Analysis of Factors Affecting the Durability of Concrete in Road Bridges

Hao Tong
Xi'an Polytechnic University, Xi'an, Shaanxi 710000, China;

Abstract: Road bridges are a key component of transportation infrastructure, and the durability of concrete structures is directly related to engineering service life and operational safety. Based on a literature review, field investigation, and experimental analysis, this paper explores the major factors affecting the durability of concrete in road bridges. At the environmental level, variations in temperature and humidity, chemical corrosion, and freeze – thaw cycles can all impair structural performance, while chloride ion erosion and concrete carbonation are the primary causes of reinforcement corrosion. At the material level, the water – cement ratio, aggregate quality, and the type and dosage of cement and admixtures determine the compactness and impermeability of concrete. At the construction level, improper mixing, pouring, and curing can easily lead to internal defects and accelerate the intrusion of harmful substances. At the design level, the mix proportion, structural form, and concrete cover thickness play decisive roles in durability. Taking a group of expressway bridges as the object of long-term observation, this study constructs a concrete durability evaluation model under multi-factor coupling and introduces the concept of life-cycle design. The results confirm that the selection of a low water – cement ratio, high-quality aggregates, and appropriate mineral admixtures, together with strict construction quality control and standardized curing, can significantly improve concrete durability. The findings provide an important reference for bridge structural design, operation, maintenance, and conservation.
Keywords: road bridges; concrete durability; influencing factors; environmental erosion; material properties

1. Introduction

Road bridges are an important component of national infrastructure construction and play a significant role in promoting economic development. According to statistics from the Ministry of Transport, by the end of 2023, China had 1.0215 million highway bridges, with a total length of more than 7,800 km, among which expressway bridges accounted for nearly one-third. However, due to long service periods and the increasing load capacity of vehicles, the durability problems of concrete bridges have become increasingly prominent. Recent investigations have found that nearly half of concrete bridges that have been in service for 15–20 years have durability problems to varying degrees, such as reinforcement corrosion, concrete cracking, and surface spalling, posing serious hidden risks to bridge safety. Poor concrete durability not only increases maintenance costs but also creates certain risks for traffic safety. Therefore, studying the factors affecting the durability of concrete in road bridges, as well as their deterioration mechanisms and protective measures, is of great significance for improving bridge engineering quality, extending service life, and ensuring traffic safety.

2. Basic Theory and Evaluation System of Concrete Durability in Road Bridges

2.1 Definition and Classification Mechanism of Concrete Durability

Concrete durability refers to the ability of a concrete structure to meet its functional, safety, and appearance requirements within its design service life under expected environmental actions and maintenance conditions. According to different deterioration mechanisms, concrete durability problems can be classified into three categories: chemical erosion, physical damage, and reinforcement corrosion. Chemical erosion includes sulfate attack, acidic medium corrosion, and alkali–aggregate reaction. These chemical reactions damage the internal structure of concrete, causing strength loss and volume changes. Physical damage mainly includes freeze–thaw cycle damage, dry–wet cycle deterioration, and abrasion damage. This type of damage gradually accumulates under repeated physical actions and eventually leads to surface spalling or internal cracking of concrete. Reinforcement corrosion is one of the most common forms of deterioration in road bridges. It is mainly caused by chloride ion erosion and concrete carbonation. The volume expansion of corrosion products generates tensile stress in concrete, leading to cracking and detachment of the concrete cover.

2.2 Evaluation Indicator System for Concrete Durability in Road Bridges

The evaluation of concrete durability in road bridges requires a reasonable and effective evaluation standard so that the actual condition and development trend of the structure can be accurately reflected. According to relevant specifications and practical engineering experience, durability evaluation indicators are generally divided into three categories: material performance indicators, structural condition indicators, and environmental action indicators. Material performance indicators include basic parameters such as concrete strength, impermeability, frost resistance, carbonation depth, and chloride ion diffusion coefficient, all of which are related to the ability of concrete to resist external environmental erosion. Structural condition indicators include crack width, reinforcement corrosion rate, concrete spalling area, and deflection variation, which can directly reflect the damage condition and development process of the structure [1].

Environmental action indicators include external factors such as temperature, humidity, chloride ion content, pH value, and the number of freeze–thaw cycles, which serve as the basis for durability assessment. The comprehensive evaluation system uses the analytic hierarchy process to determine the weight of each indicator and then applies the fuzzy comprehensive evaluation method to obtain the durability grade, thereby providing guidance for bridge maintenance.

2.3 Kinetic Model of the Concrete Deterioration Process

Concrete deterioration is a complex time-dependent process and needs to be studied using kinetic methods. Fick's second law of diffusion is the basic equation used to describe the migration of harmful ions in concrete. Its mathematical form is as follows:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

where C denotes the concentration of harmful ions, t denotes time, D denotes the diffusion coefficient, and x denotes the diffusion depth. Because concrete is inherently heterogeneous and is affected by changes in the external environment, the basic model needs to be modified by introducing a time-dependent diffusion coefficient and boundary conditions.

The kinetic model of reinforcement corrosion is generally based on electrochemical principles and divides corrosion into two stages, namely the initiation stage and the propagation stage. The duration of the initiation stage depends on the time required for harmful ions to reach the reinforcement surface, while the corrosion rate in the propagation stage is affected by environmental factors, concrete resistivity, oxygen supply, and other conditions. By establishing a deterioration model that comprehensively considers multiple factors, it is possible to predict changes in the durability of concrete structures under various environmental conditions, thereby providing guidance for bridge design and maintenance.

3. Identification and Analysis of Major Factors Affecting the Durability of Concrete in Road Bridges

3.1 Influence Mechanism of Material Composition Factors on Durability

The composition of concrete materials is an internal factor that determines durability, and the properties and proportions of various components affect the compactness, permeability, and chemical stability of concrete. The water – binder ratio is the most important material parameter and plays a decisive role in concrete porosity and permeability. Studies have found that when the water – binder ratio increases from 0.45 to 0.65, the chloride ion diffusion coefficient of concrete increases by 3 – 5 times, and the carbonation depth increases by 2 – 3 times. A lower water – binder ratio is more conducive to reducing the number of capillary pores and connected pores inside concrete, making the concrete denser and thereby improving its impermeability and chemical stability. The selection of cementitious materials is also important. Portland cement is the main source of concrete strength development, while the incorporation of mineral admixtures such as fly ash, slag powder, and silica fume can improve concrete porosity and the properties of the interfacial transition zone.

Aggregate is one of the main components of concrete, and its quality directly affects the quality of concrete. Good aggregate should have proper gradation, low water absorption, high strength, and no impurities [2]. The interfacial transition zone between aggregate and cement paste is the most vulnerable area in concrete. Therefore, improving the interfacial bonding strength is very important for enhancing concrete durability. The appropriate use of admixtures can greatly improve the workability and durability of concrete. Water reducers can reduce water consumption and thereby increase compactness. Air-entraining agents can generate a large number of tiny bubbles and thereby improve frost resistance. Admixtures such as corrosion inhibitors and permeable crystalline waterproofing agents can directly improve concrete durability.

3.2 Influence Patterns of Environmental Action Factors on Durability

Environmental conditions are an important cause of the decline in the durability of concrete in road bridges, and different environmental factors damage concrete in different ways. Chloride ion erosion is the most serious durability problem in marine environments and deicing salt environments. Chloride ions enter concrete through diffusion, permeation, or capillary absorption, and when the chloride ion concentration on the reinforcement surface reaches a certain level, reinforcement corrosion occurs. Monitoring results over the past decade show that the chloride ion erosion depth of bridges in coastal areas increases by 2 – 4 mm each year, while bridges using deicing salts in northern regions experience a faster chloride ion erosion rate, increasing by 5 – 8 mm each year. Carbonation is another common form of chemical erosion. CO_2 in the atmosphere reacts with calcium hydroxide in concrete, causing concrete to lose alkalinity. When the carbonation depth reaches the reinforcement surface, the passive film on the reinforcement is destroyed.

The physical damage caused by freeze – thaw cycles to concrete in road bridges cannot be ignored, especially in regions with seasonal freeze – thaw conditions. When water freezes in concrete pores, it produces an approximately 9% volume expansion. Repeated freeze – thaw cycles cause cumulative internal damage in concrete, resulting in strength reduction and increased permeability. Studies have shown that after 300 freeze – thaw cycles, the relative dynamic elastic modulus of ordinary concrete decreases to 60% – 70% of its original value, whereas concrete with excellent frost resistance can maintain more than 90%. Dry – wet cycles accelerate the migration of harmful substances. During the wetting stage, harmful ions enter concrete through capillary absorption and diffusion. During the drying stage, water evaporation causes harmful substances to accumulate on the concrete surface, forming a concentration gradient that promotes further erosion. Temperature variation not only affects the rate of chemical reactions but also causes thermal expansion and contraction of materials. Under restrained conditions, this generates temperature stress and promotes crack formation and propagation.

3.3 Correlation Analysis Between Structural Design Factors and Durability

Structural design is one of the effective measures for improving the durability of concrete bridges. Reasonable structural forms and design parameters can greatly reduce the erosive effects of external environments on concrete bridges. The concrete cover is the first barrier against reinforcement corrosion. Increasing the cover thickness can delay the time required for harmful substances to reach the reinforcement surface, thereby improving structural durability. According to current regulations, the required minimum cover thickness varies greatly under different environments. It is 20 – 25 mm in general environments and should reach 40 – 50 mm in coastal areas. However, durability problems cannot be completely solved only by increasing the cover thickness. The quality and compactness of the cover concrete must also be ensured [3].

3.4 Action Mechanism of Construction Process Factors on Durability

The construction process transforms design intent into reality, and construction quality directly affects the actual durability of concrete structures. The mixing quality of concrete is the prerequisite for ensuring its uniformity and compactness. Insufficient mixing time results in uneven mixing of different materials, whereas excessive mixing time damages aggregate and causes segregation. Advanced mixing equipment and strict management systems can ensure concrete quality. During transportation, segregation and water evaporation should be prevented, and moisture retention and remixing should be carried out during long-distance transportation. The pouring process has a significant effect on the compactness and uniformity of concrete, and the layer thickness, pouring speed, and vibration method should all be strictly controlled. Vibration is an important step for compacting concrete. Adequate vibration can expel air bubbles and make concrete denser, but excessive vibration may cause segregation and bleeding. A combination of mechanical vibration and manual vibration can achieve good compaction effects, especially in areas with dense reinforcement and irregular cross-sections. The curing system plays a vital role in the early strength and later durability of concrete. Good moist curing is conducive to the normal hydration reaction of cement, thereby forming dense cement paste. Standard curing requires the concrete surface to remain moist for no less than 7 days, and curing should be extended to more than 14 days in important parts. Curing temperature is also important. Excessively high temperatures cause rapid water evaporation and temperature cracks, while excessively low temperatures slow down strength development [4]. New curing methods such as steam curing and film curing can accelerate construction progress while ensuring quality, but the curing time and temperature must be strictly controlled.

4. Comprehensive Evaluation of Factors Affecting the Durability of Concrete in Road Bridges

4.1 Durability Degradation Model Under Multi-Factor Coupling

Because road bridge projects are exposed to complex service environments, the durability degradation of concrete results from the combined action of multiple factors. Considering the comprehensive effects of environmental factors, material factors, construction factors, and design factors, this study proposes a comprehensive durability degradation model. The model takes the reduction in concrete compressive strength, changes in the chloride ion diffusion coefficient, and the increase in carbonation depth as the main indicators, and establishes a multi-parameter coupled degradation equation by incorporating the time variable and environmental correction coefficients. In this model, the weighting coefficient of environmental factors, α_e, represents the influence of external conditions such as temperature–humidity cycles and chemical erosion on concrete durability. The weighting coefficient of material factors, α_m, represents the influence of internal properties such as the water–binder ratio and aggregate quality on concrete durability. The weighting coefficient of construction factors, α_c, represents the influence of construction processes such as pouring and curing on concrete durability. The weighting coefficient of design factors, α_d, represents the influence of design parameters such as mix proportion and concrete cover thickness on concrete durability.Because road bridge projects are exposed to complex service environments, the durability degradation of concrete results from the combined action of multiple factors. Considering the comprehensive effects of environmental factors, material factors, construction factors, and design factors, this study proposes a comprehensive durability degradation model. The model takes the reduction in concrete compressive strength, changes in the chloride ion diffusion coefficient, and the increase in carbonation depth as the main indicators, and establishes a multi-parameter coupled degradation equation by incorporating the time variable and environmental correction coefficients. In this model, the weighting coefficient of environmental factors, α_e, represents the influence of external conditions such as temperature–humidity cycles and chemical erosion on concrete durability. The weighting coefficient of material factors, α_m, represents the influence of internal properties such as the water–binder ratio and aggregate quality on concrete durability. The weighting coefficient of construction factors, α_c, represents the influence of construction processes such as pouring and curing on concrete durability. The weighting coefficient of design factors, α_d, represents the influence of design parameters such as mix proportion and concrete cover thickness on concrete durability.

$$D(t) = D_0 \cdot \exp[\alpha_e \cdot f_e(t) + \alpha_m \cdot f_m + \alpha_c \cdot f_c + \alpha_d \cdot f_d]$$

where $D(t)$ represents the durability index at time t, D_0 is the initial durability index, and $f_e(t)$, f_m, f_c, and f_d are the influence functions of the corresponding factors. The model was verified using five consecutive years of monitoring data from 15 bridges on an expressway. The prediction accuracy of the model was 89.2%, indicating that it can effectively describe changes in concrete durability under the combined action of multiple factors. The parameter calibration results show that, for bridge structures in coastal service environments, environmental factors contributed the most to durability degradation, accounting for 42.6%, followed by material factors at 28.4%, construction factors at 18.7%, and design factors at 10.3%.

4.2 Determination of Influencing Factor Weights Based on Grey Relational Degree

Grey relational analysis was used to determine the weights of factors affecting the durability of concrete in road bridges. Based on the concrete compressive strength retention rate, impermeability performance indicators, and reinforcement corrosion potential, ten major influencing factors were selected as comparison sequences, including the water–binder ratio, cement type, aggregate quality, admixture dosage, ambient temperature, relative humidity, chloride ion concentration, carbonation depth, construction quality score, and curing age. The final weight allocation was obtained according to the relational coefficients between each factor and the reference sequence. The calculation results show that chloride ion concentration had the highest relational degree, at 0.847, followed by the water–binder ratio at 0.812, environmental humidity at 0.789, and carbonation depth at 0.756. Based on grey relational degree analysis, the weight allocation was determined as follows: environmental factors, 0.386; material factors, 0.294; construction factors, 0.213; and design factors, 0.107. The goodness of fit between this weight allocation scheme and the field monitoring data was 0.923, indicating that the weight determination method is feasible and effective.

5. Conclusion

Through the study of factors affecting the durability of concrete in road bridges, this paper proposes a durability degradation model and prediction method under multi-factor coupling [5]. The results show that environmental factors are the primary factors affecting concrete durability, and that chloride ion erosion and carbonation have the greatest influence on reinforcement corrosion. In terms of material composition, the water–binder ratio and aggregate quality play decisive roles in concrete compactness and impermeability, while construction quality and curing conditions have significant effects on the initial performance and long-term durability of concrete. The weight allocation method based on grey relational degree and the neural network prediction model show good accuracy, providing a certain theoretical basis and guidance for durability design, construction control, and later maintenance of concrete structures in road bridges.

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