The effect of moisture and reinforcement on the self-sensing properties of hybrid-fiber-reinforced concrete

To cite this article: M Maier 2020 Eng. Res. Express 2 025026

View the article online for updates and enhancements.
The effect of moisture and reinforcement on the self-sensing properties of hybrid-fiber-reinforced concrete

M Maier
Material Technology Innsbruck (MTI), University of Innsbruck, Innsbruck, Austria
E-mail: marcus.maier@uibk.ac.at

Keywords: moisture content, fiber reinforced concrete, self-sensing concrete, piezoresistive properties, structural health monitoring

Abstract
This study presents the piezoresistive properties of a hybrid fiber-reinforced concrete (HyFRC) for structural health monitoring. This HyFRC mixture incorporates micro PVA and macro steel fibers to control the crack propagation. Investigations on self-sensing concrete (SSC) focus mainly on mixtures containing highly conductive fillers such as carbon nanotubes, graphite or nickel powder which results in a highly engineered cost-intensive mix composition for structural applications. This paper investigates the sensing ability of a cost-effective structural concrete mixture by considering the environmental conditions of engineering structures e.g. the moisture content as well as the influence of reinforcement on the electrical resistance measurement. The sensing parameters were evaluated by performing simultaneously bending tests and Electrochemical Impedance Spectroscopy (EIS) on beams with and without steel reinforcement. Furthermore, the influence of the pore solution on the EIS was investigated on specimens with varying moisture contents. The sensing behavior was compared to a control mixture without steel and PVA fibers. Results showed a significant lower initial resistivity for the HyFRC mixture compared to the ordinary concrete as well as the activation of the self-sensing properties due to the incorporated steel fibers. Finally, the influence of the pore solution on the EIS measurement is addressed and emphasizes the imperative need to consider the moisture content of self-sensing materials.

1. Introduction

Structural health monitoring has caught the attention of many researchers over recent decades. Typically, structural health monitoring (SHM) is coupled with extensive measurement instrumentation and related to high expenses. To reduce the installation effort and costs, materials that monitor themselves, so called self-sensing materials, will provide remedy. These self-sensing materials enable the in situ measurement of stress, strain, crack or damage without embedded or attached sensors. Hence, with Self-Sensing Concretes (SSCs) intelligent structures can be employed to improve serviceability, safety, reliability and durability and as a consequence lower maintenance costs.

Self-sensing properties for concrete are enabled by incorporating functional fillers to form a conductive network. This conductive network is sensitive to strain and stress or crack and damage propagation and can be captured by performing electrical resistance measurements. This investigation was done for the first time in 1993 by Chen [1]. Since then, a growing body of literature has been published on the influence of functional fillers and their sensing properties [2–6]. To achieve high sensitivity and conductivity of concrete carbon, carbon fibers, carbon nanotubes or graphite powder is added to the concrete mixtures [7–10]. These highly engineered mixtures act as a strongly sensitive material under mechanical loading as published in previous studies [11–15].

In addition, a number of authors have investigated the combination of Carbon and steel fiber-reinforced concrete as smart material [16–19]. They concluded that the combination of steel and carbon fibers is capable as a self-sensing method but is less effective than mono-fiber mixtures with exclusively carbon fibers [20–22]. However functional fillers are not the exclusive parameter that influences the self-sensing properties of concrete. Besides the beneficial effect of highly conductive materials, other parameters such as hydration time,
temperature, sand to cement ratio, gravel to sand ratio and moisture content were also identified to influence the electrical resistance of self-sensing concrete [23–25].

Although extensive research has been carried out on self-sensing concrete, most studies have focused on highly engineered concrete with excellent conductive fillers and differing fiber volume fraction. Only a number of researchers have investigated the self-sensing properties of steel fiber-reinforced concrete and comparatively few studies have addressed the influence of moisture within concrete [26, 27]. Furthermore, surprisingly little research has been published on concrete used for structural buildings combining steel fiber-reinforced concrete, the influence of moisture to represent the realistic environmental condition of structures and the investigation of the influence of the reinforcement on the electrical resistance measurement.

To fill this gap, this study aims to investigate the self-sensing properties of hybrid fiber-reinforced concrete (HyFRC). The presented mixture in this study was developed and described by Blunt and Ostertag [28] and improved by Jen et al [29] incorporating both steel and polyvinyl alcohol (PVA) fibers. To represent realistic environmental conditions, the influence of the moisture content on the self-sensing behavior is assessed. This allows a comprehensive evaluation of HyFRC regarding its ability to serve as smart material.

2. Methods

2.1. Material and mixtures

The sensing properties of a hybrid fiber-reinforced concrete (HyFRC) was compared to a reference mixture where the workability of both mixtures were adjusted by adding superplasticizer and viscosity modifying admixtures (see table 1). A total of 1.5% fiber volume fraction was split into 0.2 volume percent of 8 mm long polyvinyl alcohol (PVA) microfibers with a diameter of 38 μm and 1.3 volume percent of 30 mm long steel fibers having a diameter of 0.55 mm (see table 2). The properties of the fine and coarse aggregates are listed in table 3. To consider the sensing behavior of reinforced engineering structures, control and HyFRC specimens with an embedded single no.3 rebar (9.5 mm) were fabricated. The rebar was placed in the center of the beam with a concrete cover of 15 mm. All specimens were casted in a mold with dimensions of 76 × 76 × 280 mm³ (W x H x L), demolded after 24 h and stored in a fog room at 23 °C until the age of 28 days.

2.2. Experimental program

2.2.1. EIS-measurement

The self-sensing properties of the specimens were investigated by Electrochemical Impedance Spectroscopy measurement (EIS). To guarantee electrical conductivity, a 10 mm wide copper tape was glued to the beam using silver epoxy and additionally a copper wire was soldered to the tape which served as connector for the alligator
clips. To minimize polarization effects during the measurement, the four-probe method was chosen with inner electrodes placed 68 mm and outer electrodes placed 98 mm from the center of the beam as shown in figure 1. The experiments were performed with a GAMRY Interface 1000 Potentiostat within a frequency of 100 kHz and an amplitude of 125 mV. The GAMRY Potentiostat has five electrodes: Ground (G), Working (W), Working Sense (WS), Counter (C), and a Reference (R) electrode. When using the four-probe method, the current flows between C and W, placed on the outer electrodes, while the potential is measured between R and WS, placed on the inner electrodes, (see figure 1). With this setup, no potential for any electrochemical reaction occurring at working and counter electrode is measured and therefore the polarization effect is minimized [30].

2.2.2. Moisture content
To investigate the influence of moisture on the impedance of the concrete mixtures, EIS measurements on unloaded specimens with different saturation degree ranging from saturated to dry were performed. Varying moisture contents were achieved by drying the specimens in a temperature chamber and recording their mass loss. The initial measurement was taken on saturated specimens stored for 28 days in a fog room at 23 °C. To avoid microcracks due to a high temperature gradient, increasing temperature levels of 40/60/80/105 °C were chosen for the drying process. Specimens were considered as dry when a mass loss less than 0.1% within 24 h at 105 °C was achieved.

2.2.3. Bending tests
Bending tests were performed on beams with L x W x H of 76 × 76 × 280 mm³ to investigate their self-sensing behavior during loading. The EIS measurement was performed with an amplitude of 125 mV and a frequency of 100 kHz. As mentioned above, the moisture influence on unloaded specimens ranging from saturated to dry stage was investigated separately. Beyond that, the influence of moisture on the impedance of mechanically loading specimens is of interest. Therefore, two series of four-point bending tests were prepared for investigation. The first test series was performed on saturated specimens cured for 28 days in a fog room and the second series was conducted on dry specimens to eliminate the influence of the pore solution on the impedance measurement. Each series consisted of three beams of HyFRC and the control mixture with and without embedded rebar, giving a total of 24 bending tests.

2.2.4. Notations
Within this paper the following notations are used to verify the specimens. Co and Hy refer to the control mix and the HyFRC mixture, respectively. Co-No refers to specimens without a rebar and Co-Re to those with a rebar. Therefore, Hy-No refers to the HyFRC mixture without a rebar and Co-Re to the control mix with an embedded rebar. Table 4 lists all specimens and their notations used within this study.

---

**Figure 1.** Preparation for the 4-probe method measurement.

**Table 3.** Aggregate properties.

|                | Maximum grain size mm | Specific gravity g cm⁻³ | Water absorption % | Fine modulus |
|----------------|------------------------|-------------------------|--------------------|--------------|
| Fine aggregates| 4.75                   | 2.81                    | 0.7                | 3.2          |
| Coarse aggregates| 12.5                 | 2.89                    | 0.6                | —            |

* Specification from supplier’s datasheet (Polaris Materials, California, USA).
3. Results and discussion

3.1. Material properties

The compressive strength, obtained from three cylindrical specimens with a diameter of 101 mm and a length of 203 mm at an age of 28 days, are presented in Table 5. The mean compressive strength of the HyFRC and control mixture is $29.0 \pm 0.39$ MPa and $51.1 \pm 1.10$ MPa, respectively. The HyFRC mixture exhibits a lower compressive strength compared to the control mixture. This was also observed by authors using similar mixtures [29, 31]. A reason for the lower compressive strength could be the lower workability and viscosity of the HyFRC mixture due to the addition of fibers and a viscosity modifying admixture. This results in a higher effort to compact the concrete during casting and can result into a higher porosity. To strengthen this hypothesis, the porosity of the concrete was measured according to EN 1936 [32] and is presented in Table 5. The HyFRC mixture shows a porosity of $23.6 \pm 0.2\%$, the control mixture a porosity of $16.7 \pm 0.3\%$. This difference is an indicator for a weaker matrix of the HyFRC mixture resulting in a lower compressive strength.

| Mixture | Saturated | Dry |
|---------|-----------|-----|
| Control mix | Co-No-1 | Co-Re-1 | Co-No-4 | Co-Re-4 |
|          | Co-No-2 | Co-Re-2 | Co-No-5 | Co-Re-5 |
|          | Co-No-3 | Co-Re-3 | Co-No-6 | Co-Re-6 |
| HyFRC mix | Hy-No-7 | Hy-Re-7 | Hy-No-10 | Hy-Re-10 |
|          | Hy-No-8 | Hy-Re-8 | Hy-No-11 | Hy-Re-11 |
|          | Hy-No-9 | Hy-Re-9 | Hy-No-12 | Hy-Re-12 |

Table 5. Compressive strength

| Mixture | Compressive strength [MPa] |
|---------|---------------------------|
| Control 1 | 51.0 | HyFRC 1 | 28.5 |
| Control 2 | 49.8 | HyFRC 2 | 29.4 |
| Control 3 | 52.5 | HyFRC 3 | 29.2 |
| Mean     | 51.1 | 29.0    |
| Standard deviation | 1.10 | 0.39    |
| Porosity | 16.7 | 23.6 |
| Standard deviation | 0.3 | 0.2 |

3.2. Bending test

3.2.1. EIS measurement and polarization effect

Using alternative current (AC) for the EIS measurement is known to reduce the polarization effect compared to direct current (DC) measurement. Nevertheless, a total elimination of the polarization effect is not guaranteed. To evaluate the influence of the polarization effect during bending tests continuous EIS measurements on HyFRC and Control mixtures were conducted over 15 min. Figure 2 shows the obtained change of impedance in Ohm whereas figure 3 shows the change in percentage of the initial recorded impedance over time. Within the expected bending test duration of 10 min, a change of impedance within 0.6\% for control mix and 0.4\% for HyFRC was detected. The maximum change after 15 min was within 0.75\% of HyFRC and 0.70\% for the control mix.

3.2.2. Self-sensing properties during bending tests

In the following, the self-sensing ability of the HyFRC mixtures during loading will be assessed by evaluating the fractural change of impedance (FCI) within three different ranges. The FCI up to the peak load will be assessed as well as the values of the FCI at different mid-point deflections. According to the ASTM C 1609 [33], the load-deflection at the mid-span should be recorded to at least 2 mm.
Hence, the limit of 2 mm is selected to investigate the sensing behavior for specimens with wide crack formations and, in addition, to evaluate the sensing behavior of the beams after the peak load appeared the FCI was evaluated at 1 mm mid-span deflection. The fractural change of impedance, FCI, is evaluated by comparing the initial impedance, $R_0$, to the actual impedance, $R$, during the bending tests and is calculated as

$$ FCI = \frac{R - R_0}{R_0} $$

The presented FCI and standard deviation is calculated from 3 tested specimens.

3.2.3. Self-sensing properties of saturated specimens

Figure 4 shows the load—deflection—FCI curves of the saturated control and HyFRC mixtures during bending. A maximum bending capacity of 9.0 ± 0.62 and 13.9 ± 0.15 kN was detected for the control and HyFRC mixtures, respectively. The control mix showed no self-sensing properties during loading but exhibited a sharp increase in impedance at the maximum load and failure of the beam.

In contrast to that, the Impedance recorded for the HyFRC mixture changes for 9.3 ± 2.1% up to the peak load of 13.9 ± 0.15 kN with a steady increase from the start of the bending tests and continues to raises to 11.9 ± 1.3% at a deflection of 1 mm and 16.6 ± 3.1% at 2 mm deflection. A detailed list of all FCI at each evaluated deflection as their standard deviations can be found in table 6.
This shows that the steel fibers within the HyFRC mixture form a conductive network and hence enable the self-sensing ability of the mixture. The mixture is able to sense the increasing stress within the matrix up to the peak load as well as the post-crack behavior. After the peak load, cracks appear within the tension zone and are bridge by the steel fibers. Those fibers provide a pathway for the electron to pass through the crack opening and enable further sensing [20].

The bending and sensing behavior of the saturated control and HyFRC mixture with an embedded rebar is shown in Figure 5. The addition of the rebar activates the sensing behavior of the control mixture resulting in a FCI of 33.0 ± 4.7 at the peak load of 30.7 ± 1.26 kN. With increasing loading the FCI of the control mixture increases to 57.6 ± 10.9% at 1 mm and 72.2 ± 22.4% at 2 mm deflection.
The HyFRC mixture with embedded rebar shows a similar behavior but with a less pronounced FCI compared to the control mixture. The fractural change of impedance at the peak load of 35.5 ± 2.58 kN is 21.3 ± 4.8% and increases to 37.7 ± 5.6% at 1 mm deflection and 104.3 ± 33.7% at 2 mm deflection. All details for the FCI at peak load and different deflections can be found in table 7.

Considering the FCI at the peak load and at 1 mm deflection, the HyFRC exhibit a lower change of impedance than the control mixture. This can be explained by the combination of steel fibers with the rebar resulting in a higher amount of steel available to form a conductive and stable network. A decreasing FCI with increasing steel was also found by Ding et al.[34].

The performance of the dry control and HyFRC mixture with embedded reinforcement does not differ much from the behavior of the dry mixtures without rebars. Almost no change of impedance was detected for the control mixture within the start of the bending test to the peak load. Close to the peak load, the EIS measurement system showed high scattering data and finally aborted the measurement during testing. Therefore, the FCI could not be calculated for this batch at peak load and at 1 and 2 mm deflection.

All three HyFRC specimens showed an almost constant impedance up to 0.5, 0.7 and 1.4 mm deflection with an erratic rise of 11, 12 and 58% (see figure 7 right). Only the 58% sudden increase of specimen Re-Hy-12 appears within the range of the peak load and therefore could be associated to a crack opening. The 11 and 12%

### Table 7. Fractural change of impedance, FCI, and maximal force during bending of dry control and HyFRC specimens.

| Dry specimens      | Control mix | HyFRC mix | Control mix with rebar | HyFRC mix with rebar |
|--------------------|-------------|-----------|------------------------|----------------------|
| Fmax [kN]          | 16.4 ± 0.90 | 11.9 ± 1.51 | 34.6 ± 2.31            | 42.3 ± 1.30          |
| SD [%]             | 5.5         | 12.7      | 6.7                    | 3.1                  |
| FCI @ F max [%]    | No meas. a  | 1.0 ± 0.41 | No meas. a            | 11.4 ± 6.4          |
| SD [%]             | —           | 40.8      | —                     | 56.4                 |
| FCI @ 1 mm [%]     | No meas. a  | 1.6 ± 0.86 | No meas. a            | 11.6 ± 7.1          |
| SD [%]             | —           | 55.2      | —                     | 61.1                 |
| FCI @ 2 mm [%]     | No meas. a  | 2.4 ± 0.65 | No meas. a            | 33.7 ± 22.2         |
| SD [%]             | —           | 27.0      | —                     | 65.7                 |

* No measurement could be obtained due to failure of the specimen or abruption of EIS measurement of the specimens.

3.2.4. Self-sensing properties of dry specimens

By assessing the sensing behavior of the dry specimens, the contribution of the pore solution on the sensing ability becomes apparent resulting in a noisier recorded data compared to the saturated batch (seen figures 6 and figure 7). The control mixture does not exhibit any sensing behavior due to the fact that no conductive material and pore solution is present in the matrix. The HyFRC mixture however does not show an improvement of the sensing ability either despite the incorporated steel fibers. The FCI at the peak load of the HyFRC (11.9 ± 1.51 kN) was evaluated to be 1.0 ± 0.41%, at 1 mm deflection 1.6 ± 0.86% and at 2 mm deflection 2.4 ± 0.65% (see figure 6 and table 7). This shows that the incorporation of steel fibers alone does not enhance the sensing behavior much rather the combination of functional fillers with a certain degree of conductive pore solution is needed to activate the sensing behavior of the mixture.

The performance of the dry control and HyFRC mixture with embedded reinforcement does not differ much from the behavior of the dry mixtures without rebars. Almost no change of impedance was detected for the control mixture within the start of the bending test to the peak load. Close to the peak load, the EIS measurement system showed high scattering data and finally aborted the measurement during testing. Therefore, the FCI could not be calculated for this batch at peak load and at 1 and 2 mm deflection.

All three HyFRC specimens showed an almost constant impedance up to 0.5, 0.7 and 1.4 mm deflection with an erratic rise of 11, 12 and 58% (see figure 7 right). Only the 58% sudden increase of specimen Re-Hy-12 appears within the range of the peak load and therefore could be associated to a crack opening. The 11 and 12%
sharp increase appear before the peak load is reached and cannot clearly be associated to any crack appearance and are rather a sign of the poor sensing properties of the dry mixtures.

The poor sensing properties of the mixtures becomes apparent when the initial impedances at the beginning of the bending tests are compared. As can be seen in table 8, the initial impedance of the dry specimens are $119,510 \pm 29,767$ and $110,332 \pm 14,510$ for the Control and HyFRC compared to the saturated initial impedance of $2,319 \pm 69$ (Control) and $714 \pm 63$ (HyFRC). This indicates that the electrons are not able to penetrate deep into the concrete and reach the steel reinforcement without the conductive pore solution. Furthermore, the incorporated steel fibers are not able to bridge the gaps within the matrix and to the rebar to form a conductive network without a presence of a pore solution. The limited penetration of electrons into the concrete matrix for the applied four-probe method was numerically investigated by Zhu and Chung in [35] and shows the suitability of this method to detect surface near crack developments.

To visualize the fiber distribution and to inspect if fibers are present within the surface zone and the embedded rebar, specimens were sliced and a representative picture of each mixture is presented in figure 8. The
Figures show that fibers are present in the near surface zone and between surface and steel reinforcement. Nevertheless, the electrons were not able to pass through the gaps between the fibers without the presence of a certain amount conductive pores solution. To investigate the influence of the pore solution on the EIS measurement, measurements on beams ranging from saturated to dry pore solutions are taken and discussed in the following section.

### 3.3. Moisture effect

As discussed earlier, the pore solution contributes significantly to the EIS measurement and the sensing behavior of the mixtures. To assess this influence, beams ranging from saturated to dry pore solution were prepared and their initial impedance in an unloaded stage was evaluated. Specimen dimensions and EIS measurement setup were kept the same as for the bending tests experiments. After casting, the beams were cured in a fog room for 28 days before the EIS measurement was performed and those specimens were considered as saturated. Partially saturated and dry specimens were obtained by drying the samples in an oven for various durations as explained in section 3. The resistivity, R, was then calculated with

\[ R = \frac{I}{A} \]

where R is the resistivity in Ohm-cm, I is the measured Impedance in Ohm, L the distance between the inner electrodes in cm and A the electrode conductive surface in cm².
Figure 9 presents the resistivity as a function of moisture loss for a 100 kHz frequency measurement. The hollow markers refer to the mixtures without a rebar, solid markers to mixtures with embedded rebar. Zero mass loss indicates saturated specimens whereas the highest mass loss (6–7 M%) represents dry specimens without pore water within the matrix.

These results highlight the significant influence of the moisture content. Dry specimens exhibit a significant higher resistivity than saturated specimens. Moreover, the HyFRC mixtures show a lower resistivity than the control mix due to the conductive steel fibers. HyFRC specimens with an embedded rebar show the lowest resistivity for saturated samples, the control without rebar the highest.

To underline the influence of moisture, the initial impedance of dry and saturated specimens is compared in figure 10 and table 9. Values shown are the mean values and standard deviation taken from 3 measurements. The significant difference between saturated and dry specimens became visible for all mixtures regardless if reinforced or non-reinforced specimens were used. Nevertheless, specimens with an embedded rebar exhibited a lower resistivity compared to specimens without a rebar for both, dry and saturated pore-space.

The presented results show that the obtained resistivity strongly depends on different parameters: (i) the influence of the moisture content, (ii) the influence of the fibers and (iii) the influence of the embedded rebar and needs to be considered when performing EIS measurements.

4. Conclusion

The self-sensing ability of a HyFRC mixture containing steel and PVA fibers was evaluated and compared to a concrete mixture without fibers by performing simultaneously bending tests and Electrochemical Impedance Spectroscopy measurements. To investigate the influence of the reinforcement on the electrical properties additional specimens with an embedded rebar were prepared and analyzed. Furthermore, the impact of the water content was addressed by assessing the impedance on specimens with varying moisture contents, ranging from saturated to dry. Based on the experimental results the following conclusions can be drawn:

- The control mixture was not able to show any self-sensing ability for both saturated and dry specimens.
- The saturated HyFRC mixture exhibited a change of impedance from the beginning of the test and shows the ability of the mixture to sense the load increase during bending.
- The steel rebar enhances the conductivity of the control and HyFRC mixture for the saturated samples whereas the HyFRC mixtures showed an overall lower change of impedance during bending. This is an implication that the combination of steel fibers and rebar form a higher and more stable conductive network within the matrix.
- Dry specimens were not able to show any self-sensing behavior neither the control mixture nor the HyFRC mixture. This shows that steel fibers alone does not improve the sensing capacity of the mixture but rather the combination of functional fillers with a certain amount of conductive pore solution is needed.
- Both dry specimens, control and HyFRC, with embedded rebar showed little improvement of the sensitivity compare to dry specimens without a rebar. This implies that the electrons are not able to penetrate deep into the matrix and reach the rebar within a dry mixture without the presence of a certain amount of conductive pore solution and the incorporated steel fibers were not able to bridge these conductivity gaps.
- EIS measurements on samples ranging from dry to saturated pore structure showed a significant reduction of the resistivity for saturated specimens. Moreover, the embedded reinforcement further reduced the resistivity for both the control and HyFRC mixture.
The presented results in this study show that the obtained resistivity strongly depends on the following parameters; (i) the moisture content, (ii) the incorporated steel fibers and (iii) embedded rebar and shows the importance to consider all these parameters when assessing concrete mixtures with EIS measurements.

Acknowledgments

The author would like to thank Professor Claudia Ostertag from the Department of Civil and Environmental Engineering at the University of California, Berkeley, USA, for her support, for granting access to the laboratory and measurement devices as well as for the donation of all materials. This research was enabled through a grant (643–836–14–15–2015) from the Austrian Marshall Plan Foundation in Vienna, Austria.

ORCID iDs

M Maier © https://orcid.org/0000-0003-0112-8949

References

[1] Pu-Woei Chen D D L C 1993 and Carbon fiber reinforced concrete for smart structures capable of non-destructive flaw detection Smart Mater. Struct. 2 22
[2] Liu Q, Xu Q, Yu Q, Gao R and Tong T 2016 Experimental investigation on mechanical and piezoresistive properties of cementitious materials containing graphene and graphene oxide nanoplatelets Constr. Build. Mater. 127 765–76
[3] Han B, Yu X and Ou J 2014 Self-Sensing Concrete in Smart Structures. The Boulevard, Langford Lane (Kidlington, Oxford, UK: Butterworth-Heinemann)
[4] Han B, Ding S and Yu X 2015 Intrinsic self-sensing concrete and structures: a review Measurement 59 110–28
[5] Polder R B 2001 Test methods for on site measurement of resistivity of concrete—a RILEM TC-154 technical recommendation Constr. Build. Mater. 15 125–31
[6] Stad H, Larcheri M, Sarmaraz M, Mesbah H A and Hosain K A 2018 Advanced engineered cementitious composites with combined self-sensing and self-healing functionalities Constr. Build. Mater. 176 112–22
[7] Wen S and Chung D D L 2006 Self-sensing of flexural damage and strain in carbon fiber reinforced cement and effect of embedded steel reinforcing bars Carbon 44 1496–502
[8] Yeh F-Y, Chang K-C and Liao W-C 2015 Experimental investigation of self-sensing carbon fiber reinforced cementitious composite for strain measurement of an RC portal frame Int. J. Distrib. Sens. Netw. 11
[9] Wen S and Chung D D L 2007 Partial replacement of carbon fiber by carbon black in multifunctional cement–matrix composites Carbon 45 505–13
[10] Yang C Q, Wu Z S and Huang H 2007 Electrical properties of different types of carbon fiber reinforced plastics (CFRPs) and hybrid CFRPs Carbon 45 3027–35
[11] Wen S and Chung D D 2006 Effects of strain and damage on strain-sensing ability of carbon fiber cement J. Mater. Civ. Eng. 18 355–60
[12] Wen S and Chung D D L 2006 Spatially resolved self-sensing of strain and damage in carbon fiber cement J. Mater. Sci. 41 4823–31
[13] Wen S and Chung D D L 2000 Uniaxial tension in carbon fiber reinforced cement, sensed by electrical resistivity measurement in longitudinal and transverse directions Cem. Concr. Res. 30 1289–94
[14] Ding Y, Chen Z, Han Z, Zhang Y and Pacheco-Torgal F 2013 Nano-carbon black and carbon fiber as conductive materials for the diagnosing of the damage of concrete beam Constr. Build. Mater. 43 235–41
[15] Chen B, Liu J and Wu K 2015 Electrical responses of carbon fiber reinforced cementitious composites to monotonic and cyclic loading Cem. Concr. Res. 35 2183–91
[16] Banthia N, Djerdan S and Pigeon M 1992 Electrical resistivity of carbon and steel micro-fiber reinforced cements Cem. Concr. Res. Pergammon Press Ltd 22 804–14
[17] Chung D D L 2002 Piezoresistive cement-based materials for strain sensing J. Intell. Mater. Syst. Struct. 13 599–609
[18] Huang Y and Qian S 2016 Self-Sensing Properties of Engineered Cementitious Composites (Vancouver, Canada: presented at the 9th RILEM International Symposium on Fiber Reinforced Concrete)
[19] Lee S H, Le H V and Kim D J 2019 Self-stress sensing smart concrete containing fine steel slag aggregates and steel fibers under high compressive stress Constr. Build. Mater. 220 149–60
[20] Lee S H, Kim S and Yoo D-Y 2018 Hybrid effects of steel fiber and carbon nanotube on self-sensing capability of ultra-high-performance concrete Constr. Build. Mater. 185 530–44
[21] Wen S and Chung D D L 2003 A comparative study of steel- and carbon-fibre cement as piezoresistive strain sensors Advances in Cement Research (https://doi.org/10.1680/adcr.2003.153.3.119)
[22] Solgaard A O S, Geiker M, Edvardsen C and Küter A 2014 Observations on the electrical resistivity of steel fibre reinforced concrete Mater. Struct. 47 335–50
[23] Chiarello M and Zinno R 2004 Electrical conductivity of self-monitoring CFRC Cem. Concr. Compos. 27
[24] Azhari F 2008 Cement-Based Sensors For Structural Health Monitoring Master of applied science, The University of British Columbia (Vancouver)
[25] Baeza F J, Chung D D L, Zornova E, Andión L G and García P 2010 Triple percolation in concrete reinforced with carbon fiber ACI Mater. J. 107–M46 396–402
[26] Han B, Zhang L and Ou J 2010 Influence of water content on conductivity and piezoresistivity of cement-based material with both carbon fiber and carbon black Journal of Wuhan University of Technology-Mater. Sci. Ed. 25 147–51
[27] Han B, Yu X and Ou J 2010 Effect of water content on the piezoresistivity of MWNT/cement composites J. Mater. Sci. 45 3714–9
[28] Blunt J and Ostertag C P 2009 Performance-based approach for the design of a deflection hardened hybrid fiber-reinforced concrete J. Eng. Mech. 135 978–86
[29] Jen G, Trono W and Ostertag C P 2016 Self-consolidating hybrid fiber reinforced concrete: development, properties and composite behavior Constr. Build. Mater. 104 63–71
[30] Gamry-Apn-2 G 2015 Potensiotstat fundamentals Application Note Rev. 3.0, Gamry Instruments www.gamry.com
[31] Moreno D M, Trono W, Jen G, Ostertag C and Billington S L 2012 Tension-stiffening in reinforced high performance fiber-reinforced cement-based composites under direct tension ed G J Parra-Montesinos, H W Reinhardt and A E Naaman Eds High Performance Fiber Reinforced Cement Composites 6: HPF RCC 6 (Dordrecht: Springer Netherlands) pp 263–70
[32] ÖNORM - EN 1936 2007 Natural stone test method - Determination of real density and apparent density and of total and open porosity A. Standards
[33] ASTM C1609 2011 ‘Standard test method for flexural performance of fiber-reinforced concrete,’
[34] Ding Y, Liu G, Hussain A, Pacheco-Torgal F and Zhang Y 2019 Effect of steel fiber and carbon black on the self-sensing ability of concrete cracks under bending Constr. Build. Mater. 207 630–9
[35] Zhu S and Chung D D L 2007 Numerical assessment of the methods of measurement of the electrical resistance in carbon fiber reinforced cement Smart Mater. Struct. 16