Concrete–A Faithful Servant

Hundreds of millions of people have walked on concrete, and skipped over, stood on, stomped on, sat on, leaned against, pounded on, driven over, parked on, slept on, roller skated on, been protected by, and probably stumbled over concrete from the time they learned to walk in the man-made concrete forests of the world

CARL F. CRUMPTON

Concrete is the world's most abundantly used building material. Hundreds of thousands of people have made concrete; some of it well and some of it not so well. Even though concrete is common throughout the world, little is known about it. Like snowflakes, no two concretes are the same—and no one concrete is the same.

TURNING CEMENT TO CONCRETE

Much literature exists that describes concrete and its composition. A good rich concrete can be made from (in volume percentages): about 15 percent portland cement, 18 percent water, 8 percent air, 31 percent coarse aggregate as gravel or crushed stone, and 28 percent fine aggregate as sand. Dependent on whether the aggregates are rounded or angular, the concrete could be classed as a man-made conglomerate or breccia.

After the ingredients are mixed and placed, the concrete begins to set. Minerals with strange-sounding names form from the combining of the cement

Crumpton is Engineer of Research, Kansas Department of Transportation.

Crumpton Receives Award

Carl Crumpton, Engineer of Research at the Materials and Research Center, Kansas Department of Transportation, has been presented with the Kansas State University Distinguished Service Award. The Award recognizes graduates who have, by their service to their profession, brought honor to Kansas State.

Crumpton, originally from Ogden, Kansas, majored in geology at KSU, receiving a Bachelor of Science degree in 1949 and a Master of Science degree in 1951. He began his career with KDOT as a geologist in the Design Department in 1951; he has served as Engineer of Research since 1965.

An author of numerous research reports, Crumpton serves as a chairman or a member of various advisory committees, and has received national and international recognition for his achievements in the area of concrete and bridge deck performance. His current TRB activities include: chairman of the Corrosion Committee, member of the Committee on Basic Research Pertaining to Portland Cement and Concrete, and Kansas State representative to TRB.

and the water, such as portlandite, which is calcium hydroxide; ettringite, which is calcium alumino-sulfate high hydrate; hydrogarnets composed of calcium aluminum silicate hydrate, often with iron substituting for some aluminum; and tobermorite, a calcium silicate hydrate. Several variations of these minerals plus as many as a dozen or so other minerals may form in smaller amounts depending on the composition of the cement, the additives, and the environmental conditions at the time of setting. The cementing agent that holds it all together as concrete is primarily tobermorite. Tobermorite is the heart and glue of concrete. And the more gel-like the tobermorite, the better it binds together the sand and gravel or crushed stone in this man-made rock called concrete.

So the next time you try to slip softly over a concrete floor remember that you are tiptoeing over tobermorite. Or when you stumble on concrete stairs you are tripping over tobermorite. Without the strength of the tobermorite the stairs would not hold together—they would just be rubble.

To give concrete some extra strength and help hold it together, engineers more than 150 years ago, probably following early Roman examples, began to add a skeleton of iron rods and bars to the concrete. But it was not until 1877, when Thaddeus Hyatt issued a book in London on cement combined with iron and the experimental basis for its design, that we got our first broad treatise in English on truly reinforced concrete. (Being a native Kansan, I must mention the accomplishments of Thaddeus Hyatt. He was a prime mover in raising a million dollars for relief in Kansas before the Civil War.)

THE FORCES OF NATURE

Concrete is often reinforced with steel to survive the ravages of nature. In Kansas most concrete is placed during the summer months, which tend to be hot and dry. Kansas has the highest number of summer degree-hours above 85°F of any spot in the nation (Figure 1). Hot (summer temperatures can get as high as 110° to 120°F) and windy weather leads to high evaporation rates.

Freshly placed concrete must be protected from hot dry winds for many days to keep as much of the water as possible in the concrete mix for as long as possible so it will continue to combine with the cement and keep making tobermorite gel to glue everything together. Because the evaporation rate is higher than the precipitation rate in Kansas, keeping the water in the concrete is not always an easy task. If, by proper protection, however, the concrete can be kept from rapidly drying

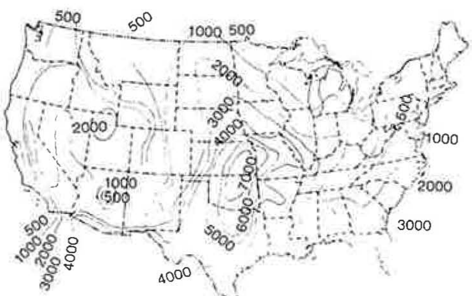


FIGURE 1 Summer degree-hours above 85°F.

out, then it matures, gains strength, and can eventually withstand its design compressive loads of 4,000 to 6,000 pounds or more per square inch, and develops a tensile strength of 600 or more psi. The reinforced concrete, whether in a pavement or a bridge, is then sufficiently strong to drive on.

In winter, the concrete must withstand different extremes in temperature; it may get as cold as 30° to 40°F below zero in Kansas. Freeze-thaw cycles, the nightly freezing and daily thawing of water trapped in the concrete, are even more damaging than very frigid temperatures. At least 68 freeze-thaw cycles occur each winter in Kansas. In anticipation of such conditions approximately 8 percent air is put in the concrete. This entrained air

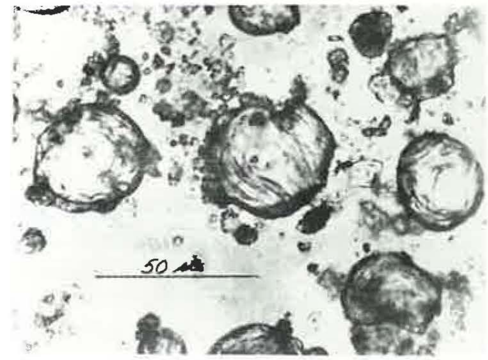


FIGURE 2 Entrained air bubbles produced in fresh cement slurry.

is present as tiny spherical voids less than 8 mils apart (Figure 2). These voids provide space for ice crystals to form, thereby protecting the concrete from the pressures of growing ice. Without this entrained air, freeze-thaw cycles will cause scaling of the concrete surface.

EFFECT OF ROAD SALT ON CONCRETE

During snowstorms, the maintenance forces plow away the bulk of the snow and spread salt to melt the rest. Kansas is a big producer of halite, or rock salt; thus the use of this mineral as a deicer is natural. For several years a combination of those kissing halide cousins, sodium and calcium chloride, was used until the escalating costs of calcium chloride made its use uneconomical.

Once spread the salt does not lie inert on the surface—it penetrates. Salt is not showy or spectacular; it is simple, silent, and persistent, slowly permeating the concrete of bridge decks or pavements. When salt water permeates concrete it does more than just make salty concrete. As it penetrates, salt dissolves small amounts of some concrete components such as calcium hydroxide, which is more soluble in salt water than in fresh water. Calcium hydroxide is also more soluble at low temperatures than at higher temperatures.

Sooner or later permeation of the

salt water reaches an equilibrium and the drying process follows. The evaporation rate may remain high during cold weather. During the winter, relative humidity is usually quite low, and salt is an evaporite mineral. The salty meltwater that has penetrated the concrete starts back toward the surface. The water evaporates, but the salt stays behind. The solution at the evaporative front becomes increasingly concentrated—even supersaturated. Crystallization of the salt within the concrete begins near the exposed top surface where the water is evaporating (Figure 3). As evaporation continues more salt solution is drawn upward from below.

The growth of salt crystals in rock due to evaporation has long been reported to develop sufficient pressures to dislodge flakes or shatter rocks and other objects. Even the 5,000-year-old Sphinx is said to be a victim of salt crystal growth. Concrete is merely a man-made rock and the same principles apply to it.

During crystallization, many factors come into play, including nucleation, surface energy, diffusion rate, reaction rates, and driving forces such as evaporative tension, osmotic pressure, concentration gradient, and capillary rise. Nevertheless, calculations using the Correns equation indicate that the crystallization pressure of halite can be more than 8,100 pounds per square inch at a supersaturation ratio of 2 and at a temperature of 0°C. The internal crystal growth pressures can be several times higher than the tensile strength of the concrete near the surface where evaporation takes place.

A saturation ratio of 1 or less is enough to dislodge thin flakes from concrete. Concrete scaling without freeze-thaw usually produces oatmeal-sized pieces that are soon removed by traffic, wind, rain, and so forth. In a freeze-thaw environment where salt is used, the two aid and abet one another to cause problems not existing previously.

AN EXAMPLE

My own driveway in Topeka is a good example of the mischief a little salt can do to concrete. For 25 years the driveway stood up well to severe Kansas winters. The driveway was not salted during those years; the snow was shoveled off. Then the city of Topeka began salting the streets to melt snow and ice. During the first winter of Topeka's salting program, my concrete driveway began to scale where salty meltwater dripped from my car. My driveway had made it through 25 winters with no scale until one winter of street salting and dripping salt water. This is an example of what has previously been observed—salt and freeze-thaw make concrete weather far more rapidly than freezing and thawing alone.

Looking at salted concrete with the scanning electron microscope has revealed the same types of salt crystal growths in concrete as reported for halite from caves in limestone and tubes in lava. In those places, helectites, stalactites, stalagmites, columns, crusts, and euhedral crystals of common salt have been observed. Inside the air voids in the concrete, fibers, spirals, ribbons, columns, and bundles of fibers have been seen. These studies have shown the importance of that 8 percent air in providing tiny voids for the salt crystals to grow into without disrupting the concrete (Figure 4). My driveway was not air entrained, and thus it succumbed to the pressures of salt crystal growth and freeze-thaw cycling.

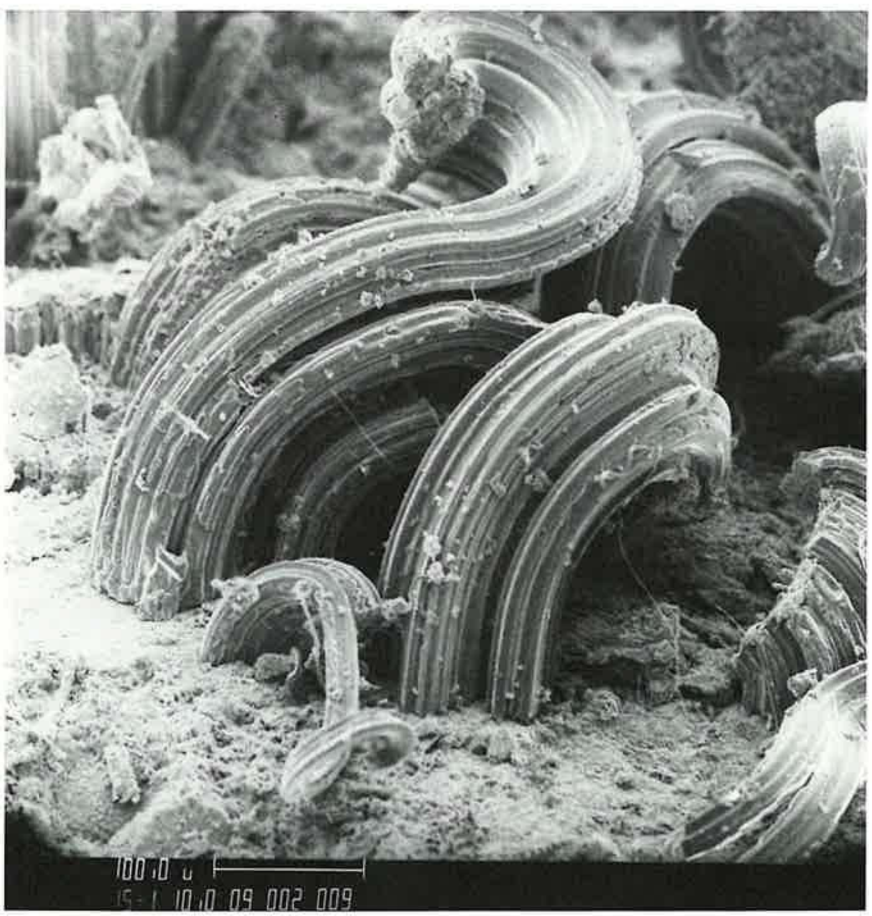
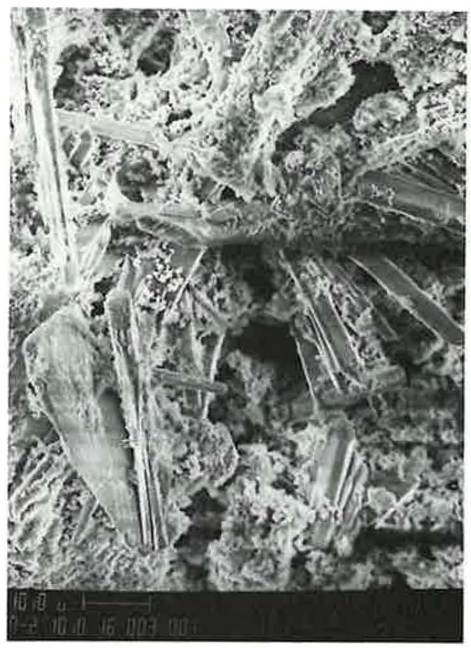


FIGURE 3 Crystalline halite (salt) fibers growing in concrete.

FIGURE 4 Air void in concrete with fibrous halite crystals.

A



B

FIGURE 5 *A*, Swordlike crystals of rust from a corroding reinforcing bar protruding into a concrete cavity.
B, Rust crystals found 2 inches from corroding reinforcing steel.

SALT AND REINFORCING STEEL

Suppose the concrete has a perfect void system—is it then safe from salt damage? Not quite. In unprotected conventional bridge decks, the salt will eventually permeate to the reinforcing steel. When salt comes in contact with steel it causes corrosion. Corrosion products can create expansion pressures of as much as 4,700 pounds per square inch and volume increases of as much as 13-fold. California studies have shown that metal loss from a corrosion pit less than 1 mil deep can produce enough corrosion products to crack a concrete cover 875 mils thick.

With the electron microscope, the Kansas DOT has scanned concrete taken from as near a corroding rebar as possible. Swordlike laths of rust were seen thrusting into the concrete near the steel (Figure 5*A*,*B*). Other forms of rust seen were boxworks and fretworks of thin-walled, apparently triangular crystals with one of the points of the triangles growing away from the reinforcing steel (Figure 6). Eventually the lathlike and fretwork structures become filled with massive rust. Black, brown, and red layers of such rust gradually build up. These often contain what appears to be drying shrinkage cracks.

X-ray diffraction studies of the layered rust showed the minerals goethite and magnetite. The lathlike and fretwork crystal forms are common for

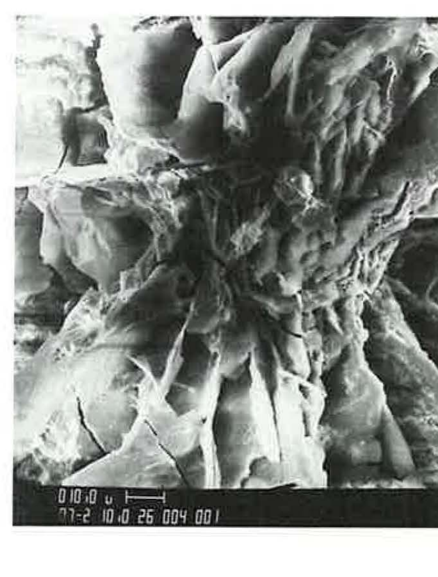


FIGURE 6 Boxwork rust crystals growing within portland cement concrete.

goethite. The bulk of the massive or globular rust appears to be amorphous limonite, which does not show in the diffraction patterns.

FIGURE 8 Exposed rock often weathers more quickly than exposed concrete.

THIN, BONDED OVERLAYS

The early signs of salt-induced corrosion are concrete delaminations and surface spalls (Figure 7). Without some type of protection, many decks need extensive repairs after 10 or 15 years of service. In 1966 the Kansas DOT began using bonded concrete overlays. For one 15-year-old bridge deck, the deteriorating concrete, down to the level of the steel, was removed from 45 percent of the surface. The steel was blasted clean and new concrete added to the entire deck surface with a cement sand grout to bond the new concrete to the old.

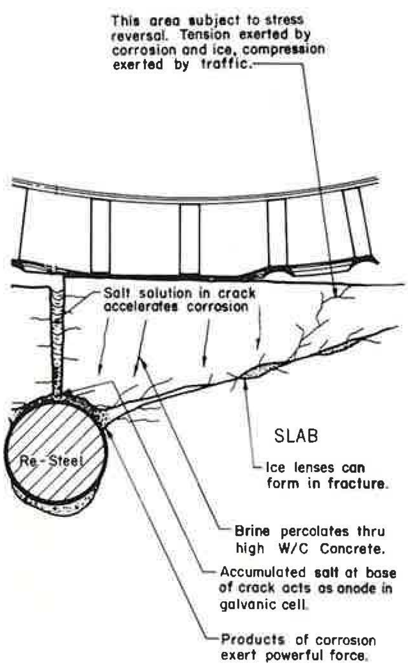


FIGURE 7 Combined effects of deicing salt and freeze-thaw cycles in creating concrete spalls.

The new concrete added 2 extra inches to the old deck thickness. Now almost 19 years later the deck with its thin, bonded overlay is still performing very well.

The decision to use that type of repair was based on research done on another bridge 5 years earlier in 1961. That deck surface was in nearly perfect condition at the end of 5 years. Scores of other overlays have followed since then with great success and years of extra life added to each old deck.

There are several reasons why thin, bonded concrete overlays work even though there may still be salt at the level of the steel. Temperature, moisture, and oxygen content at the level of the steel are all reduced. Salt and moisture already present begin to move upward. The ingress of salt, water, and oxygen is severely retarded. More important, however, is the fact that thin, bonded concrete overlays have worked—for up to 24 years.

CONCRETE PERFORMANCE

The wedding of concrete and steel has been an ideal union, and much reinforced concrete has been used for bridge decks. Unfortunately, instead of the traditional symbol of fertility, rice, being tossed, salt to melt snow and ice was tossed and brought irritation, tensions, and erosion of previously good marital relations. No longer could the two exist in blissful union, the seeds of destruction had been planted, and the stage was set for today's concrete scaling and reinforcing steel corrosion problems.

Even so this man-made rock called concrete often performs better than some of nature's own rocks. Many concrete pavements are in better condition after 20 years of exposure to weather, salt, and traffic than are the 300-million-year-old rocks first exposed to the weather in cutslopes during road construction. Those rocks did not receive the direct pounding of millions of cars and trucks nor the direct application of deicing salts that the pavements received to render them snow- and ice-free for travelers, yet they have weathered even more rapidly (Figure 8).

Despite high temperatures, low temperatures, free-thaw cycles, deicing salts, traffic pounding, and so forth, many concrete roadways have outlived their design life. They are still in everyday use and have not become the concrete outbacks of the highway infrastructure. Despite being beyond their design "old age," they are still bearing more than their anticipated share of traffic.