HYBRID USE OF STEEL- AND CARBON-FIBER REINFORCED CONCRETE FOR MONITORING OF CRACK BEHAVIOR

Y. DING [1*], Z. HAN[1], Y. ZHANG[2], C.Azevedo[3]

[1]*State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, 116024 Dalian, China*
[2] *Civil Engineering Colleges, Guangzhou University, 510006 Guangzhou, China*
[3]*Center of Mathematics, University of Minho, Portugal*

Keywords: Hybrid fibers, conductive concrete, fractional change in resistance, crack width

Abstract

In order to study the damage after concrete cracking, the influence of the combined use of steel fiber and carbon fiber on the conductivity and crack resistance of concrete beam under flexural loading were investigated. Carbon fiber and steel fiber were added as diphasic conductive materials to produce the electric conductive and ductile concrete. This paper reports the experimental and analytical work associated with establishing the crack width in relation to the fractional change in resistance of electric conductive concrete. After cracking, the electrical resistance change was found to correlate linearly with the crack width on the tension side of concrete beam.

1 Introduction

Damage sensing is essential for the safety and durability of concrete member. The carbon fiber (CF) or steel fiber (SF) reinforced cement-based materials are able to sense its own strain and damage by the electrical resistance measurement [1-6]. Compared to embedded or attached sensors, the self-sensing ability is advantageous in the low cost, high durability and absence of mechanical property loss before cracking. Furthermore, the electric conductive cement-based materials also provide wide prospect in specialist applications that can utilize its multifunctionality, notably electromagnetic shielding, traffic monitoring and de-icing [7-9].

Electric conductive fibers, such as carbon and steel fibers, are effective as admixtures for providing electric conductive cement-based materials due to the formation of a continuous conducting path [10]. The investigations on the strain and damage of micro carbon fiber and micro steel fiber reinforced cement specimens under compression, tension or flexural loading have been carried out in previous studies [1-11], which are mainly concentrated on the damage sensing of cement samples before cracking. In fact, the concrete member works usually with cracks during the service period in the practice, and there is still a lack of the self-sensing ability regarding the cracking behaviour of concrete member under bending, hence it is important to study the relationship between the FCR and the crack width of beam.

After concrete cracking, macro SF are able to restrict of the cracking development, mitigate the stress concentration and increase the energy absorption capacity. The hybrid use of macro SF and short CF into concrete can both show the advantage of the conductive network of CF and make use of electric characteristics of macro SF, and also provides the conductive concrete with well mechanical property after cracking. As macro steel fibers are effective for enhancing the tensile, flexure properties of concrete beams before, during and after cracking, it is possible to investigate the relationship between the crack-width and electric conductivity of diphasic electrical conduction concrete beams.

This work is mainly aimed at investigating of the effect of hybrid use of macro SF and short CF on the self-sensing of damage of concrete beams under bending during the cracking development and in the post-crack region. The relationship between the FCR and crack width on the beam bottom has been established using the regression analysis.

2 Experimental methods

2.1 Materials and mixture design

In this test program, the base mix design of concrete without conductive admixture (reference concrete) is illustrated in Table 1.

Cement (kg/m^3)	**Fly ash (kg/m^3)**	**Fine aggregate (kg/m^3)**	**Coarse aggregate (kg/m^3)**	**Water (kg/m^3)**	**SP (kg/m^3)**
373.33	160	733.33	733.33	240	5.33

Table 1. Mix design of reference concrete

The carbon fiber was isotropic pitch based and unsized (Fig.1a). The carbon fiber diameter was 15 μ m. The nominal fiber length was 6 mm. The density was 1.6 g/cm^3 The steel fiber contents for tests were 30 and 50 kg/m^3, with a fibre length of 35 mm and diameter of 0.55 mm (Fig.1b). The density of steel fiber was 7.85 g/cm^3. In case that carbon fiber was used, a methylcellulose was used in the amount of 0.4% by mass of cement and a defoamer was used in the amount of 0.19% of sample volume.

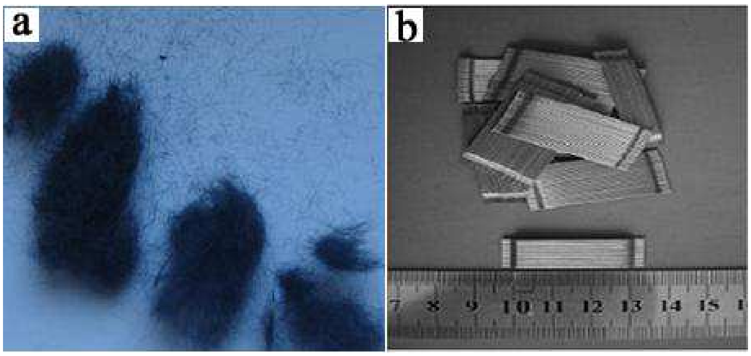

Figure 1. Carbon fiber and steel fiber

Three groups of samples were tested based on different contents of the combined use of conductive admixtures in the concrete. The conductive admixtures of various test groups used in this work are given in Table 2.

Series	Content of CF(kg/m^3)	Content of SF(kg/m^3)
SC304	1.5	30
SC308	3.0	30
SC508	3.0	50

Table 2. Conductive admixtures content of various test group.

2.2 Samples and set-up description

A forced mixer was used for mixing. Methylcellulose was dissolved in water and then the defoamer and carbon fiber were added and stirred by hand for about 2 min. Then, this methylcellulose mixture, cement, water, aggregate, steel fiber and Superplasticizer were mixed for 3 min. After this, the mix was poured into 100×100×400mm steel moulds to produce test beams. The beams were covered with polyethylene sheeting and stored on-site for 24 h before demoulded and then allowed to cure at room temperature in air (relative humidity = 100%) for 28 days.

Electrical resistance measurement was conducted using the four-probe method. Electrical contacts in the form of conductive adhesive tape were placed along the whole perimeter in four parallel planes, as illustrated in Fig.2. Contacts A and D were for passing current while contacts B and C were for measuring of voltage.

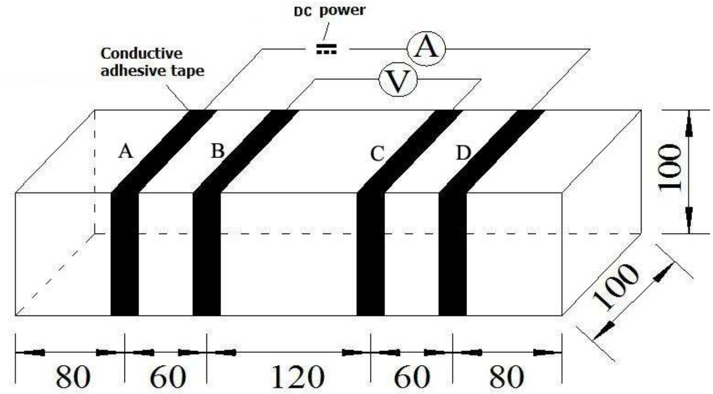

Figure 2. Specimen configuration for measurement of resistance.

2.3 Test methods

Specimens were tested in flexure over a span of 300mm in third-point loading using a hydraulic serve testing machine. Tests were performed under closed-loop control of displacement. An extensometer was attached to the tension side of the beam to measure the crack width during the test (see Fig.3). Other experimental instruments include A.C. stabilized voltage supply, IMC Intelligence Data Collecting System, fixed resistor and AC/DC converter.

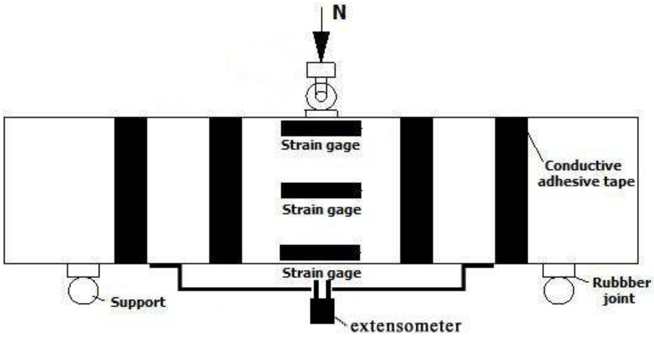

Figure 3. Schematic view of beam under loading with extensometer and electrodes.

3 Results and discussion

3.1 Effect of conductive admixtures (macro SF and micro CF) as function materials on the initial resistance (R_0)

Table 3 shows the influence of conductive admixture on the initial resistance of concrete beam. In comparison with the beam of PC (concrete without conductive admixture), the resistance of SC304 (30 kg/m³ macro SF and 1.5 kg/m³ micro CF), SC308 (30 kg/m³ macro SF and 3 kg/m³ micro CF), and SC508 (50 kg/m³ macro SF and 3 kg/m³ micro CF) beams is decreased by 83.1%, 87.1% and 93.7% respectively. It can be seen that the hybrid use of SF and CF is very effective in decreasing the resistance of concrete beam.

Serial number	PC	SC304	SC308	SC508
R_0 (Ω)	3213.78	542.9	417.2	203.4

Table 3. Initial resistance (R_0) of conductive concrete beams before flexural testing.

3.2 Comparison of the effects of macro SF and micro CF as structure materials on the crack width and residual load bearing capacity

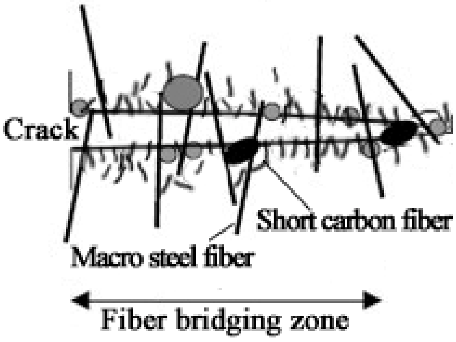

Figure 4. Schematic view of crack of hybrid fiber reinforced concrete under loading

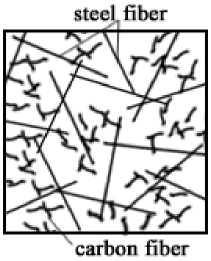

Figure 5. Hybrid fiber dispersion

After cracking, the stress transfer over the crack in the fiber bridging zone is undertaken by the macro steel fibers across the crack, which also makes the interrupted conduction path continuous, as illustrated in Fig.4. Fig.5 shows that the hybrid fiber is effective in reducing the resistance of concrete. Macro SF provides a long conduction path within the matrix and short CF fill the space between macro SF.

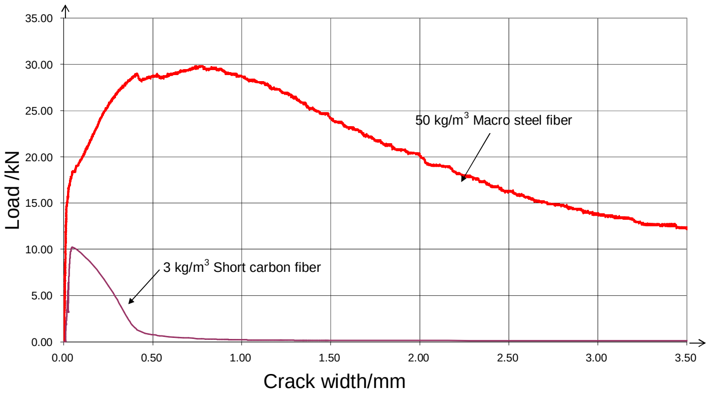

Figure 6. Comparison of load-crack width curves of 50 kg/m³ steel fibre content with 3 kg/m³ carbon fiber content on the cracked section

Fig.6 illustrates the comparisons of the load – crack width curves between beam with 50 kg/m^3 macro SF and beam with 3 kg/m^3 short CF. Only the addition of short CF shows small influence on the flexural strength and toughness. Compared to the load–crack width curve of beam with only short CF, the steel fiber reinforced concrete beam indicates clear crack width-hardening behaviour after cracking and very improved post-peak properties over the entire cracking range because the steel fibers can bridge the cracking. The well conductive macro SF can greatly enhance the ultimate flexural load, the toughness and the post crack properties of beam significantly. This shows an important advantage of macro steel fiber.

The average values, and the increase rate of the residual load after cracking of beams with different fiber types and fiber contents at crack width from 0.5 mm to 3.5 mm are illustrated in Table 4. Compared to the reference beam with 3 kg/m3 short carbon fiber, the residual load of beam with 50 kg/m^3 fiber increased about 500% at crack width of 0.5 mm, and 230% at crack width of 3.5 mm[12]. It means that in addition to the well conductivity of macro SF, the toughness and the post crack properties of beam can be greatly increased by adding macro steel fibers.

Series	**Crack width (mm)**	0.5	3.5
Reference beam with 3 kg/m3 short CF	Residual load	4.68	3.824
Beam with 50 kg/m3 macro SF	Residual load	28.07	12.63

Table 4. Comparison of the residual load and the increase rate of beams with macro SF and short CF

3.3 Influence of conductive admixture on the relationship between fractional change in resistance and crack width

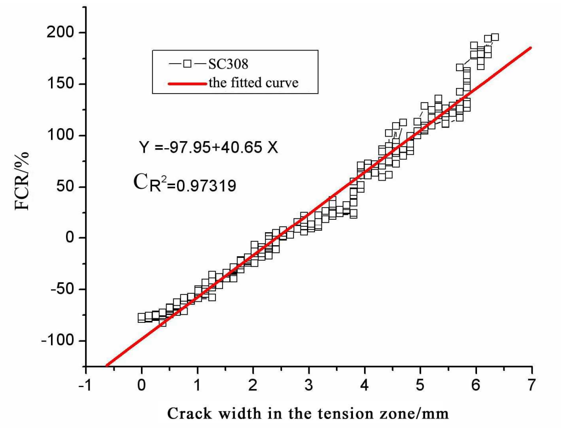

Figure 7. Relationship between FCR and the crack width

Fig.7 illustrates the relationship between fractional change in resistance and crack width in the tension zone for the beam of SC308 during flexural loading. It can be seen that the FCR increases linearly with the increasing of crack width (ω) in the beam tension zone. The relationship between them can be expressed in Eqn. (1):

$$\mathrm{FCR} = \mathrm{a}\,\omega + \mathrm{b} \qquad (1)$$

where a and b are parameters related to the types and the contents of electric conductive phases, the variable ω (mm) is the crack width of beam.

Serial number	**a**	**b**	**C_R^2**
SC304	39.37	-80.23	0.95522
SC308	40.65	-97.95	0.97319
SC508	42.12	-35.33	0.95309

Table 5. Fitted parameters of regression equation.

Table 5 shows the parameters fitted and the correlation coefficients (C_R^2) of all electric conductive concrete beams with various contents of SF and CF. It can be seen that the correlation coefficients are higher than 0.9, which means that the relationship between FCR and the crack width in the tension zone shows a good agreement with Eqn. (1).

4 Conclusion

In this paper, a series of experiments and analysis on the resistance and fractional change in resistance, the crack width and the mechanical properties like the load – crack width curve as well as the residual load of beam with conductive materials have been performed, and the effects of hybrid use of macro SF and short CF as diphasic electric conductive admixtures on the relationship between the fractional change in resistance and the crack width of beams under flexural loading has been investigated. The experimental and analytical results have led to the following conclusions:

1. The well conductive macro SF can greatly enhance the ultimate flexural load, the toughness and the post crack properties of beam significantly;
2. The hybrid use of macro SF and short CF is very effective in decreasing the resistance of concrete beams;
3. The FCR increases linearly with the increasing of crack width of diphasic conductive concrete beam under bending;
4. The fractional change in resistance can be utilized for the self-sensing of damage after cracking of diphasic conductive concrete beam under bending.

5 Acknowledgement

The authors acknowledge the National Natural Science Foundation of China (Grant: 50278013) and Fundação para a Ciência e a Tecnologia (SFRH/BPD/22680/2005) and The FEDER Funds through “Programa Operacional Factores de Competitividade - COMPETE" and by Portuguese Funds through FCT - within the Projects PEst-CMAT/UI0013/2011.

Reference

[1] Sihai Wen, D.D.L. Chung, Self-sensing of flexural damage and strain in carbon fiber reinforced cement and effect of embedded steel reinforcing bars. *Carbon*, **44,**

pp.1496–1502 (2006).

[2] Sihai Wen, D.D.L. Chung, Partial replacement of carbon fiber by carbon black in multifunctional cement–matrix composites. *Carbon*, **45**, pp. 505–513 (2007).

[3] Sihai Wen, D.D.L. Chung, Uniaxial tension in carbon fiber reinforced cement, sensed by electrical resistivity measurement in longitudinal and transverse directions. *Cement and Concrete Research*, **30**, pp.1289-1294 (2000).

[4] Sihai Wen, D.D.L. Chung, Uniaxial compression in carbon fiber reinforced cement, sensed by electrical resistivity measurement in longitudinal and transverse directions. *Cement and Concrete Research*, **31**, pp.297-301 (2001).

[5] Sihai Wen, D.D.L. Chung, A comparative study of steel- and carbon-fiber cement as pirzoresistive strain sensors. *Advances in Cement Research*, **15(3)**, pp. 119-128 (2003).

[6] Sihai Wen, D.D.L. Chung, Effects of strain and damage on the strain sensing ability of carbon fiber cement. *J Mater Civil Eng*, **18(3)**, pp. 355–360 (2006).

[7] Chung DDL, Electromagnetic interference shielding effectiveness of carbon materials. *Carbon*, **39(2)**, pp. 279–85 (2001).

[8] Zengqiang Shi, D.D.L.Chung, Carbon fiber reinforced concrete for traffic monitoring and weighing in motion. *Cement and Concrete Research*, **29**,pp.435-439 (1999).

[9] Sherif Yehia, Christopher Y Tuan, Conductive concrete overlay for bridge deck deicing. *ACI Material Journal*, **96(3)**, pp. 382-390 (1999).

[10] Chung DDL. Electrically conductive cement-based materials. *Advances in Cement Research*, **16(4)**, pp. 167–176 (2004).

[11] Yining Ding, Longfeng Chen, Experimental Studies of Diphasic Electric Conduction Concrete Applying in the Diagnosis of the Damnification. *Acta Materiae Compositae Sinica*, **27(3)**, pp. 184-189 (2010).

[12] Yining Ding, Investigations into the Relationship between Deflection and Crack Mouth Opening Displacement of SFRC beam. *Construction and Building Materials*, **25**, pp. 2432-2440 (2011).