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Review

Review on Durability Deterioration and Mitigation of Concrete Structures

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Abstract

Concrete bridges, as a vital component of modern transportation infrastructure, have their structural durability directly tied to safety and service life. In recent years, with the aging of bridge structures and increasingly complex environmental conditions, various durability-related deteriorations have become more prominent, significantly affecting structural performance and maintenance costs. This paper presents a systematic analysis of concrete carbonation as a key chemical process and its impact on durability-related pathologies. Particular attention is given to the formation mechanisms and influencing factors of critical deterioration modes such as cracking, reinforcement corrosion, and freeze–thaw damage. A multi-level prevention and mitigation strategy is proposed, encompassing optimized structural material design, strict construction quality control, and effective maintenance and repair techniques. The study concludes that the durability issues of concrete bridge structures exhibit a strong multi-factor coupling effect and proposes a core durability assurance framework. Finally, the paper briefly outlines emerging trends in intelligent monitoring and digital operation and maintenance, offering insights for future durability management of bridges.

Keywords: concrete bridges; durability deterioration; carbonation; cracking; reinforcement corrosion; freeze–thaw damage; mitigation strategies

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Academic Editor: Paolo Castaldo

Received: 11 July 2025
Revised: 12 August 2025
Accepted: 19 August 2025
Published: 22 August 2025

Citation: Ma, J.; Yang, Q.; Peng, X.; Xia, K. Review on Durability Deterioration and Mitigation of Concrete Structures. *Coatings* **2025**, *15*, 982. https://doi.org/10.3390/coatings15090982

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1. Introduction

In the field of transportation engineering, the construction of concrete bridge structures holds a position of paramount importance, serving as an indispensable component of transportation infrastructure [1]. The structural durability of concrete bridges refers to their ability to maintain safety, functionality, and aesthetic integrity throughout their designed service life. This endurance persists despite exposure to environmental erosion, operational stresses, and material-related degradation—without necessitating extensive reinforcement or reconstruction. Neglecting the issue of durability can have severe consequences. Over time, many bridges may experience progressive structural deterioration due to insufficient durability, ultimately requiring premature demolition and replacement. More alarmingly, numerous bridges demand frequent maintenance and reinforcement well before reaching their intended service life, resulting in considerable financial costs and placing a heavy burden on public finances. These interventions also disrupt traffic

flow, leading to widespread socio-economic consequences [2,3]. In-depth research into the durability of concrete bridge structures is therefore of strategic importance. Such studies are essential for the early identification and effective mitigation of structural damage, ensuring safe and stable bridge operation, prolonging service life, and reducing long-term maintenance costs. Moreover, they offer a robust scientific foundation for the planning, construction, and post-construction management of new bridges. This not only enhances durability design standards and drives technological innovation in bridge construction but also reinforces the reliability of infrastructure that supports sustainable economic and social development [4–8].

In the 20th century, both academia and the engineering community conducted comprehensive and in-depth research on the durability-related deterioration of concrete bridges and corresponding mitigation strategies, achieving a series of landmark breakthroughs. Researchers meticulously investigated the underlying causes of key durability issues such as reinforcement corrosion, concrete cracking, spalling damage, and alkali–aggregate reactions [9–13]. Building on this solid foundation, systematic strategies were proposed across multiple critical dimensions, including design concept optimization, the development of advanced materials, quality control during construction, and long-term maintenance management. These strategies specifically encompassed the enhancement of durability-oriented structural design principles, the development and application of high-performance concrete and corrosion-resistant reinforcement, rigorous quality assurance throughout construction processes, the establishment of scientific inspection and evaluation systems, and the adoption of efficient repair technologies for already deteriorated structures. The fundamental goal of these innovative initiatives was to significantly reduce the incidence of durability-related deterioration and ensure the long-term safety, stability, and reliability of concrete bridges. In doing so, they laid a solid foundation for the sustainable development of bridge engineering and provided valuable theoretical and practical guidance for future projects of a similar nature. However, researchers also faced numerous challenges in their efforts to explore durability deterioration and mitigation strategies. The underlying mechanisms of deterioration are highly complex, often interdisciplinary in nature, and influenced by multiple environmental factors, making them difficult to analyze comprehensively. Long-term data collection posed another major difficulty, as limitations in monitoring technologies restricted the ability to track internal structural conditions and environmental interactions over extended periods. In addition, discrepancies between laboratory simulations and real bridge environments—due to the inability to replicate complex environmental conditions and size effects—often led to deviations in experimental results. Furthermore, evaluating the effectiveness of mitigation strategies remains challenging, requiring multi-factor analyses that consider long-term performance as well as economic feasibility. These obstacles represented significant barriers to research at the time and continue to pose challenges to the advancement of durability studies in concrete bridge engineering [14,15].

In contemporary research on the durability of concrete bridge structures, there has been a marked advancement in both depth and precision. The application of cutting-edge microscopic analysis techniques and the development of sophisticated multi-field coupled models have significantly improved our understanding of the fundamental mechanisms behind deterioration processes. The integration of non-destructive testing (NDT) methods and long-term structural health monitoring systems has greatly enhanced the efficiency and accuracy of condition assessments, enabling reliable real-time evaluations of bridge performance. High-performance materials and a wide array of innovative repair technologies have been extensively applied in practice, leading to substantial improvements in structural durability. Meanwhile, the integration of durability-based design concepts with full life-cycle design approaches has become a core component of modern bridge engi-

neering codes and standards. However, a range of formidable challenges remains. These include the complex interactions of multiple deterioration factors under harsh environmental conditions, the impacts of extreme weather events, the limited accuracy of long-term performance prediction models, insufficient accumulation of long-term monitoring data, uncertainties regarding the long-term aging behavior of new materials, and the urgent need to optimize maintenance decision-making and ensure the applicability of maintenance technologies. Together, these factors continue to impede progress in the field of bridge durability research [16,17]. To address these challenges, a comprehensive summary and analysis of deterioration mechanisms and corresponding mitigation strategies is essential. Such efforts can facilitate the development of more scientific evaluation standards [18], support the formulation of comprehensive maintenance strategies and technical solutions, and enable more adaptive responses to the specific demands of different bridge types and regional conditions. Ultimately, these advances will provide a solid foundation for ensuring the long-term safe and reliable service performance of concrete bridge structures.

2. Durability Degradation Mechanisms of Concrete Structures

2.1. Concrete Carbonation

The chemical process of concrete carbonation involves complex mass transfer and chemical equilibrium among multiphase media at the microscopic level. During cement hydration, a large amount of calcium hydroxide [$Ca(OH)_2$] is produced, forming a saturated solution within the pore structure that maintains a highly alkaline environment inside the concrete (pH 12.5–13.5). This alkaline system protects the embedded steel reinforcement through the formation of a passive film, a dense oxide layer composed primarily of Fe_2O_3 and Fe_3O_4 with a thickness of approximately 5–10 nm. This passive film enhances corrosion resistance by inhibiting the transport of oxygen and electrons. Studies have shown that the passive film remains stable as long as the pore solution pH stays above 11.5; however, once the pH drops below this critical threshold due to carbonation, the passive film dissolves, leading to an increased risk of steel reinforcement corrosion. This deterioration mechanism is especially pronounced in atmospheric environments, where CO_2 diffuses through the pore structure into the concrete and reacts with $Ca(OH)_2$ to form calcium carbonate ($CaCO_3$). This reaction reduces the alkalinity of the pore solution and alters the microstructure of the concrete [19,20], as described by the carbonation reaction Equations (1) and (2). Therefore, an in-depth understanding of the chemical kinetics and mass transfer processes during carbonation is essential for predicting the long-term service performance of concrete structures.

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \quad (1)$$

$$3CaO \cdot 2SiO_2 \cdot 3H_2O + 3CO_2 = 3CaCO_3 + 2SiO_2 + 3H_2O \quad (2)$$

The carbonation behavior of concrete is influenced by a combination of environmental, material, and mechanical factors, among which environmental conditions play a predominant role. Climatic variables such as temperature and relative humidity have significant effects on the carbonation process. Elevated temperatures accelerate both the diffusion of carbon dioxide (CO_2) and the rate of the chemical reactions involved. Relative humidity levels between 50% and 75% are considered optimal for carbonation, as CO_2 dissolves and diffuses most efficiently in the pore solution within this range, resulting in the highest carbonation rates. Conversely, excessively high or low humidity levels suppress the carbonation reaction. Air quality also exerts a notable influence. Acidic gases such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x) in the atmosphere readily dissolve in the moisture retained on the surface and within the pore structure of concrete. Through a series of

complex chemical reactions, strong acids such as nitric acid and sulfuric acid are ultimately formed. The accumulation of these acidic substances inside the concrete not only alters its chemical properties but also may induce material corrosion and structural deterioration, severely compromising the durability and service life of concrete structures such as bridges. Groundwater level fluctuations further impact carbonation dynamics. When the water table is high, concrete pores remain saturated for extended periods, hindering CO_2 diffusion and slowing carbonation. As the water level recedes, pore saturation decreases, enhancing gas exchange and allowing CO_2 to diffuse more rapidly, significantly increasing the carbonation rate. In terms of material properties, the concrete mix design and compressive strength are critical factors. The water-to-binder (w/b) ratio directly affects porosity and density: a lower w/b ratio leads to a denser microstructure, reducing CO_2 penetration. The type and dosage of mineral admixtures also influence the alkalinity and microstructure of concrete. For example, incorporating fly ash or ground granulated blast-furnace slag can enhance workability but may reduce the early-age alkalinity reserve, thereby increasing carbonation susceptibility. Concrete strength is closely related to carbonation resistance. High-strength concrete typically exhibits a denser microstructure and lower porosity, resulting in significantly slower carbonation under identical environmental conditions compared to low-strength concrete. It is important to note that these influencing factors do not operate independently; rather, they interact in complex ways. A comprehensive understanding of the synergistic effects among these factors is essential for accurately predicting and effectively controlling the carbonation process, thereby ensuring the long-term durability of concrete structures [21–25]. The specific impacts of carbonation on the durability of bridge structures are summarized in Table 1.

Table 1. Factors influencing concrete carbonation.

Category	Specific Factors	Influence Pattern
Material Properties	Water–cement ratio, cement content, aggregate size, admixtures	Carbonation rate increases with higher water–cement ratio and larger aggregate size; it decreases with higher cement content. Water-reducing agents and air-entraining agents tend to reduce carbonation rate.
Environmental Conditions	Relative humidity, temperature, CO_2 concentration	Carbonation proceeds most rapidly at a relative humidity of 70%–80%. Higher temperatures accelerate carbonation. The carbonation rate increases proportionally with CO_2 concentration.

The impact of concrete carbonation on the durability of bridge structures can be quantitatively assessed using the carbonation depth as a key indicator. For the calculation of carbonation depth, the Alexeyev carbonation model is commonly employed. Based on references [26,27], the mathematical expression of this model is given as follows:

$$X_c = \sqrt{\frac{2DC}{m}}\sqrt{t} \tag{3}$$

Based on Equation (3), Reference [28] replaces the carbon dioxide uptake per unit volume of concrete with the concentrations of $Ca(OH)_2$, CSH, C_3S, and C_2S. Building on

this substitution, the study further improved and expanded the mathematical model, such as Equation (4), to better represent the carbonation process in the concrete matrix.

$$x = \sqrt{\frac{2DC}{C_{Ca(OH)_2} + 3C_{CSH} + 3C_{C3S} + 2C_{C2S}}}\sqrt{t} \quad (4)$$

Reference [29] improves upon Fick's law by incorporating several influencing factors, including the 28-day compressive strength of concrete, clinker content, carbon dioxide concentration, and the equivalent water absorption capacity of the aggregate mixture. On this basis, the following mathematical model is proposed:

$$x = K_C\sqrt{t} = (72.470 - 0.772f_c - 0.117C_0 + 4.617c + 1.594EWA) \cdot \sqrt{t} \quad (5)$$

Reference [30] primarily focuses on the effect of the water–cement ratio on the carbonation behavior of concrete. The corresponding mathematical expressions are presented as follows:

$$x = -0.56213 - \frac{8.792}{\sqrt{t}} + 17.8372(w/c) \quad (6)$$

The risk of reinforcement corrosion induced by concrete carbonation, along with the resulting deterioration in structural performance, poses a serious threat to the long-term durability of infrastructure. In recent years, numerous researchers have conducted in-depth investigations into carbonation-related issues. Studies have shown that carbonation-induced steel corrosion and degradation of concrete properties can cause the actual load-bearing capacity of bridge structures to fall below their design capacity over time. Under service loads such as vehicular traffic and wind, these weakened structures are more susceptible to deformation, crack propagation, and other failure mechanisms. For example, Reference [31] presents a case study of a Yangtze River bridge where the concrete has been exposed to atmospheric conditions for over 50 years without effective protective coatings. The carbonation process was significantly accelerated, and prolonged rainwater erosion further exacerbated surface degradation, posing serious safety risks. Moreover, carbonation-induced deterioration is often latent and progressive, making early detection difficult. Once damage becomes severe, repair becomes both technically challenging and costly and may even require traffic closures, resulting in substantial economic losses and social disruption. In coastal regions, carbonation compromises the protective properties of concrete, facilitating the ingress of chloride ions and accelerating steel corrosion. In cold climates, carbonation-induced cracking provides pathways for moisture ingress; during freeze–thaw cycles, this leads to spalling and fragmentation of concrete, severely impairing the bridge's functionality and structural safety [32–36]. Table 2 summarizes the concrete carbonation deterioration mechanism.

Table 2. Summary of concrete carbonation deterioration mechanism.

Reference	Research Content/Model	Main Factors	Mechanism/Pattern	Impact on Structural Durability
[19,20]	The chemical reaction process of carbonation (Equations (1) and (2)), emphasizing the loss of alkalinity leading to the dissolution of the steel passive film	Micro-scale chemical reactions, CO_2 diffusion	pH > 11.5: passive film remains stable; pH < 11.5: passive film deteriorates, increasing steel corrosion susceptibility	Higher risk of reinforcement corrosion and reduced structural durability
[21–25]	Influence of environmental factors on carbonation	Temperature, relative humidity, air pollutants, groundwater level fluctuation	Optimal RH: 50%–75%; higher temperature accelerates reactions; SO_2 and NO_x produce strong acids, corroding concrete; groundwater fluctuations alter pore saturation, affecting CO_2 diffusion	Accelerated carbonation, changes in chemical properties, and potential structural damage

Table 2. *Cont.*

Reference	Research Content/Model	Main Factors	Mechanism/Pattern	Impact on Structural Durability
[21–25]	Influence of material factors on carbonation	Water-to-binder ratio, mineral admixtures, strength grade	Higher w/b ratio → higher porosity → faster carbonation; mineral admixtures may reduce early-age alkalinity reserve; high-strength concrete → lower porosity → slower carbonation	Higher carbonation risk in concretes with high porosity and low alkalinity reserve
[26,27]	Alexeyev carbonation model (Equation (3))	Carbonation depth calculation	Predicts carbonation depth based on CO_2 uptake and time	Used for service life and durability prediction
[28]	Improved Alexeyev model (Equation (4))	Concentrations of $Ca(OH)_2$, CSH, C_3S, and C_2S	Replaces CO_2 uptake with concentrations of hydration products to better represent the carbonation process	Improves model accuracy and facilitates material optimization
[29]	Carbonation model based on improved Fick's law (Equation (5))	28-day compressive strength, clinker content, CO_2 concentration, aggregate water absorption capacity	Incorporates multiple influencing factors for more realistic carbonation depth estimation	More accurate reflection of service environment effects
[30]	Influence of water–cement ratio on carbonation (Equation (6))	Water–cement ratio	Higher w/c ratio → higher porosity → faster carbonation	Provides guidance for mix design optimization
[31]	Long-term carbonation case study (Yangtze River Bridge)	Atmospheric exposure, rainwater erosion	Over 50 years of exposure without protection → accelerated carbonation → surface degradation	Safety risks and high maintenance costs
[32–36]	Coupled effects of carbonation and other environmental factors	Chloride ingress, freeze–thaw cycles	Carbonation reduces protective capacity → facilitates chloride penetration; cracks + freeze–thaw cause spalling	Reduced load-bearing capacity and impaired functionality

2.2. Concrete Crack

Cracking is one of the most common durability-related defects in concrete bridges during long-term service, and it can be classified into various types based on their causes. Load-induced cracks result from mechanical actions, primarily static and dynamic loads. Cracks may develop during any phase of the bridge lifecycle, including investigation, design, construction, and operation. In the design stage, inaccuracies in load calculations, inappropriate modeling assumptions, or inadequate reinforcement design can cause discrepancies between actual and theoretical stress distributions. When the applied stress exceeds the tensile strength of concrete, cracking occurs. During construction, many factors can lead to cracking, with non-compliant construction practices being the most prominent. Improper placement of construction equipment, incorrect sequencing of construction steps, and alterations in the designed load-bearing mechanisms can all induce structural cracking. In the service stage, impacts from vehicles or ships, extreme weather events, and seismic activity are also significant contributors to cracking. Due to the varying magnitude and nature of applied loads, the distribution patterns of load-induced cracks also differ. Typically, such cracks appear in tensile zones, shear zones, and areas subject to strong vibrations [37–39]. Figures 1–4 present a summary of macroscopic images of concrete cracks as compiled by the author in reference [40].

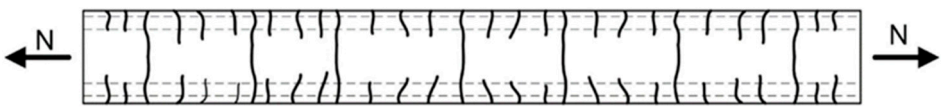

Figure 1. Cracks caused by tension; N—axial force [40].

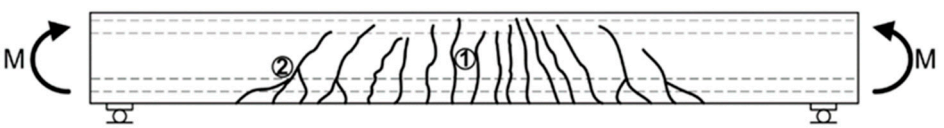

Figure 2. Flexural cracks; 1—single crack, 2—multiple cracks, M—bending moment [40].

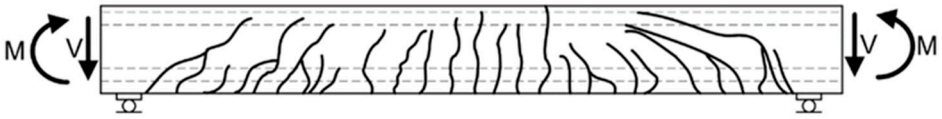

Figure 3. Shear-induced cracks; M—bending moment, V—shear force [40].

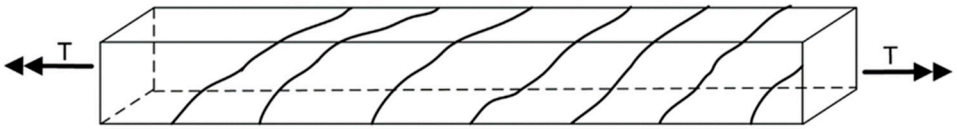

Figure 4. Torsion-induced cracks; T—torque [40].

Temperature variations are another major cause of cracking in concrete. Due to thermal expansion and contraction, concrete deforms with temperature changes. When exposed to significant temperature fluctuations in the external environment, differential temperatures can develop within the bridge structure. For instance, during hot summer periods, the surface of the concrete heats up faster than the interior. As the surface expands, the cooler inner concrete resists this movement, generating tensile stresses. Conversely, in cold winter conditions, the surface contracts more quickly than the inner layers, again inducing tensile stresses. When these thermally induced tensile stresses exceed the tensile strength of concrete, temperature-induced cracks can form [40–42]. In addition, the hydration of Portland cement releases a significant amount of heat. When there is a substantial temperature difference between the concrete and its surrounding environment, internal temperature gradients can develop, leading to non-uniform thermal expansion and contraction. This, in turn, may induce early-age thermal cracking. Such cracks are commonly observed in mass concrete structures or under construction conditions with sharp temperature fluctuations. If not properly controlled, they can adversely affect the overall durability of the structure.

Concrete shrinkage is also a key factor contributing to cracking [43–45]. During the hardening process, cement hydration consumes water, resulting in autogenous shrinkage. Simultaneously, water evaporation from the surface leads to drying shrinkage. If the shrinkage deformation is restrained—such as by abutments or piers—tensile stresses develop within the concrete, leading to shrinkage cracks.

Reinforcement corrosion is another significant cause of cracking. When steel bars embedded in concrete corrode, the resulting rust products expand. The volume of these corrosion products typically ranges from two to six times the original volume of the steel [46]. This expansion exerts radial pressure on the surrounding concrete. Once this pressure exceeds the tensile strength of the concrete, cracks propagate along the reinforcement, forming corrosion-induced cracks. The presence of such cracks facilitates the ingress of moisture, oxygen, and other aggressive agents, which in turn accelerates the corrosion process, creating a vicious cycle that severely undermines the durability of the bridge structure [47,48]. Table 3 summarizes the causes for concrete cracking.

Table 3. Summary of causes for concrete cracking.

Reference	Stage	Frost Damage	Plastic Stage Characteristics	Construction Activities	Physicochemical Factors	Structural Design Factors	Volume Change Factors
[40–42]	Before Concrete Hardening	Early-age frost damage	Plastic shrinkage cracking	Formwork displacement and deformation	—	—	—
		Surface scaling, map cracking	Plastic settlement cracking	Uneven foundation settlement	—	—	Autogenous volume shrinkage
[40,43]	After Concrete Hardening	Freeze–thaw cycles	—	—	Alkali–aggregate reaction	Design load and overloading	Drying shrinkage
		—	—	—	Reinforcement corrosion	Thermal stress	Thermal expansion and contraction
		—	—	—	—	Material fatigue	Creep deformation

2.3. Reinforcement Corrosion

Steel reinforcement corrosion primarily follows the principles of electrochemical corrosion. Within the concrete environment, due to the inherent heterogeneity of the steel material and the presence of electrolyte solutions in the concrete pores, potential differences tend to form on the steel surface. This results in the formation of anodic and cathodic regions. At the anodic site, iron undergoes oxidation, losing electrons to form ferrous ions (Fe^{2+}). These electrons are conducted through the steel to the cathodic site, where they react with dissolved oxygen in the pore water, resulting in the formation of hydroxide ions (OH^-). The ferrous ions then combine with hydroxide ions to form ferrous hydroxide [$Fe(OH)_2$], which is further oxidized in the presence of oxygen to form ferric hydroxide [$Fe(OH)_3$], commonly known as rust [49,50].

$$Fe \rightarrow Fe^{2+} + 2e^- \tag{7}$$

$$H_2O + 1/2O_2 + 2e^- \rightarrow 2OH^- \tag{8}$$

$$Fe^{2+} + OH^- \rightarrow Fe(OH)_2 \tag{9}$$

$$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3 \tag{10}$$

Equations (7)–(10) represent the primary chemical reactions involved in the corrosion of steel reinforcement:

Moisture, oxygen, and chloride ions are key environmental factors influencing the rate of steel reinforcement corrosion. Moisture acts as the medium for ion transport and is a fundamental prerequisite for electrochemical corrosion reactions. Oxygen, as the main reactant in the cathodic process, contributes to an increased corrosion rate with rising concentrations. Chloride ions are considered one of the most critical and aggressive agents in initiating depassivation and accelerating steel corrosion. They can disrupt the passive film on the steel surface and form localized corrosion cells within the concrete matrix, thereby facilitating electron migration and significantly increasing the corrosion rate. Once corrosion occurs, the steel cross-section is reduced and its load-carrying capacity is diminished. Additionally, corrosion products lead to the loss of bond strength between steel and concrete, ultimately undermining the structural integrity and durability of reinforced concrete bridges [51,52].

The impact of chloride ions on steel reinforcement corrosion can be assessed from multiple perspectives, including the time to corrosion initiation, defined as the moment when the chloride concentration at the steel surface reaches a critical threshold; the progressive reduction in steel bar diameter over time; and the degradation of mechanical properties of the reinforcement under chloride-induced attack. Based on Fick's diffusion theory and other relevant models, researchers have developed a range of mathematical formulations to quantitatively describe these processes. Drawing from references [53,54], the following mathematical models have been established:

Reference [54] proposed that if the critical chloride ion concentration on the surface of reinforcement at the initiation of corrosion is defined as C_{cr}, then the time of corrosion initiation can be derived based on the diffusion behavior of chloride ions in concrete. This is typically modeled using Fick's Second Law of Diffusion, as expressed in Equation (11):

$$T_{cor} = \left\{ \frac{d_c^2}{4k_e k_t k_c D_0 (t_0)^n} \left[erf^{-1}\left(\frac{C_s - C_{cr}}{C_s} \right) \right]^{-2} \right\}^{\frac{1}{1-n}} \tag{11}$$

In Equation (11), T_{cor} represents the time to corrosion initiation of the reinforcing steel (d), while d_c denotes the thickness of the concrete cover (mm). The coefficients k_e, k_t, and

k_c are correction factors accounting for environmental conditions, testing methods, and curing conditions, respectively. D_0 is the apparent diffusion coefficient of chloride ions in concrete (m^2/s), n is the time-dependent decay exponent reflecting the reduction in diffusion over time, and C_s is the chloride ion concentration at the surface of the reinforced concrete structure (kg/m^3).

Reference [55] pointed out that once reinforcement begins to be attacked by chloride ions and corrosion occurs, pitting will gradually appear on the steel surface, leading to a reduction in diameter and cross-sectional area, thereby causing a progressive decline in the structural resistance provided by the reinforcement. Assuming uniform corrosion of the steel, this process can be described by Equation (12):

$$d(t) = \begin{cases} d_0, & T \le T_{cor} \\ d_0 - 2\lambda(T - T_{cor}), & T_{cor} < T \le [T_{cor} + d_0/(2\lambda)] \\ 0, & T > [T_{cor} + d_0/(2\lambda)] \end{cases} \quad (12)$$

In Equation (12), $d(t)$ is the time-dependent reduction in the diameter of reinforcing steel (mm) and λ is the steel corrosion rate.

Reference [56] proposed that, based on the corrosion mechanism of reinforcement and the associated corrosion rate theory, and by considering the degradation of reinforcement material properties under chloride-induced corrosion conditions, a corresponding degradation model can be established, as shown in Equation (13):

$$\begin{cases} f_y = (1 - \beta_y \rho_s)\, f_{y0} \\ f_u = (1 - \beta_u \rho_s)\, f_{u0} \end{cases} \quad (13)$$

In Equation (13), f_y is the yield strength of reinforcing steel after corrosion (MPa), f_{y0} is the initial (uncorroded) theoretical yield strength of steel (MPa), β_y is the reduction coefficient of yield strength due to chloride-induced corrosion, ρ_s is the corrosion rate of reinforcing steel, f_u is the ultimate strength of reinforcing steel after corrosion (MPa), f_{u0} is the initial (uncorroded) theoretical ultimate strength of steel (MPa), and β_u is the reduction coefficient of ultimate strength due to chloride-induced corrosion.

As shown in the following table, Table 4 summarizes the steel reinforcement corrosion deterioration mechanism.

Table 4. Summary of steel reinforcement corrosion deterioration mechanism.

Reference	Research Content/Model Formula	Main Influencing Factors	Mechanism/Pattern	Impact on Structural Durability
[49,50]	The electrochemical corrosion principles of steel in concrete and the main reaction (Equations (7)–(10))	Electrolyte solution in concrete pores, steel material heterogeneity, moisture, oxygen	Formation of anodic and cathodic regions on the steel surface, with electron transfer triggering corrosion reactions	Reduction of steel cross-section, loss of bond strength between steel and concrete, decreased structural load-bearing capacity, and durability
[51,52]	Destructive effects of chloride ions on steel reinforcement	Chloride ions, moisture, oxygen	Chloride ions disrupt the passive film, form localized corrosion cells, and accelerate electron migration and corrosion rate	Accelerated loss of steel cross-section and reduced bond performance, leading to premature structural deterioration
[54]	Prediction model for time to corrosion initiation based on Fick's Second Law (Equation (11))	Chloride ion diffusion coefficient, concrete cover thickness, environmental correction factors, surface chloride concentration	Calculates time to corrosion initiation when chloride concentration at the steel surface reaches the critical threshold	Used for service life assessment and durability design
[55]	Corrosion model describing uniform reduction in steel diameter over time (Equation (12))	Steel corrosion rate, time	Assumes uniform corrosion; steel diameter decreases linearly with time	Reduction in cross-sectional area, progressive loss of load-bearing capacity
[56]	Material property degradation model of steel reinforcement under chloride-induced corrosion (Equation (13))	Yield strength, ultimate strength, corrosion rate, strength reduction coefficients	Corrosion leads to reduction in yield and ultimate strength; the model predicts deterioration based on corrosion rate	Decrease in steel load-bearing capacity and reduction in structural safety margin

2.4. Freeze–Thaw Damage

In cold climate conditions, concrete bridge structures often suffer from durability degradation due to freeze–thaw cycles. When the ambient temperature drops below 0 °C, the free water within the concrete pores begins to freeze. Because water expands by approximately 9% upon freezing, significant tensile stresses are exerted on the pore walls. Due to the heterogeneous distribution of pores in concrete, water in larger capillary pores freezes first, forming so-called "ice lenses". As the temperature continues to fall, water in smaller pores gradually freezes, further expanding the ice volume. This expansion drives unfrozen water toward the freezing front, resulting in the accumulation of hydrostatic pressure within the pore structure. When the internal freezing pressure exceeds the tensile strength of the concrete, microcracks may form within the material. As the temperature rises and the ice melts, water is drawn back into the cracks and pores by capillary action. Under repeated freeze–thaw cycles, these microcracks progressively propagate and interconnect, causing ongoing internal damage to the concrete structure [32,57,58]. Studies have shown that the moisture content of concrete is one of the critical factors influencing its freeze–thaw resistance. The higher the moisture content, the more ice forms during freezing, leading to increased internal stresses and a significantly higher risk of freeze–thaw damage. Moreover, the number of freeze–thaw cycles has a cumulative effect on the extent of deterioration. As the number of cycles increases, concrete strength declines markedly, often accompanied by surface scaling, cracking, and spalling, all of which can severely compromise the structural safety and service life of bridge structures [59–61].

Freeze–thaw damage in concrete occurs only when two fundamental conditions are met: the material is in a near-saturated state, and it undergoes repeated cycles of freezing and thawing. Salt freeze damage, a particular form of freeze–thaw deterioration, shares certain mechanistic similarities with ordinary freeze–thaw processes but also exhibits notable differences. Mechanistically, salt freeze damage still relies on the freezing of pore water. However, in saline environments, the increased concentration of salt ions in the pore solution raises the osmotic pressure, which partially suppresses the freezing process. Despite this inhibition, salts continuously precipitate and crystallize within the pores during moisture evaporation, generating substantial crystallization pressure. This crystallization pressure exacerbates internal structural damage in the concrete. Thus, salt freeze damage essentially results from the combined effects of freeze–thaw action and salt erosion, and its destructive impact is often significantly greater than that of freeze–thaw alone.

Currently, many bridge structures are located not only in cold climates but also in high-salinity environments such as mining areas, salt lakes, or coastal regions, which further aggravates concrete durability degradation [62,63]. Xu et al. [64] demonstrated that the damage to concrete after multiple freeze–thaw cycles exhibits a pronounced cumulative effect. With increasing freeze–thaw cycles, the relative dynamic elastic modulus of concrete decreases continuously. Notably, C30 concrete shows a more rapid deterioration in freeze–thaw resistance compared to C40 and C50 concretes, highlighting the significant influence of strength grade on freeze–thaw performance. Related studies also indicate that freeze–thaw cycling substantially weakens the mechanical properties of concrete. This deterioration process involves not only physical aspects, such as pore expansion and crack formation, but also chemical degradation of cement hydration products and ionic migration, making the mechanism complex and slowly progressive.

In practice, various factors affecting the durability of concrete bridges often interact and exacerbate each other. The most common manifestation of freeze–thaw damage is crack propagation. These cracks not only compromise the overall structural integrity of the concrete but also create pathways for external corrosive agents (e.g., chlorides) to penetrate, accelerating reinforcement corrosion and significantly reducing the load-

bearing capacity and service life of structural elements. Under prolonged freeze–thaw exposure, the rate of concrete deterioration accelerates markedly. In real service conditions, the lower parts of concrete bridges are particularly susceptible to freeze–thaw damage. Components such as piers and pile foundations are often located within the freezing zone influenced by the interaction of surface water and groundwater. Subjected to cyclical temperature variations, these areas frequently experience freezing and thawing cycles, making them high-risk zones for freeze–thaw damage. Inspection data reveal that, after approximately 10 years in service, bridges in severe cold regions commonly exhibit varying degrees of freeze–thaw deterioration in their lower structures. Typical damage includes crack propagation, surface scaling, and exposed corroded reinforcement [65–67]. These deterioration phenomena reduce the effective load-bearing cross-section of the elements, leading to decreased structural capacity and safety risks in mild cases and potentially causing component instability or failure in severe cases, thereby posing a serious threat to the overall structural safety and service life of the bridge. Table 5 summarizes the deterioration mechanism of freeze-thaw damage.

Table 5. Summary of freeze–thaw damage deterioration mechanism.

Reference	Research Content/Model Formula	Main Influencing Factors	Mechanism/Pattern	Impact on Structural Durability
[32,57,58]	Under freeze–thaw cycles, pore water in concrete freezes and expands, generating tensile stresses. Ice lenses first form in larger pores, followed by gradual freezing in smaller pores, driving unfrozen water toward the freezing front, causing capillary pressure buildup and microcrack formation.	Ambient temperature, pore structure, moisture content	Freezing expansion pressure exceeds tensile strength of concrete → microcrack formation → crack propagation under repeated freeze–thaw cycles	Accumulation of internal microcracks, reduction in structural strength, surface scaling, and cracking
[59–61]	High moisture content and numerous freeze–thaw cycles lead to cumulative deterioration, significant strength loss, and occurrences of surface scaling, cracking, and spalling.	Moisture content, number of freeze–thaw cycles	Higher moisture content → more ice → greater internal stresses; clear cumulative effect of cycles	Reduction in load-bearing capacity, diminished durability, increased structural safety risks
[62,63]	Mechanism and hazards of salt freeze damage	Saline environments (salt lakes, mining areas, coastal regions), temperature variation	Salt freeze damage combines freeze–thaw action and salt attack; salt ions increase osmotic pressure, partially suppressing freezing, but salt crystallization during evaporation generates crystallization pressure → exacerbates structural damage	More harmful than freeze–thaw alone, severe damage to pore structure
[64]	Cumulative freeze–thaw damage effects in concretes of different strength grades	Concrete strength grade, number of freeze–thaw cycles	Increasing cycles → continuous decrease in relative dynamic elastic modulus; C30 deteriorates faster than C40/C50	Strength grade significantly affects frost resistance
[65–67]	Substructures of bridges (piers, pile foundations) in freezing zones are prone to freeze–thaw damage, often showing cracks, scaling, and exposed reinforcement after 10 years	Location (influenced by surface water/groundwater), service time, temperature variation	Freeze–thaw induces crack propagation, providing pathways for chlorides and other corrosive agents → accelerates steel reinforcement corrosion	Reduction of effective load-bearing cross-section; in severe cases, component instability or failure, threatening overall structural safety and service life

3. Durability Prevention Strategies for Concrete Structures

3.1. Carbonation

To address the durability deterioration of concrete structures caused by carbonation, Li et al. analyzed actual engineering conditions and proposed corresponding anti-corrosion strategies. They emphasized the need to improve the effectiveness of protection measures during construction. Two solutions were proposed: firstly, applying protective coatings to the concrete surface, a common physical barrier method that forms a layer to reduce the carbonation-induced corrosion of reinforcement; secondly, adding inhibitors directly into the concrete mixture, which proved to be more practical and efficient in real-world applications. Comparative analysis showed that the first method has a lower cost-effectiveness and is technically challenging for large-scale implementation. In contrast, the second method

offers easier application and better anti-carbonation performance, making it more widely adopted in construction [68].

Li further theorized that concrete carbonation occurs primarily because constituents within the concrete readily react with carbon dioxide in the air to form carbonation products. Thus, applying a surface coating can act as a physical shield to block direct contact between concrete and air, effectively slowing down the carbonation process. However, this approach has clear drawbacks—it is costly and requires skilled labor for execution. Based on theoretical and practical studies, introducing corrosion inhibitors during the concrete mixing stage has emerged as a more mature and efficient strategy. Through extensive experimentation and optimization, it has been demonstrated that, when the type and dosage of inhibitors are properly controlled, concrete can remain largely unaffected by carbonation over extended periods [69].

Yang [70] emphasized that delaying carbonation and improving structural durability require comprehensive consideration during the design and application of concrete materials. Firstly, the type of cement should match the environmental conditions in which the structure operates. Empirical studies show that, under the same cement content, Portland cement demonstrates the slowest carbonation rate, making it an ideal choice. Secondly, aggregate properties—including type and particle size—also affect the carbonation rate. For instance, if volcanic ash is present in the aggregate, it may react with siliceous aggregates under heat curing conditions in an alkali–aggregate reaction, which consumes alkaline reserves and accelerates carbonation. Thirdly, controlling the water–cement ratio is critical, as it directly influences the internal pore structure of concrete. A higher water–cement ratio increases porosity and the effective diffusion coefficient of CO_2, thereby accelerating carbonation.

Research by L and PAM et al. found that increasing sand content can reduce the water–cement ratio and complicate permeability pathways, thus decreasing both carbonation depth and air permeability [71].

Zhou and Gencturk et al. observed that using well-graded fine aggregates in concrete is more effective in delaying CO_2 ingress than using sand alone. Well-graded aggregates help block diffusion pathways, thereby enhancing carbonation resistance. In addition, applying thicker concrete cover or plaster coatings has been shown to delay CO_2 penetration into reinforced concrete structures, extending their service life [72].

Huang and Jiang et al. proposed that CO_2 diffusion and carbonation reactions mainly occur within the mortar phase, which comprises water, cement, and sand. This implies that reducing the amount of mortar or using coarser aggregates can help lower carbonation depth. Moreover, using smaller-sized coarse aggregates further reduces carbonation depth due to their larger surface area, which creates a longer and more tortuous path for CO_2 diffusion [73]. Table 6 presents a comparative analysis of protective measures against concrete carbonation.

Although significant progress has been made in the study of carbonation mechanisms, current models are mostly based on simplified assumptions and have not fully accounted for the nonlinear effects of environmental disturbances such as temperature and humidity variations and wet–dry cycles on the carbonation process. In addition, the coupling effects between carbonation and other deterioration factors (e.g., steel corrosion, freeze–thaw damage) remain insufficiently and systematically modeled, which limits the accuracy of predictions. Future research should focus on developing coupled carbonation–corrosion models under multi-factor interactions, incorporating both field data and accelerated testing to improve the reliability and applicability of durability assessments.

Table 6. Comparative analysis of protective measures against concrete carbonation.

Reference	Main Findings/Insights	Protective Measures	Advantages	Disadvantages
[68]	Based on field analysis, two corrosion protection schemes were proposed	1. Surface coating of concrete (physical barrier) 2. Addition of buffering agents (e.g., corrosion inhibitors)	Adding buffering agents is simple and highly effective in protection	Surface coatings have low cost-effectiveness and high construction difficulty
[69]	Carbonation is caused by reactions between concrete components and atmospheric substances	Coating to isolate air; addition of corrosion inhibitors during mixing	Corrosion inhibitor strategies are mature, economical, and efficient	Coating method is costly and requires high technical skill
[70]	Concrete material design should comprehensively consider multiple factors to delay carbonation	1. Selection of suitable cement types (e.g., silicate cement) 2. Control of aggregate properties 3. Proper water–cement ratio control	Silicate cement slows carbonation; low water–cement ratio reduces porosity	High water–cement ratio accelerates carbonation; poor aggregates may cause alkali–aggregate reaction
[71]	Increasing sand content can reduce water–cement ratio and improve protection	Increasing sand reduces carbonation depth and permeability	Reduces carbonation depth and results in a denser structure	Sand content must be controlled properly to avoid affecting other properties
[72]	Well-graded fine aggregates perform better than single sand	Use of well-graded fine aggregates; application of thick protective or plaster layers	Delays CO_2 penetration and extends service life	Requires strict control of grading during construction
[73]	Diffusion and carbonation mainly occur in the mortar phase	Reduce mortar content; use small particle coarse aggregates	Decreases carbonation depth; provides longer diffusion paths	Precise selection of small particle coarse aggregates needed; increases mixing difficulty

3.2. Crack

Cracking is one of the primary durability-related defects in bridge structures during their service life. It not only compromises the overall load-bearing capacity of the structure but also accelerates reinforcement corrosion and material degradation, thereby posing a serious threat to the long-term safety and service life of bridges. In recent years, researchers have conducted multi-dimensional and multi-level studies on various types of bridge cracking and proposed corresponding prevention and repair technologies. Chen et al. conducted on-site surveys and analytical assessments of bridge cracks and systematically developed a treatment strategy for existing cracks in box girders. Their study indicated that cracks with widths less than 0.15 mm should be sealed using epoxy mortar, whereas those with widths equal to or greater than 0.15 mm should be repaired using the "Bekaphen Method" (i.e., pressure injection of epoxy grout). This method has been shown to effectively mitigate the impact of cracks on structural performance [74]. To prevent longitudinal cracking in box girder segments, Ruan et al. proposed a set of integrated measures [75]: (1) strictly control the age difference of concrete between adjacent segments during casting [76,77]; (2) enhance structural crack resistance by adding anti-crack reinforcement meshes in the bottom slab and web to reduce temperature and shrinkage-induced stresses; (3) optimize the concrete curing process, with special attention to bottom slab maintenance—ensuring water curing for no less than 7 days—and controlling the internal–external temperature gradient during curing, while appropriately extending the formwork removal period. These measures significantly improve the crack resistance of precast box girder segments. Han addressed the issue of thermal shrinkage cracking in mass concrete abutments caused by heat of hydration and identified excessive internal–external temperature differentials as the primary cause. Through the use of thermal insulation layers, optimized casting times, and controlled cement content, thermal control techniques were successfully implemented to suppress cracking and improve the thermal adaptability of the structure [78]. Focusing on abutment sidewall cracking, Liu analyzed the causes from the perspectives of asynchronous concrete creep, accumulation of hydration heat, and inadequate curing practices. He proposed a grout-based repair method using mineral admixtures and achieved effective restoration of structural performance by optimizing the repair mix design and grouting process [79]. Wu concentrated on deep structural cracks in road and bridge concrete. Given

the limitations of traditional repair methods in penetrating deep into narrow cracks, he adopted a combined approach using polymer-modified cement grout, high-pressure injection, and rotary jet grouting. This method effectively sealed deep cracks and significantly enhanced the structure's shear and flexural capacities [80]. Tan conducted a systematic analysis of cracks in concrete bridge structures caused by common factors such as loading, temperature variation, foundation deformation, and reinforcement corrosion. The study examined crack patterns, depths, and propagation trends and proposed a graded repair standard based on crack width. Specifically, cracks with a width less than 0.1 mm may be left untreated temporarily. However, once the width exceeds 0.1 mm, appropriate remedial measures must be taken. Repair and reinforcement techniques such as surface bonding, shotcreting, and carbon fiber strengthening can be employed. The crack treatment standard is illustrated in Table 7 [81]. Together, these studies offer valuable theoretical foundations and engineering insights into crack identification, cause analysis, and repair and reinforcement technologies. They provide important references for the prevention and management of structural deterioration throughout the entire life cycle of bridges. Table 8 presents a comparative analysis of crack prevention and repair technologies for concrete structures.

Table 7. Standards for bridge crack treatment.

Crack Width (x/mm)	Treatment Method
$x < 0.1$	Leave untreated
$0.1 \leq x \leq 0.2$	Seal with adhesive
$x > 0.2$	Repair (structural)

Table 8. Comparative analysis of crack prevention and repair technologies for concrete structures.

Reference	Research Object	Cause Analysis	Repair/Preventive Measures	Features
[74]	Cracks in precast box girders	–	1. Cracks < 0.15 mm: sealed with epoxy mortar 2. Cracks > 0.15 mm: epoxy grout injection (Wikona method)	Crack width grading allows for precise repair and improved efficiency
[75]	Segmental cracks in box girders	1. Differences in concrete age; high thermal and shrinkage stress 2. Inadequate curing	1. Control concrete age differences 2. Install anti-crack reinforcement mesh at the bottom and web 3. Enhance curing (≥7 days), control internal–external temperature differences	Improved crack resistance from construction, structural, and curing perspectives
[78]	Cracks in mass concrete abutments	Large internal–external temperature difference due to heat of hydration	1. Install thermal insulation layers 2. Optimize pouring schedule 3. Control cement content	Effective mitigation of thermal shrinkage cracks through temperature control
[79]	Cracks in abutment sidewalls	1. Unsynchronized creep and heat buildup 2. Inadequate curing measures	Grouting with mineral admixtures; optimize material proportions and grouting process	Restores structural performance; suitable for structural crack repair
[80]	Deep structural cracks in road bridges	Cracks are deep; traditional methods lack penetration	1. Polymer cement slurry 2. High-pressure grouting with rotary jetting technique	Reinforces and seals deep cracks; enhances shear and flexural strength
[81]	Common bridge cracks (various causes)	Load, temperature variation, foundation deformation, corrosion, etc.	1. Graded crack treatment 2. Surface bonding, shotcreting, and CFRP reinforcement	Proposes a systematic crack identification, strengthening, and repair technology system

The formation and propagation of concrete cracks are influenced by various factors, including environmental conditions, applied loads, and construction defects. These cracks often exhibit coupled interactions with other forms of deterioration, such as carbonation and chloride-induced corrosion, mutually accelerating structural degradation. Most existing studies focus on the identification of static cracks while lacking dynamic descriptions of crack evolution over time. Additionally, certain crack prevention measures or repair materials show limited adaptability under complex service conditions. Future research should focus on elucidating the mechanisms linking crack development to structural

durability, exploring AI-based methods for crack identification and evolution prediction, and advancing the application of intelligent self-healing materials in bridge crack repair.

3.3. Reinforcement Corrosion

Corrosion of reinforcement is one of the primary durability issues affecting concrete bridge structures, with chloride-induced corrosion being particularly critical. As a result, extensive research has been conducted to investigate the mechanisms of chloride ion ingress and effective mitigation strategies. Suo [82] recommended incorporating 5%–10% fly ash and 3%–5% silica fume into concrete mixtures to enhance impermeability. Additionally, he emphasized the importance of strictly controlling the water-to-binder ratio and improving concrete density to effectively slow down chloride ion diffusion and thereby inhibit steel corrosion. Dhir and Jones [83] proposed the use of low-lime fly ash to refine pore structure and improve the chloride-binding capacity of concrete, leading to the development of mixtures with superior chloride resistance. They further demonstrated that blending cement with fly ash, silica fume, or metakaolin resulted in optimal resistance to chloride ingress. Hossain et al. [84] found that the inclusion of ultrafine fly ash (UFFA) significantly enhanced both the compressive strength and chloride penetration resistance of concrete, with silica fume playing a particularly prominent role. Hariharan et al. [85] also reported that ternary blends—where 30%–50% of cement is replaced with Class C fly ash and 6%–10% silica fume—effectively improved compressive strength and reduced chloride permeability. Thomas and Bamforth [86] developed models to predict chloride ion diffusion. Their data indicated that although the early-age resistance to chloride ingress may not be substantially improved by the addition of fly ash or ground granulated blast furnace slag (GGBS), long-term exposure over several years reveals significant performance benefits.

In terms of material protection, in the marine splash zone, KOBAYASHI and TAKEWAKA compared the test results of epoxy-coated reinforcement with untreated galvanized steel. The results indicated that epoxy-coated reinforcement exhibited significantly superior corrosion resistance compared to galvanized steel [87]. Similarly, SWAMY and KOYAMA discussed the engineering performance of epoxy-coated bars, showing that when exposed to natural and harsh marine environments, the epoxy coating demonstrated excellent corrosion resistance. Even when the coating was damaged and left unrepaired, the extent of corrosion was still much lower than that observed in uncoated or galvanized steel bars [88]. Many engineers consider GFRP (Glass Fiber Reinforced Polymer) to be one of the most innovative materials capable of overcoming the inherent vulnerability of steel-reinforced concrete structures to corrosion in aggressive environments. ALSAYED et al. investigated GFRP bars and concluded that they possess higher corrosion resistance, greater tensile strength, and lighter weight. However, their low elastic modulus and lack of ductility are recognized as major engineering drawbacks. Therefore, extensive laboratory and field testing is still required to validate their long-term performance [89].

In terms of improving concrete performance, the use of mineral admixtures can effectively mitigate steel reinforcement corrosion caused by alkali–silica reaction (ASR) [90–92]. Papadakis [28] found that partially replacing aggregates with silica fume, low-calcium fly ash, or high-calcium fly ash can enhance the carbonation resistance of concrete. Gonen and Yazicioglu [93] reported that replacing 10% of cement with silica fume and 20% with fly ash significantly improved the concrete's resistance to wet–dry cycles, reduced capillary water absorption, and enhanced carbonation resistance. Furthermore, Shashiprakash and Thomas [94] demonstrated that mortar incorporating low-calcium fly ash or appropriate amounts of ultrafine fly ash exhibited good resistance to sulfate attack. These findings, from various perspectives, underscore the critical role of mineral admixtures in the prevention and control of steel corrosion. Although mineral admixtures may slightly slow the

early-age strength development of concrete, studies have shown that they do not adversely affect the long-term mechanical performance. On the contrary, they may even enhance the long-term strength development. Concrete mixtures incorporating high volumes of fly ash or blended with ground granulated blast-furnace slag (GGBS) exhibit excellent workability, high compressive strength, and superior durability, thereby significantly inhibiting reinforcement corrosion [95,96]. Table 9 presents a comparative analysis of reinforcement corrosion prevention measures.

Table 9. Comparative analysis of reinforcement corrosion prevention measures.

Scholar/Research Team	Research Focus	Type and Dosage of SCMs	Technical Highlights	Conclusions and Effects
[82]	Chloride diffusion control	Fly ash 5%–10%, silica fume 3%–5%	Controlled water–binder ratio, enhanced compactness	Significantly improved impermeability, delayed chloride diffusion, inhibited corrosion
[83]	Pore structure improvement and chloride binding	Low-lime fly ash + silica fume/metakaolin	Optimized mix design	Cement–mineral blends exhibited the best chloride resistance
[84]	Role of ultra-fine fly ash	Ultra-fine fly ash (UFFA), silica fume	Enhanced chloride resistance and strength	UFFA notably improved early-age strength and chloride resistance
[85]	Performance of ternary SCM systems	Class C fly ash 30%–50%, silica fume 6%–10%	Partial cement replacement	Enhanced compressive strength and reduced chloride permeability
[86]	Chloride diffusion modeling	Fly ash, slag	Long-term performance modeling	Limited early improvement, but significant long-term chloride resistance
[87–89]	Reinforcement protection	Epoxy coating	Surface coating for corrosion protection	Demonstrated excellent anti-corrosion performance
[28]	Carbonation resistance	Silica fume and low/high-calcium fly ash replacing aggregate	Altered alkalinity and carbonation path	Improved carbonation resistance, indirectly reducing corrosion risk
[93]	Dry–wet cycling and capillary absorption	Silica fume 10% + fly ash 20% (cement replacement)	Enhanced surface density	Significantly enhanced resistance to carbonation and water ingress
[94]	Sulfate attack resistance	Low-calcium fly ash, UFFA	Reduced deterioration under aggressive environment	Improved chemical resistance and overall durability
[95,96]	Long-term performance and strength development	High-volume fly ash + slag	Combined SCM optimization	Slightly lower early strength, but excellent long-term performance and corrosion control

Although the initiation mechanisms of steel reinforcement corrosion are relatively well understood, significant deviations still exist in predicting corrosion rates under the combined influence of multiple factors, such as the synergistic effects of chloride ingress and carbonation [97]. Moreover, current protective measures (e.g., coatings and admixtures) exhibit limited durability and stability in extreme environments, and there is a lack of standardized evaluation systems. The accuracy and adaptability of existing structural health monitoring techniques for early-stage corrosion detection also require improvement. Future research should focus on the integrated study of corrosion–crack–structural performance degradation mechanisms, promote long-term validation of novel protective materials [98] in real bridge applications, and develop online corrosion monitoring technologies that can be embedded within structural systems.

3.4. Freeze–Thaw Damage

The complexity of freeze–thaw controlling factors presents significant challenges in the design and construction of bridge structures within civil engineering projects. In cold and permafrost regions, structural frost heave and shrinkage induced by fluctuating environmental temperatures have been widely documented, causing various structural damages and even safety incidents in practical engineering. To minimize the risk of structural failures triggered by freeze–thaw (FT) cycles, current research primarily focuses on the mechanisms by which FT cycles affect the strength of bridge materials, component durability, and overall service performance. This includes investigating the formation and progression of freeze–thaw damage as well as its long-term impacts on bridge safety. To

effectively mitigate concrete deterioration caused by freeze–thaw cycles, researchers have proposed various material modification strategies, among which controlling the internal pore structure is a key approach. Current techniques for regulating pore structure mainly include introducing air-entraining agents to form a stable microbubble system; using mineral admixtures (such as fly ash, silica fume, and slag) to optimize the distribution of capillary pores; incorporating nanomaterials (e.g., nano-SiO_2 and nano-Al_2O_3) to fill microvoids; and adjusting the water-to-binder ratio and curing methods to reduce overall porosity. These methods improve the compactness and impermeability of concrete from different aspects, providing diverse technological pathways to develop a pore structure favorable for frost resistance.

Among various methods, the use of air-entraining agents has been extensively studied and widely applied due to their convenience and remarkable effectiveness. Bao et al. [99] demonstrated that under the combined action of sustained compressive loading and freeze–thaw cycling, the incorporation of AEA significantly reduced concrete mass loss and the decline in relative dynamic elastic modulus (RDEM). Zhang [100] found that adding AEA during concrete mixing produces numerous uniformly distributed, disconnected microscopic air bubbles within the concrete matrix, which effectively reduce the hydrostatic pressure caused by freezing pore water in the early stages of freezing, thereby significantly improving concrete's freeze–thaw durability. Kosior-Kazberuk and Berkowski [101] further reported that air-entrained concrete subjected to combined salt freeze–thaw cycles and flexural loading exhibited a 62.8% reduction in mass loss compared to ordinary concrete, demonstrating superior resistance under complex environmental conditions. Additionally, the introduction of uniformly distributed, closed microbubbles by AEA provides internal cushioning space for ice expansion, which inhibits CO_2 diffusion and the development of freeze–thaw-induced cracking. Consequently, this significantly enhances concrete durability under the coupled effects of carbonation and freeze–thaw cycling [102].

Under complex environmental conditions such as freeze–thaw cycles, concrete inevitably experiences a certain degree of structural degradation. In such scenarios, fiber materials do not directly prevent the initiation of damage but rather play a crucial role after cracking by bridging and stabilizing the damaged matrix through their excellent crack resistance and toughening capabilities. As a result, fibers significantly enhance the integrity and durability of the overall structure, demonstrating their importance as an effective material for improving concrete durability under multiple environmental stressors. Yuan et al. [103] demonstrated that the incorporation of polypropylene fibers (PPF) and polyvinyl alcohol fibers (PVAF) significantly reduced the loss of relative dynamic elastic modulus (RDEM) of concrete under the combined effects of freeze–thaw cycling and compressive loading, with the loss reduced by 77.5%. Ren and Lai [104] further found that concrete containing 0.2% PPF exhibited a 32.4% reduction in compressive strength loss after undergoing 120 cycles of sulfate freeze–thaw exposure. Experimental results from Kosior-Kazberuk and Berkowski [101] also showed that under 90 cycles of salt freeze–thaw cycling combined with flexural loading, steel fiber (SF) reinforced concrete experienced an 80% reduction in mass loss compared to ordinary concrete. Notably, when air-entraining agents are combined with steel fibers in concrete, the composite material exhibits even greater improvements in freeze–thaw resistance under external loading conditions [97].

In terms of binder material substitution, pozzolanic mineral admixtures have also demonstrated significant potential for enhancing freeze–thaw resistance. Besheli et al. [105] reported that after 55 freeze–thaw (FT) cycles in a 4% NaCl solution, concrete partially replaced with 15% metakaolin or zeolite exhibited an 86.7% reduction in mass loss compared to plain concrete, indicating a substantial improvement in freeze–thaw durability. Tian et al. [106] pointed out that fly ash (FA) and blast furnace slag (BFS) generate secondary

hydration products through pozzolanic reactions, thereby refining the pore structure and enhancing overall density and impermeability, which effectively slows down deterioration caused by the coupling of freeze–thaw and salt exposure. Furthermore, Li et al. [107] conducted 300 freeze–thaw cycles in a 5% NaCl solution and found that concrete with 25% FA replacement showed reductions of 2.3% and 3.2% in the loss of relative dynamic elastic modulus (RDEM) and compressive strength, respectively, compared to ordinary concrete. This improvement is primarily attributed to the higher glass content and purer reactive components in FA, which promote densification of the interfacial transition zone (ITZ), thereby enhancing resistance to freeze–thaw damage. In summary, pozzolanic mineral admixtures, when used at appropriate dosages and under favorable reactivity conditions, can enhance the mechanical properties and durability of concrete subjected to freeze–thaw cycles and chloride-induced deterioration. This improvement is mainly achieved through mechanisms such as refining the concrete's microstructure, increasing the density of the interfacial transition zone, and delaying crack propagation. However, the actual freeze–thaw resistance imparted by these mineral admixtures strongly depends on their specific types, reactive indices, dosage, and particle morphology. Improper use may even adversely affect concrete performance. Therefore, in cold climate regions—especially those at high risk of severe freeze–thaw damage—it is not recommended to use cements with a high content of non-clinker components. Scientific selection and validation based on the local environment and material characteristics are essential.

In addition to commonly used modification methods such as air-entraining agents, fiber materials, and mineral admixtures, various novel approaches have recently shown promising effects in enhancing freeze–thaw durability. Research indicates that the incorporation of viscosity-modifying agents (VMA) can optimize the rheological properties of fresh concrete mixtures, leading to the formation of a more uniform microporous structure during curing, thereby effectively improving freeze–thaw resistance [108]. Moreover, glazed hollow beads (GHB), a type of solid air-entraining material, have demonstrated significant advantages in resisting salt freeze–thaw environments. Experimental results showed that after 100 cycles of salt freeze–thaw, concrete incorporating GHB exhibited reductions of 74.6% in mass loss and 8.5% in relative dynamic elastic modulus (RDEM) loss [109]. Pang et al. [110] confirmed that partially replacing conventional coarse aggregates with carbonated steel slag aggregates (CSA) effectively enhances concrete's resistance to salt freeze–thaw damage. After 85 freeze–thaw cycles in a 3% chloride solution, CSA concrete achieved a mass loss reduction of up to 75.8%. Additionally, early-stage carbonation curing techniques have attracted extensive attention. Introducing a CO_2-rich environment during the initial setting phase promotes uniform precipitation of calcium carbonate ($CaCO_3$), which improves the pore structure and densifies the interfacial transition zone (ITZ), thereby significantly mitigating deterioration caused by carbonation [111]. These findings collectively suggest that the integrated application of novel materials and curing methods provides expanded possibilities for improving concrete freeze–thaw durability under complex environments, offering both theoretical support and practical pathways for the design and maintenance of future high-performance bridge structures [112–116]. Table 10 presents methods for mitigating concrete deterioration under freeze-thaw damage.

Most existing freeze–thaw cycle tests are conducted under standardized laboratory conditions, which fail to accurately capture the coupled effects of temperature gradients, moisture migration, and chloride action in real service environments. In addition, freeze–thaw deterioration often interacts with other damage processes such as cracking and carbonation, potentially forming feedback mechanisms that accelerate structural degradation and complicate durability modeling. It is recommended that future research establish in-situ monitoring systems on bridges located in representative climate zones and integrate

multi-scale studies of freeze–thaw damage mechanisms. This will support the development of evaluation methods for freeze–thaw deterioration in extreme environments and facilitate the design and validation of new freeze-resistant concrete materials.

Table 10. Methods to mitigate concrete deterioration under freeze–thaw damage.

Reference	Mitigation Method	Additive Type	Experimental Condition	Experimental Result
[99–101]	Air-Entraining Agent	—	Compressive load and freeze–thaw cycle	Reduced concrete mass loss and RDEM loss [99]
		—	Concrete mixing	Reduced hydrostatic pressure inside concrete pores [100]
		Saponified liquid resin	Salt freeze–thaw cycle and flexural load	Reduced concrete mass loss by 62.8% [101]
[101–103]	Fibers	Polypropylene fibers (PPF) and polyvinyl alcohol fibers (PVAF)	Freeze–thaw cycle and compressive load	Reduced RDEM loss by 77.5% [102]
		Polypropylene fibers (PPF)	Salt freeze–thaw cycle	Reduced compressive strength loss by 32.4% [103]
		Steel fibers (SF)	Salt freeze–thaw cycle and flexural load	Reduced mass loss of SF concrete by 80% [101]
[105–107]	Pozzolanic Materials	Metakaolin or zeolite	Salt freeze–thaw cycle	Reduced concrete mass loss by 86.7% [105]
		Fly ash (FA) and blast furnace slag (BFS)	Salt freeze–thaw cycle	Improved concrete density and impermeability [106]
		Fly ash (FA)	Salt freeze–thaw cycle	Reduced RDEM loss by 2.3% and compressive strength loss by 3.2% [107]
[108–110]	Other Methods	Viscosity-modifying agent (VMA)	Flexural load	Reduced RDEM loss [108]
		Glazed hollow beads (GHB)	Salt freeze–thaw cycle	Reduced mass loss by 74.6% and RDEM loss by 8.5% [109]
		Carbonated steel slag aggregate (CSA)	Salt freeze–thaw cycle	Reduced concrete mass loss by 75.8% [110]

3.5. Evaluation Criteria for Durability Prevention Strategies

Unlike the singular performance indicators commonly used in laboratory studies, practical engineering demands a more comprehensive assessment of how various prevention strategies perform under complex service conditions. Therefore, when assessing the applicability of durability prevention strategies in practical engineering projects, as indicated in Reference [18], it is crucial to establish more detailed evaluation criteria that reflect the multifaceted requirements for durability in real-world engineering scenarios. Based on the recommendations of some existing literature [18,81,97,98,110], the following six aspects can be adopted as evaluation criteria for durability prevention strategies.

3.5.1. Specificity to Deterioration Mechanisms

Each type of deterioration—carbonation, corrosion, cracking, and freeze–thaw damage—has its own unique cause and progression pathway. Therefore, a core standard is whether a technique effectively targets the critical stages of a given degradation process. For instance, surface treatments can efficiently slow CO_2 penetration and prevent carbonation but offer limited benefit once corrosion has occurred [81]. On the other hand, cathodic protection is highly effective for halting steel corrosion but irrelevant for crack sealing. This criterion helps avoid the misapplication of solutions to problems for which they are not designed.

3.5.2. Long-Term Performance in Field Conditions

Durability by nature emphasizes performance over time. Thus, the second criterion focuses on how well a method maintains its effectiveness under long-term service conditions, including fluctuating humidity, chloride ingress, repetitive loads, and seasonal temperature variations [97]. Some methods may perform well in short-term tests but fail to

withstand the cumulative environmental stresses found in real-world applications, limiting their practical value.

3.5.3. Structural Compatibility

In bridge maintenance and rehabilitation, it is crucial that new materials and technologies are compatible with existing structural components in terms of mechanical behavior, volumetric changes, and chemical properties. Incompatibilities can lead to issues like interface cracking or secondary damage, compromising the repair outcome [98]. Hence, material compatibility and the integration capacity with existing structures are vital evaluation factors.

3.5.4. Monitoring and Quantifiability

With the growing adoption of structural health monitoring technologies, it is increasingly desirable that repair or protection measures allow for quantifiable, traceable performance data. For parameters such as corrosion rate, carbonation depth, or crack propagation, a lack of effective monitoring makes it difficult for engineers to plan maintenance cycles or interventions. Therefore, the adaptability of a technique to real-time or periodic monitoring is an important consideration.

3.5.5. Economic Feasibility and Constructability

Given limited maintenance budgets, cost-effectiveness and ease of application are major factors influencing the viability of a solution. Techniques that require specialized labor, expensive equipment, or complicated procedures may be less attractive despite strong technical performance. Thus, aspects such as material cost, labor demand, installation difficulty, and disruption to traffic should all be taken into account.

3.5.6. Environmental Impact and Regulatory Compliance

As sustainability becomes a central goal in infrastructure management, the environmental implications of repair strategies must also be addressed [110]. Whether a material contains hazardous substances, generates pollutants during use, or complies with local environmental and construction regulations are key factors in modern durability evaluation.

Together, these six dimensions provide a comprehensive framework for evaluating and comparing different durability interventions. This structured approach also supports more informed decision-making in bridge maintenance planning and reflects the broader trend toward data-driven and systematic infrastructure management.

4. Durability Enhancement Strategies at the Whole Life Cycle Level for Concrete Structures

Based on the analyses of concrete carbonation, cracking, steel bar corrosion, and freeze–thaw damage presented in Sections 2 and 3, Table 11 summarizes a multi-level durability enhancement framework from the perspective of the entire life cycle of concrete structures. The table categorizes a comprehensive set of strategies proposed by researchers in recent years for preventing and mitigating concrete deterioration at each stage, according to the four stages of the concrete structure's life cycle. It reflects the latest research advancements on durability-related issues since the release of important codes and guidelines, such as the Eurocode EN 1992-1-1 Durability Guide [117] and relevant approaches from the American Concrete Institute (ACI). Compared with existing review literature [118–124], this review systematically integrates various common durability distresses and their prevention and mitigation strategies within a unified framework, facilitating the development of more targeted and synergistic durability enhancement strategies from a whole life cycle perspective.

Table 11. Comparison of strategies for enhancing durability of concrete structures at different life cycle stages.

Reference	Durability Distress	Design Stage	Construction Stage	Service Stage	Repair Stage
[68–72,118,119]	Carbonation [118,119]	1. Preferably select cement types (e.g., Portland cement has a slower carbonation rate) [70]. 2. Use well-graded fine aggregates and coarse aggregates [71,72]. 3. Reasonably control the water–cement ratio to reduce porosity and CO_2 diffusion channels [70,71]. 4. Increase the thickness of the concrete cover [72].	1. Strengthen wet curing to avoid early drying cracks. 2. Minimize the use of materials with high carbonation rates. 3. Add an appropriate amount of corrosion inhibitors during material mixing to enhance anti-carbonation capability [68,69].	1. Regularly inspect the carbonation depth of concrete and CO_2 concentration. 2. Apply protective coatings on the concrete surface or construct physical barriers to isolate air contact [68]. 3. Perform spray-type realkalization treatment when necessary.	1. Remove severely carbonated areas and re-pour or repair. 2. Adopt electrochemical realkalization or deep coating penetration technology. 3. Implement local anti-corrosion treatment for damaged rebars in the area [68,69].
[74–81,119,120]	Cracking [119,120]	1. Reasonably arrange the structure, optimize reinforcement design, and set anti-crack rebar nets at the bottom and web plates. 2. Select materials with good temperature control performance to reduce heat of hydration concentration [75].	1. Control the age difference of segments to avoid early shrinkage-induced cracks. 2. Optimize pouring sequence and time, and use insulation layers to control internal and external temperature differences [75,78].	1. Monitor cracks and assess their grades to identify crack development trends and impacts. 2. Set repair grades and cycles according to crack width classification [81].	1. For cracks < 0.15 mm: seal with epoxy putty. 2. For cracks $\geq$ 0.15 mm: inject with "Bike method" epoxy mortar. 3. For deep structural cracks: use high-pressure grouting, polymer cement, or rotary jet grouting for reinforcement. 4. For cracks caused by loads or corrosion: use carbon fiber reinforcement, the shotcrete method, or surface bonding [74,79–81].
[82–96,122]	Steel Bar Corrosion [122]	1. Optimize concrete mix ratio, control water–cement ratio, and enhance compactness. 2. Add mineral admixtures (such as 10% coal fly ash, 3%–5% silica fume, or metakaolin) to disperse and retard chloride ion diffusion. 3. Adopt anti-chloride ion permeable mixture systems (such as UFFA, slag, and ternary systems). 4. Reasonably set the thickness of the steel bar protective layer [82–86,95,96].	1. Strictly control construction quality to prevent honeycombs, pits, and voids. 2. Precisely control raw material ratios and mixing time to improve uniformity and compactness. 3. Ensure sufficient vibration and compaction, and reduce permeable channels [82,83].	1. Regularly monitor the steel bar potential, chloride ion concentration, and carbonation depth. 2. Surface treatment: spray anti-chloride ion agents or chloride ion retarders. 3. If the structure is in a heavy chloride salt pollution area, adopt electrochemical chlorine removal or migration technology [87–89,93,94].	1. Locally apply high-performance repair mortar in damaged areas. 2. For severely corroded components, implement electrochemical protection or cathodic protection technology. 3. If necessary, replace damaged steel bars and re-apply protective layers [87–89].

Table 11. *Cont.*

Reference	Durability Distress	Design Stage	Construction Stage	Service Stage	Repair Stage
[99–116,123,124]	Freeze–thaw Damage [123,124]	1. Add air-entraining agent (AEA) to form closed air bubbles and relieve freezing expansion pressure [99–102]. 2. Incorporate polypropylene fiber (PPF), steel fiber (SF), etc., to enhance crack resistance and freeze–thaw resistance [105–107]. 3. Add volcanic ash mineral admixtures (such as coal fly ash, metakaolin, zeolite, and BFS) to improve pore structure and enhance freeze–thaw and anti-permeability performance. 4. Optimize water–cement ratio, improve concrete compactness, and transition zone (ITZ) performance. 5. Air-entrained materials such as glazed hollow beads (GHB) can be used to enhance salt-freeze resistance [101–104].	1. Incorporate viscosity-modifying admixtures (VMA) to improve the fluidity and deformability of the mixture and form a uniform micro-pore structure [108]. 2. Use carbonized steel slag materials (CSA) to partially replace ordinary coarse aggregates and improve freeze–thaw resistance [110]. 3. Ensure a suitable construction environment temperature to reduce early freeze damage.	1. Regularly detect the concrete relative dynamic elastic modulus (RDEM) and mass loss rate, and monitor the freeze–thaw damage evolution trend. 2. Set drainage slopes and systems to prevent water retention and penetration.	1. For freeze–thaw damaged areas, apply surface waterproof coatings and seal with air-retarding agents. 2. Locally repair and reuse high-freeze-resistance performance repair materials or fiber-reinforced mortar. 3. For severe freeze–thaw cracks, combine surface sealing and internal grouting technology for repair [109,111–116].

5. Conclusions

Concrete bridge structures are an essential component of modern transportation infrastructure. Their durability during service life is directly related to structural safety, service lifespan, and subsequent maintenance and repair costs. This paper systematically reviews the common durability-related deteriorations in concrete bridges, analyzing the underlying mechanisms, influencing factors, and manifestations in engineering practice across four major categories of damage. Based on current research findings and practical experience, corresponding prevention and control strategies are proposed. At the end of each damage section, the paper summarizes the existing mitigation measures and their limitations and offers suggestions for future research. The main conclusions regarding the types of deterioration discussed in this study are as follows:

1. Based on existing studies, concrete carbonation, as a long-standing and widely studied durability deterioration mechanism, fundamentally involves the reaction between atmospheric carbon dioxide and alkaline substances within the concrete. This process reduces the alkalinity of the concrete, thereby weakening the stability of the passive film on the reinforcement surface and indirectly triggering reinforcement corrosion. The carbonation rate and its impact on structural performance are influenced by multiple factors, including the water-to-binder ratio, cover thickness, environmental humidity, and temperature. In current engineering practice, carbonation is regarded as one of the critical factors affecting the long-term service performance of reinforced concrete structures and serves as an important basis for durability design, material selection, and subsequent maintenance strategies.
2. Cracking not only indicates the degradation of the structure's mechanical integrity but also serves as a pathway for the ingress of aggressive agents such as moisture, chloride ions, and carbon dioxide. This accelerates carbonation, freeze–thaw damage, and

reinforcement corrosion. Crack formation is complex and multi-factorial, commonly associated with material shrinkage, construction practices, and load-induced stresses.

3. Reinforcement corrosion is one of the most prevalent and severe durability issues in concrete bridges. The expansive corrosion products can cause concrete cover spalling, crack propagation, and a significant reduction in load-bearing capacity, thus posing a direct threat to structural safety. Corrosion is primarily driven by chloride ingress and carbonation, with a concealed and time-delayed progression that makes it difficult to detect in early stages.
4. Freeze–thaw damage predominantly occurs in cold or seasonally freezing regions. The expansion of pore water during freezing disrupts the concrete's density and integrity, promoting crack initiation and propagation and accelerating overall structural degradation. Enhancing the freeze–thaw resistance of concrete requires a comprehensive approach involving material design, optimization of air-void structure, and waterproofing protection.
5. In response to these durability challenges, this study proposes a holistic prevention and control framework encompassing the design, construction, operation, and maintenance phases. Studies have shown that novel materials such as ultra-high-performance concrete (UHPC) have been widely applied in bridges and related structures, significantly enhancing their durability and service life. The appropriate selection of these advanced materials, in combination with optimized structural detailing, strict construction quality control, and the integration of intelligent monitoring technologies, remains a key approach to improving the long-term performance of bridges. Although existing durability models have partially incorporated the unique properties of new materials such as UHPC—particularly in terms of modified diffusion coefficients, permeability, and damage-healing mechanisms—most remain at the stage of theoretical exploration or experimental fitting and lack mature, widely accepted generalized models.

Author Contributions: Conceptualization, J.M., Q.Y., X.P. and K.X.; investigation, J.M., Q.Y., X.P. and K.X.; writing—original draft preparation, J.M., Q.Y., X.P. and K.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare that there are no conflicts of interest. The funders had no role in the collection, analyses, or interpretation of data or in the decision to publish the results.

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