Concrete Solutions to Concrete Rehabilitation

A concrete bridge parapet wall exhibits severe deterioration caused by repeated freezing and thawing cycles.

by Steven J. Susca, PE

All images courtesy Hoffmann Architects

SHRINKING, CREEPING, CRACKING—THEY SOUND LIKE THINGS THAT HAPPEN IN A GRADE-B HORROR FLICK, YET HIT THE NAIL ON THE HEAD WHEN DESCRIBING PROBLEMS WITH CONCRETE.

Concrete's versatility, durability, and economy have made it the world's most highly used construction material. It is crush- and fire-resistant, while providing insulation against sound and heat. The material is also durable, and long-lasting, even in extreme temperatures. Americans pour about 260 million m^3 (340 million cy) of ready-mixed concrete each year. It is used in highways, streets, parking lots and garages, bridges, buildings, dams, homes, floors, stairways, sidewalks, driveways, countertops, and even artwork.

Not only is concrete ubiquitous, it has a long history. In ancient times, the Assyrians and Babylonians employed clay as a bonding substance; Egyptians used lime and gypsum. Modern concrete came into play in 1756 when British engineer John Smeaton added pebbles as a coarse aggregate, mixing powdered brick into the cement. In 1824, England's Joseph Aspdin invented Portland cement, which became the dominant cement used in concrete production.[1]

It has been said concrete is one of the world's most important materials. There is certainly no denying it is one of the simplest—a mixture of cement, sand, gravel, and water. Typically, concrete comprises 60 to 70 percent sand and gravel or crushed stone, 15 to 20 percent water, and 10 to 15 percent cement by volume. Additionally, admixtures can also be added to concrete to improve on certain requirements of the specific mixture.

Nothing lasts forever, and concrete is no exception. There are many internal and external forces leading to deterioration and premature failure of cured concrete. Some common causes of concrete failure can include water infiltration, carbonation, corrosion of reinforcing steel, shrinkage, drying, thermal contraction, inadequate design, and poor placement practices.

Water—friend and foe

Although water is a necessary component of concrete, it is possible to have too much of a good thing. Either directly or indirectly, water is one of the leading causes of concrete deterioration. While the combination of water and favorable temperatures can generally help increase the strength of concrete throughout its life cycle, it can also prove fatal, serving as a mechanism for deterioration.

Porous, water-saturated concrete without adequate strength and entrained air is prone to scaling—a form of deterioration caused by freezing of water in concrete. Water expands as it freezes, which can impart great internal pressure into concrete. Over time, as these freeze-thaw cycles continue, the concrete eventually weakens and fails. This type of deterioration is easy to recognize—concrete subjected to freeze-thaw damage has the appearance of being pulverized or crushed.

Water can carry into the concrete aggressive chemicals such as acids, sulfates, or chlorides that then cause corrosion of reinforcing steel. Concrete containing alkali-reactive aggregates—discussed later in this article—is also subject to subtle and harmful expansion forces caused by a reaction between the aggregate and the alkali hydroxides, formed during the hydration process. High moisture content within the concrete while in service facilitates this reaction.

Carbonation

Hardened concrete is a highly alkaline substance, typically with a pH above 12.5. This environment is created by high levels of calcium hydroxide in the concrete and helps protect embedded steel from corrosive forces. Essentially, a passivating film is created around embedded steel reinforcement. Since steel corrosion needs a neutral or acidic environment to flourish, the steel is effectively protected from corrosive forces.

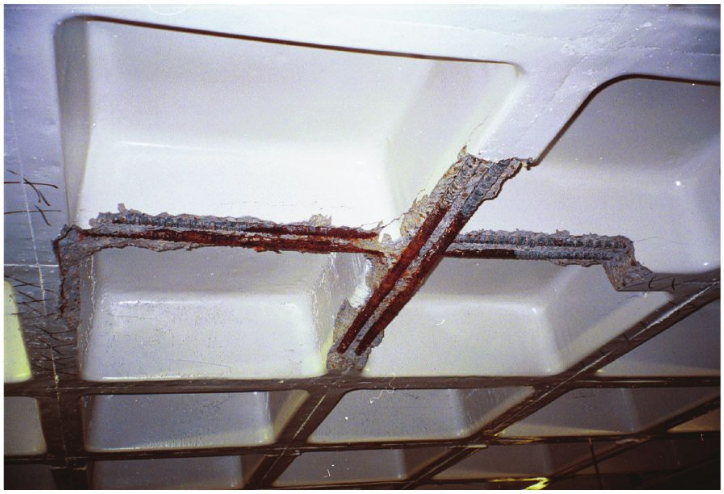
Rainwater combines with carbon dioxide in the air to form carbonic acid. Over time, this carbonic acid infiltrates the concrete and, through a process called carbonation, combines with the calcium hydroxide to create calcium carbonate. This calcium carbonate has the effect of lowering the pH of the concrete, thereby eliminating the protective passivating layer around the steel. While carbonation itself is not a significant cause of corrosion, it allows a corrosive environment to develop at the surface of the steel. It does not take much to encourage corrosion—simply introducing moisture and air and a sprinkling of chlorides from road salts can do the trick.

In situations where concrete has deteriorated, carbonation is one of the usual culprits. Chemical analysis of damaged concrete helps measure the severity of the carbonation issue. One way to help combat the effects of carbonation and slow its progress is to apply water repellant to the concrete surface. In more severe situations, an elastomeric waterproofing coating can be applied. These precautions, preferably taken before the deterioration has occurred, limit future carbonation by restricting the entry of carbonic acid into the concrete.

Corrosion

Corrosion of embedded steel items is both a cause and a symptom of deterioration in concrete. Several different mechanisms can work alone or together to cause steel corrosion. However, for steel corrosion to occur, three ingredients must be present: moisture, oxygen, and an electrolyte. Since moisture and oxygen are found nearly everywhere, the only thing missing is an electrolyte. This can come in the form of de-icing salts entering the concrete through water infiltration.

As steel corrodes, iron oxide is formed. This rust occupies a much greater amount of space than the steel from which it was created. When embedded in concrete, corroding steel imparts great internal pressure into the cement matrix. This eventually results in the formation of a subsurface crack. As the crack grows, it reaches the surface of the concrete and creates a spall.



A spall at the underside of a waffle slab caused by corroding reinforcement.

Fine cracks, or crazing, due to alkali-aggregate reaction.

The photo above shows a crumbling concrete sidewalk due to freeze-thaw cycling and applied de-icing compounds.

Concrete that is often saturated with water and exposed to freeze-thaw cycles may experience scaling, or flaking and peeling of the surface.

Surface spalling on a concrete parking deck due to corrosion of embedded steel reinforcement.

The result of the spalled concrete is a reduction in the protective cover over the rebar. This allows corrosive elements like moisture and oxygen to easily infiltrate the concrete to the depth of the reinforcement, further exacerbating the ongoing corrosion. As this occurs, the cycle repeats itself at a continually increasing rate. In addition to the damage imparted to the concrete, this cumulative process eventually reduces the effective cross-sectional area of the reinforcing steel, ultimately, compromising the structural integrity of the concrete member.

Corrosion of embedded reinforcing steel is a serious issue that needs to be addressed in a timely manner to avoid costly repairs in the future. If not caught quickly, corrosion results in irreparable damage to the concrete. Early detection can mean relatively easy repairs.

Cracking

All concrete crack eventually, but problems arise only when it cracks unexpectedly and in unanticipated locations. Cracking can be the result of one or a combination of factors, such as drying, shrinkage, thermal contraction, poor placement, restraint (external or internal) to shortening, subgrade settlement, and applied loads. Problems with cracking can be significantly reduced by examining the causes and taking preventative steps.

Crazing

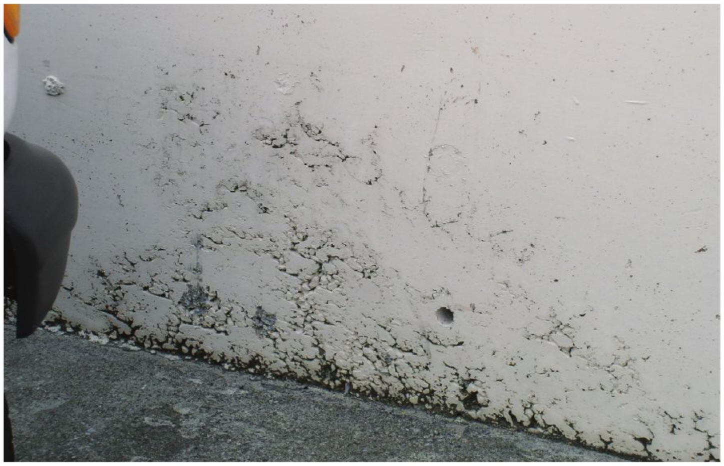
Crazing is a pattern of fine cracks that do not penetrate much below the surface and generally pose only a cosmetic problem. They are barely visible, except when the concrete is drying after the surface has been wet.

Plastic shrinkage cracking

A result of improper curing, plastic shrinkage cracking occurs when water evaporates from the surface of freshly placed concrete faster than it is replaced by bleed water (*i.e.* excess water in the mix that works its way to the surface during the initial stages of curing), causing the surface concrete to shrink. Due to the restraint provided by the concrete below the drying surface layer, tensile stresses develop in the hardening concrete, resulting in shallow cracks of varying depth. Usually appearing within two days of placement, this type of cracking is often fairly wide at the surface.

Drying shrinkage

Drying shrinkage is a common issue in concrete. As almost all concrete is mixed with more water than needed to hydrate the cement, much of the remaining water evaporates, causing the concrete to shrink. Restraint to shrinkage, provided by the subgrade, reinforcement, or another part of the structure, causes tensile stresses to develop in the



Poor consolidation of concrete within forms when placed, known as honeycombing, can leave gaps (shown above) that are deep enough to expose the embedded reinforcing steel.

BEST PRACTICES FOR CURING

Proper curing procedures should be employed to ensure the concrete achieves its intended design strength and durability. Some methods of concrete curing include:

- applying a fog spray or water mist to exposed concrete surfaces;
- covering exposed surfaces with wet burlap or other moisture-retaining cloth;
- spraying a concrete curing compound to the surface; and
- covering the top surface of the concrete with plastic sheeting in order to retain moisture.

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cured concrete. In many applications, drying shrinkage cracking is inevitable. Therefore, contraction (control) joints are placed in concrete to predetermine the site of drying shrinkage cracks.

D-cracking

A form of freeze-thaw deterioration, D-cracking is observed in some pavements after three or more years of service. Due to the natural accumulation of water in the base and sub-base of pavements, the aggregate may eventually become saturated. Then with freezing and thawing cycles, cracking of the concrete starts in the saturated aggregate at the bottom of the slab and progresses upward until it reaches the wearing surface. D-cracking usually starts near pavement joints.

Thermal cracks

Thermal cracks are formed when the heat of hydration of cementitious materials leads to rising temperatures. Thermal cracks are commonly found in mass concrete placements, such as deep footings or bridge abutments, as opposed to thin slabs or beams. As the interior concrete increases in temperature and expands, the surface concrete may be cooling and contracting. This causes tensile stresses, resulting in surface thermal cracks if the temperature differential between the surface and center is too great. The width and depth of cracks depend on the temperature differential, physical properties of the concrete, and configuration of the reinforcing steel.

Loss of support beneath concrete structures

Settling or washout of soils and sub-base materials can cause various problems in concrete structures—from cracking and performance problems to structural failure. Loss of support can also occur during construction due to inadequate formwork support or premature removal of forms or shores.

Alkali-aggregate reaction

This type of reaction occurs when the active minerals in some aggregates react with the alkali hydroxides in the concrete. Cracks are characterized by crazing—fine cracks forming a pattern similar to an alligator skin. These cracks allow more moisture to enter the concrete, further exacerbating the situation. Alkali-aggregate reactivity occurs in two forms: alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR).

ASR occurs when certain siliceous aggregates react with the alkali hydroxides to form a silica gel. In turn, this absorbs water and expands, imparting great pressures within the concrete, eventually causing cracks. ACR is a result of a reaction between alkali hydroxides and carbonate rock particles.

Alkali aggregate reaction is very difficult to stop once it has begun. The best way to guard against this failure is to ensure non-reactive aggregates are used.

An ounce of prevention

Concrete failure can be kept at bay by taking proper precautions during the construction phase. If the concrete is correctly placed, consolidated, finished, and cured, it has a good start to a prolonged life and delayed deterioration.

One must always select the proper materials for the concrete mix as well as ensure the coarse aggregate is properly sized for the particular application. A chemical analysis should be performed to ensure it is not alkali-reactive. Water for the mix should be potable and free of any chlorides or other deleterious chemicals.

When it is time to mix the concrete, one must use the lowest amount of mix water needed for workability because overly wet consistencies can reduce concrete's strength and durability. To minimize the amount of mix water, the largest size aggregate suitable for the project must be employed. Water-reducing agents (WRAs), or superplasticizers, can be added to the mix to help increase the workability of fresh concrete without adding water.

The most important aspect of a concrete mix design is the water-to-cement ratio. This is defined as the ratio between the total weight of water in the mix and the total weight of cement. This ratio determines the overall quality of the concrete mixture and to a great extent, its strength. Generally speaking, a lower water-to-cement (w/c) ratio will result in higher quality concrete. However, one must not sacrifice the workability (*i.e.* the ability to pour, place, and finish) of the fresh concrete by making it too dry.

When casting concrete against the earth, it is extremely important to properly prepare and compact the subgrade. Choosing the proper sub-base material helps provide uniform support to the slab, reducing the chance of settlement cracks.

Spray-applied finishing aids or plastic sheets can be employed as vapor retarders to avoid rapid loss of surface moisture, aid in curing, and prevent plastic-shrinkage cracks and curling of the slab edges. Finishing operations should not begin until the water sheen on the surface is gone and excess bleed water has evaporated. Application of additional 'finishing water' must be avoided at all costs. If any excess water is worked into the concrete during finishing operations, the concrete paste at the surface will contain too much water, which will likely result in scaling.

In concrete slabs, walls, and other large members, it helps to provide contraction or control joints at reasonable intervals. When the concrete cracks, it will do so in a predetermined location, rather than randomly throughout the member. The American Concrete Institute (ACI) has published guidelines on the placement of such joints in these members.

Precautions must be taken when casting concrete in very high or low temperatures. In areas with freezing temperatures, air-entraining admixtures should be added to the mix to improve freeze-thaw resistance. Some of the mix water can be replaced by ice (on a by-weight basis) to extend the working time of the mix in hot weather. Extreme temperature changes must be avoided during the curing process.

Once the concrete is in place, it is important to ensure it is cured properly. Curing is the process of maintaining a good balance of temperature and humidity around fresh concrete for a specific amount of time, so the concrete can achieve proper strength and durability.


Disintegrated concrete overlay on top deck of precast concrete parking structure. Concrete overlays can easily chip and spall when the edges are feathered out instead of squared off.

As concrete cures, it gains strength. The initial curing period generally lasts from seven to 28 days and is when the concrete attains most of its strength. However, the actual hardening process continues for years, albeit at a much slower rate, allowing the concrete to get stronger as it gets older.

Keeping on top of things

Once the concrete is in place, there are ways to ensure it remains functional and intact for many years. To help extend the life of concrete, it is important to maintain it and keep a watchful eye for issues that might arise. Regular inspections can reveal problems still in the manageable and affordable repair stages.

Control, reduce, or prevent cracking

As noted, all concrete eventually cracks. The installation of control joints at regular intervals will cause this to occur in predetermined locations, thereby minimizing unanticipated cracking. When cracks are discovered, an analysis should be done to determine the cause prior to making any repairs. The crack can then be sealed from moisture infiltration or injected with grout or epoxy. It is important, prior to repairs, to first determine the cause of the cracking and if ongoing expansion of the cracking exists.

Prevent corrosion

When placing new concrete in locations that might experience a high rate of corrosion, such as parking garages, several methods can be used. Options include:

- placing sacrificial anodes within the concrete formwork and bonding them electrically to embedded steel items to provide a form of passive cathodic protection;

Chevron cracks, such as the parallel diagonal fissures that are shown above in a repeating 'V' pattern, are typically caused by shear stress.

- employing epoxy-coated or galvanized rebar instead of regular rebar as an additional safeguard;
- including corrosion protection admixtures in the concrete mix;
- applying a migrating corrosion inhibitor to the surface of cured concrete to help protect embedded reinforcement; or
- applying a waterproof traffic-bearing membrane to the surface in areas where deicing salts are used. This, however, would require regular maintenance. This work should be included as part of a regular maintenance budget.

Air and water infiltration

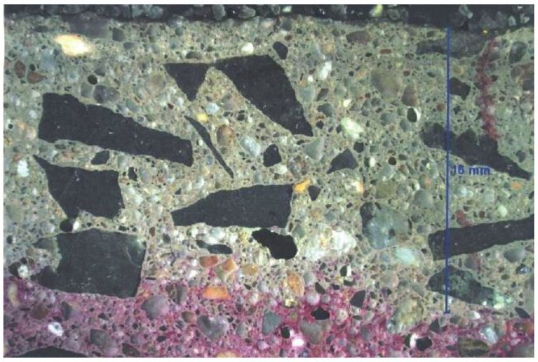
Options to prevent air and water infiltration include:

- removing damaged areas and replacing with relatively non-porous patching material;
- ensuring proper drainage for concrete floor slabs to avoid pooling/ponding water;
- covering reinforcing steel with a minimum of 38 mm (1 ½ in.) of concrete, dense enough to limit chloride, water, and air migration; and
- applying a suitable penetrating concrete sealer to new concrete to limit the amount of moisture entering the member.

Any proposed sealers should be researched for applicability to the intended usage and environmental conditions, as well as regarding their compatibility with curing compounds.

Chloride contamination

Many concrete applications will experience the application of de-icing salts. However, there are several types available on the market. Sodium chloride has little or no effect on properly air-entrained concrete, but will corrode metal. A weak dose of calcium chloride has little effect on concrete, but strong calcium chloride solutions can be a different story. Effects of magnesium chloride vary, from slight deterioration to aggressive damage, especially in wet-dry and freeze-thaw conditions.



Laboratory testing of this concrete sample reveals carbonation to a significant depth (unstained portion).

It is a good idea to try to reduce or eliminate chloride use near exposed concrete surfaces. One can employ less damaging alternatives to de-icing salts (*e.g.* calcium magnesium acetate). Other options include applying protective coatings to inhibit the intrusion of chlorides, air, and water.

Rehabilitation

Even if building owners have been less than diligent in the maintenance and upkeep of their concrete structures, all is not lost when defects and deterioration are discovered. Many products are available to rehabilitate a concrete structure suffering from virtually any combination of issues.

Penetrating concrete sealers

Penetrating sealers are chemicals applied to the concrete surface to protect against water infiltration. Due to their low viscosity, they are able to penetrate deep into hardened concrete to form a barrier, preventing liquid water from entering, but allowing water vapor to evaporate from the concrete. This can help reduce carbonation, freeze-thaw damage, and corrosion of embedded steel items. Typical sealers in this category include silanes and siloxanes or a combination of the two.

Epoxies

Numerous products fall under the 'epoxy' category; they can be used in a wide range of applications. Epoxies with low viscosity and a high modulus of elasticity can be either gravity-fed or injected into cracks to repair them. Crack movement and expansion should be monitored and proven to not exist prior to utilizing this repair. Using high-strength epoxy paste adhesives also provides a way to structurally bond to concrete.

Map cracking, or pattern cracking, may be caused by alkali-aggregate reaction, restrained thermal contraction, or drying shrinkage.

A class of epoxies known as healer/sealers can be applied to the surface of a concrete slab to repair cracks and seal pores, protecting the concrete from water infiltration.

Patching mortars

When concrete is spalled or deteriorated and requires repair, many product solutions are available. Each has advantages and disadvantages based on the particular application in which it will be used.

The wide variety of patching mortars can be overwhelming. Some mortars are best used in vertical or overhead applications, while others are more suitable for underwater repairs. Some have integral migrating corrosion inhibitors to protect the existing rebar from further damage, while others have rapid curing capabilities to allow the structure to be put back into service more quickly. One must research each mortar for compatibility to application before usage.

Conclusion

Concrete is one of the world's most popular construction materials. With proper installation procedures and regular maintenance, this versatile substance can last many years. If addressed in a proper and timely manner, many types of defects can be repaired and the concrete restored to like-new condition.

It is important to realize faulty concrete repair work can actually worsen structural problems or lead to further damage and even safety hazards. Therefore, when it is time to do repairs, building owners must consult a qualified concrete repair professional. **CS**

Note

[1] Many people incorrectly use the words 'cement' and 'concrete' interchangeably. It is critical to understand the difference between the two. Think about comparing flour to a chocolate chip cookie; the flour is simply one ingredient used to bake a cookie. Similarly, cement is only one component of concrete; when mixed with water it forms a paste in a process called hydration. This paste coats the surfaces of the fine aggregate (sand) and coarse aggregate (gravel or crushed stone), binding them together and forming concrete.

ADDITIONAL **INFORMATION**

Author

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Abstract

Concrete's versatility, durability, and economy have made it the world's most highly used construction material. Crush- and fire-resistant while offering insulation against sound and heat, it is also durable. Of course, nothing lasts forever. This article examines the many internal and external forces leading to deterioration and premature failure of cured concrete, ranging from water infiltration, carbonation, corrosion of reinforcing steel, shrinkage, and drying challenges to thermal contraction and poor placement practices.

MasterFormat No.

03 01 00–Maintenance of Concrete
03 20 00–Concrete Reinforcing
03 35 00–Concrete Finishing
03 39 00–Concrete Curing
09 90 00–Painting and Coating
13 47 13.19–Cathodic Protection for Concrete Reinforcing

UniFormat No.

A1010–Standard Foundations
A4010–Standard Slabs-on-grade
A4020–Structural Slabs-on-grade
B2010–Exterior Walls
G2010–Roadways
G2020–Parking Lots
G2030–Pedestrian Plazas and Walkways

Key Words

Divisions 03, 09, 13
Carbonation
Concrete
Corrosion
Cracking
Expoxies
Reinforcing steel
Thermal contraction