stretched and grouted in grooves 19 mm (0.75 in) deep midway between the transverse rebars. They were thus 152 mm (6 in) from each transverse bar. Where they crossed the longitudinal bars, however, they were only about 55 mm (2 in) above them. There would be, then, three times the current density flowing at each longitudinal rebar crossing as was flowing to each point on the transverse rebars. This concentrated current could weaken the bond between the rebar and the concrete after a period of time. This loss of strength might not be too serious in a slab bridge deck where the deck is supported on beams. It could, however, be a serious matter if the system were applied to, say, a parking garage floor in which there are no supporting beams between the pillars or to a support system under a bridge deck.

In the preceding section, it was shown that in order to get the necessary polarized voltage on the rebars, it would be necessary to use a 300-mm spacing of the wires. There would then be many points on each crossing rebar where the bond would be weakened, thus reducing the strength of the structure to which it was applied, whether it was a deck, parking garage floor, or a supporting structure for a bridge.

CONCLUSIONS

The conductivity of concrete is too low to permit an even distribution of power to the rebars by using a wire anode system without a conductive surface layer. The high DC voltages necessary to achieve the minimum polarized protection level of -0.8 V (with respect to the copper and copper sulfate half-cell) will overprotect some areas and could cause disbonding of the concrete from the rebars and reduce the strength of the structure.

The high DC voltages applied to the rebars at-

tract chloride ions and cause an acid situation to develop. The acid attacks and destroys the concrete grout surrounding the wire and bares it. This reduces electrical contact with the concrete structure and reduces still further the passage of current into the structure.

The wire anode system is a good method for applying the current necessary for cathodic protection of bridge substructures, but it will have to be used in conjunction with a conductive surface layer. This is necessary so that a low applied potential can be used and still obtain an even distribution of current across the structure.

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Scanning Rust Crystals and Salt Crystals with Electron Microscope

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Corrosion of reinforcing steel in concrete can create expansion pressures of 4700 psi. At 0° C, salt (halite) crystal growths can create pressures of 8140 psi at a supersaturation ratio of 2. Scanning electron micrographs of rust from corroding reinforcing steel in concrete show crystal laths and fretwork or boxwork crystals that eventually fill in and build up in layers. X-ray diffraction showed goethite and magnetite in the layers. Limonite, which is non-crystalline and does not show in X-rays, was also present. Halite crystal forms observed in air voids were fibers, columns, spirals, and ribbons. Entrained air voids help prevent or reduce salt crystals to grow into. Scanning electron micrographs of the rust crystals and salt crystals are included.

Kansas salt corrosion studies of concrete reinforcing steel were done to see how volume increases of up to 13 times (<u>1</u>) and expansion pressures of as much as 4700 psi (<u>2</u>) could occur from the corrosion process. Studies were made on the scanning electron microscope at Kansas State University with some concrete taken from as near a freshly corroding rebar as possible. Swordlike laths of rust were found growing into the concrete near the steel as seen in Figure 1. Concrete petrographers can recognize the potential for one-dimensional growth here and also see the shape similarity to minerals such as ettringite, the growth of which in hardened concrete is known to be detrimental $(\underline{3})$.

Another form of rust observed was a boxwork (Figure 2) or a fretwork of thin, apparently triangular-shaped walls with one of the points of the triangles growing away from the reinforcing steel such as that shown in Figure 3. Eventually both the lathlike and the fretwork structures become filled in with massive rust as seen in Figure 4, in which a few laths can still be seen around the edges of the glob of massive rust. Eventually reddish-, brownish-, and blackish-hued layers of such rust build up. These often contain what appears to be drying shrinkage cracks as shown in Figure 5.

Through X-ray diffraction studies of the layered rust we found the minerals goethite and magnetite.

Figure 1. Lathlike crystals of rust from corroding reinforcing bar protruding into concrete void (scale = 1μ).



Figure 2. Boxwork of rust crystals in concrete (scale = 10μ).



Figure 3. Fretwork of triangular rust crystals (scale = 1μ).



The lathlike and fretwork crystal forms shown in Figures 1, 2, and 3 are common forms for goethite $(\underline{4})$. The bulk of the massive or globular rust seems to be limonite, which would not show up in the X-ray because limonite is noncrystalline. The rust laths were found in rusty spots at the surface of concrete as much as 2 in above the corroding reinforcing steel. Figure 6 was made at such a location.

From these studies and pictures, it began to be apparent how, as Spellman and Stratfull reported, the metal loss from a corrosion pit of less than 1-mil depth can produce sufficient corrosion products to crack a concrete cover of 875-mil thickness $(\underline{5})$.

Growth of salt crystals in rock due to evaporation concentration precipitation can result in pressures that are capable of dislodging flakes of rock or of shattering objects (6). Calculations of the crystallization pressure of halite (NaCl) show that it can be more than 8140 psi at a supersaturation ratio of 2 and at a temperature of 0 °C. At higher temperatures or higher supersaturation ratios, the pressure increases (7).

Another salt-related mechanical weathering process is due to the volume expansion of hydrating

Figure 4. Cluster of rust crystal laths being filled in with more massive rust.



Figure 5. Built-up layer of massive rust obliterating original crystal forms.



salt minerals ($\underline{6}$). A well-defined hydrate of common salt, hydrohalite (NaCl*2H₂O), is known and is stable at or below 0°C ($\underline{8}$). Since millions of tons of salt are used nationwide as a deicing chemical ($\underline{9}$), the probability of hydrohalite formation and of damaging evaporation concentration precipitation of salt crystals in concrete is high. The formation of salt crystals has been suggested to contribute to the scaling type of concrete deterioration ($\underline{10}, \underline{11}$).

Helectites, stalactites, stalagmites, columns, crusts, and euhedral cubic crystals of common salt have been reported from caves in limestone and tubes in lava (12). In these studies, salt crystals were observed to grow in some of the salt-treated concrete as it dried. The salt crystals were first seen in air voids with a stereomicroscope but were studied in more detail with the scanning electron microscope. Sawed and polished faces of concrete cannot be used because the wet-preparation process would dissolve and wash away the salt crystals. Just as they do in caves, the halite crystals in concrete exhibit a wide variety of shapes, including fibers (Figure 7), columns (Figure 8), and spirals and ribbons (Figure 9). Similar fibers composed of

Figure 6. Rust crystal laths found at surface of concrete 2 in above corroding reinforcing steel.



In a few instances, concrete particles and quartz grains were observed at the free end of the salt fibers. Some of the salt crystals, such as those shown in Figure 10, look as though they were extruded from the concrete pores. Closer views show surface structures that suggest some growth by accretion and the bundle of fibers does not appear to extend down into the concrete but rests on its surface (Figure 11). To verify this, a cluster of salt fibers was dislodged with a micromanipulator. The area below the salt showed quite small pores in the concrete (Figure 12). The pores were much smaller than the salt crystals, as can be seen by comparing Figures 10 and 12. This indicates that the salt crystals grew by accretion from their base at the concrete surface rather than being extrusions from concrete pores.

No hydrohalite was found, but it is unstable at temperatures above 0° C. The concrete was not kept frozen before being examined; therefore, it is not known whether any hydrohalite had formed, nor is it





Figure 7. Fibrous crystal growths of salt (halite) in air void in concrete.





Figure 9. Spiral, ribbon, and fiber crystal growths of halite in concrete.



Figure 10. Ropelike cluster of halite fibers that look almost like extrusion from concrete pores (arrow points to same spot as arrow in Figures 11 and 12).



Figure 11. Enlarged view of interface of cluster of halite fibers with concrete at same location shown by arrow in Figure 10.



known whether other hydrated salts might have formed. As pointed out by Holden and Singer, any salt in which more than one state of hydration can form the higher hydrate always occurs at lower temperatures $(\underline{14})$.

As early as 1905, it was demonstrated that crystal growth can exert a linear force (15,16). Hence the crystallization of salt similar to some of the forms shown can develop sufficient pressure to cause concrete deterioration. If one considers that one-dimensional growth of salt crystals and rust crystals might go on synergistically along with the formation of ice, it is easy to imagine what the combined effects on the concrete could be. The deterioration of bridge decks is good testimony to such destructive forces. The illustrations used here also show the importance of entrained air voids in helping prevent salt crystal growth damage. In the same way that they do for ice crystals, air voids provide empty space in the concrete for salt crystals to grow into.

Figure 12. Cluster of salt fibers removed with micromanipulator (same scale as Figure 10).



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