Grout	Charge Passed coulombs	Wet Resistivity ohm-cm
Commercial	14,390	3,400
SF Modified	116	195,000

Obviously, the silica fume admixture greatly improved the corrosion resisting properties of the grout. The permeability was reduced by 99 percent and the resistivity was increased 5,700 percent (i.e. 57 times). The modified grout was successfully used to grout all the collars on the parking garage in 1983. The material was prepackaged such that one bag of commercial sand-cement grout, one bag of silica fume admixture and 1 gallon (3.8 L) of water was mixed in a mortar mixer. The mixed grout was placed in the pump hopper and pumped with normal grouting equipment. Quality control in the field was accomplished using "resistivity cups" (100ml plastic beakers fitted with four platinized wires). A grout sample was made from each batch, covered with plastic for one day and then placed in limewater. By monitoring the AC resistance with time and converting this to resistivity using the experimentally determined cell constant, it was determined that the field grout provided a cured resistivity in excess of 75,000 ohm-cm in all cases. The beam/column connections were inspected in 1990, seven years after installation. All collars remained in place with no signs of grout or surrounding concrete deterioration.

A second silica fume grout project was undertaken in 1986 for the purpose of grouting prestressed tieback anchors (in acid soil), for a highway retaining wall, located in Virginia. Both portland cement and cement-sand grout were studied and modified with 20 percent silica fume and powdered superplasticizer. Approximately 87 tieback anchors, 9 inches (22.9 cm) in diameter and 50 feet (15m) long were involved in this project. Grout consistency was defined using a flow cone time (ASTM C939) in the range of 15 to 30 seconds. Because of the short time span for project implementation, it was necessary to use autogenous curing to accelerate all tests. This was accomplished in accordance with ASTM C684. The silica fume grout utilized significant superplasticizer and had a W/C+S ratio of 0.33, while the control portland cement grout had a W/C ratio of 0.40. The average permeabilities and resistivities of the various grouts are given below:

Grout	Charge Passed coulombs	Wet Resistivity ohm-cm
Portland Cement	32,097	960
20% SF + Cement	260	58,000
20% SF, Sand/Cement	134	147,000

The portland cement grout had very high permeability and very low resistivity. A limewater cured sample at 21 days of age exhibited a charge passed of 20,600 coulombs and a resistivity of 2,900 ohm-cm. Although slightly better, these values will provide little protection against ingress of adverse ions and corrosion. The high shrinkage of the

portland cement grout is one cause of the high permeability. The best grout was obviously the 20% silica fume, Sand/Cement Grout (2.9 sand/cement ratio by weight); probably because of reduced shrinkage. Seven day compressive strengths of the silica fume grouts ranged from 6,500 (44.9) to 10,000 psi (69 Mpa). A 20% silica fume + cement grout (with superplasticizer) was used on the field project. The 3 day accelerated cure compressive strength of a sample obtained from the first trial field batch was 10,250 psi (70.7 Mpa); and the 21 day limewater cured permeability averaged 121 coulombs. The estimated resistivity averaged 163,000 ohm-cm at 21 days. The water for use in this trial batch was determined manually. Quality control on this project also involved the use of accelerated cured resistivity specimens indicated that a high quality material was not being made. The problem was traced to a faulty water meter, which was inputting 6.2 gallons (24 L) of water but only registering 3 gallons (11.5 L) which was then corrected. This experience certainly emphasizes the value of using resistivity and accelerated curing in quality control programs.

Silica Fume Shotcrete:

Shotcrete modified silica fume admixture (20 percent by weight of cement) was used to repair beam and column damage as a result of corrosion, induced by magnesium chloride manufacturing, in a Texas chemical plant. In 1983, cores were obtained from the completed project and the permeability and resistivity were defined. The average charge passed (3 specimens) was 128 coulombs, and the average wet resistivity was 184,000 ohm-cm. Conventional shotcrete tested in another program exhibited an average charge passed of 6,800 coulombs and an average wet resistivity of 2,750 ohm-cm.[2] Obviously, shotcrete durability properties, in adverse chloride environments, are improved greatly when 20% silica fume is used. A check with the company engineer in 1991, showed that the column and beam members, repaired with silica fume shotcrete, have performed well (over 8 years), with no additional repair required. A large shotcrete test program was completed in April 1991, which evaluated different silica fume product forms, for both wet and dry shotcrete.[2] Parameters measured were; shooting characteristics, plastic properties, strength, shrinkage, absorption, permeability and resistivity.

Test Program for Silica Fume Concrete for Patching:

Because of the high resistivity of silica fume concrete, its use was considered in parking garage patching in the mid 1980's. One major problem when patching a salt-contaminated structure, is the effect of the patched area on corrosion of the steel in the remaining salty concrete. The steel corrosion rate is very dependant upon oxygen reduction at the cathode. The cathode is the non-corroding side of the corrosion battery where the electrons released at the corroding site (anode) are consumed. When deteriorated concrete is removed, the rebar is cleaned and a normal concrete patch is placed, a new cathode is created. This tends to concentrate corrosion in the unpatched concrete directly around the patch and often results in premature failure there; and is the cause of the so called "ring effect" or "spall around a spall" phenomenon. Silica fume concrete had the potential to minimize this effect because its very high resistivity prevents steel in the patched area from coupling electrically with the steel in the original concrete by minimizing ion flow between the steel in the two areas. To confirm this hypothesis, concrete slabs with four corroding rebars in the top mat, were rehabilitated such that the concrete surrounding bars 1 and 4 (i.e. the outside bars) was removed (see Figure 5). The area with bar 1 was patched with silica fume concrete containing 20 percent fume by weight of cement, and the area around bar 4 was patched using a latex modified concrete (styrene-butadiene, 15% latex solids by weight of cement). Conventional concrete patches were not studied, since it was known that they would perform poorly (the resistivity of conventional concrete is less than that of latex modified concrete). Since the four top mat bars were not continuous within the concrete, they were rewired such that the actual electrons of corrosion could be measured via an external resistor. Portions of two slabs were patched with silica fume concrete and other portions were patched with latex modified concrete. Bars 1 and 2 (i.e. latex patch to original salty concrete) were so interconnected, as were bars 3 and 4 (salty original concrete to silica fume patch). Upon completion of the patches and wiring and three days of moist curing the slabs were exposed on above-ground racks at the KCC INC outdoor exposure facility in Virginia. Monthly, the corrosion of each patch-original concrete cell was monitored using macrocell corrosion measurements, half-cell potential measurements and AC resistance measurements. Monitoring began in October 1983 and continued thru April 1992 (i.e. 8.5 years). The average macrocell corrosion currents and the concrete resistance between the two test bars for each cell and patch material during the 8.5 years of testing are presented below.

Patch Concrete	Avg. Macrocell Corrosion Current microAmps	Avg. Concrete Resistance ohms
Latex Modified	58	760
20% Silica Fume	23	3,685

Thus, this 8.5 year test program shows that the best concrete for use in minimizing the aggravation of corrosion during patching is a silica fume concrete. For 20 percent silica fume patching, the corrosion current will be about 3 times less than if latex modified concrete is used. This will extend the time until corrosion induced cracking of the steel in the remaining salty concrete, but will not, of course, completely stop it; because, self corrosion of that steel and other macrocells (ex. bottom mat steel cathodes) continue to plaque the structure. In this test program, it was not possible to directly (i.e. visually) compare the times to cracking because the bars in salty concrete had undergone an unknown, but undoubtedly differing amount of corrosion prior to patching. Such was not necessary however, since it is known that the time to corrosion induced distress is proportional to macrocell current and will also increase the time to distress. This is shown in Figure 6 in which the cumulative macrocell current-time is plotted, for each patch material. The "cumulative macrocell current" is the area under a plot of corrosion current versus time (expressed as mA-yrs/sq ft), and is the measure which directly relates to corrosion, until concrete cracking. It is actually a current density-time relation and is expressed

per square foot of macroanode to allow comparison of data, for different specimen configurations. Other studies at KCC INC have shown that severe cracking of conventional concrete occurs at a cumulative macrocell current density-time of about 2 mA-yrs/sq ft. The latex modified concrete patch reached this value (on the average) after about 4 years. The silica fume concrete patch did not reach 2 mA-yrs/sq ft, during the 8.5 years of testing. Projecting forward, about 12 years would be required. This 8 years of increased life is quite significant. The silica fume patch material used in the above studies had 20 percent silica fume by weight of cement, 750 lbs (441 Kg/m³) of cement per cubic yard, and a W/C+S ratio of 0.28. A prepackaged patch material was produced in 1986 and it was tested in the KCC INC laboratories. The mix contained dry uncompacted silica fume, superplasticizer and air entraining agent, plus dry sand, stone and portland cement. Only water was added when the material was mixed. The slump was 8 to 10 inches, (19.6 to 25.4 mm), the unit weight was 134.4 pcf and the air content was 5.7 percent. Rapid permeability and resistivity tests were performed on cylinders subjected to accelerated curing (autogenous container), to a limewater cure of 6 days and to a limewater cure of 28 days followed by 18 days of outdoor exposure (46 days of age). the average permeabilities and resistivities are presented below:

Cure	Charge Passed coulombs	Wet Resistivity ohm-cm
Accelerated	66	340,000
6 Day Limewater	938	29,400
45 Day (LW + Air)	354	64,000

The untested cylinders were placed under natural weathering exposure at the KCC INC outdoor facility in Virginia. After 5 years, they were retested for permeability and resistivity. The average charge passed was 59 coulombs and the average wet resistivity was 394,800 ohm-cm, after exposure to hundreds of freeze-thaw, wetting and drying, and heating and cooling cycles.

Field Projects; Silica Fume Concrete Patching:

Field projects involving patching of parking decks and other structures with silica fume concrete began in 1985 with work in Ohio, Illinois and Missouri. In all cases except the first, twenty percent silica fume admixture (dry silica fume and superplasticizer) was added by the bag to ready mix concrete on site. The mix design was typically 750 lbs/yd³ (441 kg/m³) of cement with 165 lbs/yd³ (97 kg/m³) of silica fume admixture. The findings from the quality assurance programs on select project are discussed below.

The Illinois project involved prepackaged patching material for use in night-shift patching of a high-rise office building (the lightweight concrete was placed with calcium chloride and thick sections covered with tile were badly delaminated, over the reinforcing steel). On one night shift, the floor covering and the deteriorated concrete were removed and the area was covered with plywood for use the next day. The next night the plywood was removed, the concrete prepared by wetting, the prepackaged material was combined with one gallon (3.8 L) of water in a small "wheelbarrow" rotary drum mixer, mixed and then placed, consolidated, finished and recovered with plastic and plywood for use of the area the following day. After 3 days of curing, the plywood was removed and carpet tiles were installed (again at night). Thus, the patching was completed without loss of space use to the tenants. A freight elevator was used as the staging area and for material and equipment storage during the day. Resistivity specimens made from prepackaged material and subjected to a similar curing sequence, exhibited a 21 day resistivity which averaged 313,500 ohm-cm. This project started in 1985 and is still an ongoing application. After 7 years, the owners are still using the material and report satisfactory performance from the patched concrete.

This 1986 project in Ohio involved ready-mix silica fume concrete for patching a parking deck. .The 40 day (28 day moist and 12 day lab air cure) field cylinders exhibited an average charge passed of 164 coulombs, with a range of 87 to 242 coulombs. The average wet resistivity was 86,829 ohm-cm, with a range of 56,700 to 147,000 ohm-cm. One cylinder was made prior to the addition of silica fume to a mix. This specimen showed a charged passed of 1,696 coulombs and a wet resistivity of 11,550 ohm-cm. The patches have now been in service on this structure for about 5.5 years (a membrane was installed to prevent additional chloride ingress into the unpatched areas). The project engineering consultant, THP Limited, reports excellent performance with no additional repair required to date. They also report similar satisfactory performance on four other silica fume concrete parking garage patching efforts.

Silica fume parking garage patching was specified in Missouri by Structural Engineering Associates (SEA) in 1986 as a substitute for latex modified concrete. The procedures and mixes were similar to those used in Ohio and these decks were also covered with waterproof membranes. SEA engineers indicated in 1992 that they were pleased with the performance of the silica fume patches and believed they performed better than latex modified concrete in that less additional delamination developed with time, when silica fume patching was used. Such, of course, agrees with the findings of the long term outdoor exposure study described above.

FHWA Silica Fume Concrete Test Program:

Silica fume concrete overlays were included in the United States Federal Highway Administration (FHWA) Time-to-Corrosion Rehabilitation studies in 1984.[4-6] The original 20 sq ft (1.86 m^2) Time-to-Corrosion slabs were cast, in 1971, as part of the FHWA research program to combat premature bridge deck deterioration. The slabs were salted daily, with 3 percent sodium chloride solution, for several years and then monitored throughout the 1970's. At nine years of age, the 0.50 water-cement ratio slabs, with one inch (25.4 mm) cover, all exhibited corrosion damage in the form of rust staining, cracking,

delamination and spalling. The slabs originally contained only a top mat of reinforcing steel.

To facilitate use in rehabilitation studies, a bottom mat of steel in salt free concrete (W/C = 0.50) was added, as well as, select instrumentation (resistivity monitoring and rate of corrosion probes). All delaminations and spalls were patched with 0.50 W/C concrete or mortar and then, various rehabilitation overlays, membranes and sealers were placed on all slabs, except for select controls. The effect of the rehabilitations, on continued corrosion in the originally sound, but salty concrete, has been monitored. The measurements include macrocell corrosion current, half cell potential and resistance and temperature, as well as visual and delamination surveys. In 1980, the original rehabilitation series was initiated. This included latex modified concrete (cracked and uncracked), low W/C (0.32) conventional concrete, 0.45 W/C conventional concrete and internally sealed concrete overlays. Silica fume concrete overlays were added in 1984.

The silica fume (twenty percent by weight of cement) concrete was made using dry, uncompacted silica fume and superplasticizer. The cement content was 750 lbs/cy (441 kg/m) and a vinsol resin air entraining agent was used to provide a six percent entrained air. The coarse aggregate was Riverton limestone, 1/2 inch (12.7 mm) maximum size meeting AASHTO M43 size no. 7. The overlays were two inches (50.8 mm) thick and were placed, onto the damp concrete surface, after placement of a cement slurry bonding agent. The overlay concrete was consolidated using a vibrating screed, wood floated, broomed and cured for 3 days, using wet burlap and plastic. Two Time-to-Corrosion slabs were overlaid. Rapid permeability tests, at 35 days of age on cores (four total), from field cured companion slabs, averaged 520 coulombs and the resistivity averaged 41,000 ohm-cm. After 2.5 years of exposure at the FHWA outdoor test facility, in McLean, Virginia, the overlays were evaluated for soundness, permeability, resistivity and bond strength. Three cores containing overlay and base concrete were obtained from each slab. No delaminations, or overlay debonding had occurred, on either of the silica fume concrete slabs. No freeze-thaw or other damage was seen, except for very small, short shrinkage cracks which had formed during curing. The cracks had not increased in size or severity since the curing was removed 2.5 years earlier. The charge passed, averaged 92 coulombs with 5 of the 6 specimens yielding values of less than 100 coulombs. The average wet resistivity was 22,000 ohm-cm. The overlay bond was evaluated in shear. Shear breaks were preformed at the bond line, in the original base concrete, and in the silica fume concrete. The findings are summarized below.

Shear Plane	Shear Strength, psi (Mpa)	
	Average	Range
Base Concrete	1,075 (7.4)	942 to 1,250 (6.5-8.6)
Bond line	1,238 (8.5)	1,159 to 1,377 (8.0-9.5)
Silica Fume concrete	1,214 (8.4)	942 to 1,540 (6.4-10.6)

These data indicate that the overlay bond strength was excellent and greater than the shear strength of the underlying concrete.

Visual examinations, at 3.5 and 7.5 years, indicated that the overlays were in excellent condition. The small shrinkage cracks had not extended or enlarged and no freeze-thaw damage was present. Interestingly, during both surveys, the overlays on many of the other slabs (latex and conventional concrete) showed full length cracks over the top mat rebars in the original salty concrete, probably the result of continued corrosion; while the silica fume overlay slabs did not. Thus, although the silica fume concrete overlay does not halt corrosion of the steel in the underlying concrete, it does seem to physically resist the forces of continued corrosion for a longer time than that provided by the other overlay concretes which were tested.

CONCLUSIONS

1. Concretes made with 10 to 22 percent silica fume by weight of portland cement exhibit:

Very high strength

Negligible or very low permeability

Very high electrical resistivity

Excellent bond strength

Excellent freeze-thaw durability, and

provide excellent protection to embedded reinforcing steel in adverse salt environments. As these materials age they become even stronger, lower in permeability and higher in resistivity.

2. The use of concrete with 20 percent silica fume for patching structures where sound, but salty concrete will remain in place, minimizes aggravation of the corrosion process and will result in longer term performance than the use of conventional or latex modified concretes.

3. Concretes (normal and lightweight), grouts, and shotcrete, which contain from 10 to 22 percent silica fume (by weight of cement) have been successfully used in both new construction and in rehabilitation efforts, for over 10 years in the United States. The resultant materials provide the best cementitious product available for adverse environments. Although some special construction precautions are required because of the very small amount of bleed water and the overall cohesiveness of the mix, these have not prevented implementations, from either technological or cost standpoints.

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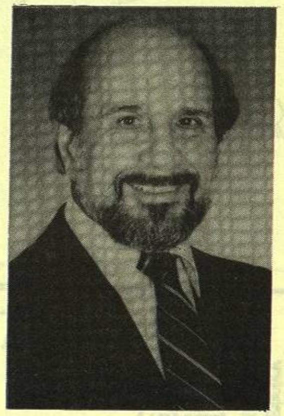

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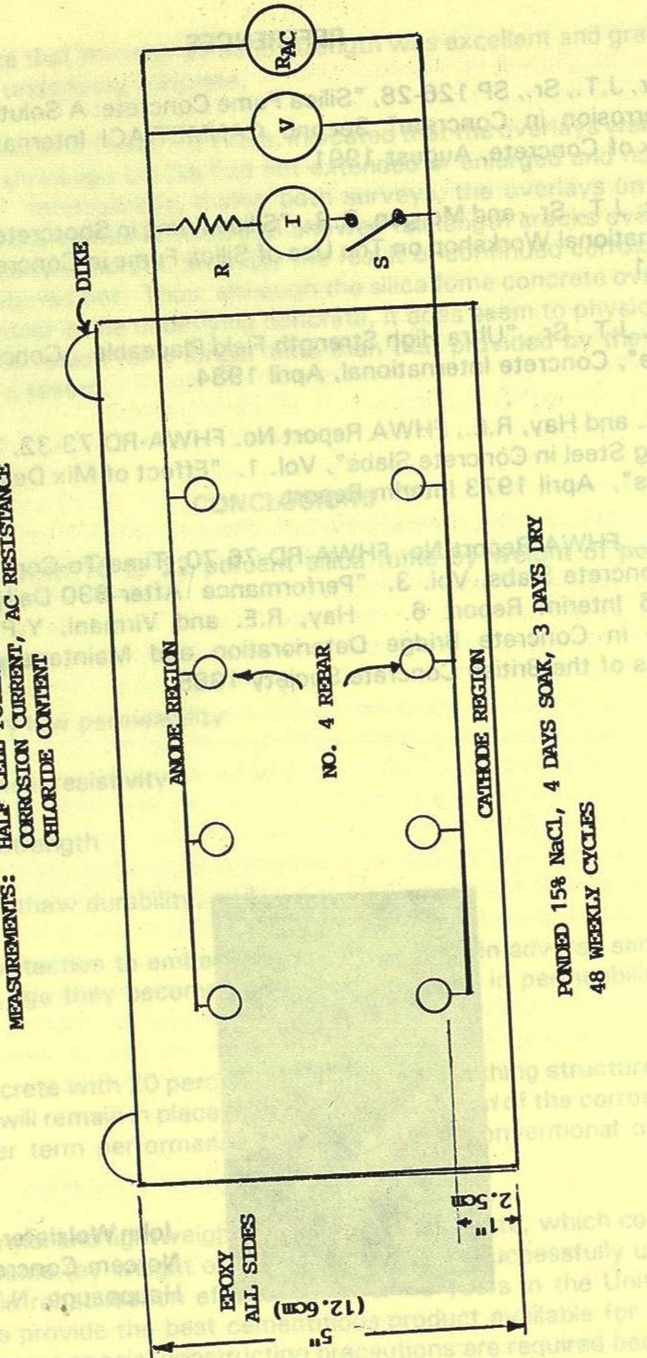

Fig. 1. Time-to-Corrosion NCHRP slab test southern exposure

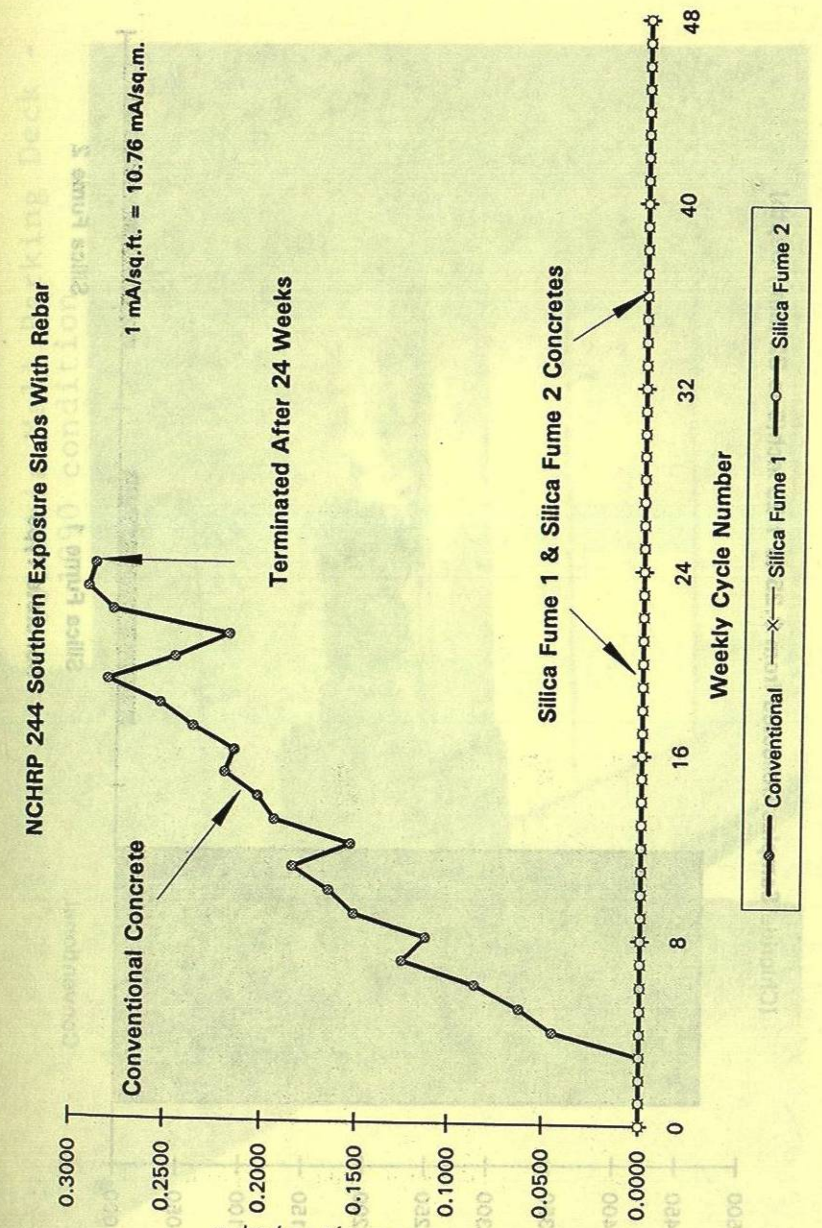

Fig 2. Macrocell Corrosion Current Density vs. Time