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A Review of Research on Durability of New and Old Concrete

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Abstract

The purpose of this study is to deeply explore the phenomenon of carbonization, chloride ion erosion and freeze-thaw at the joint of old and new concrete, in order to fully understand its impact on the structural performance of concrete. In the design of durable concrete structures, steel corrosion and concrete corrosion are two common damage mechanisms, while the joint of old and new concrete may face more complex durability problems due to differences in structure and materials. The carbonization mechanism is deeply analyzed, with special attention to the development characteristics of carbonization at the joint of old and new concrete. Considering the different material properties of the two, we explore the impact of carbonization on the joint area and how to effectively predict and control the carbonization depth. A detailed study of chloride ion erosion is carried out, focusing on the key areas of chloride ion transport at the joint of old and new concrete. Considering that the old concrete may have been eroded by chloride ions, we explore the particularity of the joint area in terms of chloride ion erosion and propose effective prevention and control measures. Aiming at the freeze-thaw problem, this study analyzes the performance changes of the connection of old and new concrete under cold climate conditions. Considering the weakness of the structure and the possibility of cracks.

Keywords

New-old Concrete; Chloride Erosion; Freeze and Thaw; Carbonization.

1. Introduction

Concrete structures constitute a crucial component of modern construction and infrastructure, and their durability is a key factor influencing structural lifespan and safety. However, during their service life, concrete structures often face erosion from various environmental factors, leading to a decline in structural performance and, in some cases, structural damage. Among the common mechanisms of damage in concrete structures, steel corrosion and concrete corrosion are prevalent, often closely associated with durability issues such as carbonation, chloride ion ingress, and freeze-thaw effects. Therefore, in-depth research into the durability of concrete structures is of significant theoretical importance and practical value for enhancing the design, maintenance, and repair of concrete structures, ultimately extending their service life.

In concrete structures, the connection between new and old concrete is a distinctive and critical area, typically found in scenarios such as precast concrete structures, concrete repair projects, and concrete reinforcement projects. Due to structural and material differences between new and old concrete, the connection points are susceptible to various damage mechanisms, including steel corrosion and concrete corrosion, and these mechanisms may exhibit complex interactions and coupling effects. Consequently, the durability of the connection between new and old concrete is a challenging issue that demands attention in concrete structure design.

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This paper aims to summary the durability issues of the connection between new and old concrete, with a specific focus on the impact mechanisms of carbonation, chloride ion ingress, and freeze-thaw effects on the structural performance and durability of concrete. Initially, the paper introduces the structural characteristics and common damage mechanisms of the connection between new and old concrete. Subsequently, under both stress-free and stressed conditions, the paper comprehensively reviews experimental studies and theoretical analyses of carbonation, chloride ion ingress, and freeze-thaw phenomena under different research conditions. It reveals the carbonation characteristics, chloride ion transport patterns, and freeze-thaw diffusion phenomena at the interface of new and old concrete. The paper also highlights the influence of surface contamination before repair on the durability of concrete restoration. Finally, the paper summarizes the main research findings and contributions, along with identified shortcomings and directions for further research.

The study and conclusions presented in this paper provide a comprehensive theoretical foundation for the design, maintenance, and repair of concrete structures, contributing to the extension of their service life. The research methodology and insights also offer valuable references and insights for the study of the durability of other types of concrete structures. This research is of significant guidance and practical value for engineers, architects, and professionals involved in concrete structures.

2. Influence of Freezing and Thawing on New and Old Concrete

This article explores the freeze-thaw performance of the connection zones between new and old concrete, a crucial factor affecting the durability of concrete structures. Due to material and structural differences between new and old concrete, these connection zones are susceptible to damage from freeze-thaw cycles, impacting their cracking and bonding strength. The paper comprehensively analyzes freeze-thaw performance under different research conditions, considering material properties, interface treatment methods, and coupled effects.

2.1 Impact of Freeze-Thaw on Bonding Strength

To investigate the influence of material properties on the freeze-thaw performance of new-old concrete structures, Gao et al. [1] conducted splitting tensile tests to study the effects of freeze-thaw cycles and steel fiber volume fraction on the bonding performance of new and old concrete. The results indicate that with an increase in freeze-thaw cycles, the bonding splitting tensile strength between steel fiber concrete and old concrete decreases, while an increase in steel fiber volume fraction can enhance bonding splitting tensile strength to a certain extent. Luo et al.'s study [2] further confirms a monotonic decrease in shear strength of both concrete body and interface between new and old concrete with an increase in freeze-thaw cycles. The use of high compressive strength new concrete enhances the shear strength of the interface. Li and Geissert's experiments [3] reveal a significant decrease in splitting tensile strength of concrete specimens during freeze-thaw cycles, especially when the damage predominantly occurs in the old concrete. Research by Li Pingxian et al. [4-5] also demonstrates that the increase in freeze-thaw cycles leads to a significant reduction in the splitting tensile strength of the interface between new and old concrete. They further compare the effects of different types of adhesives on splitting tensile strength. Additionally, Yi et al. [6], utilizing ultrasonic non-destructive testing and relative dynamic modulus detection, thoroughly investigate the relationship between splitting tensile strength of new-old concrete and durability during freeze-thaw cycles. They identify two stages of freeze-thaw damage: the first stage is mainly caused by interface damage, leading to a rapid increase in F-T damage, while the second stage primarily manifests as damage to the base material and cover layer, with a slower increase in F-T damage. They employ fractal dimension (D) to describe the roughness of different interfaces and study the influence of different roughness, different ages of old concrete, and different F-T cycle numbers on interface bonding performance through splitting tensile tests. Sun et al. [7] establish an F-T damage constitutive model, introducing a cohesion reduction parameter to improve the accuracy of the concrete damage constitutive model. Shang et al. [8], studying the mechanical properties of F-T concrete under biaxial compression, consider the effects of F-T cycle numbers and stress ratios, thereby establishing a

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biaxial constitutive model. Furthermore, Wang et al. [9] propose a macro-micro coupled damage constitutive model, which comprehensively considers the coupling of F-T cycles and loads, providing a new approach for evaluating the durability of concrete materials.

2.2 Interface Processing Method

Concerning the interface treatment methods in new-old concrete structures, scholars have proposed various perspectives and conclusions through extensive experiments and research, delving into the impact of these methods on freeze-thaw performance.

Li et al. [10] studied the influence of cyclic freeze-thaw on the interface strength of new-old concrete. Their results indicate a sharp decline in interface shear strength between new and old concrete with an increase in freeze-thaw cycles. The degree of decline is influenced by the compressive strength of new and old concrete and interface characteristics (such as interface treatment methods and interface agent performance). Nader [11] noted that 300 freeze-thaw cycles can lead to an approximately 80% reduction in shear bond strength of resin mortar, while 200 cycles of temperature variation can decrease the original shear bond strength of cement mortar by about 90%. Luo et al. [2], by comparing shear strength at different rough interfaces, different concrete strength grades, and different freezing temperatures, concluded that the shear strength of both concrete body and the interface between new and old concrete decreases monotonically with an increase in freeze-thaw cycles. The impact of freeze-thaw cycles on the compressive strength of concrete cubes lags behind the shear strength of concrete cubes and the shear strength of the interface between new and old concrete. Using new concrete with higher compressive strength can enhance the shear strength of the interface. This necessitates research on the frost resistance of the interface between new and old concrete. Yi et al. [12] discussed the deterioration process of new-old concrete specimens with different base material surface roughness under freeze-thaw cycles, analyzing the freeze-thaw damage at the interface and the influence of different base material surface roughness on frost resistance. They proposed a freeze-thaw damage model applicable to new-old concrete. Guo et al. [13] found that the splitting tensile strength of specimens with low and high roughness decreased to 44.2% and 74.5%, respectively, after 100 freeze-thaw cycles.

Qiao and colleagues [14] conducted experiments to study the frost resistance of bonded specimens of new and old concrete under the action of cement slurry interface agent and a new modified epoxy interface agent. They analyzed the changing patterns and mechanisms of different interface agents' impact on bonding frost resistance. The results showed that the frost resistance of bonded specimens using a newly modified epoxy interface agent was superior to those using a cement slurry interface agent. Feng and colleagues [15] experimentally studied the frost resistance of the bond between new concrete and carbonized concrete, analyzing the impact of cement slurry interface agent, silica fume interface agent, and expansive interface agent on the frost resistance of the bond between new and old concrete. The results indicated that the bonded surface of new-old concrete is a frost-vulnerable area. The carbonation of old concrete can enhance the frost resistance of the bond between new and old concrete when using cement slurry interface agent and expansive interface agent. Using the expansive interface agent yields the optimal frost resistance of the bonded specimens, followed by the use of cement slurry interface agent, with silica fume interface agent being the least effective.

Therefore, from these summarized studies, differences in various interface treatment methods are apparent, and some universally applicable principles can be distilled. Novel modified epoxy interface agents and expansive interface agents may have significant potential in enhancing frost resistance. However, these conclusions need validation in more engineering practices to ensure their applicability and reliability.

3. Chloride Erosion

3.1 Experimental Studies

3.1.1 Experiments under No Stress Conditions

Li et al. [18] investigated the chloride ion permeation characteristics in the interface zone between prefabricated and cast-in-place components under no stress conditions. Results revealed that the chloride content in the interface zone was higher than in other areas. The interface zone effect (IZE) was mathematically described using a Gaussian Ampère function based on chloride ion measurements. Udaipurwala et al. [19] conducted chloride solution immersion tests on post-pour concrete specimens with and without pre-existing cracks and incorporating three different admixtures. The corrosion activity at joints was found to be higher under all conditions, especially at pre-existing cracks.

Surveying prestressed concrete bridge structures in the northern Hebei region of China, Yu Dongchao [20] identified the joint sections of prefabricated segmental beams as the earliest sites of damage and the most severely affected areas in concrete bridge structures. Barman et al. [21] indicated that better joint performance corresponds to longer concrete lifespan, primarily associated with concrete strength and surface smoothness.

Investigating the impact of joint roughness on chloride ion transport characteristics in the interface zone, Luo [22] found that excessive roughness at joints could lead to aggregate loosening in the interface, thereby reducing the chloride salt erosion resistance of jointed concrete. Li Guoping et al. [23-24] conducted durability tests on commonly used direct wet joints, roughened wet joints, dry joints, and epoxy adhesive joints in segmented formed bridge concrete structures. The results indicated varying durability performances among different joint types, all of which constituted weak links in concrete structures. Factors such as cement mortar matrix at joints and construction damage were identified as the main contributors to reduced durability.

Yan et al.[25] conducted a study to investigate the influence of different joint types and limestone powder content on the durability of concrete components in a chloride environment. The study involved a combination of specimens using ordinary concrete on one side and limestone powder concrete on the other side, with different joint types in between. The specimens were immersed in a 10% concentration chloride solution for a total of 270 days. The results showed that, within the same specimen, the chloride ion concentration at the joint was the highest. The chloride ion concentration within the concrete gradually decreased from 0 to 20 mm from the joint, while beyond 20 mm from the joint, the chloride ion concentration in the concrete was relatively consistent. Under the same erosion time, the chloride ion concentration within the direct wet joint was the highest, followed by the roughened joint, and the joint with interface agent had the lowest concentration. Through fitting, apparent chloride ion diffusion coefficients for the three types of joints were obtained, which were 1.95 times, 1.87 times, and 1.83 times that of the matrix concrete, respectively. The study also found that, at the same distance on both sides of the joint, the chloride ion concentration in limestone powder concrete was higher than that in ordinary concrete. When the limestone powder content was 10%, 20%, and 30%, the apparent chloride ion diffusion coefficient of concrete increased by 9.8%, 11.8%, and 65.8%, respectively.

3.1.2 Experiments under Stress Conditions

Zhao et al. [26] experimentally studied the chloride ion migration behavior in the interface zone of new and old concrete joints in prefabricated concrete structures under the combined action of fatigue loads and chloride ion penetration. Key variables included fatigue stress range and exposure time. The results showed that under the combined action of fatigue stress and chloride ion penetration, the chloride content in the interface zone was higher than in other areas, indicating the Interface Zone Effect (IZE). By introducing the IZE index, researchers revealed the influence of fatigue stress range and exposure time on IZE. Based on the definition of IZE, Zhao et al. [27] analyzed the effect of constant compressive stress on chloride ion transport behavior in the interface zone. The results

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indicated that the chloride ion diffusion coefficient and surface chloride ion concentration in the interface zone were related to distance and stress. Additionally, based on the Gauss-Amp function, empirical models for chloride ion diffusion coefficients and surface chloride ion concentration, considering the influence of constant compressive stress, were proposed.

Existing research indicates that joints are the weakest parts of concrete structures in service under harsh environmental conditions, such as coastal areas. Li et al. [28] pointed out that prestressed concrete beams are widely used in Chinese bridges; however, sectional construction introduces multiple construction joints, where damage at joints is a common issue. By defining the characteristics of joint damage through reasonable parameter settings, the authors discussed the damage mechanism and analyzed in-depth the impact of damage on structural performance. The research results provide substantial support for the reliability assessment of existing bridges and the design of new bridge joint structures.

3.2 Numerical Analysis

Yan et al. [25] conducted a study to investigate the impact of different joint types and limestone powder content on the durability of concrete components in a chloride environment. They established a 2D model for jointed specimens, where the thickness on both sides of the joint area was set to 1mm. Concrete was chosen as the material on both sides of the joint, while cement mortar was used at the joint. The physical field selected was dilute substance transfer, with equations consistent with Fick's second law. The top surface was set as the chloride ion concentration boundary, and all other surfaces were set as no-flux boundaries. Free triangular elements were used, totaling 1444 elements. The element size was smaller near the joint, with a minimum of 0.09mm, and larger away from the joint, with a maximum of 20.2mm. The analysis step was 10 days, and the total simulation time was 270 days. The simulation results closely matched the experimental results for chloride ion concentrations at different depths, indicating that when simulating, the uniqueness of the joint should be considered. Different surface chloride ion concentrations and apparent chloride ion diffusion coefficients should be used at the joint to obtain more accurate results.

Wall et al. [29] calculated the corrosion initiation probability of each rebar in a rectangular section and used the finite element method (FEM) to replace the complex decomposition method, effectively simulating chloride ion diffusion in irregular section shapes. Guzman et al. [30], based on the finite element method, established a numerical model for chloride ion diffusion that can reproduce complex section geometry. They validated its applicability by simulating the chloride ion diffusion process in cracked concrete. For example, Seyoon [31] used FEM and finite difference method (FDM) to study the effect of concrete surface coatings on chloride ion diffusion, establishing a numerical model for chloride ion diffusion. Results showed that FEM and FDM had similar accuracy, and in the absence of considering the effect of the electric field, FDM had higher computational efficiency. Maha [32], building on the finite element analysis by Yan [33], used FDM to simulate the non-steady-state two-dimensional chloride ion diffusion process in a rectangular section concrete column. They established numerical model coefficients considering the chloride ion apparent concentration and time dependency of chloride ion diffusion, simplifying the calculation process. However, for highly complex structures, the computational degrees of freedom for the above methods are too high. Therefore, considering computational time, it is difficult to meet the requirements of practical engineering.

Boundary Element Method (BEM) [34] can eliminate the discretization of spatial domains, reduce system degrees of freedom by dimensionality reduction, and simplify the iterative process. Based on BEM, Lu et al. [35], proposed a compensation length and compensation coefficient for chloride ion diffusion in concrete based on an error function. They obtained the numerical solution of the partial differential equation for chloride ion diffusion in concrete and compared it with the results of the finite element method. The results showed that the boundary element method significantly reduced the unknowns in chloride ion diffusion analysis, improving computational efficiency. However, research on simulating the chloride ion diffusion process using the boundary element method is relatively limited and immature. Studies [36] also indicate that sometimes, the boundary element method cannot obtain satisfactory results when concrete is exposed to chloride erosion for an extended period. Wu et al [37], based on the gamma process, established a stochastic durability degradation model for RC structures under chloride ion erosion, achieving the probability prediction of structural lifespan. They addressed the problem of chloride ion diffusion transport in RC structures exposed to chloride erosion and proposed a new method to predict the lifespan of RC structures in chloride ion erosion environments.

4. Concrete Carbonation Assessment

The evaluation of concrete resistance to carbonation follows a general procedure: concrete specimens are exposed to a specific concentration of CO2, and cracks develop perpendicular to the exposed surface. The freshly formed crack surfaces are treated with a phenolphthalein solution, turning the areas with pH>8.2–9.8 into purple. The cracks must be treated immediately after formation to prevent the carbonate formation on the crack surfaces. Subsequently, the carbonation depth is measured, and carbonation rate or inverse carbonation resistance is calculated. Variations in test procedures include relative humidity (r.h.) and carbon dioxide concentration to achieve accelerated testing. The inverse effective carbonation resistance R-1ACC,0[s] is calculated using Formula(1), including the carbonation depth xc (in [m]) produced by the exposure duration t, and the elevated CO2 concentration ΔCs (in [kg/m3]).[38].

$$R_{ACC,0}^{-1}=(\frac{X_c}{\sqrt{2\times\Delta C_s\times t}})2[\frac{m^2}{s}/\frac{kg}{m^3}] \quad (1)$$

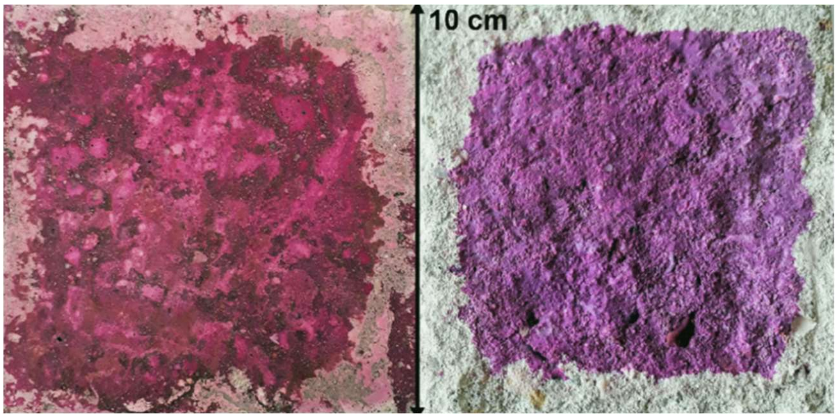

Figure 1. Phenolphthalein indicator test on carbonated interface with joints.[38]
Left: Stored under wet hessian bag, Right: Stored underwater before the second layer of concrete is added.

The phenolphthalein indicator test can be easily used for the evaluation of concrete joints. It predefines the crack paths and requires no adjustments. The color change due to the phenolphthalein solution can be observed in advance.

Höffgen et al. [38] conducted accelerated carbonation tests on new and old concrete. Samples were stored under wet coarse hessian cloth at 20°C between the first and second layers and during the subsequent 7 days. A second series of carbonation tests involved switching between storage under wet hessian cloth and water storage. After growing for 28 days, specimens were exposed to an environment of 3% CO2, 65% relative humidity, and 20°C. After 28 days of exposure to CO2, the samples were separated at the joint plane, and the depth of color change at 24 points was measured and averaged. The experimental results indicated significant color changes for the front half of the specimen stored underwater, suggesting carbonation depth. When the first layer of concrete was

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stored under wet coarse hessian cloth, the phenolphthalein indicator test did not produce usable results. High relative humidity did not entirely prevent carbonation at the joint interface before the second layer was poured. The indicator test showed no significant color change, as shown in Figure 1. Simplified measurements were obtained for joints compared to overall concrete due to the lack of coarse aggregates. The subsequently calculated inverse effective anti-carbonation performance is presented in Table 1. The joints exhibited 1.8 to 3.5 times higher resistance to carbonation than the overall concrete, emphasizing the need for further research.

Table 1. Inverse Effective Carbonization Resistance under Different Treatment Methods

processing method	$R_{ACC,0}^{-1}[10^{-11}\frac{m^2}{s}/\frac{kg}{m^3}]$
monolithic concrete	17.2±2.0
Concrete in water at intervals	30.7±7.5
Concrete exposed to air at intervals	60.2±33.1

5. Conclusion

(1) This paper meticulously delineates the impact of carbonation, chloride ion ingress, and freeze-thaw phenomena on the performance of concrete structures at the interface between new and old concrete. By providing a detailed summary of the damage mechanisms in durable concrete structure design, the paper consolidates numerous research findings in the areas of carbonation, chloride ion ingress, and freeze-thaw. Regarding the mechanisms and developmental characteristics of carbonation at the interface between new and old concrete, the article offers a comprehensive summary. Considering the differences in material properties between the two, a series of feasible methods are summarized to predict and control carbonation depth, providing valuable references for design and maintenance.

(2) The paper categorically summarizes the mechanisms of chloride ion ingress, comprehensively understanding the challenges faced by the interface between new and old concrete in terms of chloride ion transport. Emphasizing the specificity of the joint area, especially considering the potential chloride ion ingress into old concrete, the article consolidates multiple experimental studies and numerical analyses to comprehensively understand the chloride ion ingress performance in the joint area.

(3) A thorough analysis of performance changes in the interface between new and old concrete under cold climatic conditions is conducted, and improvement recommendations are proposed to enhance the freeze-thaw resistance of concrete structures and extend their service life. By considering structural weaknesses and cracks, a series of feasible improvement suggestions are summarized to enhance the freeze-thaw resistance of concrete structures.

In summary, this paper takes a comprehensive and summarizing perspective to delineate the impact of carbonation, chloride ion ingress, and freeze-thaw phenomena on the performance of concrete structures at the interface between new and old concrete. This summary provides valuable lessons for the future development of concrete technologies and offers theoretical support for design and maintenance. Looking ahead, more in-depth empirical research can provide more precise and reliable guidance for concrete structure design and maintenance, thus promoting the continuous advancement of sustainable construction.

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