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Study on Durability of Concrete based on Multi-scale Structural Optimization

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Abstract

This paper discusses the durability of concrete through multi-scale structural optimization, and studies it from macro, meso and micro levels by combining experiments and theoretical analysis. On the macro scale, the mechanical properties and structural strength of concrete are evaluated, and it is found that the higher the water-cement ratio, the more obvious the decrease of compressive strength in carbonation environment. The fracture development and pore structure were observed at mesoscale, and it was pointed out that the cracks in the samples with high water cement ratio expanded rapidly and the pore structure was loose. The research shows that multi-scale structural optimization is of great significance to improve durability and provides scientific basis.

Keywords

Multiscale Analysis; Durability of Concrete; Concrete.

1. Introduction

As the main structural material of modern buildings, the durability of concrete plays a vital role in ensuring the safety and service life of buildings. However, in the complex and changeable use environment, concrete is often challenged by many erosive factors, such as carbonation and chloride ion penetration, which seriously affect the durability of concrete [1-2]. Therefore, it is of great significance to explore the methods and technologies to improve the durability of concrete for ensuring the long-term stability and safety of building structures.

In recent years, with the continuous development of materials science and computational mechanics, multi-scale analysis method has gradually become a new way to study the properties of concrete [3]. Multi-scale structural optimization can not only examine the overall performance of concrete from a macro perspective, but also go deep into the micro level to reveal the internal mechanism of material performance changes [4-5]. The purpose of this study is to systematically explore the durability of concrete at different scales by means of multi-scale structural optimization, so as to provide scientific basis for the durability design and improvement of concrete.

This study will combine experimental tests and theoretical analysis to conduct a comprehensive and in-depth study on the durability of concrete from macro, meso and micro scales. By comparing the differences in durability between traditional concrete and concrete with multi-scale structural optimization, the potential advantages and practical application value of multi-scale structural optimization in improving concrete durability are revealed. At the same time, this study will also discuss the key factors affecting the durability of concrete at different scales, in order to provide new ideas and methods for the durability design of concrete.

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2. Research Methods and Experimental Design

2.1 Multiscale Analysis Method

In this study, the durability of concrete is deeply studied by multi-scale analysis method. This method combines macro, meso and micro analysis to fully understand the performance changes of concrete under various environmental conditions [6-7].

On the macro scale, the overall strength and durability of concrete samples are evaluated by traditional mechanical properties testing and structural analysis methods. This includes measuring key indexes such as compressive strength and flexural strength, and using finite element analysis (FEA) method to simulate the stress of concrete in practical engineering application. Through these tests and analysis, we can understand the overall performance and possible weaknesses of concrete structures from a macro perspective.

On the meso-scale, X-ray CT scanning with high-resolution imaging technology is used to observe the micro-damage such as crack development and pore structure in concrete. These data are reconstructed and analyzed by image processing software to reveal the detailed changes of concrete internal structure [8]. In addition, the discrete element method (DEM) is used to simulate and analyze the crack propagation and damage evolution of concrete under stress.

At the same time, molecular dynamics simulation method is used to explore the interaction and performance changes of various components in concrete from atomic and molecular levels [9].

In order to correlate the analysis of these three scales, multi-scale modeling method will be adopted. Use the following formula to describe the performance relationship of concrete at different scales:

$$\sigma_{macro} = f(\sigma_{meso}, \sigma_{micro}) \quad (1)$$

Among them, σ_{macro} represents the stress on macro scale, and $\sigma_{meso}, \sigma_{micro}$ represents the stress on meso scale and micro scale respectively. The function f represents the relationship of stress among these three scales.

2.2 Experimental Design

When preparing concrete specimens, 42.5 grade ordinary Portland cement is chosen as the foundational component to guarantee the concrete's adequate strength and longevity. As for fine aggregates, medium-grained sand with a fineness modulus of 2.6 is opted for, contributing to superior workability and structural integrity. In terms of coarse aggregates, crushed stones with a maximum particle diameter not surpassing 20 millimeters are employed to augment the concrete's overall strength. Municipal tap water is utilized to modify the concrete's consistency and to facilitate the hydration process of the cement.

In order to study the influence of different water-cement ratios on the durability of concrete, the following three mix proportions are designed (Table 1):

Table 1. Design of mix proportion

mixing proportion	water cement ratio	Cement: sand: stone
A	0.45	1:2:4
B	0.50	1:2:4
C	0.55	1:2:4

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According to the above mixture ratio, the required cement, sand, stone and water are weighed respectively. Use a concrete mixer to mix the materials thoroughly and evenly. The mixed concrete is poured into a 100mm×100mm×100mm cubic mold. Place the poured sample in a standard curing room for 28 days to ensure that the concrete is fully hardened.

In order to simulate the influence of carbonation environment on the durability of concrete, a constant temperature and humidity box which can control the environment is used and its conditions are set. The temperature was set at 20℃, the humidity was controlled at 60%RH, and the CO2 concentration was set at 20%.

In order to study the durability of concrete under stress, this experiment applies continuous axial pressure to some samples through a press, and the load is set to 30% of the compressive strength of the samples. This loading condition is designed to simulate the continuous loading environment that concrete may face in practical engineering [10]. The experiment lasted for 90 days to evaluate and observe the performance changes of concrete samples under long-term carbonation environment, so as to understand the influence of different water-cement ratio and continuous load on concrete durability more comprehensively.

During the experiment, in order to comprehensively monitor the performance changes of concrete samples, detailed detection and data collection are carried out every 15 days. The compressive strength of the sample was tested by a press to evaluate its mechanical properties changing with time. The carbonation depth of the sample was measured by phenolphthalein reagent method, so as to understand the influence of carbonation environment on the sample.

2.3 Experimental Techniques and Instruments

Finite element analysis serves as a numerical technique for addressing intricate engineering and physical challenges. In this research, finite element analysis is employed to replicate the stress distribution, deformation patterns, and failure mechanisms of concrete subjected to varying environmental conditions and loads. A finite element model of concrete is constructed to forecast its mechanical reactions at diverse scales, followed by an assessment of its durability.

In the finite element analysis, for the two-dimensional plane stress problem, the modeling formula is as follows:

$$\begin{aligned} \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} = 0 \\ \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} = 0 \end{aligned} \tag{2}$$

Where σ_x, σ_y is the normal stress in x, y direction and τ_{xy} is the shear stress.

Geometric equation (strain-displacement relationship):

$$\begin{aligned} \varepsilon_x &= \frac{\partial u}{\partial x} \\ \varepsilon_y &= \frac{\partial v}{\partial y} \\ \gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{aligned} \tag{3}$$

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Where $\varepsilon_x, \varepsilon_y$ is the normal strain in the x, y direction, γ_{xy} is the shear strain and u, v is the displacement in the x, y direction.

Physical equation (constitutive relation):

$$\begin{aligned} \sigma_x &= E\varepsilon_x + v\sigma_y \\ \sigma_y &= E\varepsilon_y + v\sigma_x \\ \tau_{xy} &= G\gamma_{xy} \end{aligned} \tag{4}$$

Where E is elastic modulus, v is Poisson's ratio and G is shear modulus.

In order to carry out the above experimental technology, the following instruments are used: finite element analysis software ANSYS, material testing machine for testing the mechanical properties of concrete, and high-resolution imaging equipment X-ray CT scanner for observing the microstructure and damage of concrete.

3. Results and Discussion

From a macroscopic perspective, the emphasis is primarily on concrete's compressive strength and carbonation depth. The empirical findings indicate that there is a decrease in the compressive strength of concrete specimens with varying water-cement ratios when exposed to a carbonation environment. Notably, as the water-cement ratio rises, the reduction in strength becomes more pronounced. Concurrently, an elevation in the water-cement ratio leads to an increased carbonation depth. Under the action of continuous load, the compressive strength of the sample decreases faster (Figure 1, Table 2).

Figure 1 shows the changes of compressive strength of three concrete samples with different water-cement ratios (0.45, 0.50 and 0.55) during the 90-day experiment. As can be seen from the figure, the compressive strength of concrete samples with all water-cement ratios gradually decreases with the passage of time. This reflects that the performance of concrete is gradually degraded under carbonation environment and (possible) continuous load.

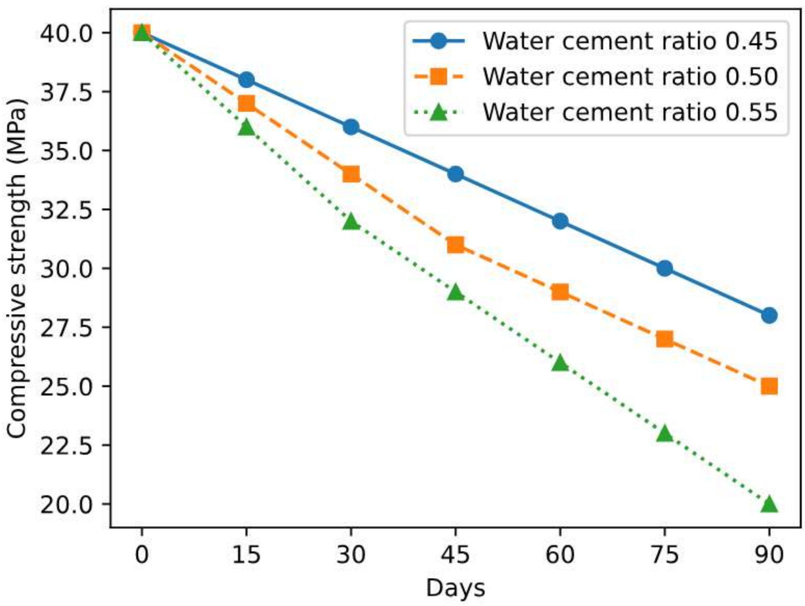

Figure 1. Changes of compressive strength of concrete samples with different water-cement ratio during the experiment

Within the scope of this investigation, the fluctuating proportions of water to cement notably influenced the endurance and compressive robustness of the concrete test pieces. The sample with a water-to-cement proportion of 0.45 displayed elevated initial compressive robustness and commendable steadiness, accompanied by a progressive decline in robustness, hinting at augmented endurance and resilience against carbonation. Upon escalating the water-to-cement proportion to 0.50, a minor diminution in the sample's compressive robustness was detected, signifying that endurance wanes as the water-to-cement proportion ascends. Concerning the sample with a water-to-cement proportion of 0.55, the diminution in compressive robustness was most conspicuous, mirroring an augmentation in internal voids due to the elevated water-to-cement proportion, thus intensifying carbonation corrosion and forfeiture of mechanical attributes. Throughout the experimental process, it was discerned that the sample with a water-to-cement proportion of 0.55 endured the most severe forfeiture of compressive robustness, whereas the sample with a proportion of 0.45 suffered the least forfeiture, accentuating the pivotal role of the water-to-cement proportion in dictating the endurance and compressive robustness of concrete.

With the increase of water-cement ratio, the compressive strength of concrete decreases faster and its durability decreases. Therefore, in practical engineering, the water-cement ratio of concrete should be strictly controlled to improve its durability and long-term performance. In addition, for the concrete structure in harsh environment, additional protective measures are needed to delay the influence of unfavorable factors such as carbonization on its performance.

Table 2. Carbonization depth of samples with different water cement ratio at the same time point

Time (days)	Carbonization depth (mm)		
	Mix ratio A	Mix ratio B	Mix ratio C
0	0	0	0
15	0.5	0.7	0.9
30	1.0	1.4	1.8
45	1.4	2.0	2.5
60	1.8	2.5	3.2
75	2.1	2.9	3.8
90	2.4	3.3	4.3

From the data analysis in Table 2 above, it is known that the carbonation depth of concrete samples continues to increase with time, indicating that carbonation is a time-related process, which gradually destroys the concrete structure and affects its durability. At the same time, the data show that the water-cement ratio is directly proportional to the carbonization depth; The experimental results of 90 days show that the carbonation depth of the sample with water-cement ratio of 0.45 is 2.4 mm, while that of the sample with water-cement ratio of 0.55 is increased to 4.3 mm. This trend emphasizes the importance of water-cement ratio in controlling the performance and durability of concrete. The high porosity caused by high water-cement ratio facilitates the infiltration of carbon dioxide and accelerates the carbonation process.

The development of cracks in concrete and the change of pore structure were observed by high resolution imaging technology. It is found that the cracks in the samples with higher water-cement ratio expand more rapidly and the pore structure is looser. Under the action of continuous load, the crack propagation speed is further accelerated (Figure 2).

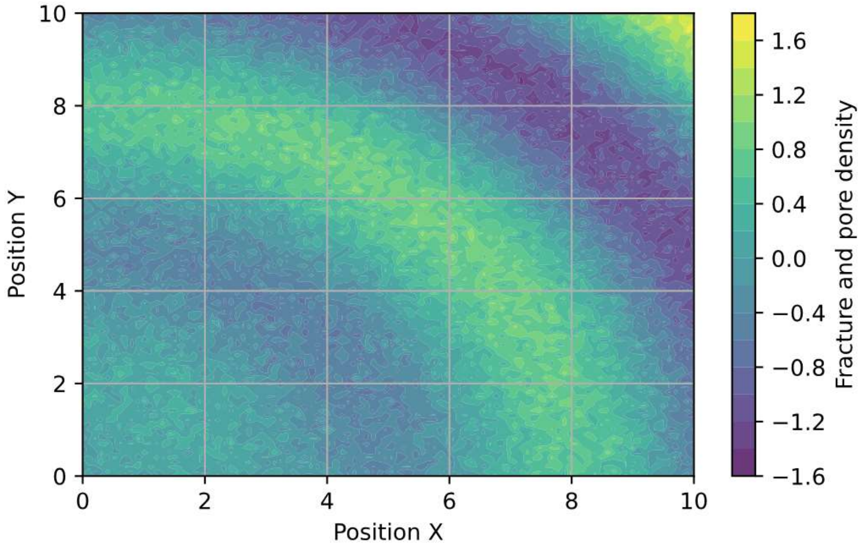

Figure 2. Contour map of crack and pore distribution in concrete (water cement ratio 0.55)

As can be seen from the figure, the density of cracks and pores is not evenly distributed throughout the concrete. There are some areas with high density, while others have relatively low density. This inhomogeneity may be caused by the inhomogeneity of concrete materials, defects in the preparation process, and stress concentration under external environment and load. In dark areas, that is, areas with dense contours or dark colors, it can be considered that the density of cracks and pores in these areas is high. These high-density areas may correspond to the weak points in concrete, and they are more susceptible to carbonation, erosion or stress, which leads to performance degradation.

Compared with traditional methods, multi-scale analysis method can reveal the influencing factors and mechanism of concrete durability more comprehensively. Through the comprehensive analysis of macro, meso and micro scales, the performance changes of concrete in different environments can be predicted more accurately, and scientific basis can be provided for the optimal design of concrete. The advantage of this method lies in its comprehensiveness and depth, which can provide strong support for the durability design and improvement of concrete. In the stage of material design, the microstructure of concrete can be optimized by reasonably adjusting parameters such as water-cement ratio, so as to improve its durability. In addition, in the process of concrete use, through reasonable curing and maintenance measures, the decline speed of concrete performance can also be delayed.

This research delves into the resilience of concrete through a multi-level examination approach. The empirical outcomes indicate that structural refinement on multiple scales plays a crucial role in enhancing the resilience of concrete. Moreover, the multi-level analytical technique offers us an efficacious avenue for gaining a thorough and profound comprehension of the resilience principles underlying concrete.

4. Conclusion

In this study, the durability of concrete is deeply discussed by using multi-scale analysis method, and the performance changes of concrete under various environmental conditions are comprehensively understood from macro, meso and micro scales. The empirical findings reveal that the compressive robustness of concrete specimens with varying water-to-cement proportions diminishes in a carbonated milieu, with a more pronounced reduction in robustness accompanying higher water-to-cement ratios. Concurrently, the extent of carbonation deepens as the water-to-cement ratio escalates. Under sustained loading, the compressive robustness of the specimens declines at a quicker pace. Furthermore, high-definition imaging techniques were employed to observe the progression of fissures and shifts in the porous architecture within the concrete, revealing that fissures in specimens with elevated water-to-cement ratios widen more swiftly and the porous structure is less compact. In

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carbonation environment, these unhydrated particles are more susceptible to erosion, which leads to the decline of concrete performance. To sum up, this study shows that multi-scale structural optimization is of great significance to improve the durability of concrete. The advantage of this method lies in its comprehensiveness and depth, which can provide strong support for the durability design and improvement of concrete.

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