs and the average wet resistivity was 358,000 ohm-cm. Examination of this structure in 1990 showed that both the rehabilitated and new silica fume concrete was performing well.

A prestressed parking deck was constructed in New Jersey in 1988. Eleven percent silica fume was utilized, with a cement content of 658 lb/yd³ (388 kg/m³) and the W/C+S ratio was 0.34. The charge passed, on boil cured field cylinders, averaged 517 coulombs and the wet resistivity averaged 46,700 ohm-cm.

A prestressed Missouri airport terminal parking garage, constructed in 1988, utilized 10.5 percent dry, compacted silica fume. Superplasticizer was used and the W/C+S ratio was 0.32. The average charge passed for 32 ninety day field cores was 30 coulombs. The wet resistivities were in excess of 45,000 ohm-cm.

Silica fume admixture in concrete was used in 1983 in construction of a one mile long channel at a New York State power station. The 14 foot (4.3m) wide channel encircled a coal storage pile (on plastic liner), and was utilized to channel sulfuric acid run-off to a neutralization pond. The silica fume concrete mix design had a 750 lb/yd³ (441 kg/m³) cement factor, and a 165/yd³ (97.4 kg/m³) silica fume admixture (SF 20% by weight of cement). Cores were extracted from the completed structure and tested in RPT. The average charge passed for two cores was 252 coulombs and the average wet resistivity was 72,000 ohm-cm. Conversations with a plant supervisor, in 1991, indicated the channel was in good condition.

Silica Fume Grout:

Silica fume was first considered, by the authors as a means of decreasing the permeability and increasing the resistivity of portland cement grout in 1982. A Maryland parking deck rehabilitation required the installation and grouting of steel collars, on select beam/column connections, because stirrup steel had not been properly used during construction. Through the garage's 10 years of service life, the prestressed beams had shortened and were becoming separated from the columns. Severe chloride contamination had occurred at the beam/column connections as a result of improper calcium chloride additions during construction, and/or deicing salt leakage. The structural detail desired was a steel collar, surrounding both the beam end and the top portion of the column (see Figure 4), which was bolted in place to the existing concrete. Because of the high concentration of steel in the concrete, preventing electrical contact between the collar and the reinforcing was impractical. Thus, once the grout was placed, it was feared that the inside steel surface of the collar would be cathodic to the reinforcing and prestressing steels, in the structure and greatly increase their corrosion rates. The only viable means of avoiding this was to increase the grout resistivity to an extremely high value. The cost of doing so with polymer mortar was prohibitive. A commercially available non-shrink grout (sand/cement grout) was tested and found to exhibit low wet resistivity. Therefore, a program of modifying the grout with dry, uncompacted silica fume was undertaken. A twenty percent dry silica fume admixture (silica fume and superplasticizer) was added by weight of cement to the grout. The water content of the mix was adjusted for equal grout flow and tests were conducted to determine placement time (workability loss with time), strength, permeability and resistivity. A mini-slump cone with measurements of slump and spread was used to define workability with time. The mix water for equal flow and pumpability was reduced by 25 percent, when the silica fume admixture was added. The working time (considered as the time until 50% loss in slump or spread) was increased, from 30 minutes for the commercial grout, to 45 minutes for the silica fume modified grout. The 28 day moist cured cylinder strength was 6,197 psi (42.7 Mpa) for the commercial grout and 8,300 psi (57.2 Mpa), for the silica fume modified grout. The permeability and resistivity findings (averages, 60 day water cure) were as follows: