

Influence of Carbonation on Mechanical Properties of Concrete

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Abstract As one of the most important factors that determine the lifespan of a reinforced concrete structure, carbonation not only corrodes the reinforcing steel, but also changes the mechanical properties of concrete. For better understanding the performance of carbonated concrete structure, it is necessary to study the mechanical properties of carbonated concrete. The stress-strain relationship of carbonated concrete was analyzed on the basis of experiments. The specimens were made by means of accelerated carbonation and then compressed on the testing machine. Some very important characteristics of carbonated concrete were revealed by the testing results. In addition, a useful constitutive model of carbonated concrete, which proved to be suitable for analyzing carbonated concrete members, was established in this research.

Key words: carbonation; concrete; acceleration; mechanical properties; stress-strain relationship

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Introduction

Reinforced concrete structures, exposed to the air containing about 0.03% CO₂, are under carbonation during their lifespan even at the very beginning of their construction. Carbonation is widely recognized as a significant cause of corrosion of reinforced bar in concrete¹. However, in addition to the deterioration of reinforced bar, carbonation also changes the mechanical properties of concrete. Properties of carbonated concrete are different from those of fresh concrete. It is also well accepted that as long as the constitutive model of concrete changes, the mechanical properties of concrete member will certainly change. Most of present researches are interested in physicochemical processes of concrete carbonation, corrosion of reinforced bar and durability of reinforced concrete influenced by carbonation, etc². But few of them have paid attention to the changes in the mechanical properties of concrete caused by carbonation.

The results of the influence of carbonation on mechanical properties of concrete are to be reported

in this paper. The compressive stress-strain relationship of carbonated concrete was modeled mathematically and applied to the analysis of carbonated concrete members.

1 Experimental Procedures

1.1 Carbonation Process

Traditionally, carbonation of concrete is defined as the chemical reaction between atmospheric carbon dioxide and the products of cement hydration Ca(OH)₂, in accordance with the reaction as Eq (1):



However, it is now accepted that other hydration products also react with CO₂. Carbonation not only destroys concrete's alkalinity, leading to the depassivation of the steel, but also changes the microstructure of concrete, and consequently influences the mechanical properties of concrete³.

1.2 Preparation of Test Specimens

The experimental procedures and materials used in this research conformed to the relevant Chinese standard specifications. The mix proportions of the tested specimens were shown in Tab. 1. Two types of specimens were provided. The number of prism measuring 100 mm × 100 mm × 300 mm was 16 and the number of prism measuring

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40 mm × 40 mm × 100 mm was 24. These specimens were designed for different purposes. Some were cast to measure the depth of carbonation, some uncarbonated served as the control group, and the others were carbonated for compressive tests. After 28 days of water curing, the testing specimens, except control group's specimens, were transferred to the carbonation chamber to get carbonated specimens by means of accelerated carbonation. To simplify the analysis of experimental results, two end sides were coated with a carbonation-resistant wax to assure that CO₂ can enter only from the other four sides of the specimens.

Tab 1 Mix proportions of the tested specimens

Type	Specimen dimension (mm × mm × mm)	Num.	Water	Cement	Sand	Aggregates
			/(kg · m ⁻³)			
T ₁	40 × 40 × 100	24	215	345	508	1 332
T ₂	100 × 100 × 400	16	215	345	508	1 332

The carbonation chamber contains 10% CO₂ and is 70% in humidity. At the various intervals, some prism specimens were taken out of the carbonation chamber to measure the depth of carbonation in concrete. The depth of carbonation was indicated by the phenolphthalein solution. After 170 days of accelerated carbonation, the specimens were taken out and tested on the compressive testing machine. The experimental results were recorded in load-deformation curves with automatic X-Y recorder.

2 Experimental Results

2.1 Carbonation Depth and Area

The results of the carbonation test are shown in Tab 2. In this test, the carbonation rate was slower than expected. The cause might be that the strength of concrete in this test was higher than the designed. However, this did not affect our research because the focus of this research was the relative carbonation area of the specimen sections and the carbonation depth was nearly even in the four sides. The relative carbonation area was calculated and shown in Tab 2.

2.2 Results of Compressive Tests

In this test, the ultimate strain of concrete was defined when the stress decreased to 85% of

the maximum stress in the declined stage. The average stress and strain of all specimens in each group in the compressive test were summarized in Tab 3.

Tab 2 Average carbonation depth and area

Type	Group	Num.	Aver carbonation depth/mm	Carbonation area/%
T ₁	Carbonated	10	9.06	70.1
T ₁	Uncarbonated	10	0	0
T ₂	Carbonated	6	14.9	50.7
T ₂	Uncarbonated	6	0	0

Tab 3 Results of compressive test

Type	Group	Aver max stress /MPa	Aver strain under max stress × 10 ³	Aver ultimate strain × 10 ³
T ₁	Carbonated	50.9	1.98	2.40
	Uncarbonated	34.9	2.03	3.59
T ₂	Carbonated	43.7	1.92	2.77
	Uncarbonated	33.6	1.90	3.80

3 Analysis of Experimental Results

Based on the experimental results, some changes of properties in the carbonated concrete comparing with those of the uncarbonated concrete are summarized. These changes are decisive parameters in the stress-strain relationship of carbonated concrete.

3.1 Strain of Carbonated Concrete under the Maximum Stress

Comparing the strain under the maximum stress of the carbonated concrete with that of the uncarbonated concrete (listed in Tab 3), the ratio of them was approximately equal to 1.00 (the ratio of T₁ was 0.98, and the ratio of T₂ was 1.01). It appears that the strain of concrete under the maximum stress was less affected by carbonation. This is illustrated in Fig 1.

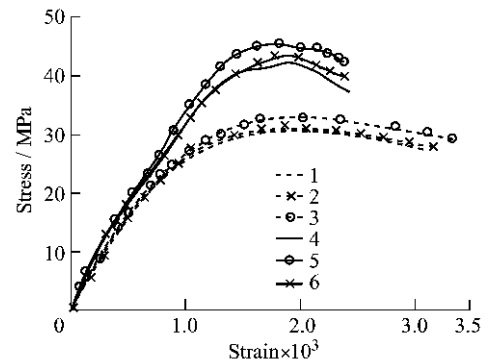


Fig 1 Comparison of strain under the maximum stress (T₂ specimens)

1, 2, 3- Uncarbonated concrete; 4, 5, 6- Carbonated concrete

3.2 The Maximum Stress of Carbonated Concrete

The cross section in the specimens can be separated into two parts after carbonation: carbonated region and uncarbonated region as showed in Fig. 2. These two parts perform different constitutive laws, so it is essential to analyze the mixed section problem. It is assumed that: (a) the strain is compatible and consistent between the carbonated and uncarbonated concrete at the interface; (b) the strain distributes linearly along the depth of the section; (c) the shear deformations are negligible and not considered. Thus the carbonated specimen in compression is divided into two parts:

$$P = P_c + P_u \quad (2)$$

P —force on the full section of specimen,

P_c —force on the carbonated section,

P_u —force on the uncarbonated section.

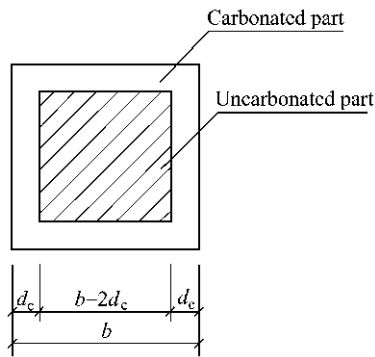


Fig. 2 Separating of section

If the average stress on this section, stress of uncarbonated section and area of uncarbonated section are known, the stress of fully carbonated concrete can be calculated out. Then the constitutive law of fully carbonated concrete can be developed. The ultimate stress of the fully carbonated concrete calculated by this method is shown in Tab. 4. The maximum stress of carbonated concrete was improved by approximately 60% as compared with that of uncarbonated concrete.

Tab. 4 The calculated ultimate stress of fully carbonated concrete

Type	Calculated ultimate stress of fully carbonated concrete/MPa	Ratio of strength improved by carbonation/%
T ₁	57.7	65.4
T ₂	54.3	61.3

3.3 The Ultimate Strain of Carbonated Concrete

Comparing the ultimate strain of carbonated concrete with that of uncarbonated concrete (listed in Tab. 3), the reduction in the ratio of ultimate strain caused by carbonation was approximately equal to 30% (that of type 1 was 33.1%, that of type 2 was 27.1%). The details were shown in Fig. 1 and Fig. 3, and the data also illustrated that carbonation decreased the ductility of concrete.

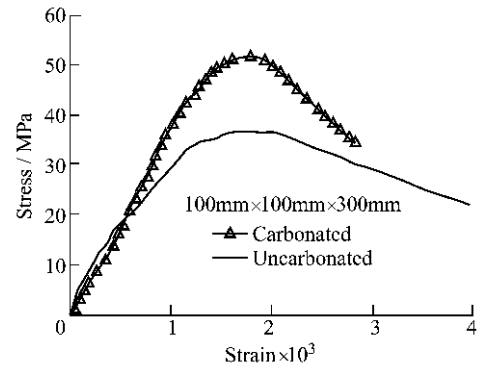


Fig. 3 Representative stress-strain relationship of carbonated and uncarbonated concrete

4 Stress-Strain Relationship of Carbonated Concrete and Application

The stress-strain relationship of concrete given by Hognestad was an extensively used model for normal concrete. It was shown in Fig. 4⁴. To analyze the carbonated concrete member, the model must be modified according to the characteristics of carbonated concrete. From the analysis above, it is proposed that the stress-strain relationship of carbonated concrete could be derived based on the stress-strain relationship of uncarbonated concrete by increasing the maximum stress by 60%,

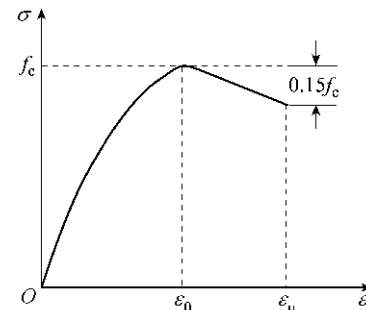


Fig. 4 Hognestad model of stress-strain relationship for ordinary concrete

decreasing the ultimate strain by 30% and maintaining the same strain under the maximum stress. The stress-strain relationship of carbonated concrete was expressed as follows:

$$\left. \begin{aligned} \sigma &= 1.6f_c \left[2 \frac{\epsilon}{\epsilon_0} - \left(\frac{\epsilon}{\epsilon_0} \right)^2 \right] \\ &\quad \text{for } \epsilon \leq \epsilon_0 \\ \sigma &= 1.6f_c \left[1 - 0.15 \frac{\epsilon - \epsilon_0}{0.7\epsilon_u - \epsilon_0} \right] \\ &\quad \text{for } \epsilon_0 < \epsilon \leq 0.7\epsilon_u \end{aligned} \right\} \quad (3)$$

where ϵ , σ is the strain and stress of carbonated concrete respectively; f_c , ϵ_0 , ϵ_u is the maximum stress, the strain under the maximum stress and the ultimate strain of uncarbonated concrete respectively.

The modified model for carbonated concrete was applied to analyze of the mechanical properties of carbonated concrete beams in this test. The testing beam is a simply supported beam and its length is 12.0 m. The cross section is 100 mm $\times$ 150 mm and the carbonated depth of concrete is about 11.6 mm. The compressive strength of concrete of about 25.0 MPa. The analytical results of them were shown in Fig. 5. The theoretical load-deflection curve of beam is in good agreement with

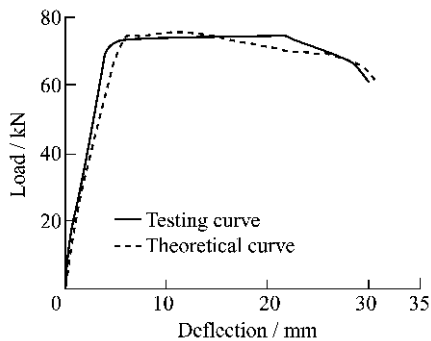


Fig. 5 Comparison of load-deflection curves

that of test. So the model of carbonated concrete's stress-strain relationship was proved to be suitable for analyzing the carbonated concrete member.

5 Conclusion

Carbonation changes the mechanical properties of concrete. In one hand, it increases the strength of concrete, on the other hand, it decreases the ultimate strain of concrete. So carbonation may decrease the ductility of concrete member. When analyzing the seriously carbonated concrete member, it was suggested that the influence of carbonation on the mechanical properties of concrete should be taken into account. The model proposed in this paper is simple and suitable for analyzing the carbonated concrete member.

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