Chemical degradation and rehabilitation of concrete structures

by

Courtney Holt

B.S., Kansas State University, 2025

A REPORT

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

G.E. Johnson Department of Architectural Engineering and Construction Science
Carl R. Ice College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2026

Approved by:

Major Professor
Bill Zhang

Copyright

Abstract

Concrete is one of the most widely used structural materials in modern infrastructure, yet long-term environmental exposure and internal chemical reactions can gradually degrade its internal microstructure and structural performance. Chemical degradation mechanisms such as carbonation, sulfate attack, alkali–silica reaction, and chloride ingress alter hydration products within the cement matrix, modify pore structure, and promote the development of microcracking within concrete. Although these reactions originate at the microscopic level, their effects propagate through structural elements by reducing stiffness, increasing permeability, and influencing cracking behavior and dimensional stability. Understanding how these degradation mechanisms affect structural performance is essential for evaluating the condition of existing concrete structures and selecting appropriate rehabilitation strategies.

This report examines the relationship between chemical degradation mechanisms in concrete and structural rehabilitation techniques used to preserve deteriorated structures. The discussion first investigates the chemical processes responsible for deterioration and the environmental conditions that influence their development within the cementitious matrix. The structural implications of these degradation mechanisms are then evaluated, including their effects on stiffness degradation, tensile cracking, volumetric expansion, and transport properties within structural concrete.

Following this evaluation, several rehabilitation approaches are examined that address both the chemical and structural consequences of deterioration. Migration control techniques, including carbonation barrier coatings, hydrophobic impregnation, and pore structure densification, are discussed as methods for limiting the transport of aggressive agents through the concrete pore network. Neutralization treatments such as lithium nitrate application and

electrochemical realkalization are examined as approaches for modifying the chemical environment within the concrete to stabilize ongoing reactions. Structural repair methods including epoxy injection, stitching, post-tensioning, autogenous healing, and fiber-reinforced polymer strengthening are also considered for restoring load transfer, improving stiffness, and enhancing the structural performance of degraded concrete elements.

Through the evaluation of degradation mechanisms and corresponding rehabilitation techniques, this report demonstrates how deteriorated concrete structures can be stabilized and preserved while maintaining their structural integrity. Understanding the interaction between chemical deterioration processes and structural repair strategies allows engineers to extend the service life of existing infrastructure and develop effective rehabilitation solutions for aging concrete structures.

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

Concrete has been one of the most widely used structural materials for centuries, serves as a primary component in many structural systems including buildings, bridges, and other infrastructure. A large portion of existing structural infrastructure relies on concrete as a primary load-bearing material because of its high compressive strength, durability, and availability of constituent materials. Concrete has also been used for utilitarian, ornamental, and monumental structures for many centuries, demonstrating its broad applicability in construction and structural engineering practice. Despite its reputation as a durable material, concrete is not immune to deterioration. Long-term environmental exposure and chemical reactions within the cementitious matrix can gradually alter the internal microstructure of the material and influence its structural performance over time (Delatte, 2009).

The deterioration of historic concrete structures presents a particularly important challenge in structural engineering. Many concrete structures constructed during the early development of modern concrete technology possess architectural, cultural, or engineering significance and therefore cannot simply be replaced when deterioration occurs. Historic concrete structures represent an important part of the built environment and often serve as valuable examples of early construction techniques and materials. When deterioration develops, structural engineers must evaluate the underlying causes of distress and develop rehabilitation strategies that preserve the existing structure while restoring structural integrity. Preservation of historic concrete therefore requires a comprehensive understanding of both the degradation mechanisms affecting the material and the structural implications that result from these processes (Gaudette & Slaton, 2007).

Among the various causes of deterioration in concrete structures, chemical degradation play a particularly significant role. Chemical reactions such as carbonation, sulfate, and alkali–silica, alter hydration products within the cement paste and modify the pore structure of the material. These chemical processes may reduce alkalinity, produce expansive reaction products, and initiate microcracking within the cement matrix. Although these reactions occur at the microscopic level, their effects progressively influence the macroscopic behavior of structural concrete by increasing permeability, reducing stiffness, and promoting cracking within the structural. As deterioration progresses, these changes can affect the ability of structural elements to maintain their intended load-carrying capacity and long-term serviceability performance (Fuhaid & Naiz, 2022; U.S. Nuclear Regulatory Commission, 2011).

In many situations, deterioration does not require demolition of the structure but instead can be addressed through appropriate rehabilitation and preservation techniques that extend the service life of the concrete. Structural rehabilitation methods may include crack repair, surface treatments, strengthening systems, and chemical mitigation techniques designed to stabilize the internal environment of the concrete. Effective rehabilitation requires that the underlying deterioration mechanisms be properly identified and controlled prior to implementing structural repair methods. If degradation reactions remain active within the material, repair systems may only provide temporary improvement before deterioration continues beneath the repaired surface (ACI Committee 562, 2019).

This report examines the relationship between chemical degradation mechanisms in concrete and structural rehabilitation techniques used to preserve deteriorated structures. The discussion first investigates the primary chemical processes responsible for deterioration within concrete and the ways in which these processes influence the internal microstructure of the

material. The structural implications of these degradation mechanisms are then considered to understand how deterioration affects stiffness, cracking behavior, dimensional stability, and transport properties within structural concrete. Following this evaluation, several rehabilitation approaches are examined that address both the chemical and structural consequences of degradation. These approaches include techniques that limit the migration of aggressive agents, treatments that modify the chemical environment of the concrete, and structural repair systems used to restore load transfer and improve structural performance.

Through the evaluation of degradation mechanisms and corresponding rehabilitation techniques, this report investigates methods that allow deteriorated concrete structures to be stabilized and preserved while maintaining their structural integrity and historical significance.

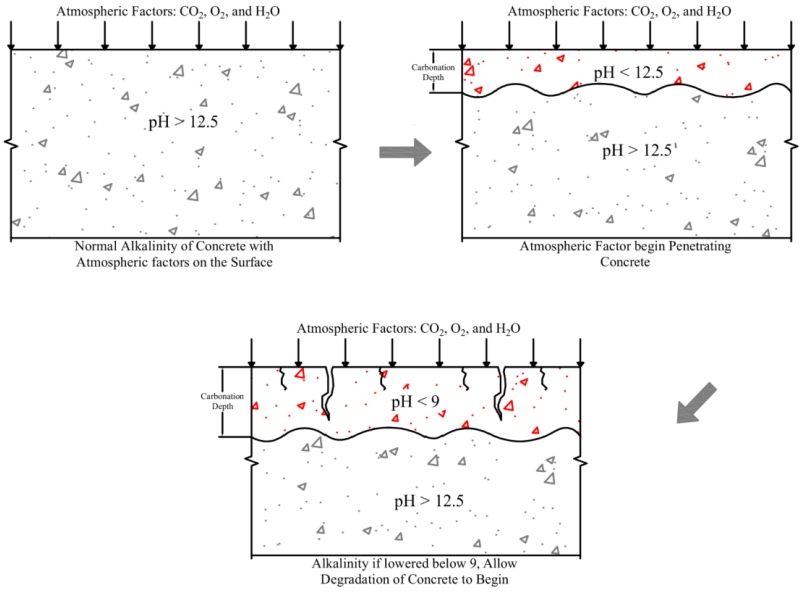
Chapter 2. Chemical Degradation Mechanisms in Concrete

2.1 Carbonation

Carbonation reaction is an environmentally driven degradation mechanism initiated by the ingress of atmospheric carbon dioxide (CO_2) into hardened concrete. Carbon dioxide penetrates the cementitious matrix through interconnected capillary pores, with transport governed by pore structure, moisture content, and exposure conditions. The rate of carbonation is strongly influenced by environmental conditions, particularly relative humidity and temperature. Optimal reaction conditions typically occur when relative humidity ranges between approximately 50–70%, since insufficient moisture limits carbon dioxide dissolution, while excessive moisture restricts carbon dioxide diffusion into the concrete (Fuhaid & Niaz, 2022). Elevated temperatures can further accelerate carbonation by increasing gas diffusion rates and reaction kinetics within the cement matrix (Banerjee, 2024).

Once carbon dioxide dissolves in pore water, it forms carbonic acid (H_2CO_3), which reacts with calcium hydroxide ($Ca(OH)_2$), commonly referred to as portlandite, present in the cement paste to produce calcium carbonate ($CaCO_3$) and water (H_2O). This carbonic acid reduces alkalinity by consuming hydroxide ions (OH^-) in the pore solution and progressively depleting calcium hydroxide, which serves as a primary source of alkalinity and buffering capacity (Fuhaid & Niaz, 2022). Portland cement concrete typically maintains pore solution pH values between approximately 12.5 and 13.5; however, carbonation reactions can lower the pH to values near 8–9, significantly altering the chemical environment of the cement matrix (Banerjee, 2024).

Figure 1. Carbonation Process



The precipitation of calcium carbonate modifies the internal phase composition and pore structure of the cement matrix as carbonation progresses. In regions near exposed surfaces, carbonate formation may temporarily densify portions of the pore structure; however, continued carbonation promotes decalcification of calcium silicate hydrate (C–S–H) and destabilization of hydration products. These chemical alterations alter the microstructure of the cement paste and may lead to localized shrinkage and microcracking within the affected zone (Delatte, 2009).

2.2 Sulfate

Sulfate reaction originates from the interaction between sulfate ions and hydrated cement phases within concrete. However, this sulfate reaction can be either externally or internally driven. External sulfates are introduced through environmental exposure conditions such as sulfate-bearing soils, groundwater, seawater, or industrial environments, while internal sulfates

may originate from contaminated aggregates or sulfate-rich cementitious materials (Lv et al., 2022).

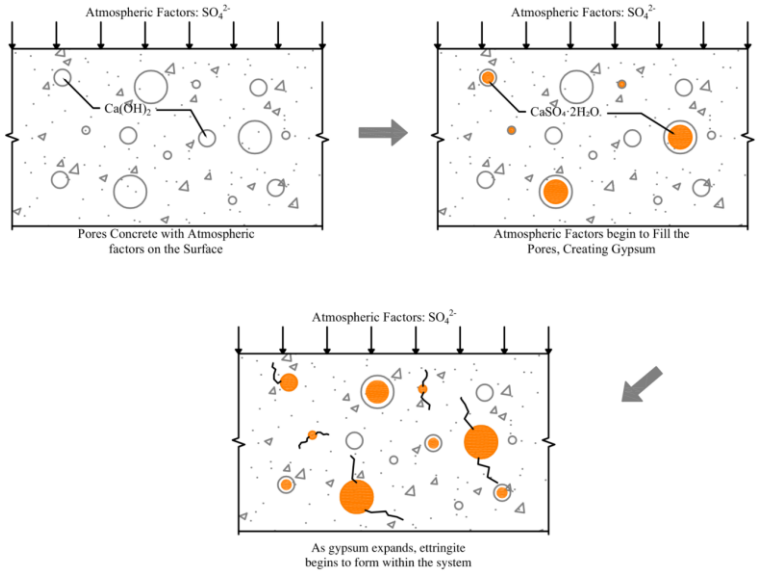
The progression of sulfate attack is strongly governed by external environmental conditions, particularly moisture availability, temperature, sulfate concentration, and cyclic wetting and drying. Moisture is essential for dissolving sulfate ions and enabling their transport through the pore solution, while cyclic wetting and drying accelerates ingress by repeatedly introducing sulfate-rich fluids into the concrete. Temperature influences both sulfate transport and reaction kinetics, increasing the rate at which chemical reactions occur within the cement matrix. Additionally, higher sulfate concentrations in the surrounding environment increase the concentration gradient, which drives diffusion of sulfate ions into the concrete (Zhang et al., 2024; Lv et al., 2022; Delatte, 2009).

External sulfate (SO_4^{2-}) ions migrate into concrete primarily through transport through the pore network. The penetration depth is governed by the connectivity of capillary pores and the presence of microstructural discontinuities that facilitate ion movement into the cement matrix. In contrast, internal sulfate sources may remain chemically inactive until environmental conditions, such as increased moisture or temperature variations, activate reactions that allow sulfates to interact with cement hydration products (Lv et al., 2022).

Once sulfate ions enter the cementitious matrix, they react with calcium hydroxide ($Ca(OH)_2$) to form gypsum, calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), which reduces the alkalinity of the pore solution by consuming a primary source of hydroxide (OH^-) ions responsible for maintaining the high pH of concrete. As $Ca(OH)_2$ is depleted and replaced by gypsum, which does not contribute hydroxide ions, the pore solution pH decreases, leading to a less stable cementitious matrix. The presence of gypsum then enables reactions with calcium

aluminate phases within the cement paste, such as tricalcium aluminate (C_3A) or monosulfate phases. These reactions produce ettringite, an expansive sulfate-bearing compound that forms within the pore structure (Zhang et al., 2024).

Figure 2. External Sulfate Process



The formation of gypsum and ettringite within confined pore spaces results in volumetric expansion due to their larger molar volumes relative to the original hydration products. While localized precipitation of reaction products may temporarily reduce pore connectivity by partially filling pore spaces, the associated expansion disrupts the cement matrix and contributes to the development of localized microcracking. As these microcracks form and link previously isolated pores, pore connectivity increases, leading to higher permeability and facilitating continued sulfate ingress, allowing progressive deterioration of the concrete over time (Zhang et al., 2024; Delatte, 2009).

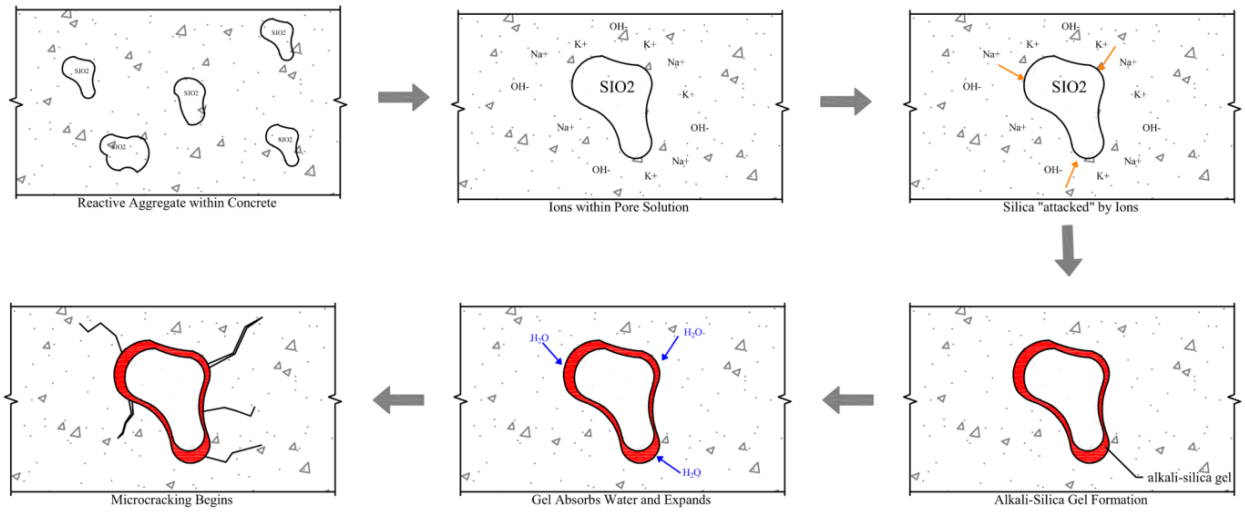
2.3 Alkali–Silica Reaction

Alkali–silica reaction (ASR) is an internally driven chemical degradation process that occurs when reactive forms of silica present in aggregates interact with alkali hydroxides in the pore solution of concrete. Reactive silica phases may include minerals such as opal, chert, strained quartz, or microcrystalline quartz. The pore solution of Portland cement concrete is highly alkaline due to the presence of sodium (Na) and potassium hydroxides (KOH) derived from cement alkalis, creating favorable conditions for silica dissolution and chemical reaction (NRC, 2011).

Alkalis contributing to ASR may originate from several sources including cement, supplementary cementitious materials, aggregates, deicing salts, or groundwater (Almakrab et al., 2024). Although these constituents are present when concrete is initially mixed, ASR may not begin immediately. Sustained moisture exposure and elevated temperature conditions are often necessary to activate the reaction and influence its rate of progression.

Under highly alkaline conditions, reactive silica dissolves and combines with alkali ions to form an amorphous alkali–silica gel. This gel accumulates around aggregate particles and within microdefects in the aggregate structure. Because the gel has a strong affinity for water, it can absorb moisture and expand within the surrounding cement matrix (NRC, 2011).

Figure 3. ASR Process



When sufficient moisture is present, the alkali–silica gel absorbs water and undergoes volumetric expansion within the surrounding cement matrix. While localized gel accumulation may partially fill pore spaces, the associated expansion disrupts the cement paste and contributes to the development of microcracking around affected aggregates and along interfacial transition zones. As microcracking develops, previously isolated pores become connected, allowing additional moisture to enter the concrete and sustain the reaction, producing characteristic map cracking patterns associated with distributed expansion within the material (Almakrab et al., 2024).

2.4 Chloride

Chloride reaction differs from other degradation mechanisms in that it primarily affects embedded reinforcement rather than directly altering the cementitious matrix. Chloride ions enter concrete through the pore structure, driven by concentration gradients and moisture conditions,

and may be accelerated by cyclic wetting and drying or the presence of cracks (Fuhaid & Niaz, 2022; Hartell & Zeng, 2020).

Under normal conditions, the pore solution surrounding embedded reinforcement is highly alkaline, which supports the formation of a stable passive oxide layer on the steel surface. This passive layer limits metal dissolution and protects the reinforcement from corrosion. As chloride ions accumulate at the reinforcement level, a portion may become chemically bound within the cement matrix, while free chlorides continue to concentrate near the steel surface. Once a critical threshold is exceeded, these free chlorides locally disrupt the passive oxide layer, leading to depassivation of the steel. Unlike carbonation or sulfate attack, this process does not require a reduction in pH but instead results from localized chemical breakdown of the protective film (Delatte, 2009; Fuhaid & Niaz, 2022).

Following breakdown of the passive layer, corrosion initiates as an electrochemical process in which iron dissolves at regions where corrosion begins, while reactions involving oxygen and moisture occur within the pore solution. The resulting corrosion products occupy a greater volume than the original steel, causing expansion at the steel–concrete interface and leading to cracking, delamination, and eventual spalling of the cover, which exposes the reinforcement and allows corrosion to continue. Although these effects significantly influence the durability of reinforced concrete systems, chloride ingress is considered a secondary mechanism with respect to degradation of the concrete matrix, as its primary role is associated with the initiation and progression of reinforcement corrosion (Delatte, 2009; Fuhaid & Niaz, 2022).

Chapter 3. Structural Implications of Chemical Degradation

Chemical degradation alters the internal structure of concrete by modifying hydration products, pore structure, and the internal stress state of the cementitious matrix. These changes originate at the microstructural level but progressively influence material properties that govern structural performance. As deterioration advances, properties such as stiffness, tensile resistance, dimensional stability, and transport behavior evolve, affecting how concrete responds to mechanical loading and environmental exposure. The resulting microcracking, expansion, and pore structure changes affect deformation behavior, cracking patterns, and the long-term stability of the material (Delatte, 2009). Changes in pore connectivity and hydration product composition can also alter stress distribution within the cement matrix, further contributing to reductions in mechanical performance.

3.1 Stiffness Degradation and Load–Deformation Behavior

The stiffness of concrete elements is directly related to the elastic modulus of the material, which governs resistance to deformation under applied loading. Chemical degradation reduces stiffness through disruption of the cement matrix and the development of distributed microcracking (Delatte, 2009). Sulfate and alkali–silica reactions are particularly influential because both mechanisms generate internal expansion that produces tensile stresses within the cement paste and at the aggregate–paste interface. The resulting microcracks interrupt the continuity of the cementitious skeleton and reduce the effective elastic modulus of the composite material, leading to increased deformation under load (Zhang et al., 2024).

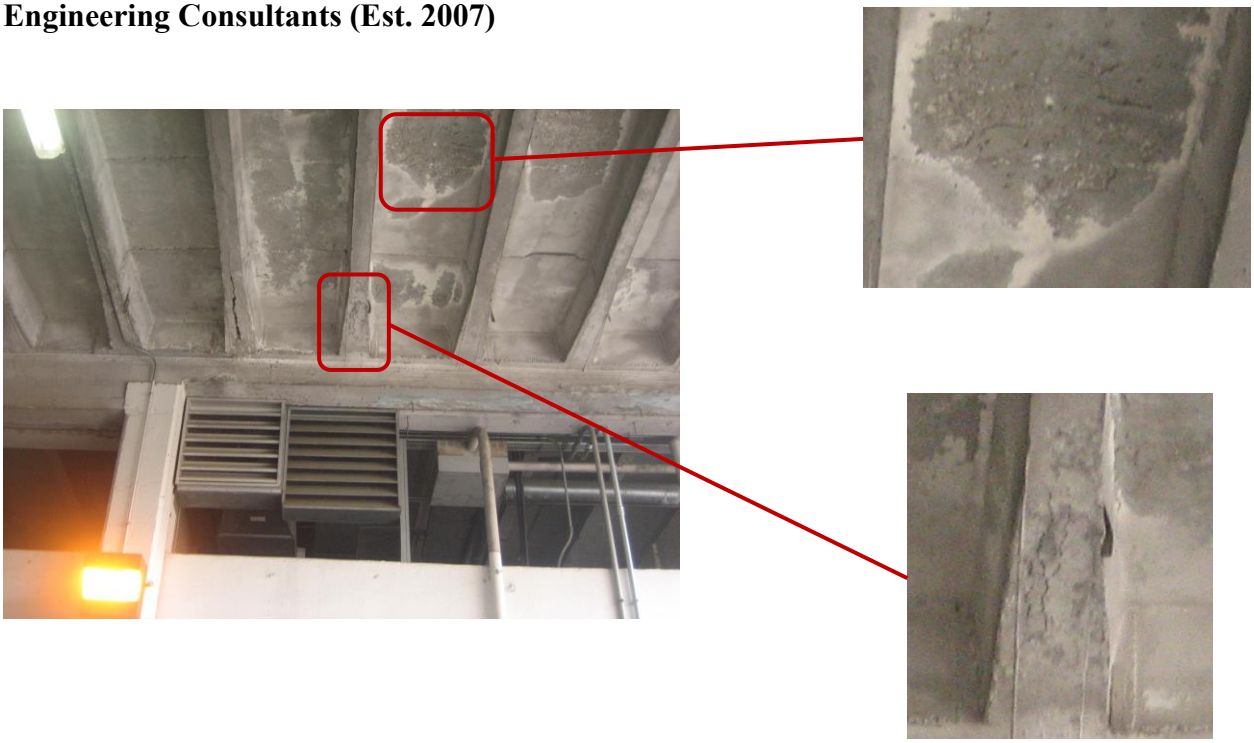
Carbonation also contributes to stiffness reduction through progressive modification of hydration products and associated shrinkage within affected regions of the concrete. These

changes alter the microstructure of the cement matrix and reduce its ability to resist deformation. Evidence of carbonation-related surface degradation is shown in Figure 04, where exposed concrete surfaces exhibit discoloration and localized deterioration associated with near-surface chemical alteration.

Figure 4. Carbonation-Induced Degradation of Exposed Concrete Surfaces, by ASM Engineering Consultants (Est. 2007)

Additional carbonation-related deterioration is illustrated in Figure 05, where surface degradation patterns indicate progressive disruption of the cementitious material. Although localized densification may occur during early stages, continued degradation and shrinkage-related cracking reduce the effective elastic modulus, resulting in decreased resistance to deformation under loading.

Figure 5. Concrete Degradation Associated with Carbonation Reactions, by ASM Engineering Consultants (Est. 2007)



3.2 Tensile Strength

The tensile capacity of concrete, defined as its ability to resist pulling or stretching forces, governs resistance to crack initiation and propagation and is therefore highly sensitive to degradation processes. Alkali–silica reaction reduces tensile strength through the formation of expansive gel that absorbs moisture and induces cracking around reactive aggregates. As these cracks extend into the surrounding cement matrix, the material becomes more susceptible to crack growth under mechanical loading (NRC, 2011).

An example of cracking associated with this degradation mechanism is shown in Figure 06, where expansion caused by alkali–silica reaction produces distributed cracking patterns across the concrete surface. These cracks reflect a loss of tensile capacity as internal expansion exceeds the material's resistance to cracking.

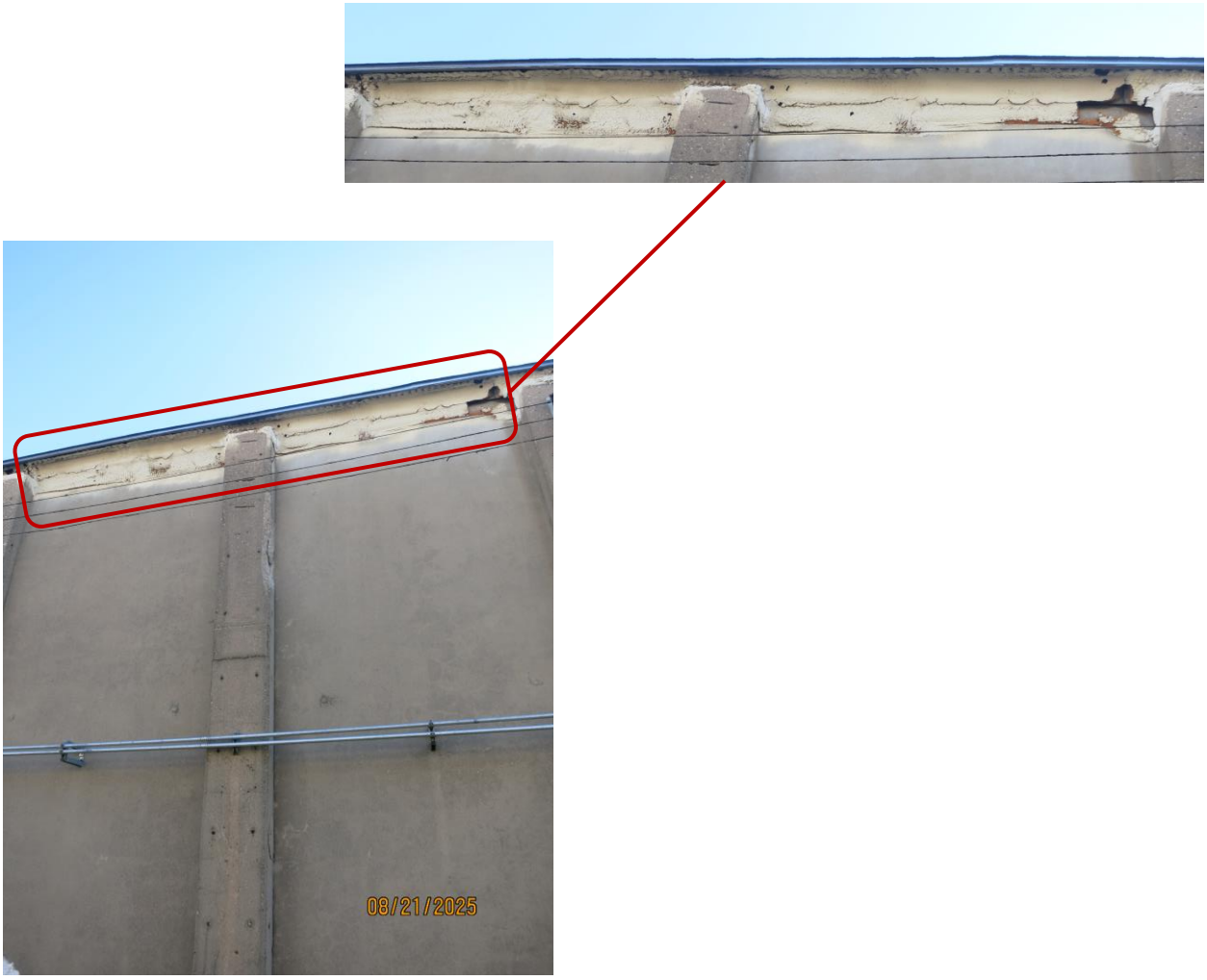
Figure 6. Concrete Degradation Caused by Alkali–Silica Reaction Expansion, by ASM Engineering Consultants (Est. 2007)

Sulfate exposure produces similar reductions in tensile capacity through the formation of expansive reaction products within pore spaces. As gypsum and ettringite develop within the cement matrix, the resulting expansion promotes cracking throughout the paste and interfacial transition zones, weakening the material's ability to resist tensile stresses (Zhang et al., 2024).

The visible effects of sulfate-related deterioration are shown in Figure 07, where exposed concrete surfaces exhibit material distress associated with sulfate attack. Surface scaling of ettringite indicate progressive loss of tensile resistance resulting from internal expansion. As tensile capacity decreases, concrete becomes more susceptible to crack initiation under lower applied loads and allows existing cracks to propagate more readily. This results in earlier

cracking, increased crack widths, and reduced serviceability performance, while also promoting the development of additional transport pathways that can accelerate further deterioration.

Figure 7. Concrete Degradation Caused by Sulfate Attack at Exposed Surfaces, by Engineering Consultants (Est. 2007)



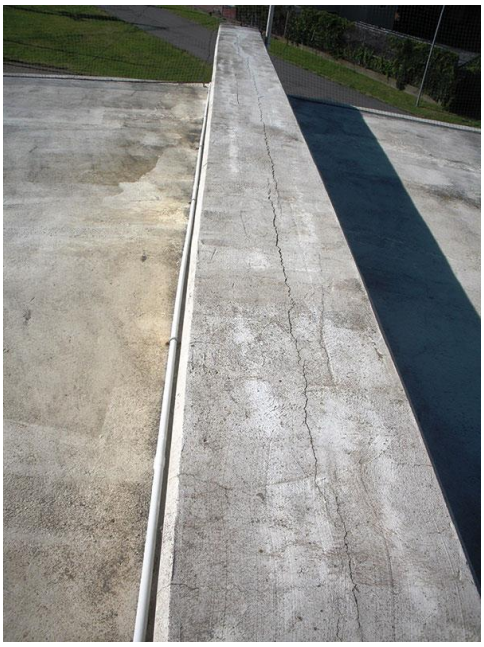
3.3 Dimensional Stability

Chemical degradation mechanisms can also influence the dimensional stability of concrete, defined as its ability to maintain its original volume and shape, by introducing volumetric changes within the cementitious matrix. Alkali–silica reaction is strongly associated

with expansion caused by moisture absorption within alkali–silica gel. As the gel swells, internal pressure develops around affected aggregates and produces widespread cracking throughout the surrounding matrix (NRC, 2011; Almakrab et al., 2024).

The expansion and surface deterioration associated with these reactions can be observed in Figure 08, where characteristic cracking patterns associated with alkali–silica reaction are visible across the concrete surface. These cracking patterns are commonly referred to as map cracking and indicate distributed expansion within the material.

Figure 8. Concrete Degradation Characterized by Alkali–Silica Reaction Cracking (Barnes & Zamora, 2015)



Sulfate exposure can similarly produce volumetric expansion due to the formation of reaction products with larger molar volumes than the original hydration phases. Growth of gypsum and ettringite within confined pore spaces generates internal stresses that disrupt the cement matrix and contribute to cracking and surface deterioration (Zhang et al., 2024).

An example of sulfate-related surface deterioration is illustrated in Figure 09, where chemical reactions within the cement matrix contribute to material degradation and salt crystallization along exposed surfaces.

Figure 9. Concrete Degradation Caused by Sulfate Attack and Salt Crystallization (Skillsitc, 2023)

In contrast to expansive degradation mechanisms such as sulfate attack and alkali–silica reaction, carbonation is typically associated with localized shrinkage within altered regions of the concrete. Differential shrinkage between carbonated and uncarbonated zones can introduce internal stresses that contribute to cracking and dimensional instability over time (Banerjee, 2024).

3.4 Transport Properties and Permeability

Transport behavior plays a critical role in the progression of degradation processes because it governs the movement of moisture, gases, and dissolved ions within concrete, thereby influencing the rate at which structural deterioration develops over time. Changes in pore

structure and the development of cracking can significantly alter permeability and influence the rate at which aggressive agents penetrate the material.

Cracking associated with expansive degradation mechanisms such as sulfate exposure and alkali–silica reaction increases pore connectivity and creates pathways for fluid movement, allowing environmental agents to migrate deeper into the concrete.

An example of deterioration influenced by transport processes is shown in Figure 10, where surface degradation associated with chloride ingress illustrates the movement of dissolved ions into the concrete matrix. Although chloride ingress does not typically produce expansive reaction products within the cement matrix, the presence of chlorides modifies the chemical environment of the concrete and may contribute to deterioration processes occurring within the material.

Figure 10. Concrete Degradation Associated with Chloride Ingress, by ASM Engineering Consultants (Est. 2007)

As deterioration progresses and cracking becomes more extensive, permeability increases and aggressive substances can migrate further into the concrete. This interaction between chemical reactions and transport processes accelerates degradation and contributes to the continued deterioration of the cement matrix.

Chapter 4. Chemical Neutralization and Migration Control Techniques

Before structural rehabilitation methods can be applied, it is necessary to address the chemical conditions that allow deterioration to continue within the concrete. If degradation reactions remain active, repair measures may be compromised as expansion, cracking, or chemical alteration continues beneath repaired surfaces. For this reason, rehabilitation strategies often begin by stabilizing the chemical environment of the concrete so that subsequent repair and strengthening methods can perform effectively. Approaches that control the transport of aggressive substances or modify the chemical conditions within the cement matrix can therefore play an important role in preparing deteriorated structures for rehabilitation (Khan et al., 2019). These stabilization measures are also emphasized in repair planning guidelines, which recommend controlling ongoing deterioration mechanisms prior to applying structural repair systems (ACI Committee 562, 2019).

4.1 Migration

Migration control techniques limit the movement of external substances that sustain chemical reactions within the cementitious matrix, this is not a neutralization technique. Many degradation mechanisms depend on the transport of gases, moisture, or dissolved ions through the pore structure of concrete. By restricting these migration pathways, the supply of reactants necessary for continued chemical reactions is reduced, slowing the progression of deterioration. Limiting the movement of aggressive agents through the pore system can significantly influence degradation rates because transport processes control the availability of reactants required for chemical reactions within the cement matrix. Stabilizing these environmental conditions is

therefore an important step prior to structural rehabilitation because continued chemical activity beneath repaired surfaces may lead to renewed cracking or deterioration of repair materials (Delatte, 2009; ACI Committee 562, 2019).

4.1.1 Carbonation Barrier Coatings

Carbonation barrier coatings are protective surface treatments designed to limit the diffusion of carbon dioxide into concrete. These coatings form a low-permeability layer at the surface, reducing the rate at which atmospheric gases migrate through the pore structure of the cement matrix. Because carbonation reactions rely on the inward diffusion of carbon dioxide, restricting gas transport directly reduces the availability of the primary reactant and slows the progression of the carbonation front (Fuhaid & Niaz, 2022; Banerjee, 2024). This method is most effective for carbonation-related deterioration, where gas diffusion is the governing transport mechanism. Polymer-based materials such as acrylics, epoxies, and polyurethane membranes are commonly used due to their significantly lower gas permeability compared to concrete, allowing them to function as effective diffusion barriers that help maintain a more stable internal chemical environment (Gaudette & Slaton, 2007; Delatte, 2009).

Figure 11. Carbonation Barrier Coatings Application (Constro Facilitator, 2021)

However, the effectiveness of carbonation barrier coatings is limited when deterioration is driven by internal chemical reactions or moisture-based ion transport. Alkali–silica reaction (ASR) originates from interactions between alkalis and reactive aggregates already present within the concrete, meaning that restricting external carbon dioxide does not influence the reaction process (NRC, 2011). Similarly, sulfate attack depends on the ingress of sulfate-bearing solutions rather than gas diffusion. While coatings may slightly reduce moisture penetration at the surface, they cannot prevent reactions involving sulfates already present within the pore solution or surrounding environment (Zhang et al., 2024). Overall, carbonation barrier coatings are best suited for controlling carbonation exposure by stabilizing the chemical environment prior to repair and reducing the risk of continued carbonation beneath rehabilitated surfaces, thereby improving long-term performance and durability of repair systems (ACI Committee 562, 2019).

4.1.2 Hydrophobic Impregnation

Hydrophobic impregnation treatments reduce the movement of liquid water into concrete by altering the surface chemistry of the pore structure. Silane or siloxane compounds penetrate into near-surface pores and chemically bond with mineral surfaces, forming a water-repellent lining along pore walls. This reduces capillary suction and limits liquid water ingress while still allowing vapor diffusion, preserving the ability of the concrete to release internal moisture and avoid vapor pressure buildup (Gaudette & Slaton, 2007). This method is most effective for sulfate attack and moisture-dependent alkali–silica reaction (ASR) because both mechanisms rely heavily on the presence and transport of water within the concrete.

Sulfate attack requires the ingress of sulfate-bearing solutions before chemical reactions with hydration products can occur. By limiting water penetration, hydrophobic treatments reduce sulfate ion mobility and slow the formation of expansive reaction products such as gypsum and ettringite, which are responsible for cracking and deterioration (Zhang et al., 2024). For ASR, the availability of moisture is essential for gel expansion; therefore, reducing internal moisture limits swelling of the alkali–silica gel, decreases expansion potential, and slows crack initiation and propagation (Almakrab et al., 2024).

In contrast, hydrophobic treatments are not effective for carbonation, since carbonation is governed by carbon dioxide diffusion through the pore system rather than liquid transport. As a result, modifying the interaction between water and the pore structure does not significantly reduce gas ingress or carbonation depth (Fuhaid & Niaz, 2022). Overall, hydrophobic impregnation functions as a targeted moisture-control technique that is particularly effective for sulfate attack and ASR, while providing minimal benefit for carbonation, making it best suited for environments where liquid transport governs deterioration.

4.1.3 Silicate Densification

Silicate densification treatments modify the internal microstructure of hardened concrete by reacting with calcium hydroxide in the cement paste to form additional calcium silicate hydrate (C–S–H) gel. This additional C–S–H refines the pore structure by reducing both the size and connectivity of capillary pores within the cement matrix, resulting in lower permeability and reduced transport of gases, liquids, and dissolved ions (Delatte, 2009). Because this method improves the overall density of the concrete and reduces permeability across the pore network, it provides broad effectiveness across carbonation, sulfate attack, and ASR, although it is not the most targeted solution for any single mechanism.

Carbonation is slowed due to reduced carbon dioxide diffusion through the refined pore structure, while sulfate attack is limited by decreased ion ingress and reduced transport of sulfate-bearing solutions. Similarly, ASR progression is reduced through restricted moisture movement and decreased availability of water required for gel expansion (Zhang et al., 2024; Almakrab et al., 2024). However, these benefits are primarily associated with transport reduction rather than chemical alteration. Silicate densification does not neutralize ongoing reactions, meaning that if ASR or sulfate attack has already initiated, the reactions may continue as long as sufficient reactants remain present within the concrete (NRC, 2011).

Overall, silicate densification serves as a general transport-control method effective for all three mechanisms, typically used as a complementary approach to stabilize conditions prior to repair. By reducing permeability and limiting ingress, it enhances the effectiveness of subsequent rehabilitation strategies and helps prevent continued deterioration beneath repaired surfaces (ACI Committee 562, 2019).

4.2 Neutralization

Neutralization techniques modify the internal chemical environment of concrete to stabilize degradation reactions occurring within the cement matrix. Unlike migration control methods that limit the movement of external reactants, neutralization approaches act directly on the chemical processes responsible for deterioration by altering pore solution chemistry or modifying reaction products. Through these mechanisms, neutralization treatments can reduce expansion, cracking, or chemical alteration associated with ongoing degradation and help stabilize the material prior to structural rehabilitation (Khan et al., 2019). Repair guidelines emphasize that such stabilization is often necessary before structural strengthening methods are applied (ACI Committee 562, 2019).

4.2.1 Lithium Nitrate Treatment

Lithium nitrate treatment is a chemical stabilization technique used to mitigate alkali–silica reaction by directly modifying the reaction products formed within the concrete matrix. This approach acts internally by altering the chemistry of the expansive alkali–silica gel responsible for volumetric instability and cracking.

In practice, lithium nitrate is applied as a water-based, penetrating chemical solution rather than a coating, sealant, or epoxy system. The treatment is introduced into the concrete through surface application or localized injection, depending on the required depth of treatment. When applied to the surface, the solution is absorbed into the pore structure through capillary action, allowing lithium ions to enter the pore solution. For deeper or more severely affected

regions, the solution may be injected to improve distribution within the interior of the concrete (Thomas et al., 2007; Delatte, 2009).

Once inside the concrete, lithium ions interact with reactive silica and alkali hydroxides present in the pore solution. This interaction reduces the formation of expansive alkali–silica gel or alters its composition such that it exhibits significantly lower swelling potential. As a result, the internal stresses responsible for cracking and expansion are reduced, helping to stabilize the ongoing degradation process (Thomas et al., 2007; Almakrab et al., 2024). The effectiveness of lithium nitrate treatment depends on the stage of ASR development, with the greatest benefit observed when applied during early or moderate stages before extensive cracking has occurred. In advanced stages, the treatment may limit additional expansion but cannot reverse existing damage (U.S. Nuclear Regulatory Commission, 2011).

Figure 12. Spraying $LiNO_3$ solution with handheld spray applicator on barrier wall (Federal Highway Administration, 2007)

Lithium nitrate treatment is specific to alkali–silica reaction and does not provide effective mitigation for other chemical degradation mechanisms such as sulfate attack or carbonation. Although sulfate attack may also originate internally, such as in cases of delayed ettringite formation or sulfate-contaminated materials, the governing reaction mechanism differs fundamentally from ASR. Sulfate-related deterioration is driven by the formation of expansive crystalline products, including gypsum and ettringite, resulting from reactions between sulfate ions and cement hydration phases, which are not influenced by lithium ions (Zhang et al., 2024). Similarly, lithium nitrate treatment is not effective for carbonation-related deterioration, as carbonation is governed by the reduction of pore solution pH due to the reaction between carbon dioxide and calcium hydroxide. Lithium ions do not restore alkalinity or reverse this chemical change, and therefore do not address the mechanism driving carbonation (Fuhaid & Niaz, 2022).

From a structural standpoint, lithium nitrate treatment contributes to improved dimensional stability by reducing expansion-induced internal stresses associated with ASR, thereby limiting further crack propagation and helping maintain the integrity of the concrete matrix. However, because the treatment does not restore mechanical properties or repair existing cracks, it is typically followed by structural repair methods where necessary (Delatte, 2009; ACI Committee 562, 2019). Overall, lithium nitrate treatment is most effective for alkali–silica reaction, as it directly targets the chemical mechanism responsible for expansion and associated cracking, while remaining ineffective for degradation processes governed by different chemical reactions.

4.2.2 Electrochemical Realkalization

Silicate densification treatments modify the internal microstructure of hardened concrete by reacting with calcium hydroxide in the cement paste to form additional calcium silicate hydrate (C–S–H) gel. This additional C–S–H refines the pore structure by reducing both the size and connectivity of capillary pores within the cement matrix, resulting in lower permeability and reduced transport of gases, liquids, and dissolved ions (Delatte, 2009). Because this method improves the overall density of the concrete and reduces permeability across the pore network, it provides broad effectiveness across carbonation, sulfate attack, and ASR, although it is not the most targeted solution for any single mechanism.

Carbonation is slowed due to reduced carbon dioxide diffusion through the refined pore structure, while sulfate attack is limited by decreased ion ingress and reduced transport of sulfate-bearing solutions. Similarly, ASR progression is reduced through restricted moisture movement and decreased availability of water required for gel expansion (Zhang et al., 2024; Almakrab et al., 2024). However, these benefits are primarily associated with transport reduction rather than chemical alteration. Silicate densification does not neutralize ongoing reactions, meaning that if ASR or sulfate attack has already initiated, the reactions may continue as long as sufficient reactants remain present within the concrete (NRC, 2011).

Overall, silicate densification serves as a general transport-control method effective for all three mechanisms, typically used as a complementary approach to stabilize conditions prior to repair. By reducing permeability and limiting ingress, it enhances the effectiveness of subsequent rehabilitation strategies and helps prevent continued deterioration beneath repaired surfaces (ACI Committee 562, 2019).

4.3 Summary

Overall, the techniques presented in this chapter demonstrate that stabilization methods must be selected based on the governing degradation mechanism within the concrete. Migration control approaches, such as barrier coatings, hydrophobic treatments, and pore densification, primarily limit the transport of gases, moisture, and ions, making them effective for carbonation and sulfate-related deterioration as well as moisture-dependent reactions like alkali–silica reaction. In contrast, neutralization methods act directly on the chemical processes, with lithium nitrate treatment specifically targeting alkali–silica reaction and electrochemical realkalization addressing carbonation. Because each technique is mechanism-dependent and does not universally mitigate all forms of deterioration, appropriate selection is essential to effectively stabilize the concrete prior to the application of structural repair and strengthening methods.

Table 1. Summarization of Migration and Neutralization Controls for Chemical Degradations

Degradation Mechanism	Barrier Coatings	Hydrophobic Impregnation	Silicate Densification	Lithium Nitrate	Electrochemical Realkalization
Carbonation	High	Low	Moderate	None	High
Sulfate Attack	Low	High	High	None	None
Alkali–Silica Reaction (ASR)	None	High	High	High	None

Chapter 5. Crack Repair Rehabilitation and Preservation Techniques

Concrete deterioration often manifests structurally through the development of cracks within the concrete matrix. These cracks disrupt internal force transfer, increase permeability, and can reduce stiffness and serviceability performance. Addressing cracking is therefore an important component of structural rehabilitation. Effective stabilization requires selecting techniques based on the governing degradation mechanism within the concrete. Migration control approaches, such as barrier coatings, hydrophobic treatments, and pore densification, primarily limit the transport of gases, moisture, and ions, making them effective for carbonation- and sulfate-related deterioration as well as moisture-dependent reactions like alkali–silica reaction. In contrast, neutralization methods act directly on the chemical processes, with lithium nitrate treatment specifically targeting alkali–silica reaction and electrochemical realkalization addressing carbonation. Because each technique is mechanism-dependent and does not universally mitigate all forms of deterioration, appropriate selection is essential to stabilize the concrete prior to repair. Repair guidelines emphasize that deterioration mechanisms should be evaluated and stabilized before structural repair methods are applied so that repairs can perform effectively over the long term (ACI Committee 562, 2019).

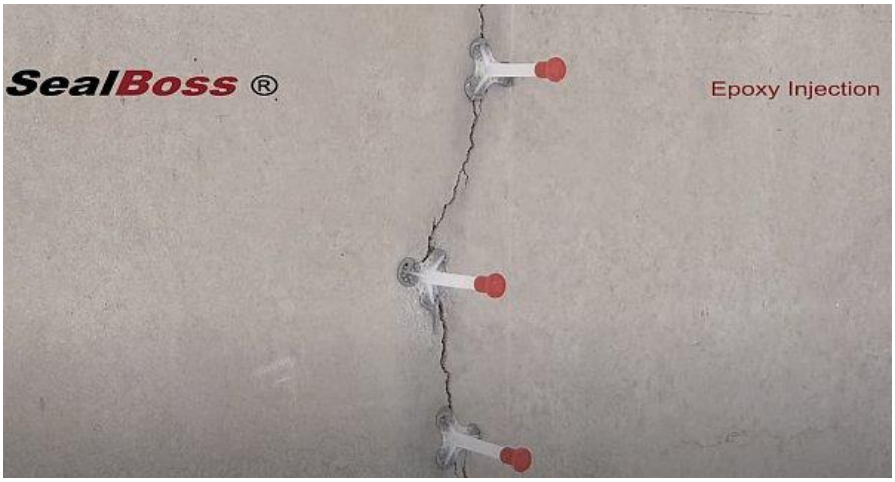
This chapter presents several crack repair techniques used to restore force transfer across cracked concrete sections, control crack propagation, and reduce transport pathways that may accelerate deterioration. Methods including epoxy injection, stitching, post-tensioning, and autogenous or crystalline healing are discussed as approaches for improving the structural performance and durability of cracked concrete

5.1 Epoxy Injection

Epoxy injection is a crack repair technique used to restore structural continuity in cracked concrete by bonding crack faces together with a high-strength thermosetting resin. When cracking disrupts the continuity of the cementitious matrix, tensile and shear stresses can no longer be transmitted across the crack plane, resulting in reduced stiffness and altered load transfer within the section. By filling and bonding the crack, epoxy injection restores stress transfer across the discontinuity so that the repaired region can again behave similarly to an uncracked monolithic element (ACI Committee 224, 2007). This technique is widely used in structural repair because epoxy resins can develop tensile and shear strengths that exceed those of the surrounding concrete (ACI Committee 503, 1993).

The repair process involves sealing the crack surface and installing injection ports along the crack length. A low-viscosity epoxy resin is then pressure-injected so that the material penetrates the full depth of the crack. Once injected, the epoxy cures and polymerizes into a rigid material that adheres strongly to hardened concrete surfaces. The bond created between the epoxy and the concrete allows stresses to be transmitted across the crack plane, restoring compatibility between previously separated crack faces (ACI Committee 503, 1993).

Figure 13. Epoxy Crack Injection Concrete Repair (SealBoss, N.d.)



Restoring continuity across the crack improves the effective stiffness of the section and reduces service-level curvature and deflection. Filling the crack also eliminates an open pathway for the movement of moisture and dissolved substances through the concrete, reducing localized permeability along the repaired plane. By limiting transport through the crack, epoxy injection contributes not only to structural restoration but also to improved durability performance of the repaired region (Delatte, 2009).

Epoxy injection is particularly effective for discrete cracks that develop in concrete following deterioration mechanisms that primarily alter the chemical environment of the cement matrix without producing sustained internal expansion. For example, carbonation-related deterioration may contribute to cracking through shrinkage or environmental exposure effects, and epoxy injection can effectively restore continuity once the deterioration process has stabilized.

Cracking associated with expansive mechanisms such as alkali–silica reaction or sulfate attack may also be repaired after expansion has ceased and the cracking has stabilized. However,

these mechanisms frequently produce distributed microcracking and localized degradation within the cement matrix, which can limit the effectiveness of the repair when compared with isolated cracks. If expansive reactions remain active, rigid bonding across the crack may lead to renewed cracking adjacent to the repair due to continued internal expansion within the concrete matrix (ACI Committee 562, 2019).

Under stabilized conditions, however, epoxy injection functions as a structural restoration technique that re-establishes stress transfer across cracks and improves the long-term performance of concrete elements such as beams, slabs, columns, and walls where discrete cracking has occurred. This method is most effective in structural members where cracks are well-defined and accessible, particularly in above-grade or exposed conditions, although it may also be applied in controlled below-grade environments once moisture-related issues have been addressed.

5.2 Stitching

Stitching is a crack repair technique used to stabilize cracked concrete by mechanically bridging the crack plane with embedded reinforcement. Steel bars installed across the crack provide an alternative path for force transfer between separated portions of the concrete. By introducing reinforcement that directly resists crack opening, stitching restores localized load-carrying capacity and improves the stability of the cracked region (ACI Committee 224, 2007).

The repair is performed by drilling holes on each side of the crack and installing U-shaped steel bars or dowels that cross the crack plane. These bars are anchored into the surrounding concrete using grout or epoxy so that tensile forces acting to widen the crack are resisted by axial tension in the embedded reinforcement. Through this connection, the

reinforcement bridges the discontinuity and re-establishes mechanical interaction between the separated concrete segments, allowing stresses to be transferred across the crack (ACI Committee 224, 2007).

Figure 14. Process of Installing Stitching and Epoxy Injection onto a Concrete Slab (Jr DeSanto, 2022)

Once installed, forces that would otherwise cause further crack opening are redirected through the reinforcing bars. This reduces relative displacement between the crack faces and decreases stress concentrations at the crack tip. When multiple stitches are installed along the crack length, tensile demand is distributed over a broader portion of the section, improving crack stability and maintaining serviceability performance (ACI Committee 562, 2019).

Stitching is particularly beneficial for discrete cracks that remain after deterioration processes affecting the cement matrix have stabilized. Cracking associated with environmental exposure or deterioration mechanisms that modify the chemical environment of the concrete without producing sustained internal expansion can often be effectively stabilized using this method. Carbonation-related deterioration, for example, may contribute to cracking through

shrinkage or environmental effects, and stitching can restore load transfer once the deterioration process has ceased.

Cracks that originated from expansive deterioration mechanisms such as alkali–silica reaction or sulfate attack may also be stabilized using stitching after expansion has stopped and the cracking has become dormant. However, these mechanisms often produce distributed cracking and localized degradation throughout the cement matrix rather than isolated crack planes. Because stitching primarily restrains movement along identifiable cracks, the effectiveness of the repair may be reduced where cracking is widespread. This technique is most effective in structural elements such as beams, slabs, and walls where discrete cracking is present and accessible, and may also be applied in columns where localized cracking has stabilized. Stitching is generally more suitable for above-grade or exposed structural components where crack locations are well-defined and accessible, allowing reinforcement to be installed effectively along the crack length (Delatte, 2009).

5.3 Post-Tensioning

Post-tensioning is a rehabilitation technique used to control cracking and improve structural performance by introducing compressive force into existing concrete members. By applying compressive stresses to the member, the method reduces the net tensile stresses that develop under service loading. When tensile stresses are reduced below the cracking threshold, crack widening is restrained and the structural response of the concrete element is improved (ACI Committee 562, 2019).

The mechanism of this repair method is based on modifying the internal stress distribution within the cracked concrete section. When tensile stresses exceed the tensile capacity

of concrete, cracking occurs and stiffness decreases. Post-tensioning introduces axial compression through stressed tendons, which counteracts the tensile stresses responsible for crack development. When tendons are installed with eccentricity, the prestressing force also produces a bending effect that further reduces tensile demand within the section. Through this redistribution of stresses, crack widths are reduced and the overall structural response becomes more stable under service loading (Khan et al., 2019).

Figure 15. External Post-Tensioning of Concrete Bridge Beams (Freyssinet, N.d.)

In rehabilitation applications, tendons are often installed externally along the concrete member and anchored at designated locations. After installation, the tendons are stressed to a specified force while accounting for expected prestress losses. Proper detailing of anchorage zones and long-term protection of tendons are necessary to ensure reliable performance of the repair system. By introducing sustained compression into the member, post-tensioning reduces crack opening and improves service-level stiffness while allowing the existing concrete section to participate more effectively in resisting applied loads (Khan et al., 2019).

Post-tensioning is particularly beneficial for cracks that developed due to tensile stresses associated with environmental exposure or deterioration mechanisms that alter the chemical condition of the cement matrix without producing sustained internal expansion. For example, carbonation-related deterioration may contribute to cracking through shrinkage effects, and the introduction of compressive force can effectively reduce crack widths once the deterioration process has stabilized.

Cracking that originated from expansive deterioration mechanisms such as alkali–silica reaction or sulfate attack may also be restrained through post-tensioning after expansion has ceased and cracking has stabilized. However, because these mechanisms often produce distributed microcracking within the cement matrix, the improvement in structural performance may be limited since the repair primarily reduces tensile stresses rather than restoring the internal microstructure of the concrete. This technique is most effective in structural elements such as beams and slabs where tensile stresses govern cracking behavior, and may also be applied in columns or walls where overall stress redistribution is required. Post-tensioning is generally more suitable for members where tendons can be properly installed and anchored, particularly in accessible and above-grade applications (Delatte, 2009).

5.4 Autogenous healing / Crystall Healing

Autogenous and crystalline healing are crack repair approaches that reduce permeability in cracked concrete through moisture-driven chemical reactions occurring within the cement matrix. Instead of externally bonding or mechanically restraining the crack, these mechanisms promote internal mineral formation within the crack plane. Through continued hydration and

precipitation reactions, cracks may become partially filled with solid reaction products that reduce permeability and restrict fluid transport through the concrete.

Autogenous healing occurs when residual unhydrated cement particles and calcium hydroxide react with water entering the crack. These reactions can produce additional hydration products, primarily calcium silicate hydrate, that accumulate within the crack space. Calcium hydroxide may also react with carbon dioxide to form calcium carbonate deposits along the crack surfaces. These mineral deposits gradually fill portions of the crack and reduce its connectivity to the surrounding pore network (Gaudette & Slaton, 2007).

Because this repair mechanism operates through internal mineral formation rather than mechanical restraint, its primary benefit is the reduction of permeability within the cracked region. Sealing microcracks limits the movement of moisture, dissolved ions, and gases through the concrete, which can improve durability performance and slow the progression of environmentally driven deterioration processes (Delatte, 2009).

Autogenous and crystalline healing are particularly effective when deterioration processes depend on the transport of moisture and aggressive substances through cracks. For example, carbonation-related deterioration progresses as carbon dioxide migrates through the pore structure and reacts with hydration products. Reducing crack permeability can therefore slow the movement of carbon dioxide into the concrete and limit continued chemical alteration of the cement matrix (Banerjee, 2024).

However, this approach is less effective for cracking produced by expansive deterioration mechanisms such as alkali–silica reaction or sulfate attack. Although sealing cracks may reduce moisture and ion transport, it does not restrain internal expansion within the concrete matrix. When expansion has already produced widespread microcracking or internal degradation, the

structural improvement provided by crack sealing alone may therefore be limited (Almakrab et al., 2024; Zhang et al., 2024).

Autogenous and crystalline healing should therefore be understood primarily as durability-oriented repair mechanisms that act within the concrete matrix rather than through external intervention. These methods are most effective in structural elements such as slabs, walls, and similar members where cracking is fine and distributed, allowing internal reactions to occur throughout the crack network. Their application is best suited to conditions where moisture is present to sustain the healing process, while their influence on structural capacity in primary load-bearing members such as beams or columns remains limited.

5.5 Summary

Table 2. Summarization of Crack Repairs for Chemical Degradations

Degradation Mechanism	Carbonation	Sulfate Attack	Alkali–Silica Reaction
Epoxy Injection	High	Moderate	Moderate
Stitching	High	Moderate	Moderate
Post-Tensioning	High	Moderate	Moderate
Autogenous healing / Crystall Healing	Moderate	High	High

Chapter 6. FRP Rehabilitation and Preservation Techniques

Fiber-reinforced polymer (FRP) strengthening is a rehabilitation technique used to improve the structural performance of deteriorated concrete through the application of externally bonded composite reinforcement. In concrete that has experienced chemical degradation, the cementitious matrix may exhibit reductions in tensile strength, stiffness, and internal cohesion. These changes often result in increased cracking, reduced rigidity, and diminished load-carrying capacity. FRP strengthening systems compensate for these deficiencies by introducing high-strength reinforcement along the surface of the concrete, allowing tensile forces to be resisted by the composite material rather than by the weakened cement matrix (Al-Mahaidi and Kalfat, 2018).

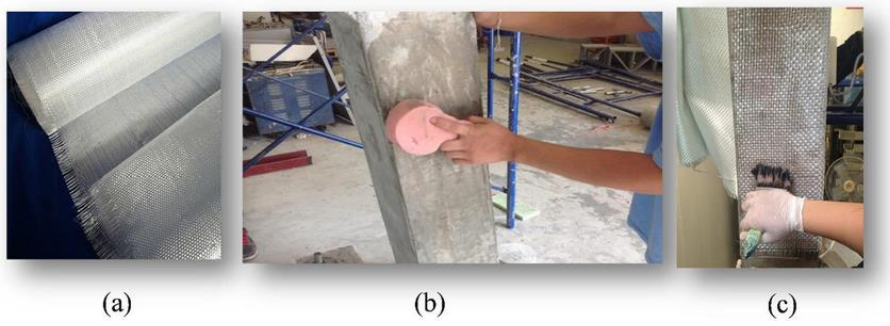
Unlike repair techniques that rely on internal chemical reactions or crack filling mechanisms, FRP strengthening modifies the structural behavior of the concrete element by introducing supplemental tensile resistance. When bonded to the surface of the concrete, the composite layer acts as an external reinforcement that engages when strain develops in the underlying substrate. Through this interaction, tensile stresses that would normally be carried by the deteriorated concrete are transferred to the high-strength fibers within the composite material. This redistribution of stresses reduces crack growth, improves stiffness, and enhances the structural performance of the repaired element (Al-Mahaidi and Kalfat, 2018).

FRP systems typically consist of high-strength fibers embedded within a polymer resin matrix. During installation, the concrete surface is prepared to remove deteriorated material and to ensure proper bond development between the composite layer and the substrate. Fiber sheets or fabrics are then saturated with resin and applied directly to the prepared concrete surface. Once the resin cures, the composite layer becomes bonded to the concrete and can transfer

tensile forces between the two materials. The effectiveness of the strengthening system therefore depends strongly on the development of adequate bond between the composite reinforcement and the existing concrete (ACI Committee 562, 2019).

The structural contribution of FRP reinforcement arises from the interaction between the composite layer and the existing concrete. Chemical degradation processes can reduce the elastic modulus and tensile strength of the cement matrix while increasing distributed microcracking throughout the material. These changes lower the effective stiffness of the concrete and accelerate crack growth under service loading conditions. When externally bonded FRP reinforcement engages, tensile stresses that would otherwise be carried by the degraded concrete are transferred to the composite layer. This redistribution of stresses reduces tensile strain demand within the concrete, increases effective flexural rigidity, and limits further crack propagation.

Figure 16. GFRP Application Process to a Test (DYWIDAG, N.d.)



FRP systems may also be used to provide confinement to concrete subjected to compressive loading. When composite sheets are wrapped around a concrete element, the FRP layer restrains lateral dilation that occurs as the material is compressed. This confinement increases the compressive strain capacity of the concrete and improves ductility, which can be particularly beneficial in concrete where degradation has reduced internal cohesion or stability of

the cement matrix. Through this mechanism, the composite wrap enhances the ability of the concrete to sustain compressive strains without experiencing brittle failure (Al-Mahaidi and Kalfat, 2018).

Two primary types of fiber reinforcement are commonly used for structural strengthening: glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP). Although both systems operate through similar mechanical principles, their structural contributions differ due to variations in stiffness and tensile strength. Glass fiber systems typically exhibit moderate tensile strength and a lower modulus of elasticity compared with carbon fibers. Because of this relatively lower stiffness, GFRP systems are often used in applications where moderate strengthening and crack control are required while allowing some deformation compatibility with the existing concrete.

Figure 17. CFRP Strengthening of Concrete Slab (DYWIDAG, N,d,)

Carbon fiber reinforced polymer systems possess significantly higher tensile strength and modulus of elasticity than glass fiber systems. Because of this increased stiffness, CFRP

reinforcement engages at lower strain levels and can produce greater improvements in structural rigidity and flexural performance. For concrete members that have experienced significant reductions in stiffness due to chemical degradation or cracking, CFRP systems can therefore provide a more substantial improvement in structural performance (Al-Mahaidi and Kalfat, 2018).

FRP strengthening is particularly beneficial for concrete affected by deterioration mechanisms that reduce stiffness or produce distributed cracking within the cement matrix. Carbonation, for example, may alter the chemical environment of the cement paste and contribute to shrinkage-related cracking or reductions in tensile capacity. Once deterioration processes have stabilized, externally bonded fiber reinforcement can restore effective stiffness and improve crack control by providing supplemental tensile resistance along the surface of the concrete (Fuhaid & Niaz, 2022).

Concrete that has experienced cracking associated with expansive deterioration mechanisms such as alkali–silica reaction or sulfate attack may also benefit from FRP confinement after expansion has stabilized. In such cases, the composite layer can restrain crack widening and provide additional confinement to the damaged matrix. However, these degradation mechanisms often produce widespread microcracking or localized deterioration throughout the cement paste. Because FRP strengthening primarily acts at the surface of the concrete, improvements in structural performance may be more limited when internal degradation is extensive (Zhang et al., 2024; Almakrab et al., 2024).

If expansive reactions remain active, continued internal expansion within the concrete can introduce stresses at the interface between the FRP layer and the concrete substrate. These stresses may lead to debonding of the composite reinforcement or renewed cracking adjacent to

the strengthened region. For this reason, FRP systems are most effective when applied to concrete in which the deterioration mechanisms responsible for cracking have been stabilized and the objective of the repair is to restore structural capacity rather than to control ongoing chemical reactions (ACI Committee 562, 2019).

Within rehabilitation practice, FRP strengthening provides a means of improving the structural response of degraded concrete by externally reinforcing the existing matrix. By increasing tensile resistance, restraining crack growth, and providing confinement, the composite reinforcement compensates for reductions in stiffness and strength caused by chemical degradation of the cementitious material (Al-Mahaidi and Kalfat, 2018).

Although FRP systems significantly improve mechanical performance, they do not alter pore chemistry, reverse chemical degradation, or restore the internal microstructure of the cement matrix. Their effectiveness depends primarily on the development of a reliable bond between the composite layer and the concrete surface as well as the stabilization of deterioration processes within the substrate. Consequently, FRP strengthening should be understood as a structural rehabilitation method that addresses the mechanical consequences of deterioration rather than the chemical reactions that originally caused the damage. This approach is most effective in structural elements such as beams, slabs, columns, and walls where additional tensile capacity or confinement can enhance structural performance, particularly in members experiencing cracking or reduced stiffness. Its application is best suited to accessible structural surfaces where proper bonding can be achieved, while its effectiveness may be reduced in cases where internal deterioration is severe or bond conditions are compromised

Chapter 7. Summary and Conclusion

This report examined the relationship between chemical degradation mechanisms in concrete and the structural rehabilitation techniques used to preserve deteriorated infrastructure. The need for this evaluation arises from the widespread presence of aging concrete structures and the importance of maintaining their structural integrity, serviceability, and, in many cases, historical significance. Understanding both the causes of deterioration and the effectiveness of rehabilitation strategies is essential for extending the service life of existing concrete systems.

Chemical degradation mechanisms such as carbonation, sulfate attack, and alkali–silica reaction originate from interactions between environmental exposure and the internal chemistry of the cementitious matrix. These processes alter hydration products, reduce alkalinity, and generate expansion or microstructural instability within the material. Although these changes occur at the microscopic level, they progressively influence the macroscopic behavior of concrete by modifying its internal structure and material properties.

As degradation develops, these chemical changes translate directly into structural consequences. Reductions in stiffness, loss of tensile capacity, volumetric instability, and increased permeability alter the mechanical response of concrete under loading. Microcracking and internal expansion disrupt force transfer within the material, while increased pore connectivity allows aggressive agents to penetrate deeper into the concrete, accelerating the deterioration process. This interaction between chemical reactions and transport behavior highlights the coupled nature of durability and structural performance.

Effective rehabilitation therefore requires addressing the underlying chemical conditions prior to implementing structural repair. Techniques that limit the ingress of aggressive agents help reduce the availability of reactants necessary for continued deterioration, while chemical

treatments that modify the internal environment can stabilize ongoing reactions. These stabilization methods play a critical role in preventing continued damage beneath repaired surfaces and ensuring the long-term effectiveness of subsequent repair strategies.

Once deterioration has been stabilized, structural repair and strengthening techniques can be applied to restore performance. Crack repair methods such as epoxy injection, stitching, post-tensioning, and autogenous or crystalline healing improve load transfer, reduce crack propagation, and limit permeability within the material. In addition, externally applied reinforcement systems, such as fiber-reinforced polymers, enhance structural capacity by providing supplemental tensile resistance and confinement. These methods address the mechanical consequences of degradation but rely on prior stabilization of chemical processes to achieve long-term effectiveness.

The findings of this report demonstrate that chemical degradation and structural performance are inherently interconnected, and that successful rehabilitation depends on addressing both aspects in a coordinated manner. Stabilizing deterioration mechanisms is necessary to prevent continued damage, while structural repair techniques restore the ability of the material to carry load and maintain serviceability.

A key conclusion is that rehabilitation strategies must be both mechanism-specific and sequential in application. No single technique is universally effective, and improper sequencing—such as applying structural repairs before stabilizing chemical reactions—can result in temporary or ineffective solutions. Instead, identifying the governing degradation mechanism, stabilizing the internal environment, and then restoring structural performance provides a comprehensive approach to rehabilitation.

Ultimately, integrating an understanding of chemical degradation processes with targeted repair and strengthening techniques allows engineers to develop effective strategies for preserving concrete structures. By addressing both the causes and consequences of deterioration, it is possible to extend the service life of aging infrastructure while maintaining structural integrity and long-term performance.

References

Almakrab, A., Elshazli, M. T., Ibrahim, A., & Khalifa, Y. A. (2024). Assessment of various mitigation strategies of alkali–silica reactions in concrete using accelerated mortar test. Materials, 17(20), 5124. https://doi.org/10.3390/ma17205124

Al-Mahaidi, R., & Kalfat, R. (2018). Rehabilitation of concrete structures with fiber-reinforced polymer. Butterworth-Heinemann

American Concrete Institute. (1993). ACI 503R-93: Use of epoxy compounds with concrete. American Concrete Institute.

American Concrete Institute. (2007). ACI 224.1R-07: Causes, evaluation, and repair of cracks in concrete structures. American Concrete Institute.

American Concrete Institute. (2019). ACI 562-19: Code requirements for assessment, repair, and rehabilitation of existing concrete structures. American Concrete Institute.

Banerjee, K. (2024, October 16). The silent invader: How carbonation is eating away at our concrete world. Medium. https://medium.com/@BanerjeeKamal/the-silent-invader-how-carbonation-is-eating-away-at-our-concrete-world-d360fb11d9f2

Barnes, C. E., & Zamora, S. (2015). A practical approach to ASR mitigation in existing structures. Structure Magazine. https://www.structuremag.org/article/a-practical-approach-to-asr-mitigation-in-existing-structures/

Constro Facilitator. (2021, January 9). *Carbonation Barrier Coatings Application* [Photograph]. https://constrofacilitator.com/advantages-and-applications-of-anti-carbonation-coatings/

Delatte, N. J. (2009). Failure, distress, and repair of concrete structures. CRC Press.

DYMIGAG. (n.d.). *CFRP Strengthening of Concrete Slab* [Photograph]. https://dywidag.com/services/strengthening/cfrp-wrapping

Federal Highway Administration. (2007, March). *Spraying LiNO3 solution with handheld spray applicator on barrier wall* (FHWA-HRT-06-133). [Photograph]. U.S. Department of Transportation. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/concrete/06133/004.cfm

Freyssinet. (n.d.). External Post-Tensioning of Concrete Beam Girders [Photograph]. https://www.freyssinet.co.nz/sites/default/files/inspection_and_maintenance_of_prestressing_tendons.pdf

Fuhaid, A. F. A., & Niaz, A. (2022). Carbonation and corrosion problems in reinforced concrete structures. Buildings, 12(5), 586. https://doi.org/10.3390/buildings12050586

Gaudette, P., & Slaton, D. (2007). Preservation brief 15: Preservation of historic concrete—Introduction to historic concrete. National Park Service. https://www.nps.gov/orgs/1739/upload/preservation-brief-15-concrete.pdf

Hartell, J. A., & Zeng, H. (2020). Concrete degradation due to moisture and low- and high-temperature cycling. ACI Materials Journal, 117(1), 129–138. https://doi.org/10.14359/51719078

JR DeSanto (2022, June 22). *Sunset over the marina* [Photograph]. Gaje Contracting LLC. https://www.gajecontracting.com/blog/concrete-slab-crack-repair-stitching-vs-epoxy-injection-foundation-phoenix-post-tension

Khan, W., Akhtar, S., & Hussain, A. (2019). Rehabilitation of concrete and masonry structures. Proceedings of the International Conference on Sustainable Materials and Structures for Civil Infrastructures (SMSCI2019). https://doi.org/10.1063/1.5127152

Lv, Y., Niu, D., & Liu, X. (2022). A theoretical model of sulfuration depth of concrete based on SO_2 reaction and mass balance. Journal of Materials Research and Technology, 21, 2038–2052. https://doi.org/10.1016/j.jmrt.2022.10.030

Ortiz-Rabell, G., Cruz-Moreno, D., Pacheco, J., Valdez-Tamez, P., & Fajardo-San-Miguel, G. (2025). Post-treatment study of electrochemical realkalisation of reinforced concrete by accelerated carbonation tests. Construction and Building Materials, 492, 143100. https://doi.org/10.1016/j.conbuildmat.2025.143100

Rodsin, K., Mehmood, T., Kolozvari, K., & others. (2022). Experimental and numerical seismic assessment of non-ductile reinforced concrete (RC) columns strengthened with glass fiber reinforced polymer (GFRP) [Image]. Bulletin of Earthquake Engineering, 20, 7185–7213. https://doi.org/10.1007/s10518-022-01479-9

SealBoss Concrete Solutions. (n.d.). *Epoxy Crack Injection Concrete Repair* [Photograph]. https://sealboss.com/epoxy-crack-injection-concrete-repair/

Skillsitc. (2023, June 25). Sulfate attack in concrete. EMSA. https://www.skillsitc.com/post/sulfate-attack-in-concrete

Thomas, M. D. A., Fournier, B., Folliard, K. J., Ideker, J. H., & Resendez, Y. (2007, March). The use of lithium to prevent or mitigate alkali–silica reaction in concrete pavements and structures (Report No. FHWA-HRT-06-133). Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/06133/

U.S. Nuclear Regulatory Commission. (2011). Concrete degradation by alkali–silica reaction (NRC Information Notice 2011-20). https://www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/2011/in201120.pdf

Yang, B., Hu, X., Li, A., Zhao, T., Sun, Y., & Fu, H. (2025). Degradation mechanism of cast-in-situ concrete under long-term sulfate saline soil attack. Construction and Building Materials, 478, 141401. https://doi.org/10.1016/j.conbuildmat.2025.141401

Zhang, C., Li, J., Yu, M., Lu, Y., & Liu, S. (2024). Mechanism and performance control methods of sulfate attack on concrete: A review. Materials, 17(19), 4836. https://doi.org/10.3390/ma17194836