

Mechanisms affecting the Durability and Longevity of Concrete and Key Methods of Mitigating Them^{©1}

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Concrete is, by far, the most widely used construction material in the world. It is a highly durable, long lasting product with excellent characteristics for building everything from roads and bridges, to floors and buildings. Its ability to be formed and shaped creates boundless architectural possibilities. Yet, its durability can easily be compromised, shortening its life and creating significant and expensive problems in even the most simple applications.

Concrete is a fairly simple product, requiring only 3 ingredients: Portland Cement, Aggregates (rock, gravel, sand), and Water. (Cement is not the same thing as concrete - Cement is a component in concrete that reacts with water to bind it all together.) While it seems simple, there are a wide range of factors that impact the quality of the concrete, including:

- ratio of water, cement, and aggregate
- placement and finishing methods
- quality of materials used in the concrete
- supplemental materials added to the mixture
- environmental conditions (temperature, humidity, etc.) at the time of placement and during the initial curing cycle

Characteristics of Good Concrete

Concrete is a product that, when mixed, placed, and finished properly, provides a hard structure capable of supporting large amounts of weight. Concrete is very strong in compression (supporting weight). However, by itself, concrete is weak in tension (bending) and torsion (twisting). The addition of steel reinforcement provides the tensional and torsional strength to concrete, allowing it to be used in bridges and other spans, as well as buildings, roadways, and other applications with moving loads.

Concrete's mix is critical to the quality of the product. The ratio of water to cement and the type and size of the aggregates (rocks, sand, etc.) used have a tremendous impact on the quality of the product. Water's primary function is to hydrate the portland cement, which creates the chemical reaction that hardens the concrete.

To a lesser degree, water is used to make the mixture workable. The more liquid, or plastic, the mixture is, the easier it is to push around and form. However, when enough water is used to make the mixture easy to place and work, there is usually too much water in the

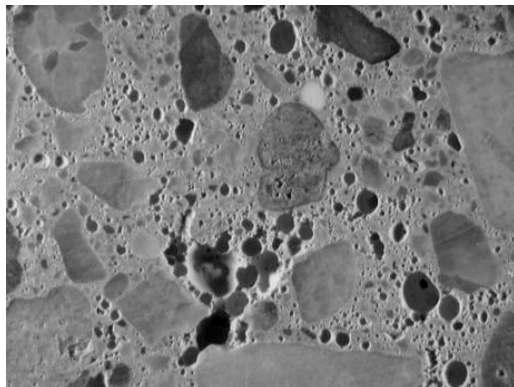
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mix. Too much water creates a weak product that is extremely porous, making it highly susceptible to damage and increasing the speed at which damage occurs. In most concrete applications, exceeding a water to cement ratio of .5:1 (1/2 pound or kilo water to 1 pound or kilo of portland cement) creates a sub-standard product, and the lower the water to cement ratio the better.² Fortunately, there is an additive that can (and should) be included in the mix that will give the concrete the workability needed without exceeding the recommended water to cement ratio. It is called a plasticizer or super-plasticizer. In any concrete placement that requires finishing or pumping, a plasticizer should be used.

Aggregate size and composition are also critical. Smaller aggregates are used in narrow or thin applications, while progressively larger aggregates are used in thicker slabs and forms. The use of non-reactive aggregates (which will be discussed later) is also critical to having a product that is stable.

Concrete is generally 75% aggregates and 25% cement paste (the product of portland cement and water). When concrete is placed, it is in a plastic-like state, easy to move and conformable to whatever shape the forms take. As concrete sets, a chemical reaction takes place. The reaction is between the portland cement³ and water. The reaction creates air bubbles, heat, Calcium Hydroxide (lime) and a product called Calcium Silicate Hydrate (C-S-H). The C-S-H is the most important product of the reaction, as it is the element that gives the concrete hardness, strength, and dimensional stability. Air and heat, the other two products of the reaction need to be properly managed. Calcium Hydroxide will remain in the matrix and is called “free lime” or “free calcium.”

If air is trapped in the mass of the concrete, the concrete is weakened substantially and



Air bubbles in the concrete paste due to lack of consolidation.

large pathways are created that allow for contaminants to enter into the concrete. Removal of the air bubbles is called “consolidation.” Good consolidation is critical for concrete to have predictable performance characteristics and resist damage. If the surface of the concrete is finished before the concrete has been consolidated, bubbles will be trapped just under the surface, and the surface will flake and spall easily.

Heat is a normal product of the chemical reaction that creates concrete. However, if the heat of the concrete mass during the hardening stage exceeds 160 degrees fahrenheit, the concrete will have thermal cracks and will crumble easily. Heat over

² Minimum water to cement ratio is .36 for concrete. A good target is a ratio of .4 - .45.

³ Portland cement is a combination of Tri-Calcium Silicate and Di-Calcium Silicate. These silicates comprise 75% of the mass of Portland Cement and are called “portlandites”

160 degrees during curing will also create expansive crystals called ettringites that will create pressure inside the concrete and cause significant cracking and deterioration.

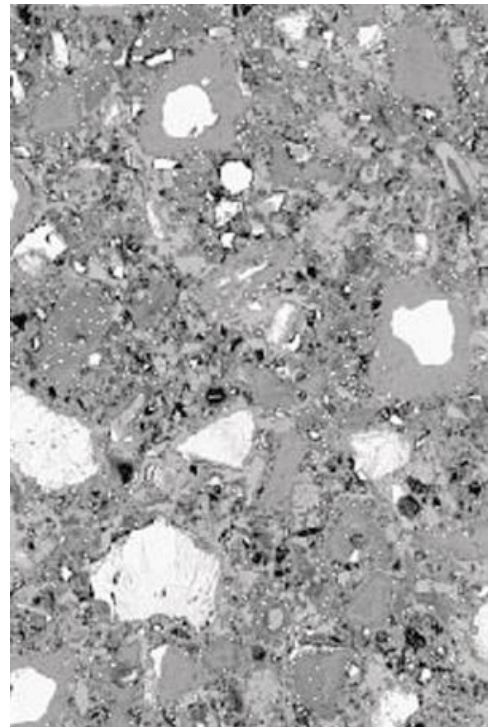
Freezing temperatures also must be avoided, as the water in the curing concrete will freeze, expand, and cause significant internal cracks. Pouring concrete in freezing temperatures requires the use of blankets or other methods to protect the concrete from freezing.

Good concrete that has been properly consolidated and finished will have a dense “matrix” of cement paste and aggregates. There should be no air voids or bubbles (unless the concrete is air-entrained - which we will discuss later). Even though there are no air voids or bubbles, good concrete has a microscopic system of tiny pores (bubbles) and capillaries. This microscopic system is left when water hydrates the portland cement during the curing process and then shrinks as it dries.

It is difficult to look at the surface of concrete and determine whether it is good or bad. Certain measurements can be taken to determine the quality of concrete, and this is typically done by taking a sample of the cured concrete and performing a Petrographic Analysis. The analysis will determine:

- the compressive strength (how much load the concrete can support - measured in either Pounds per Square Inch or MegaPascals)
- the amount and distribution of air (consolidation) and
- the quality of the cement paste (water content).

The pH is also important. Concrete is a very alkaline substance, and healthy concrete has a pH between 11 and 13. A reduction in the pH of the concrete is an indicator that damage is either starting or is already in progress.



Dense, properly consolidated concrete. Note the lack of air bubbles.

The Basic Problem with Concrete

Concrete, even good concrete, is porous. Properly mixed, placed, and finished concrete is denser and less porous than poorly done concrete. The durability of concrete starts with having a good mix of concrete, properly placed and finished. The porosity of concrete provides the pathway to destruction. The more porous, the faster the deterioration. Porosity allows water and the chemicals dissolved in water to enter the concrete. Porosity also allows introduced chlorides (from sea-water, de-icing salts, etc.) and sulfates to enter

into the concrete. The less porous the concrete, the better. But how does one achieve non-porous concrete, and what kind of damage can water, chlorides, and sulfates actually do?

The Problem: Two Primary Types of Deterioration

Two basic ways deterioration occurs:

Concrete is a stable structure. When water and/or contaminants enter into the pore and capillary structure of the concrete, it is compromised by:

1. Internal Pressure from expansion, breaking and cracking the paste and aggregates from within.
2. Acidic reaction, which dissolves the bonds that hold the concrete together. Lowered pH of the concrete makes these bonds unstable and is the indicator of acidic reaction.

Common Causes (Mechanisms) of Deterioration

Poor Quality Concrete due to problems at Formulation and Placement

The most common cause of failure in concrete is the use of too much water, followed closely by inadequate consolidation (vibration of the concrete to remove excess air and/or trapping air at the surface of the concrete by finishing it too soon). Water is necessary for the chemical reaction that causes concrete to go from a liquid consistency to a solid, and to allow for the wet concrete to be placed, formed, and finished easily. However, too much water causes a poor structure in the cement paste and allows a number of forces to attack and prematurely destroy concrete. (Cement paste is the slurry of water and portland cement that binds the aggregate together and represents about 25% of the total mass of the concrete.) Air is a byproduct of mixing and the water/cement reaction and, if not removed by proper consolidation, will create large voids in the concrete that invite damage and weaken the final product dramatically.

Even concrete mixed with a proper amount of water and consolidated well is subject to the same destructive forces. It just takes longer to do the damage in properly mixed and placed concrete. Cement paste is filled with microscopic pores and capillaries which allow water and other chemicals to penetrate into the concrete and react with elements in the mixture or the reinforcement. Excessive amounts of water create a much larger pore structure which allows for faster ingress. Even proper water to cement ratios create porosity in the concrete, and this porosity is a major pathway for damage.

Common Mechanisms that Deteriorate Concrete after it Sets:

The most common mechanisms that affect the longevity and durability of concrete are:

1. Corrosion of Reinforcement - (Internal Pressure and weakening of tensional strength)
2. Freeze/Thaw cycle damage (Internal Pressure)
3. Salt Damage (Acidic and leading to Internal Pressure)
4. Alkali-Aggregate Reaction (Internal Pressure)
5. Sulfate attack (Acidic and Internal Pressure)

Corrosion of Reinforcement:

Corrosion of reinforcement is a significant cause of concrete failure. The most common reinforcement used is steel rod (rebar), and wire mesh. When steel corrodes (rusts), it expands up to 6 times the volume of the steel. This expansion causes tremendous pressure in the concrete, causing it to crack and cause large pieces of concrete to break away. Corrosion also destroys the tensile and torsional strength of the concrete and can lead quickly to catastrophic structural failure.

Corrosion of reinforcing steel can be initiated by a number of sources:

- direct exposure to moisture and air through cracks in the concrete
- carbonation
- chloride infiltration

When steel is placed in an alkaline environment, a dense, thin layer of passive iron oxide (passive in this context means resistant to corrosion) forms over the steel to protect it. However, carbonation and chlorides attack this passive layer and expose the steel to elements that cause corrosion.

Cracking in concrete has a number of sources: inadequate reinforcement, shrinkage cracking during the curing stage, un-compacted or inadequate substrates, excessive heat during the curing process, lack of consolidation, and excessive loads. While there are other sources, these are the most common sources of cracking in concrete. When cracks reach down to or through the reinforcement layer, the reinforcement is directly exposed to the elements and corrosion is quickly initiated.



Structural failure of concrete due to corrosion of the reinforcement.

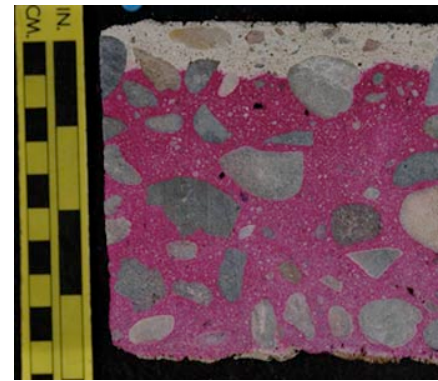
Carbonation is a reaction between carbon dioxide in the air and the cement which results in lowering the pH of the concrete and decreasing passivity (resistance to corrosion). Concrete is a highly alkaline material, with pH typically in the range of 11 - 13. As carbon dioxide found in the air contacts the concrete, it reacts with the calcium hydroxide in the concrete and creates calcium carbonate and water. The pH of the concrete is progressively lowered, which allows the water from the reaction to penetrate the thin protective layer of iron oxide that forms around the reinforcement steel, initiating the corrosion of the rebar.



Reinforcement exposed due to carbonation. Shallow placement of the rebar accelerated the corrosion.

The amount of time it takes for carbonation to affect the rebar is directly related to how deeply embedded the reinforcement is in the concrete. Depth of placement, however is critical to the tensile strength of the concrete, and is generally determined by an engineer.

Chlorides can be introduced into the concrete at the time of mixing through ad-mixes (such as calcium chloride - used to accelerate hardening in cold weather), mix water, and aggregates. However, the most common sources of chlorides in concrete are external. Chlorides are introduced into concrete through de-icing salts and chemicals, seawater, fertilizers, and groundwater. Chlorides are aggressive chemicals that break down the thin protective layer of iron oxide around the rebar and create a pathway for corrosion to start. Cracks, high water content in the mix, and poor consolidation accelerate chloride infiltration.



Cross section of concrete showing carbonation. The white area has a lowered pH, while the pink area is still above a pH of 10.

Freeze/Thaw cycle damage:

Due to the porosity of concrete, water is absorbed into the capillary and pore structure in the cement paste. When exposed to freezing temperatures, this water freezes. When water



Freeze/Thaw damage to a bridge support. Pressure created from freezing water has “exploded” the surface of the concrete.

freezes, it can expand up to 9%. This expansion creates tremendous pressure on the surrounding concrete and causes the surface to flake, delaminate, and “pop” (spall). In addition, repeated freeze/thaw cycles cause concrete to be destroyed gradually, creating cracks in the interior of the concrete which destroys the strength of the concrete and allows other destructive mechanisms to accelerate the failure of the concrete. Freeze/thaw damage is also common along the joints in the concrete, and it is common to see

large pieces of concrete dislodged or broken away along the joints and especially at the intersections of perpendicular joints.

Salt Damage:

Salt damage is most commonly due to exposure to de-icing salts. However, any chemical containing chlorides, including sodium chloride, potassium chloride, calcium chloride etc. found in “safe de-icing chemicals,” fertilizers, ocean water, etc. present a danger to the concrete. All are mildly acidic, and attack the bonds that hold concrete together.

While the exact mechanism of salt damage is not known, a number of known, related factors instigated by exposure to salt contribute to the deterioration of concrete.

First, salt, a mild acid, lowers the pH in the concrete. The acidic reaction attacks the concrete paste and aggregate, increasing the pore size and allowing additional water and chemicals into the concrete which can exacerbate the freeze/thaw cycle damage.

Secondly, salt is hygroscopic, meaning it attracts and holds water. When salts are applied to concrete, it attracts additional (up to 10% more) water into the same space in the pore structure of the concrete, allowing less room for the water to expand when it freezes, and accelerates surface damage and spalling (chipping, flaking, and popping of the surface).



Spalling associate with salt damage.

Second, salt accelerates the carbonation process. Carbonation is a process that slowly reduces the pH levels in concrete and contributes to the corrosion of reinforcing steel. Most salts are neutral to mildly acidic (pH of 4.5 - 7), and absorption of the salts (brine) by the concrete will start to lower the pH of the concrete.

Third, salts are the primary source of chlorides introduced into concrete. Chlorides are also a major player in the corrosion of reinforcement, as they pierce the thin, protective iron oxide layer surrounding the reinforcement and initiate a corrosive reaction in the steel.

Sulfate Attack:

Sulfates are, quite simply, a salt of sulfuric acid. They are found in all natural waters, and are a major dissolved component of rain.

Concrete is exposed to sulfates in two ways, externally sourced and internally sourced. Most commonly, sulfate attack occurs where concrete is exposed to a high sulfate content in the soil, in areas of run-off, and in wastewater. Secondly, portland cement contains a small percentage of gypsum (calcium sulfate dihydrate). The sulfate in the portland cement is an internal source, and is activated when the internal temperature of the curing concrete reaches 160 degrees fahrenheit, a condition which can and should be avoided.



Sulfate attack on bridge supports over a run-off canal.

Sulfates react in the alkaline environment of the concrete paste and create highly expansive crystals called Ettringites. Ettringite is calcium aluminum sulfate. Aluminum is also frequently found as a component of portland cement in trace amounts.⁴ The formation of these expansive crystals create a great deal of pressure inside the concrete and cause the concrete to crack and spall.

In addition, sulfates are acidic, break down the alkaline environment in the concrete and deteriorate the concrete paste through acidic attack. This acidic reaction causes the concrete to weaken and crumble.

Alkali-Aggregate reaction:

The selection of aggregates in concrete is not something that is generally considered by most users of concrete. The local concrete plant has a supplier of various sizes and

⁴ Aluminum is not used for reinforcement due to the sulfate reaction it would create. All components would be in place for ettringite formation if aluminum was used in concrete.

varieties of rock, and it is added to the mix based on the specific intended use. Unfortunately, some aggregates, those with silicon dioxide or dolomite, react in an alkaline environment of the concrete. Depending on the aggregates you have available in your region, it is entirely possible that a reactive aggregate could be used in the concrete.⁵

The Alkali-Aggregate Reaction (AAR) has two sub-sets: Alkali-Silica Reaction (ASR) and Alkali-Carbonate Reaction (ACR).



Alkali Silica Reaction (ASR) on a highway divider.

ASR occurs when aggregates containing silicon-dioxide (SiO_2) dissolve in the alkaline environment of concrete. When dissolved, an alkali-silica gel is formed that swells with water, causing significant internal pressure resulting in cracking in the concrete. ACR is a rare form of AAR, and is related to the use of some dolomitic limestones and other dolostones. The results are similar to that of the ASR.

Concrete needs three elements in order to initiate ASR: Silica (from the aggregate, Alkali (sodium, potassium, calcium, etc.) and

moisture. Remove any of the three elements, and the reaction is impossible.

⁵ Aggregates and minerals that are potentially reactive include : Opal, Chert, Shale, Sandstone, Basalt, Flint, Quartzite, Quartz-arenite, Gneiss, Argillite, Granite, Greywacke, Siltstone, Arenite, Arkose, Hornfels, Tridymite, Cristobalite, Volcanic glass, Microcrystalline quartz, Strained quartz.

Solutions at Concrete Formulation

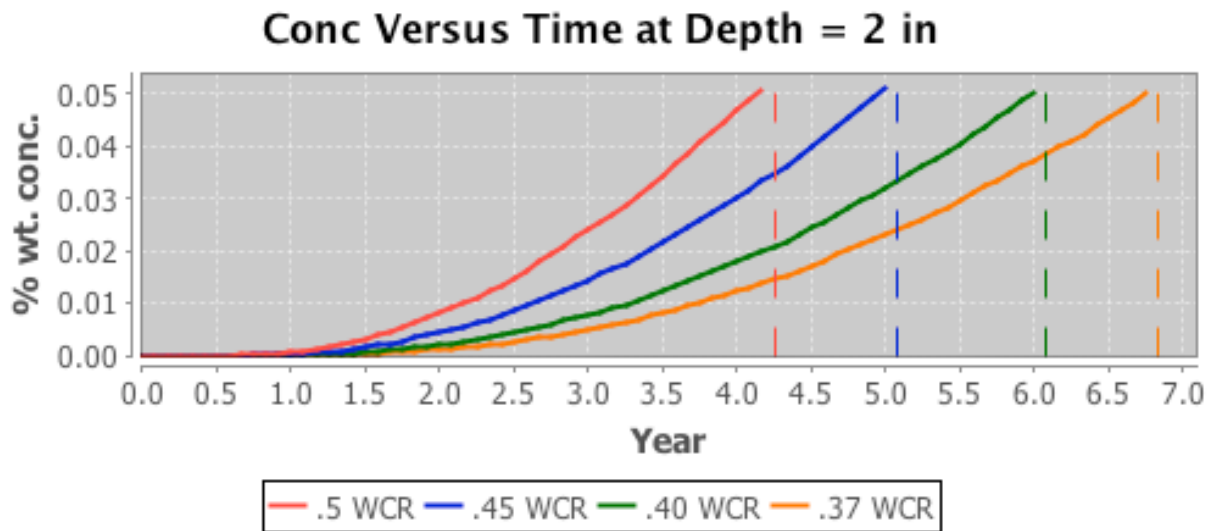
Over the past 50 years, a lot of research has been done to see what can be added to the concrete mix to limit the porosity and create a product that is resistant to the internal and external mechanisms that affect durability. A number of important advances in the manufacturing of concrete have been made:

Methods & Results

Dense Concrete

A dense concrete mixture, using a very low water to cement ratio is one of the easiest and most effective ways to achieve a durable concrete mix. Conversely, high water to cement ratios are extremely bad and actually accelerate concrete degradation. Any mix with a water to cement ratio of greater than .5:1 is considered high and should not be accepted. Plasticizers should be added to the mix to keep water to cement ratios low.

The use of some Supplemental Cementitious Materials (SCM's) such as fly ash, silica fume (micro-silica), and slag also increase the density of the concrete paste and provide a tighter pore structure. The addition of SCM's creates less porosity in the concrete paste. The addition of SCM's does not generally increase the cost per cubic yard (meter) of concrete more than a few dollars. However, a denser concrete only lengthens the time it takes to initiate damage, it does not permanently prevent corrosion or other types of damage.



The graph above shows the difference made in the time it takes for the initiation of corrosion of uncoated rebar simply by using different water to cement ratios (WCR's).

Air Entrainment

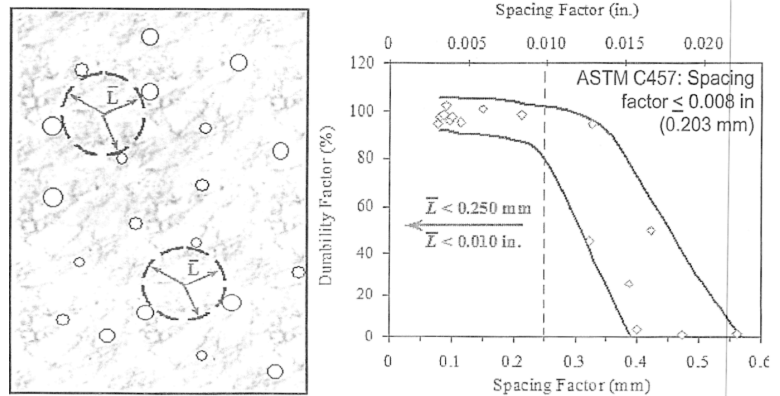
Air entrainment is a very specific process whereby an additive to the concrete mix breaks the air created in the mixing process down into very small bubbles and distributes these bubbles fairly evenly throughout the concrete paste. Measuring the amount of air entrainment is a fairly simple process, and there are a number of procedures that can be used while the concrete is being poured to determine the exact percentage of air in the mixture. However, the critical factor in air entrainment is not the percentage of air (anything from 4% to 7% prove equally effective) but the size and distribution of the air bubbles.

If the spacing of the air bubbles is greater than .2mm, the ability of the entrainment to prevent freeze/thaw damage diminishes rapidly. The bubble size must also be small (around 10-100 microns). The larger the bubbles, the less effective the entrainment. Importantly, there are no test methods that exist that can tell you if the concrete you are pouring meets these criteria. Only after the concrete is set can a sample be taken and examined. If it doesn't meet these criteria, removal and replacement of the concrete may be required. This can prove to be expensive.

Also, one must understand that for every 1% of air entrainment, concrete loses 5% of its strength. 5% air entrained concrete is 25% weaker than non-air-entrained concrete. (This means that 4000psi rated mix of concrete becomes 3000psi concrete with 5% air entrainment.)

Adjustments must be made to the mix to use a higher strength concrete when specifying air entrainment. The use of fly ash also reduces the percentage of air in a mix, and more entrainment additive must be used in mixes that contain fly ash. Class C fly ash retains more air than Class F fly ash.

Spacing Factor is more important than total air content



- **Spacing factor (\bar{L}):** the maximum distance of any point in the cement paste from the periphery of an air void.

Impact on Mechanisms & Trade-Offs

Corrosion of Reinforcing Steel:

While there are a number of mechanisms that lead to the corrosion of reinforcing steel, most of them are due to porosity, or the ability of water, chlorides, or carbon dioxide to penetrate down to the reinforcement.

Corrosion occurs in two phases, the initiation phase (or the time it takes for corrosion to start) and the propagation phase (or the time it takes for the corrosion to grow and damage the reinforcement and/or the concrete).

- **Initiation Phase:** The initiation phase is the time it takes for the thin layer of corrosion resistant (passivity) iron oxide to be compromised. The initiation phase of corrosion in rebar, whether coated or uncoated, placed 2 inches from the surface of the concrete averages 5.6 years in a climate subjected to freezing temperatures in the winter. Rebar placed deeper in the concrete will take longer to reach, and therefore it will take longer for the initiation phase to complete. However, the depth of the reinforcement is generally specified by a design engineer or professional and is not something that should be adjusted “in the field.”
- **Propagation Phase:** Once the initiation phase is complete, the propagation phase begins. Data have shown that it takes about 6 years for corrosion to become apparent and failures to occur in uncoated rebar, 20 years in epoxy coated rebar. Epoxy coated reinforcement is typically 50% more expensive than un-coated. Epoxy coated rebar lengthens the propagation phase, if there are no holes or tears in the coating. Another option is to use stainless steel rebar, which is usually 5-7 times more expensive than uncoated rebar, but can give 50-75 years or longer service.

Freeze/Thaw mitigation:

Freeze/thaw damage is very effectively managed through the use of air entrainment. Perhaps one of the most useful discoveries in the past 50 years is the use of air entrainment. Air entrainment works because it gives space for water to expand when it freezes. Unfortunately, it is not possible to know if the concrete was properly entrained until after it sets. In addition, even proper air entrainment causes two problems in concrete: 1) it weakens it, and 2) chlorides migrate more quickly through voids than through dense concrete paste. While the distribution and size of the bubbles in properly air entrained concrete do not create a “superhighway” of voids for chlorides to race through, any void will slightly accelerate chloride migration.

Salt Damage Mitigation:

Salt’s mechanism of destruction is not completely understood. It is understood that salt contributes extensively to carbonation and chloride intrusion, which accelerates the corrosion of reinforcement. Salt is also hygroscopic, which attracts more water in the same spaces inside the concrete, creating less room for expansion and, therefore, more pressure inside the concrete when it freezes. In addition, salt is acid-like, and progressively lowers the pH of the concrete and breaks down the bonds which hold it together. Water typically carries the dissolved salt into the pore structure of the concrete. Depending on the concentration of salt and the frequency of exposure, the acidic reaction could damage the concrete quickly, or slowly.

Methods to protect concrete from water intrusion, carbonation, and chloride intrusion provide the best protection. Using a low water to cement ratio, including Type F fly ash, silica fume, or slag in the mix will make a denser cement paste and assist in slowing the penetration of water into the concrete. However, these methods are not completely effective, and will only increase the amount of time it takes for salt to damage the concrete.

Sulfate Mitigation:

Controlling the exposure to sulfates is critical to the prevention of sulfate damage. External sources of sulfates penetrate the concrete matrix and create the expansive ettringites. The best mitigation methods for controlling sulfate damage are using Type II or Type V portland cement (which contain less than 8% tri-calcium aluminate). The use of fly ash also reduces the amount of portland cement in the mix, and can therefore help reduce the amount of aluminum introduced through the portland cement.

Since sulfates are also acidic, external sources of sulfates can be slowed through the use of a low water to cement ratio in the mix. Any methods that create a denser, less pervious mixture will aid in the prevention of sulfate intrusion and the acidic deterioration that they cause.

Alkali-Aggregate Mitigation:

Prevention of AAR is best accomplished by the use of the proper aggregates. However, in some geographies, this is a difficult proposition. Three elements need to be present in order to create the reaction: silica, alkali, and moisture. Using a low alkali cement⁶ will be helpful if you know that the aggregate is reactive. However the use of low alkali cement may not be enough to inhibit the reaction.

Use of Type F fly ash is effective in reducing the effect of ASR in concrete, which assists in making a denser cement paste, which will inhibit moisture intrusion. None of the methods, other than using non-reactive aggregate, will prevent AAR completely.

The in-mix methods for addressing and mitigating the mechanisms that affect the durability of concrete vary, and most have trade-offs. Clearly, utilizing a low water to cement ratio will make a big difference in the durability of concrete, and air-entrainment is very effective in eliminating freeze/thaw damage if it is properly done. The use of fly ash (and which type you use does matter) also helps to create a less pervious concrete and reduce the amount of portland cement (which can be helpful in sulfate environments). However, each method depends on proper execution in order to be effective, and it may not be possible to test the mix to determine if the method has been properly executed.

⁶ Low alkali cement is needs to be specified and can be either type I or type I/II portland. It is generally readily available, but is slightly more expensive than standard cement.

Solutions after Concrete has been Placed

For most property owners, concrete already exists and it is simply too late to use the mitigation methods that can be included in the mix. What do you do when you acquire an existing property? How do you know what was done in the concrete mix and whether it was done correctly? What can you do to existing concrete, regardless of the in-mix mitigation methods to protect your concrete investment?

The primary goal is to prevent the intrusion of water and chloride ions. If water can be kept out of the pore and capillary structure of the concrete paste, the majority of the mechanisms can be kept at bay. Chloride ion penetration is a little more complex, but creating a denser, non-porous structure is also key.

Coatings, sealers/penetrating sealers, and reactive chemical products all provide some level of protection to concrete, though the duration and effectiveness of these solutions vary widely. Each of these methods produce specific results, and some require re-application after a period of time.

Unless your concrete is brand new, it is likely that damage has already been initiated. A primary concern is arresting or stopping the progress of the damage, since all the mechanisms progress rather slowly, not instantly. In fact, if concrete is properly mixed, consolidated, and finished, damage should not quickly occur unless the environment is extremely caustic. If early damage (damage that shows up in the first 1-3 years of the concrete) occurs, the problem is almost always and entirely due to improper water/cement ratio, lack of proper consolidation, and/or poor finishing.

Methods & Results

Coatings:

Coatings are any product that can be applied to the surface of the concrete. Coatings include paint, epoxies, urethanes, and acrylic cement overlay systems, and are generally considered to be cosmetic improvements. The big benefit to coatings is that they make the surface of the concrete look better, at least for a while. Coatings can protect the concrete from water and other liquid penetration, only as long as the coating remains intact. Traffic (foot and vehicular), UV exposure, weather, and the bonding ability of the coating all contribute to the effectiveness of the coating. At best, the coating will make the surface look better for a period of time, but even if it looks good, any defect in the coating will allow moisture and other chemicals to penetrate and damage the concrete.

Additionally, and probably more importantly, coatings will not arrest the progress of damage already started in the concrete. Over time, maintenance costs of re-applying the coating (or stripping and re-applying) can create a large line item in the budget, and the concrete still may fail since the deterioration occurring inside the concrete is only covered up.

Sealers:

While coatings are primarily cosmetic (with a limited ability to prevent water intrusion), sealers may or may not have any aesthetic impact on the concrete. Sealers come in many forms, may have pigments to provide some cosmetic enhancement, and are usually temporary. Sealers are typically acrylic, silicone-based, silanes, poly-siloxanes, or methyl-siliconates.

- *Acrylic sealers* are typically very thin clear or pigmented coatings that are frequently used to give a “wet look” or glossy finish to concrete or decorative concrete. They provide very little protection to the concrete since the coating is quite thin and easily compromised. Generally, acrylic sealers need to be re-coated every year, more often in high traffic areas, even though published directions may say that re-coating is not needed for up to 5 years.
- *Silicone-based sealers* can either be surface coatings or penetrating in type. Penetrating Silicone-based sealers typically only penetrate the top 1/8th to 1/4 inch (3mm - 6mm) of the concrete, which gives them a longer life than acrylic sealers. Silicone is hydrophobic, which means it repels water. Silicone-based sealers break down when exposed to sunlight (UV's), and typically have a life of 2-4 years before needing to be re-applied. When water stops beading on the surface, the protection provided by silicone-based sealers is gone.
- *Silanes* and *poly-siloxanes* are very popular products for protecting concrete. Silanes and poly-siloxanes provide some protection against chloride infiltration. They are considered penetrating sealers, but, like silicone-based sealers, are hydrophobic (water repellants) and only penetrate 1/8th to 1/4 inch (3mm - 6mm). The life expectancy of these products is around 5 years. Once the water stops beading up on the surface, the protection is over. Silanes and Poly-siloxanes can handle traffic (including vehicular traffic) well, since they do not only sit on top of the concrete like coatings. Their limitation is the uncertainty of when the protection will fail, and the need to re-apply on a regular basis.
- *Methyl-siliconates* are another hydrophobic (water repellent) sealer, similar in characteristics to silanes and poly-siloxanes. Methyl-siliconates, however, tend to have a much longer protection cycle. Typically, methyl-siliconates only need to be re-applied every 10 years, though the same concerns regarding the ability to visually see whether the protection is still active or not applies. Methyl-siliconates also have good chloride infiltration characteristics. Regular inspection and re-application are necessary to keep the concrete fully protected.

Reactive Products:

Reactive Silicates: Concrete, when it sets, does not use all of the lime (calcium hydroxide) present in the mix for the chemical reaction that hardens the concrete. The leftover calcium and lime are known as “free calcium” or “free lime”, meaning they are un-bonded in the matrix of the concrete. There are a few products on the market that make use of the free calcium/lime to catalyze a new chemical reaction. Sodium silicates (as well as potassium silicates, colloidal silicates - meaning a combination of two or more silicates, and lithium silicates) react with the free calcium/lime in the concrete and create a gel which coats and fills the pore and capillary structure of the concrete and hardens⁷. Depending on the formulation, some silicates only penetrate a short distance (1/4 inch - 6mm) while others can penetrate and react up to 5 inches (144mm) into the concrete. The reaction and protection is permanent and can only be removed by removing the concrete.

Reactive silicates have been demonstrated to nearly completely inhibit water penetration and chloride ion infiltration, significantly reduce carbonation due to their high pH, and provide excellent protection from acidic attacks including salts and sulfates. These products are highly effective at preventing freeze/thaw damage, and do not have any negative impact on air-entrained concrete.

In addition, since reactive silicates use the free calcium in the concrete, they are excellent products to severely limit water penetration and provide a great deal of protection against Alkali-Aggregate Reaction. Sufficient testing against all reactive aggregates has not been performed, but the anecdotal evidence suggests that these products will be effective against AAR.

A unique characteristic of reactive silicates is that, as they penetrate the pore structure, they raise the pH of the concrete and can force residual salts and other impurities to the surface of the concrete. This has the effect of arresting the damage occurring in the concrete, which gives them a distinct advantage over other products. While it won't repair large voids caused by either poor placement or acidic deterioration and won't stop corrosion that is already in the propagation phase, it will have an extremely positive effect on sound concrete, even if deterioration has been initiated.

Reactive silicates have been around for over 60 years, though their use in concrete applications has been demonstrated only in the past 16 or so years. Not all reactive silicate formulations work the same, and some are only formulated for interior applications or have minimal penetration characteristics. Once properly applied, reactive silicates that penetrate at least 2 inches will last for the lifetime of the concrete. These products increase

⁷ Silicates react with calcium hydroxide and create C-S-H (calcium silicate hydrate) which is the same chemical component in cement that hardens, strengthens and gives dimensional stability to concrete. The reaction fills the pore and capillary structure left behind when the mix-water is consumed during setting.

the density of the concrete paste, and also increase the surface hardness of the concrete, making it more difficult to scratch. Application is easy, though caution must be exercised when applying near glass or aluminum.

Reactive Crystal Technology: Another reactive product is a class of products that generate crystalline structures that penetrate and seal the pore and capillary system of the concrete. The crystals are formed by wetting a mixture of tartaric acid (cream of tartar) and sodium carbonate (soda ash). When exposed to water, crystals are formed and carried into the concrete pore structure by the water. Any time the treated concrete is exposed to water, crystals will re-hydrate and new crystals will form. Some manufacturers of these products claim penetration into concrete of up to 1 meter.

Crystallization products are generally surface applied in a slurry with portland cement, or can be in a liquid form. In liquid form, the application is complicated by the need to have the surface flooded with water for up to four days after application so that the crystals can be hydrated and carried into the matrix of the concrete. In slurry form, two applications are necessary, and depending upon the manufacturer, flooding daily for 3-5 days is also required. The crystals will also continue to generate anytime they are exposed to water. This is an important feature because if the concrete were to develop a small crack, when water enters the crack, the crystals will propagate and fill the void, preventing water from progressing into the concrete. These products are effective at significantly reducing water penetration, even under significant hydrostatic pressures. They also report good results in reducing chloride penetration, usually by around 50%.

Impact on Mechanisms & Trade-Offs:

Cost is a factor when considering application of products to hardened concrete. The lifetime cost, not just the application cost, must be considered in determining the value that these products provide.

Coatings and sealers require frequent re-application, and generally range in price from \$15 - \$100+ per gallon, not including application labor and downtime. Coverage rates vary, but in general can range from 100 square feet/gallon to 500 square feet/gallon. Acrylic cementitious overlay systems range in price from \$3.00 to \$10.00 per square foot, and their effectiveness in blocking water penetration is dependent on the sealer used and the frequency of re-application.

Coatings improve the look of the concrete surface, but their effectiveness against the mechanisms that cause damage to concrete is very limited.

Sealers/penetrating sealers do little or nothing to the aesthetic appeal of the surface, but are temporarily effective at preventing moisture and chloride intrusion into the concrete. A regular schedule of re-application is required to make these products useful. They will not arrest any damage that has been initiated in concrete, though. They are most effective if they are placed on fresh concrete after the initial 28 day curing phase is complete.

Reactive Silicates do nothing for the appearance of the concrete. However, the deeply penetrating varieties are remarkably effective against all types of deterioration and provide permanent protection. Pricing of these products range from \$.50/square foot to around \$2.00. Price, however, is not an indication of effectiveness.

Crystalline technology is also effective at protecting against the sources of concrete damage. Application is far more complicated than reactive silicates, requiring the area to be flooded with water, or a slurry to be brushed on (twice) in order to activate the crystal propagation. Cost of these products range from \$2.00/square foot to over \$5.00/square foot, not including labor and downtime.

The critical factor for the success of any of these reactive products is a properly mixed and placed concrete. Excessive water in the concrete mix renders the mitigation methods ineffective. It would be wise before spending funds on any mitigation method for existing concrete to do a petrographic study to determine the quality of the concrete, including the water/cement ratio when it was poured. These studies generally cost around \$1200, and will give you a much better sense of the overall status and quality of your concrete.

Summary:

The major mechanisms that affect the durability of concrete are:

- 1. Freeze/Thaw cycles**
- 2. Corrosion of Reinforcement through:**
 - 2.1. Carbonation
 - 2.2. Chloride Infiltration
 - 2.3. Cracking
- 3. Salt**
- 4. Alkali-Aggregate Reaction**
- 5. Sulfates**

There are a number of methods used to mitigate these mechanisms in the process of mixing new concrete. They are deemed quite effective in alleviating freeze/thaw damage, but not as effective in addressing the other mechanisms. There are new products and ad-mixtures that are constantly being developed, and some show a great deal of promise in more completely mitigating the damage mechanisms.

On existing concrete, there are a number of products that can be used to help mitigate the damage, some with a great deal of success, and some even provide permanent, highly effective solutions.