Addressing Parking Garage Corrosion with Silica Fume

THOMAS C. WEIL

Because it reduces chloride penetrability, silica-fume concrete is gaining popularity as a corrosion-protection system for parking garages, bridge decks, and other structures. This paper provides an overview of experience with silica-fume concrete in the United States.

Twenty-two hundred parking areas were built between the years 1979 and 1984 in what would be considered the frost belt of the United States. Of these, 630 contained 150 spaces or more (according to the McGraw-Hill Construction Group). With more than 100 of the larger structures being constructed on an annual basis, it is important that precautions be taken to protect them against deicing salt-induced corrosion. The latest exciting product to enter the corrosion protection market is silica fume (microsilica).

Concrete in a nonaggressive environment is a very strong, durable, and long-lasting building material. In aggressive environments, some precautions may be needed to protect the concrete or embedded steel. With the use of deicing salts since the early 1960s to keep our roads clear of snow and ice, concrete transportation-type structures are now under attack. Bridges and parking garages are deteriorating at an alarming rate due to chloride-induced corrosion. Bridge decks have deicing chemicals deposited directly on the surface where the chemicals affect not only the deck but also the supporting structural members due to leakage. Although deicing chemicals are used only sporadically in parking garages, cars carry salt-infested snow into the garages. Much of this salt remains after the cars leave.

Unlike bridges, however, which are washed by spring rains, parking garages are rarely washed down in the spring. The salts deposited in the winter remain all year. Indeed, when comparing concrete chloride contents of bridge decks and parking garage decks in the same location, and all other parameters being equal, the garage decks usually show a higher chloride content at all slab depths. This chloride content is due to the presence of larger amounts of chlorides on the slab surface during warmer weather. As ambient temperatures rise, chlorides are able to diffuse through the concrete pores at a greater rate of speed.

The highly alkaline environment of concrete creates a protective passivating layer on steel that inhibits the electrochemical reaction of corrosion under normal conditions. Chlorides will move through the concrete pores as well as through the transition zone between the paste and aggregate and eventually reach the embedded steel. Penetration of the passivating layer takes place, and corrosion of the steel begins. As the chloride content around the rebar increases, so does the corrosion rate. The corrosion product will expand in size by roughly four times its original volume, creating tensile pressures on the concrete up to 10,000 psi. The concrete eventually ruptures, causing cracking and spalling which allows more chlorides to enter at an even faster rate. Eventually, the concrete will deteriorate, requiring expensive rehabilitation or causing structural failure.

Obviously, steps must be taken to protect these structures against chloride-induced corrosion. Because it is very unlikely that the use of deicing salt will cease, design engineers must rely on corrosion protection methods to protect their structures. Corrosion protection in many other industries is a normal part of the design package. For reinforced concrete structures, however, it is a fairly new feature. Even so, many types of corrosion protection products are already available on the market, and most have proven their worth.

Surface sealants and membrane systems attempt to physically block chlorides from entering the concrete and prevent them from reaching the rebar. Coated reinforcing steel attempts to place a physical barrier between the concrete and steel, thus preventing the chlorides from attacking the steel. Calcium nitrite corrosion inhibitor promotes the stabilization of the steel's natural passivating layer, thereby controlling the corrosion rate. And finally, latex modifiers and silica fume reduce the permeability of the concrete, considerably slowing the ingress of chlorides. Each of these systems has a different operational mechanism, but all help extend the service life of the structure.

Silica fume is a by-product of silicon, ferrosilicon, or other silicon alloy production in a submerged arc electric furnace. It contains a silica (SiO_2) content of 85 percent or greater and has as an extremely fine particle size, which has caused some researchers to call it a "super pozzolan." The ultra-fine particle size of roughly 0.1 micrometers allows the silica fume to fill the voids in the cement paste and between the cement paste and aggregate while the pozzolanic feature causes reaction with the excess calcium hydroxide ($Ca(OH)_2$). This process results in a far less permeable microstructure matrix that appears homogeneous and that has no gaps and no large crystals of $Ca(OH)_2$ *(1).*

Fairly long-term studies *(2)* have shown that silica fume reduces the apparent diffusion coefficient of concrete by at least an order of magnitude. Other long-term salt water ponding studies at H. R. Grace & Co.'s Construction Products Division, Cambridge, Massachusetts, are beginning to corroborate these results.

W. R. Grace & Company, Construction Products Division, Cambridge, Mass.

TABLE 1 CHLORIDE PERMEABILITY BASED ON CHARGE PASSED

Charge Passed (coulombs)	Chloride Permeability	Typical Description
4,000	High	High water-cement ratio (0.6); conventional PCC
2,000—4,000	Moderate	Moderate water-cement ratio (0.4—0.5); conventional PCC
1,000—2,000	Low	Low water-cement ratio (0.4); conventional PCC
100—1,000	Very Low	Latex-modified concrete, internally sealed concrete
100	Negligible	Polymer-impregnated concrete; polymer concrete

Actual concrete permeability is a feature that cannot, unfortunately, be measured quickly for upcoming projects. In response to this problem, the Federal Highway Administration has produced a rapid test method for determining the apparent chloride permeability of various concretes (3). The 4-in.-diameter by 2-in.-thick specimens are subjected to a 60-V potential for 6 hr to measure the charge passed in coulombs. At least a dozen parameters affect the final coulomb reading, so five chloride permeability categories were created (Table 1). Coulomb readings from different samples that fall in the same category are considered to be equivalent as far as chloride permeability is concerned. Design engineers who have specified silica fume thus far required concrete coulomb readings to be in the 100—1,000 coulomb category (very low).

Some engineers believe inaccuracies exist in the FHWA test and are not specifying coulomb levels, but rather “percent silica fume by weight of cement.” Usually a specified silica fume quantity is based on prespecification testing at a local laboratory to see what amount will attain a coulomb level of 1,000 or less. As an example, tests (4) run on a 550-lb cement factor mix with a water-cement ratio of 0.45 yielded a coulomb reading of 3,600. When 7.5 percent silica fume by weight of cement was added, a coulomb reading of 850 was produced; while a 15 percent silica-fume addition gave 200 coulombs. It is not uncommon to see silica-fume specifications of 7.5 percent by weight of cement.

Besides reducing concrete chloride permeability, silica-fume concrete has many other benefits: increased abrasion and erosion resistance; increased resistance to aggressive chemical acid attack; and most importantly, compressive and flexural strength enhancement. Silica fume develops higher strength in concrete due to the same factors that reduce chloride permeability—by combining with the excess calcium hydroxide to produce more calcium silicate hydrate paste and filling the pores between the aggregate and cement grains. More paste with fewer voids creates a better bond between the aggregate, producing higher strengths. To continue the earlier example (4), the concrete mix containing a cement factor of 550 lb of type I cement with a water-cement ratio of 0.45 will produce a 28-day compressive strength of 5,500 psi. Adding 7.5 percent silica fume by weight of cement and a high-range water reducer to insure workability produces a 28-day strength of 9,500 psi. When 15 percent silica fume is added, the 28-day strength reaches 10,300 psi (Table 2). The engineer should take advantage of this increased compressive strength and design not only for reduced concrete chloride permeability but for high concrete strengths as well.

TABLE 2 CONCRETE 28-DAY COMPRESSIVE STRENGTH AND RAPID CHLORIDE PERMEABILITY

Microsilica Content (%)	Compressive Strength (psi)	Coulombs Passed
0	5,500	3,600
7 1/4	9,500	850
15	10,300	200

NOTE: Data refer to 550 lb type 1 cement, water-cement ratio *0.45.*

Due to reduced concrete chloride permeability, silica-fume concrete is gaining popularity as a major corrosion-protection system for parking garages, bridge decks, and other structures. To date, the two major silica-fume admixture suppliers have participated in the construction of 39 parking garage projects (both completed and under construction). The first silica-fume parking garage was completed in 1984, while 27 were either completed in 1986 or under construction in 1987. The average-size project contained 3,500 yd^3 of concrete, with the smallest containing 150 yd^3. The largest, 45,000 yd^3 is under construction. Dosage rates ranged from 3.75 percent silica fume by weight of cement to 16 percent with an average of 7.5 percent. Types of projects include less permeable overlays, toppings on prestressed double tees, rehabilitation ranging from large-scale patching to completed deck replacement, and standard cast-in-place new construction.

Even with all its advantages, silica-fume concrete does require extra attention during finishing and curing. Due to the cohesiveness of silica-fume concrete, it is recommended that slumps at least an inch higher than normally placed be used. Another area of caution is the reduced amount of bleed water after a slab is placed. Above a dosage rate of 5 percent silica fume by weight of cement, the bleed rate drops dramatically. As the silica-fume content increases, the bleed rate correspondingly decreases. ACI 302, Guide for Concrete Floor and Slab Construction, or ACI 3()~, Standard Practice for Curing Concrete, should be followed to reduce the possibility of plastic shrinkage cracks. Recommended procedures include fogging during finishing and wet burlap or the use of curing compounds during curing.

In 1986, a 5,000-yd^3 parking structure owned by Crown Center Redevelopment was built in Kansas City, Missouri, to hold roughly 800 cars. A concrete mix consisting of 611 pounds of cement, water-cement ratio of 0.40, 0.75-in. aggregate, 10 percent silica fume, and 7 percent entrained air was used. A superplasticizer was added to produce a 6-in. slump. The 28-day compressive strength averaged 8,000 psi, and coulomb readings averaged 400 at 90 days. The finishing and curing procedure reflected bleeding characteristics of silica-fume concrete. Screeding was performed with an aluminum screed 2 in. x 4 in. The two passes with a vibratory bullfloat were followed by two passes with a regular bullfloat; evaporation retardant was then applied; and finally, a hand-swirl finish.

The largest silica fume-protected parking structure is presently under construction. The Capitol South parking garage in Columbus, Ohio, will have spaces for 3,000 cars and needs 45,000 yd^3 of concrete. Silica-fume concrete will be used in the slabs for corrosion protection and is being combined with a calcium nitrite corrosion inhibitor in the columns for high strength (8,000 psi) and corrosion protection. The slab mix contains a 610-lb cement factor, 90 lb of fly ash, a water— cement ratio of 0.40, and 7.5 percent silica fume by weight of cement. A superplasticizer is added to attain slump. Construction is cast-in-place posttensioned. The 28-day strengths range from 7,600 to 9,000 psi, and 28-day coulomb readings average 500. Here again, care is taken during finishing and curing. Screeding is with a 2 in. >(4 in. screed followed by a wood float and then a steel float. Fogging is then applied to maintain a moist surface until a power float is used. A broom finish is applied and then fogged until burlap can be laid down and moistened.

Although new construction is a perfect application for silica— fume concrete, its use in rehabilitation of existing structures is growing in popularity. After 20 yr of use, Old Kent Bank & Trust Company parking garage in Grand Rapids, Michigan, required rehabilitation. Two levels of parking are located below grade, and one at street level. The top deck is a 6-in.-thick, cast—in—place posttension design spanning 25 ft between supporting precast single tees. Chloride content in the top 1 in. of concrete was roughly equivalent to 8 lb of chlorides per yd^3. Reinforcing steel had between 1 in. and *1.5* in. concrete cover. A rehabilitation program called for the removal of distressed concrete, repairing or replacing damaged posttensioning and reinforcing, and a silica-fume concrete overlay. To ensure proper bonding, the surface was first shot-blasted. A bonding grout consisting of cement, water, and silica fume was then applied. The 1.5-in.-thick overlay mix consisted of *650* lb of cement, 10 percent silica fume by weight of cement, 7 percent air content, 0.625—in. maximum aggregate, a high— range water reducer, and a water-cement ratio of 0.40. Concrete strengths were 4,500 psi in 24 hr, and 8,000 psi in 28 days.

Due to the lack of bleed water in a 10 percent silica-fume mix, the finishers bull-floated the overlay directly behind the screed. Water fogging was constantly used to protect against plastic shrinkage cracks. Wet burlap was then put down for curing purposes.

It is now apparent that most transportation-type concrete structures must be protected from deicing-salt-induced corrosion. Silica—fume concrete has quickly become one of the major corrosion protection systems available to protect parking garages due to improved strengths and reduced chloride permeability. It must be remembered, however, that one must first start with quality concrete mix designs as recommended by ACI. Silica fume can then deliver those extra properties that will help the concrete structure perform for its full design life.

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