SELF-SENSING CEMENT-BASED COMPOSITE FOR STRAIN MEASUREMENT AND DAMAGE DETECTION

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1 Introduction

This article shows that carbon fiber added into concrete becomes carbon fiber reinforced concrete (CFRC) and with the functionality similar to piezoresistivity material can be used as a self-sensing material for strain measurement and damage detection. It is based on the reversible effect of strain on the volume electrical resistivity and the irreversible effect of damage on the resistivity. The strain sensing behavior is such that the resistivity decreases reversibly upon compression due to the slight push-in of crack-bridging fibers and the consequent decrease of the contact electrical resistivity of the fiber-cement interface. Similarly, the resistivity increases reversibly upon tension due to the slight pull-out of crack-bridging fibers and the consequent decrease of the contact resistivity [1, 2]. The self-sensing ability of CFRC cement-based composite has been well demonstrated under compression and under flexure. With the use of CFRC's electrical resistance change and appearance of structural cracks, we are able to derive an integration of sensors, and which also possesses material smartness quotient of self-sensing, stability and repetitiveness.

2 Experimental investigations

2.1 Materials

The design concrete strength was setting as 350kgf/cm^2. The cement was a blended Portland cement and the specimens were made from a mix with the following ratios: water-cement ratio (w/c) = 0.4; sand-cement ratio (s/c) = 0.75; silica fume by 15% weight of cement; methylcellulose by 0.4% weight of cement and carbon fiber by 0.2% of total volume. The fiber diameter was 15μm. The nominal fiber length was 5mm. A standard mixing procedure was used. A rotary mixer with flat beater was used for mixing. After pouring the mix into oiled molds, an external electric vibrator was used to facilitate compaction and decrease the amount of air bubbles.

2.2 Specimens and test setup

From the aforementioned concrete mixture, 12 concrete cylinders were produced for testing at 7, 14, 28 and 56 days age. In addition, 3 concrete cylinders were produced for high temperature curing in order to simulate the characteristics of long duration (365 days). These cylinders had dimension of 100×200 mm and be prepared for uniaxial compression test. With the same concrete mixture, six concrete beams were produced. These beams had dimension of 550 ×150×150mm and be prepared for four-point bending test. The test setup was shown in Fig. 1.

2.3 Uniaxial compression test

The monotonously compressive loading was applied on the specimen (Fig. 1(c)). The compressive strain of CFRC specimen was measured by LVDT under gauge length equal to 100 mm. The electrical resistance measurements were conducted using the four-probe method, with silver pain in conjunction with copper wires for electrical contacts and the electrode distance was equal to 80 mm (Fig. 1(b)). The Keithley 2000 digital multimeter was used to measure the electrical resistance of the specimens (Fig. 1(a)).

2.4 Four-point bending test

The cyclical loading was applied on the CFRC beam specimen (Fig. 1(d)). The dynamic strain of CFRC beam was measured by strain gauge, the central deformation was measured by LVDT, and the electrical resistance was measured by keithley 2000 digital multimeter (Fig. 1(a)).

3 Results and discussion

3.1 Uniaxial compression test

The test results of 7 days age of specimens are shown in Fig.2~4. Fig.2 shows the relationships between fractional change in electrical resistance of CFRC and strain measured by LVDT at the middle portion of the specimens. These data existed linear

relationship between fractional change in electrical resistance of CFRC and strain measured by LVDT before proportional limit. If exceed the proportional limit, the fractional change in electrical resistance decreases due to the increase of electrical resistance in CFRC specimen caused by the microstructure changes, micro crack density increases and damage occurrences.

In order to relate the fractional change in electrical resistance to compressive strain, before proportional limit there exist linear relationship between fractional change in electrical resistance and compressive strain and with strong relationship R^2=0.9905 of 7d-1 specimen, R^2 = 0.9404 of 7d-2 specimen, and R^2=0.9858 of 7d-3 specimen (Fig.3). The stress-strain curves are very similar before proportional limits but have slopes change due to electrical resistances increasing if compressive strains exceed proportional limits (Fig.4).

The similarity of fractional change in electrical resistance and compressive strain under uniaxial compressive tests can be used as a self-sensing material for strain measurement within proportional limit.

3.2 Sensitivity study of strain measurement

In order to understand the influence parameters of fractional change in resistance used in strain measurement, we consider the sensitivity study of compressive strength, initial electrical resistance, gauge factor, and proportional limit due to different age of specimens. Fig.5 shows the typical stress-strain curve of concrete, where f_c = compressive stress (kgf/cm^2); ε = compressive strain; f_c' = compressive strength of concrete; ε_c = compressive strain at peak stress; E_c = Young's modulus for concrete. The experimental specimens and test results are shown in Table 1, where R_o = initial electrical resistance; gauge factor = fractional change in electrical resistance per unit strain; SPL = strain at proportional limit; $NSPL$ = normalized strain at proportional limit = SPL / ε_c.

Table 1 shows the variation of compressive strength (f_c'), compressive strain at peak stress (ε_c), initial electrical resistance (R_o), gauge factor, strain at proportional limit (SPL); and normalized strain at proportional limit ($NSPL$) with different ages (7, 14, 28, 56, 365 days) of specimens. The test results are averaged and with stand deviations (STD). The detailed comparisons of test results are shown in Fig.6~9.

Fig.6 shows the variation of compressive strength (f_c') with different ages. The compressive strength increases with the age of the specimen and approaches the designed strength after 28 days, except for the 365 days specimens (cured at 150 ^oC and 7 days). Fig.7 shows the variation of initial electrical resistance (R_o) with different ages. The initial electrical resistance decreases with the age of the specimen, and the standard deviation (±38.01 ohms) of 14-day specimens is higher than other age of specimens. Fig.8 shows the variation of gauge factor with different ages. The gauge factor increases with the age of the specimen, and the standard deviations of 7-day specimens (±1.957) and 14-day specimens (±2.708) are lower than other age of specimens. Fig.9 shows the variation of normalized strain at proportional limit ($NSPL$) with different ages. The normalized strain at proportional limit almost approaches 50 %, except for the 7-day specimen (37.5%), but the stand deviations of 14-day specimens (±14.4%) and 56-day specimens (±14.1%) are higher than other age of specimens.

3.3 Damage detection

Based on the different phenomena of fractional change of electrical resistance, three regions are considered in this paper, (1)region-I: linear region, the strain sensing via fractional change in electrical resistance with linear relationship and reversibility; (2)region-II: plastic region, the strain sensing via fractional change in electrical resistance still with some proportional relationship and partial reversibility, owing to the crack occurrence and damage accumulation in specimen; (3)region-III: damaged region, the strain sensing via fractional change in electrical resistance is meaningless, owing to the damage occurrence and material failure in specimen.

Fig.10 shows the variation of compressive stress and fractional change in electrical resistance with compressive strain. The fractional change in electrical resistance has a linear relationship with compressive strain in region-I. In region-II they also keep the same relationship but with some slope changed. The fractional change in electrical resistance rapidly decreases in region-III, because of the electrical resistance increase quickly, due to the damage accumulation. There seems existed a damage indicator, the slope in fractional change and compressive strain diagram (gauge factor =

fractional change in electrical resistance per unit strain). Nevertheless, in practical we have to both measure the fractional change in electrical resistance and compressive strain at the same time.

For practical utility, a simple damage indicator must be considered. Fig. 11 shows the variation of fractional change in electrical resistance and slope of fractional change with time. The fractional change in electrical resistance increases with time in region-I, but the slope of fractional change with time almost keeps the same value in region-I. In region-II, the fractional change in electrical resistance also increases with time. However, the slope of fractional change increases with time at the star, but suddenly drops down near the margin between region-II and region-III, and then become minus value when passing the margin of region-III. The slope of fractional change with time is a good indicator for damage detection under compressive load, when the slope changes from positive value to negative one.

3.4 Four-point bending test

Some testing results are shown in Fig.12 and 13. The surface resistance and strain goes up and down simultaneously due to cyclical loading (Fig.12). A strong relationship (R^2=0.9554) between the fractional change in electrical resistance and strain on tension side of CFRC beam is shown in Fig.13.

Fig.12 also shows the variation of the fractional change in electrical resistance and strain with time. The fractional change with time is a good indicator for damage detection under cyclical loading, when the resistance increases abruptly on tension sides.

4 Conclusions

The similarity of fractional change in electrical resistance and compressive strain under uniaxial compressive tests can be used as a self-sensing material for strain measurement in proportional limit. The initial electrical resistance decreases with the age of CFRC, but the gauge factor increases with the age of CFRC. The normalized strain at proportional limit is almost approach 50 %, when the age of CFRC exceed 14 days.

The slope of fractional change with time is a good indicator for damage detection under compressive load, when the slope changes from positive value to negative one.

Self-sensing of static and dynamic strain and damage detection is effective in CFRC under monotonously compressive loading and cyclical loading. The self-sensing ability of CFRC, as shown for the sensing of static and dynamic strain and damage detection, is obviously presented in this paper.

Acknowledgements

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References

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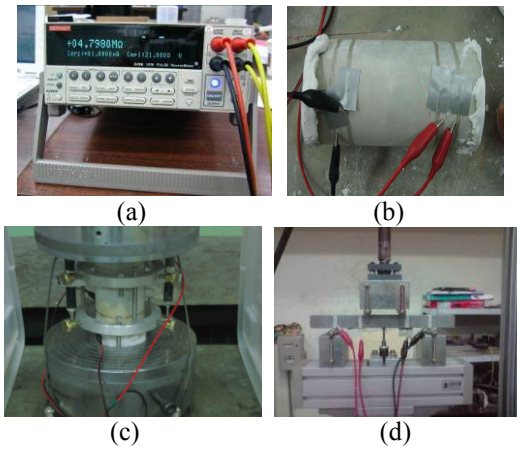

Fig.1. Test setup, (a) multimeter for electrical resistance measurement, (b) four-probe method, (c) uniaxial compression test, and (d) four-point bending test

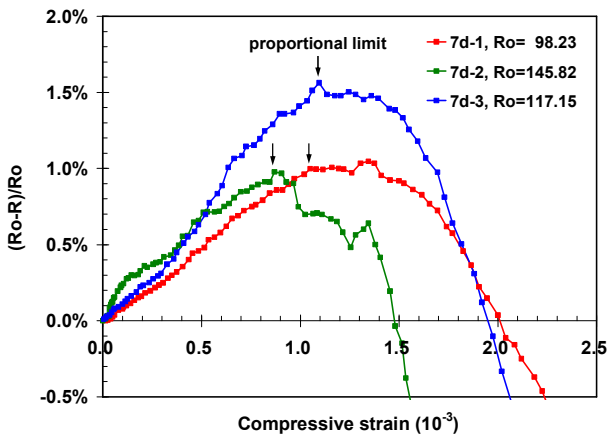

Fig.2. Comparison between fractional change in electrical resistance of CFRC and strain measured by LVDT

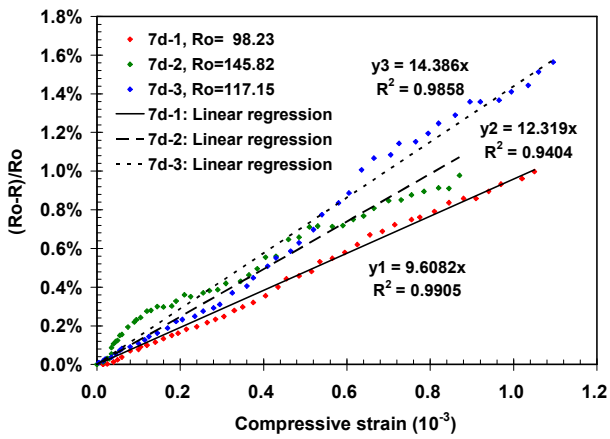

Fig.3. Comparison between fractional change in electrical resistance and strain measured by LVDT in linear region

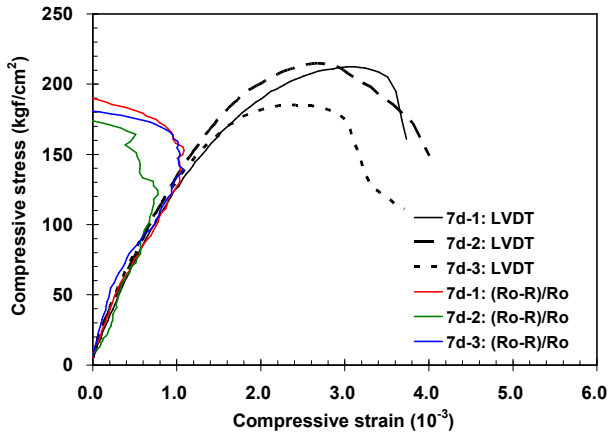

Fig.4. Variation of the fractional change in electrical resistance and compressive strain with compressive stress

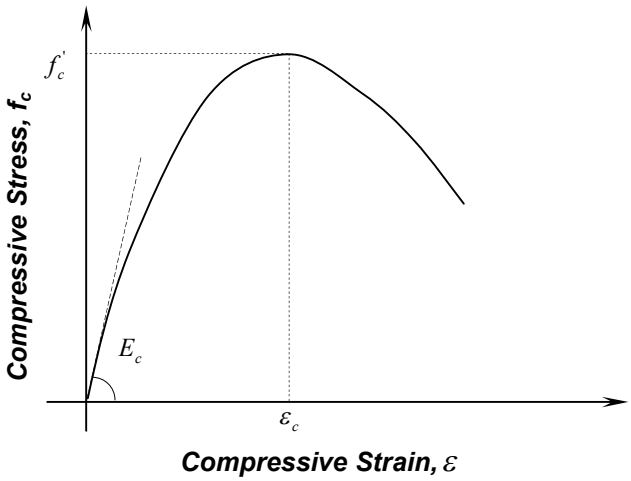

Fig.5. Typical stress-strain relationship of concrete

Table1. Uniaxial compression test results of different age of specimens

Specimen	f'_c (kgf/cm^2)	ε_c (10^{-3})	Ro (ohm)	Gauge Factor	SPL[a] (10^{-3})	NSPL[b]
7d-1	212.31	3.115	98.23	9.608	1.050	33.7%
7d-2	214.84	2.675	145.82	12.319	0.870	32.5%
7d-3	185.29	2.360	117.15	14.386	1.095	46.4%
Avg.	**204.15**	**2.717**	**120.40**	**12.104**	**1.005**	**37.5%**
STD	**13.37**	**0.310**	**19.56**	**1.957**	**0.097**	**6.3%**
14d-1	249.07	2.395	153.04	35.386	1.620	67.6%
14d-2	222.29	4.955	77.03	40.803	1.925	38.8%
Avg.	**235.68**	**3.675**	**115.03**	**38.095**	**1.773**	**53.2%**
STD	**13.39**	**1.280**	**38.01**	**2.708**	**0.153**	**14.4%**
28d-1	343.67	3.235	131.38	63.524	1.495	46.2%
28d-2	297.23	4.295	94.33	42.859	1.935	45.1%
28d-3	319.77	2.695	92.01	23.834	1.325	49.2%
28d-4	319.35	2.425	129.01	28.179	1.005	41.4%
Avg.	**320.01**	**3.163**	**111.68**	**39.599**	**1.440**	**45.5%**
STD	**16.43**	**0.716**	**18.55**	**15.508**	**0.336**	**2.8%**
56d-1	367.40	2.935	68.54	61.782	1.045	35.6%
56d-2	343.57	2.780	98.70	33.014	1.190	42.8%
56d-3	330.12	2.545	109.60	39.086	1.740	68.4%
Avg.	**347.03**	**2.753**	**92.28**	**44.627**	**1.325**	**48.9%**
STD	**15.41**	**0.160**	**17.37**	**12.381**	**0.299**	**14.1%**
LH-1	297.38	3.350	68.70	66.970	1.605	47.9%
LH-2	324.14	3.385	70.94	85.602	1.560	46.1%
LH-3	323.10	2.520	63.62	39.529	1.190	47.2%
Avg.	**314.87**	**3.085**	**67.76**	**64.034**	**1.452**	**47.1%**
STD	**12.38**	**0.400**	**3.06**	**18.923**	**0.186**	**0.8%**

[a] SPL: Strain at proportional limit
[b] NSPL: Normalized strain at proportional limit

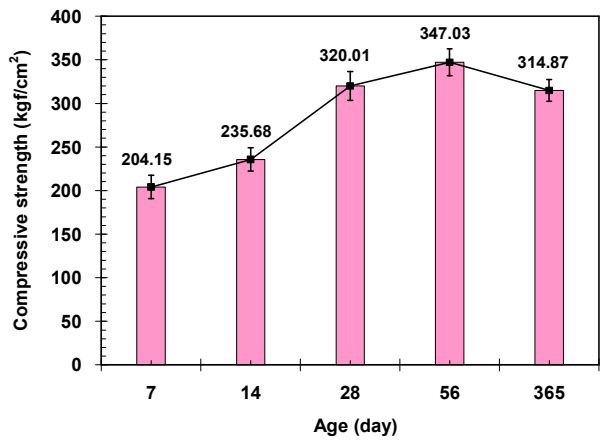

Fig.6. Variation of compressive strength with different ages (7, 14, 28, 56, and 365 days)

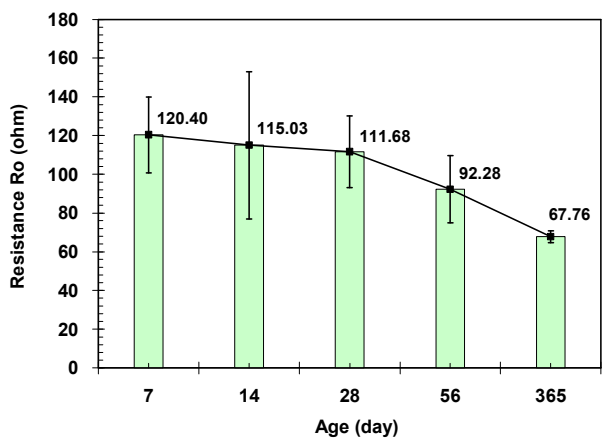

Fig.7. Variation of initial electrical resistance Ro with different ages (7, 14, 28, 56, and 365 days)

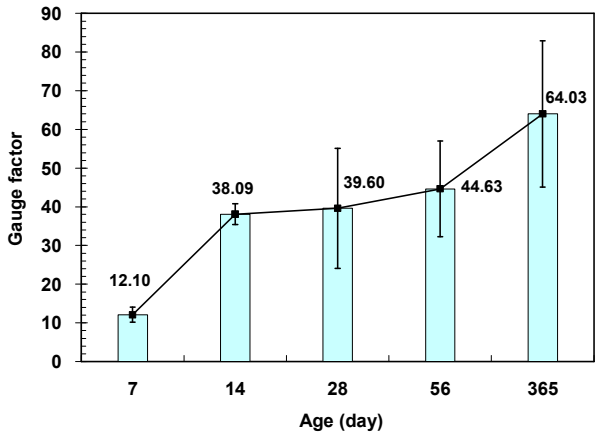

Fig.8. Variation of gauge factor (fractional change in resistance per unit strain) with different ages

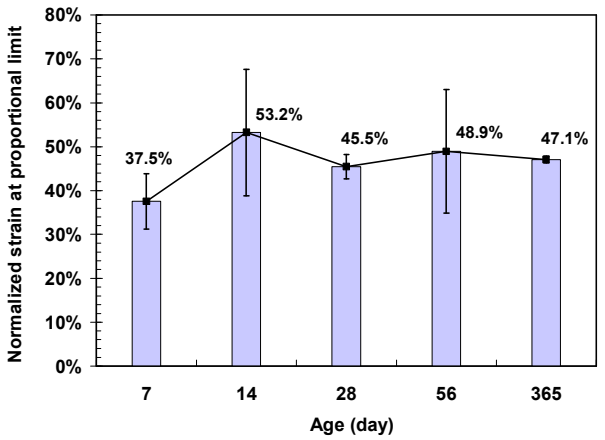

Fig.9. Variation of normalized strain at proportional limit with different ages (7, 14, 28, 56, and 365 days)

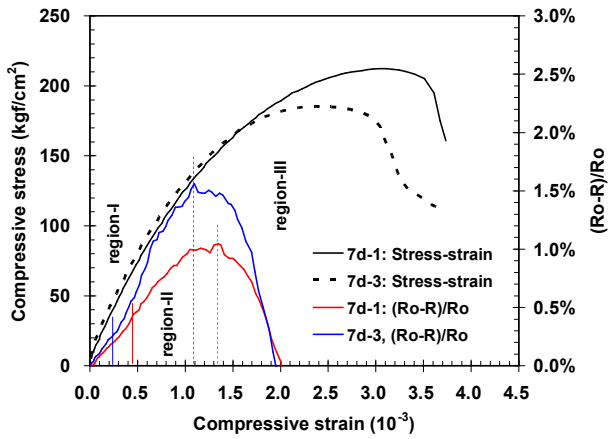

Fig.10. Variation of compressive stress and fractional change in electrical resistance with compressive strain

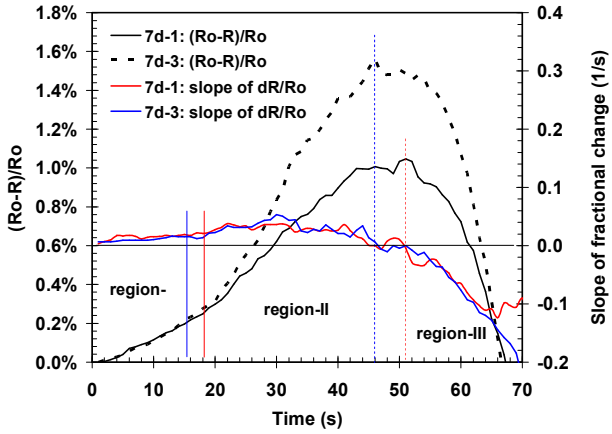

Fig.11. Variation of the fractional change in electrical resistance and slope of fractional change with time

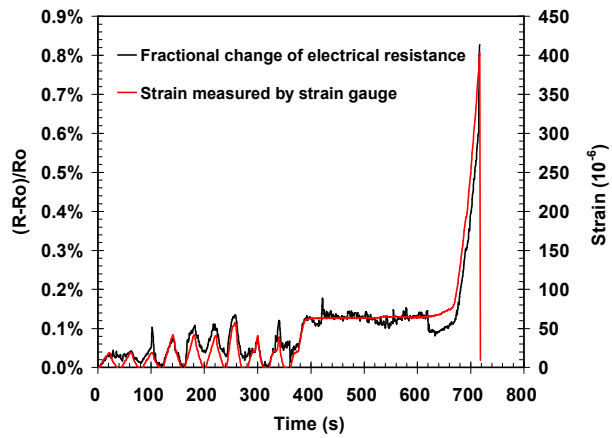

Fig.12. Variation of the fractional change in electrical resistance and strain on tension side of beam with time

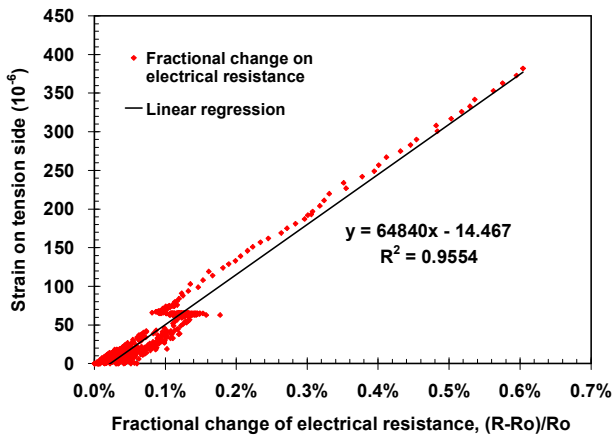

Fig.13. Comparison between fractional change in electrical resistance and strain measured by strain gauge