Study on Carbonation Index Prediction of Steel Fiber Concrete

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Abstract. The addition of short steel wire, polypropylene, basalt and other fibers can improve the durability index of concrete, such as compression resistance, cracking resistance and carbonization resistance, which has been widely recognized in the industry. For the durability of fiber concrete, most of the current researches are qualitative, and the quantitative value of various index needs to be further investigated. In view of this, linear fitting and polynomial fitting were introduced into the prediction of durability index of fiber concrete in the present paper. The results show that the fitting method proposed is feasible and accurate for the carbonation index of fiber concrete.

1 Introduction

In recent years, with the innovation of fiber material technology, engineering structure has been further developed. An increasing number of engineering applications show that the incorporation of various fibers in concrete can significantly improve various mechanical properties [1-2] and durability indexes [3] of the structure. Many scholars have conducted researches on the mechanical properties of various fiber reinforced concrete materials, such as compression, shear and bending resistance [4-6] and durability indexes, such as freeze-thaw resistance [7], carbonization [8] and salt erosion [9], and achieved certain regular results.

Carbonation damage can lead to deterioration of concrete's appearance and strength performance, thus affecting the long-term durability life of concrete, which is a typical form of concrete durability damage. Since the 1960s, the relevant countries began to study concrete carbonation. According to the influencing factors of concrete carbonation, a variety of methods of simulating carbonation test and related theoretical models were put forward. Many studies have been conducted on the carbonation effect of ordinary concrete. However, there are relatively few researches on durability indicators such as the carbonization of concrete mixed with fibers such as steel and polypropylene, and further research is needed.

2 Analysis of Carbonization Mechanism of Steel Fiber Concrete

2.1. Steel fiber impact analysis

Steel fiber is a typical concrete additive fiber. In the concrete mixing process, the gradual incorporation of steel fiber can improve the cracking resistance of concrete, reduce the weight of the concrete, increase the bond, and greatly improve the performance of concrete. The type and shape of steel fiber are shown in Table 1.

Table 1 Type and shape of steel fiber

Type	Cold-drawn steel-plastic cut-off type	Sheet shear type	Ingot milling type	Low-alloy steel melting type
Shape	End hook	Flat/ Deformed	Deformed	Large head

Compared with ordinary concrete structures, steel fiber concrete has obvious advantages. The amount of concrete with the same strength can generally be reduced by 30-50%, the amount of steel bars can be saved, the arch bridge can be shortened, and the construction is relatively simple. It is a kind of advantaged fiber-added concrete material.

The standard tensile strength of steel fiber concrete is determined according to Equation (1):

$$f_{cf} = f_f\left(1 + a_t\lambda_t\right) \tag{1}$$

Where f_f is the tensile strength standard value of concrete, unit is Mpa.

λ_t is the characteristic value of steel fiber content.

a_t is the influence factor of steel fiber on the tensile strength of concrete, as shown in Table 2.

$$\lambda_t = \rho_f l_t / d_t \tag{2}$$

Where ρ_f is the volume ratio of steel fiber.

l_t is the equivalent length of steel fiber.

d_t is the equivalent diameter of steel fiber.

The standard bending and tensile strength of steel fiber can be calculated according to Equation (3):

$$f_{ck} = f_k\left(1 + a_k\lambda_t\right) \tag{3}$$

Where f_k is the standard value of concrete bending tensile strength, unit is Mpa

a_k is the influence factor of steel fiber on the flexural

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tensile strength of concrete, as shown in Table 2.

Table 2 Corresponding strength and index influencing factors of steel fiber concrete

Type	Shape	CF strength grade	a_t	a_k
Cold-drawn steel-plastic cut-off type	End hook	20MP~45MP	0.76	1.13
		50MP~80MP	1.03	1.25
Sheet shear type	Flat	20MP~45MP	0.42	0.68
		50MP~80MP	0.46	0.75
	deformed	20MP~45MP	0.55	0.79
		50MP~80MP	0.63	0.93
Ingot milling type	Deformed	20MP~45MP	0.7	0.92
		50MP~80MP	0.84	1.1
Low-alloy steel melting type	Large head	20MP~45MP	0.52	0.73
		50MP~80MP	0.62	0.91

2.2. Carbonization mechanism analysis

The CO_2 in the air reacts easily with the alkaline substances in the concrete in a humid environment, causing the concrete to calcify. This process is called the carbonization reaction of the concrete. The main reaction equation is shown in equation (4):

$$\begin{cases} Ca(OH)_2 + H_2O + CO_2 \rightarrow CaCO_3 + 2H_2O \\ CaO\cdot 2SiO_2\cdot 3H_2O + CO_2 \rightarrow CaCO_3\cdot 2SiO_2\cdot 3H_2O \end{cases} \quad (4)$$

The carbonization reaction principle of steel fiber concrete is basically the same as that of ordinary concrete.

3 Numerical example

Age and compressive strength are the main factors that affect carbonization of steel fiber concrete under unfavorable conditions. Based on the analysis of age factors, taking C50 concrete mixed with steel fiber as an example, carbonation reaction test under different fiber content was carried out.

C50 concrete was mixed with 0%, 1%, 2% and 3% volume ratios of steel fiber to compare the carbonation depth of concrete at 7d, 14d and 28d ages, and the results were shown in Figure 1.

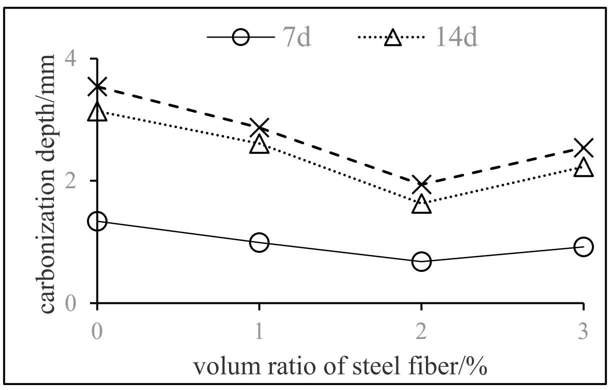

Figure 1 Comparison of carbonization depth of steel fiber concrete at 7d~28d age

The results show that the carbonation depth of concrete with different steel fiber content did not show a linear relationship, but had a certain optimal content. As can be seen from Figure 1, when the volume steel fiber content was about 2%, the carbonation depth reached the best. This conclusion indicates that the mathematical model of the carbonization depth of steel fiber concrete cannot be directly applied to the linear model based on the ordinary concrete carbonization depth model [10], but a staged model should be considered. Therefore, based on the above research, the relationship between carbonation depth, steel fiber content and concrete strength was further analyzed.

3.1. Linear fitting of carbonization depth

Table 3 shows the linear fitting results of carbonation depth under the classification accuracy of 0%, 1%, 2% and 3% steel fiber volume content for C50 concrete at 0-28d age.

Table 3 Linear fitting results of C50 concrete with different steel fiber volume ratio

Volume ratio of steel fiber/%	Carbonation depth equation	Fitness R2/%	0~28d age	
			Age carbonization coefficient k_a	Age influence coefficient η_a
0	$Y_{SC}=0.6943\sqrt{T}$	79.65	0.6943	1
1	$Y_{SC}=0.5626\sqrt{T}$	75.19		0.8103
2	$Y_{SC}=0.3706\sqrt{T}$	82.6		0.5338
3	$Y_{SC}=0.4942\sqrt{T}$	79.65		0.7118

It can be seen from Table 3 that the linear fitting method could be used to obtain the concrete carbonization depth equation under different steel fiber volume content. The carbonization depth of concrete had a certain correlation with the steel fiber volume ratio, but there was an optimal addition volume. According to this characteristic, the fitting equation of carbonation depth under different volume content of steel fiber was divided into two stages of 0%~2% and 2%~3%:

① When the volume ratio of steel fiber was 0%~2%,

$$Y_{SC} = k_a\eta_a\sqrt{T} = \begin{cases} 0.6943[-0.2331\phi(\theta)]\sqrt{T}, & R^2 = 0.9886 \\ 0.6943[-0.0434\phi^2(\theta) - 0.1463\phi(\theta) + 1]\sqrt{T}, & R^2 = 1 \end{cases} \quad (5)$$

② When the volume ratio of steel fiber was 2%~3%,

$$Y_{SC} = k_a\eta_a\sqrt{T} = 0.6943[0.178\phi(\theta) + 0.1778]\sqrt{T}, \quad R^2 = 1 \quad (6)$$

3.2. Polynomial fitting of carbonation depth

Table 4 shows the polynomial fitting results of the carbonization depth of C50 concrete under the 0%, 1%, 2%, and 3% steel fiber volume content at the 0~56d age.

Table 4 Polynomial fitting results of C50 concrete with different steel fiber volume ratio

Volume ratio of steel fiber/%	Carbonation depth equation	Fitness R2/%	0~56d age Age carbonization coefficient k_{a1}/k_{a2}	0~56d age Age influence coefficient η_{a1}/η_{a2}
0	$Y_{SC}=0.00683T+0.6638\sqrt{T}$	79.74	0.00683/0.6638	1
1	$Y_{SC}=0.01138T+0.5118\sqrt{T}$	75.5		1.6662/0.7710
2	$Y_{SC}=0.01402T+0.308\sqrt{T}$	83.74		2.0527/0.4640
3	$Y_{SC}=0.0102T+0.4486\sqrt{T}$	80		1.4934/0.6758

As can be seen from Table 4, the equation of concrete carbonation depth under different steel fiber volume content could also be obtained by polynomial fitting. The carbonation depth of concrete had a certain correlation with the volume ratio of steel fiber, but there was an optimal content. According to this characteristic, the fitting equation of carbonation depth under different volume content of steel fiber was divided into two stages of 0%~2% and 2%~3%:

①When the volume ratio of steel fiber was 0%~2%,

$$Y_{SC}=k_{a1}\eta_{a1}T+k_{a2}\eta_{a2}\sqrt{T}=\begin{cases}0.00683[0.5264\phi(\theta)+1.047]T+0.6638[-0.268\phi(\theta)+1.013]\sqrt{T}, & R_1^2=0.977, R_2^2=0.993\\0.00683[-0.1398\phi^2(\theta)+0.806\phi(\theta)+1]T+0.6638[-0.039\phi^2(\theta)-0.19\phi(\theta)+1]\sqrt{T}, & R^2=1\end{cases} \quad (7)$$

②When the volume ratio of steel fiber was 2%~3%,

$$Y_{SC}=k_{a1}\eta_{a1}T+k_{a2}\eta_{a2}\sqrt{T}=0.00683[-0.5593\phi(\theta)+3.171]T+0.6638[0.2118\phi(\theta)+0.0404]\sqrt{T}, \quad R^2=1 \quad (8)$$

4 Result

It can be seen from the above calculation examples that both linear fitting and polynomial fitting could get better prediction results. Substitute the above equation and compare with the actual measurement results, as shown in Table 5.

Table 5 Comparison of calculation effectiveness of carbonation depth of C50 concrete with different steel fiber volume ratio

Volume ratio of steel fiber/%	Age /d	Carbonation depth X/mm Actual measurement [10] X_C/mm	Carbonation depth X/mm calculation X_J/mm	Carbonation depth error comparison X_C/X_J	Effectiveness evaluation
0	7	1.34	1.8	0.74	Average value
	14	3.14	2.58	1.22	
	28	3.54	3.7	0.96	0.97
1	7	0.99	1.43	0.69	
	14	2.61	2.07	1.26	Mean square error
	28	2.87	3.03	0.95	
2	7	0.68	0.91	0.74	0.0454
	14	1.63	1.35	1.21	
	28	1.94	2.02	0.96	Variation coefficient
3	7	0.92	0.91	0.74	
	14	2.23	1.35	1.21	0.2197
	28	2.54	2.02	0.96	

As can be seen from Table 5, although the carbonation depth of steel fiber concrete was different from that of ordinary concrete on the whole, the carbonation depth of both steel fiber concrete and ordinary concrete increased with the growth of age. However, when the volume content of steel fiber was changed, there was an optimal content instead of a linear increasing relationship. Using the method proposed in the present paper to predict the carbonation depth of steel fiber concrete, the average value of the ratio between the measured value and the calculated value was -3%, the mean square error was 0.0454, and the coefficient of variation was 0.2197. The accuracy and reliability of the proposed method were justified.

5 Conclusion

The addition of steel fiber can inhibit the carbonization of concrete to some extent, but its quantitative analysis needs to be further studied. In this paper, linear fitting and polynomial fitting methods were adopted to predict the carbonation depth of steel fiber concrete under different fiber volume content, and the following conclusions are drawn.

(1) The carbonation rate of concrete can be reduced by adding steel fiber into concrete;

(2) The mathematical model of the carbonization depth of steel fiber concrete cannot be directly applied to the linear model based on the ordinary concrete carbonization depth model, but a staged model should be considered.

(3) The staged carbonation depth prediction model proposed in this paper has substantial accuracy and reliability.

(4) The addition of steel fiber can inhibit the carbonization of concrete to some extent, but its quantitative analysis needs to be further studied.

Acknowledgments

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References

1. Shen W., Yang D Y., Luo J J., et al. (2017) Research of the long-term mechanical properties of alkali resistant glass fiber concrete. Concrete, 332: 102-106.
2. Jin L.,Hang R B., Du XL., et al.(2021)Research

progress on the influence of temperature on the mechanical performance of concrete structures. China Civil Engineering Journal, 54 (03): 1-18.

3. Zhang K C.(2020)Study on the Durability of Polypropylene-Basalt Fiber Concrete.Non-Metallic Mines.43(05): 45-47+51.
4. Fan X C., Xiong L F., Wang P.(2020)Experimental Study and Theoretical Calculation on Stub Columns Eccentric Compression of BFRP Bars and Hybrid Steel Fiber Reinforced Concrete.Bulletin of the Chinese Ceramic Society,39(10): 3161-3168.
5. Liu R Y., Wang Z J.(2020)Research on crack development of unreinforced steel fiber concrete compression-bending beam. Building Structure, 50 (22): 93-98.
6. Zhang G T.,Zhang M., Zhang L Y.(2020)Prediction of Shear Strength of Fiber Concrete Beams Based on Bayesian Probability Model. Bulletin of the Chinese Ceramic Society,39(03): 770-778.
7. Ning X L.,Wang W P., Hao S., et al.(2020)Effect of Different Fibers on Frost Resistance of Concrete Under Multiple Factors. Industrial Construction, 50(10): 122-128.
8. Zhang W J., Liu B H., Zhou W., et al.(2021) Experimental study on carbonation resistance of rape straw fiber concrete. Journal of Hunan Agricultural University(Natural Sciences), 47(01): 96-100.
9. Wang Z S., Li Y K., Wei J., et al.(2020)Experimental study on corrosion behavior and mechanical properties of basalt fiber concrete by chlorine attack. Journal of Experimental Mechanics, 35(06): 1060-1070.
10. Wang Z H., Yang D J,(2015)Dynamic Response Analysis of Concrete Rectangular Steel Tube Columns Under Blasting Loading.Journal of Tianjin Chengjian University,21(04):262-266.