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Smart cement composites for durable and intelligent infrastructure

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Abstract

The self-healing and self-sensing performances of Engineered Cementitious Composite (ECC) mixtures developed recently at Heriot-Watt University are presented. In the first series of experiments, fifteen dog-bone shaped ECC samples were preloaded to known strains and then left to heal outdoors under a natural environment. Ultrasonic pulse velocity measurements were then undertaken periodically to determine the rate and extent of healing in these samples. It was found that the samples were able to heal micro-cracks and show a recovery in UPV after two loading events over a six month outdoor exposure. In another series of experiments, the effectiveness of incorporating milled carbon (MC) fibers into an ECC mix, with the aim of enhancing the self-sensing functionality of ECC, is demonstrated for the first time. The MC-ECC mix exhibited equivalent tensile response compared to the control ECC mix and displayed a strong relationship between tensile strain and the fractional change in resistivity. The inclusion of MC fibers at 0.75\% by volume was found to exhibit high sensitivity to micro-cracks formation, with gauge factor two orders of magnitude larger than that of an ordinary strain gauge, albeit less than that of the control mix. It is envisaged that the use of ECC can create an intelligent infrastructure able to sense and repair damage and monitor the recovery extent.

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Keywords: fiber reinforcement; ECC; smart material; micro-cracks; self-healing; self-sensing; outdoors; resistivity; durability; intelligent.

1. Introduction

Concrete is currently the most widely used construction material and is likely to remain the predominant material for the foreseeable future. It forms an integral part of our global civil infrastructure, ranging from small buildings to large structures such as tunnels, long-span bridges and offshore platforms. To maintain the functionality and safety

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of these structures, it is crucial to undertake periodic inspection and maintenance. In most developed countries, however, the scale of investment needed to perform these activities is immense. For example, in the UK alone, approximately half of the £110bn construction output in 2010 was spent on maintenance and refurbishment [1] which is an eightfold increase in under 35 years. The National Infrastructure Plan estimated that £383bn in investment is required by 2020, in order to upgrade UK infrastructure to an acceptable standard [2]. The problem is not exclusive to the UK and is of major concern in many developed countries worldwide, including the US and Japan [3,4].

One way forward to overcome the aforementioned problems could lie in the use of smart, multi-functional construction materials. The term ‘multi-function’ was coined to highlight the ability of a material to simultaneously serve both structural and non-structural functions [5]. In line with this definition, the UK Minister for Universities and Science recently stated that ‘the future of construction is to incorporate more functions into structural materials rather than adding them as extras’ [6].

Set against this background, the work presented in this paper directs attention to use of Engineered Cementitious Composites (ECCs) as a potential multi-functional structural material, with specific focus on its self-healing and self-sensing attributes. An ECC is a ‘damage tolerant’ concrete, exhibiting a high tensile strain capacity (in excess 3%) and a controllable crack width (<0.1 mm under service load) [7]. It is envisaged that the use of ECC (e.g. as an overlay) can resolve two challenges facing our global infrastructure. Firstly, its damage-tolerant characteristics (e.g. high tensile strain capacity and self-healing capability) can overcome the durability related problems that manifest as a result of surface cracking. Secondly, the self-sensing functionality can provide details on in-service condition and detect incipient problems. The self-monitoring feature can also allow better scheduling of maintenance programs and be used to determine the anticipated service life. The potential of ECC is illustrated in Fig. 1.

Fig. 1. Schematic showing the potential of smart material for future infrastructure and an example of micro-crack healing [8].

Much of the work into the self-healing performance of ECC has taken place in controlled laboratory environments [see, for example, 9–11]. It is only recently that ECC has been shown to be able to heal micro-cracks under the US natural environment [12,13]. Building upon this successful test, the self-healing performance of ECC under the UK weather has been recently studied over a winter period [14], presenting the first experiment of its kind to be conducted outside of Michigan. This paper presents a continuation of this work.

Research into the development of self-sensing ECC has primarily focused on developing a suitable ECC mixture [15–18]. As yet, the work is still in an early phase, with focus being directed mainly toward studying the piezo-resistive response beyond the elastic range. Moreover, it was found that, whilst the addition of carbon black powders into ECC increased the material sensitivity to cracking [17], the developed mixture was highly affected by cement hydration and thus considered not suitable for self-sensing applications. The work presented herein will be the first of its kind to utilize milled carbon fiber as conductive filler in ECC, with the aim of improving the self-sensing attribute of ECC.
2. Experimental Program

Two series of tests were undertaken. In the first series, twenty dog-bone samples, with dimensions shown in Fig. 2(a), were prepared to assess the self-healing performance of ECC: the first five were tested to failure to determine the tensile strain capacity, the next five were used as control samples to monitor the influence of continued hydration and moisture fluctuations, the other five were pre-cracked to 60% of the average strain capacity, and the last five to 30% of this value. In the second series, twenty notionally identical dog-bone samples were cast to study the self-sensing property of ECC: ten were used to determine the mechanical properties under uniaxial tensile loading and the rest were to study the immediate effects of loading on the electrical properties of the material.

In the first series of experiments, the fifteen samples were submerged in water in a laboratory environment (20±1°C). The pre-cracking was then done on the 14th day of curing and immediately after that, these samples were positioned outdoors in an open yard at our Edinburgh campus. UPV measurements were then undertaken once/twice weekly thereafter to monitor the self-healing process in these samples. Similar measurements were done before and immediately after preloading, prior to the outdoor exposure. In any case, measurements were taken by coupling two transducers in contact with longitudinally opposite ends of a sample. Detailed microscope investigation was undertaken and the results can be found in [14]. Rainfall data was taken from a local weather station (Gogarbank), which is 2 km from the exposure site. The data were accessed weekly via the Weathercast website [19]. After being exposed to the natural environment for 3 months, these samples were subjected to another tensile test to induce micro-cracks for a second time and then positioned outdoors again for another 3 months. In the second series of experiments, the samples were allowed to cure underwater in the same laboratory environment until required for testing at 28 days.

Tensile testing was performed using a 100 kN Instron machine under a crosshead speed of 0.5 mm/min, to determine the stress-strain response. The stresses were determined from the load cell readings, while the strains were obtained from the average of readings from two LVDTs attached at the middle portion of the sample (Fig. 2(b)). In the second series of experiments, a similar test configuration was used, but with the addition of two electrodes in the form of a tightly wrapped wire at a distance of 80 mm over the middle narrower portion. The wires were coated with a metallic silver paint, to ensure intimate contact with the sample surface. The wires then were connected to an Agilent 4263B LCR meter using coaxial cables, with attachment to the wire by means alligator clips (Fig. 2(c)). Electrical measurements were undertaken at 100 kHz (the frequency at which the polarization effects were minimal).

The ECC binder comprised CEM I 52.5 N cement (Procem, Lafarge) and a fine fly-ash (Superpozz SV80, Scotash), with a fly-ash-to-cement ratio 1.8 and a water/binder ratio of 0.28. A fine silica sand with a mean size of 120 μm (RH110, Minerals Marketing) was used at a constant sand-to-cement ratio of 0.6 (by mass). A high-range water-reducing admixture (Glenium C315, BASF) was added at a dosage rate of 1% by weight of cement. Standard 12 mm (long) polyvinyl alcohol (PVA) fibers (REC15, Kuraray) were used at a fixed dosage of 2% by volume. The PVA fibers had an average diameter of 39 μm and a tensile strength of 1.60 GPa. The surface of the PVA fibers was coated with a proprietary oiling agent (1.2% by weight). In addition to the PVA fibers, milled carbon (MC) fibers with an average length of 100μm (Carbiso Mil 100µ, Easy Composites) were used in the second series of experiments at dosages in the range 0.25–1.25% by volume. The MC fibers had an average diameter of 7.5 μm and a tensile strength of 3.15 GPa.

3. Test results and discussion

3.1. Self-healing performance

The average of the ratio of the UPV, $R_c$, obtained from five control samples before and after being placed outdoors, normalized by the initial average value (3446 m/s) is presented in Fig. 3(a). During the six months outdoor exposure, it is evident that $R_c$ increases during periods of prolonged rainfall, particularly in the period between weeks 2 and 12. Similarly, an increase in $R_c$ can be observed between weeks 15 and 17. As the UPV in water is one to two orders of magnitude greater than that in air [20], the increase in UPV can be attributed to an increase in moisture
content within individual samples resulting from the absorption of water into the capillary pore network. Superimposed on this mechanism will be a contribution from the progressive refinement of microstructure as a result of ongoing cement hydration and pozzolanic activity, which can also result in a greater UPV.

An opposite trend was observed when conditions were dry for an extended period of time such as during weeks 12–15, 17–20 and 21–24. During these dry periods, \( R_c \) lies within the range 0.97–1.01. The same trend can also be observed at the time of the second tensile test (between weeks 11 and 12) which can be attributed to the fact that prior to UPV measurements, the samples were moved indoors to a dry laboratory environment (22°C) for 4–5 hours whilst tensile tests were carried out. This finding suggests that changes in moisture content exert a significant influence on the measured bulk UPV.

Fig. 3(b) presents the normalised ratio of the UPV, \( R_n \), which is the ratio of the UPV of the preloaded samples to that of the control samples before and after being placed outdoors. Similar to before, the envelopes of the experimental results are also presented. The \( R_n \) values following a loading event (week 0 and between weeks 1 and 12) can give an indication of the extent of initial damage (i.e. the formation of multiple micro-cracks) [14]. It is apparent that as the level of preloading is increased, \( R_n \) decreases. The average \( R_n \) values after the first tensile loading were 85% and 73% of the pre-test value for samples damaged to 30% and 60% of the strain capacity, respectively. The corresponding values following the second tensile test were 81% and 70%, respectively. The larger decrease in UPV in samples tested to 60% strain capacity can be due to either an increased number of micro-cracks or an increased width of individual micro-cracks. However, this single measurement after tensile testing does not provide adequate information to allow for the determination of the relative contribution of each of these factors to the bulk UPV.

The \( R_n \) values presented in Fig. 3(b) can also be used to give an indication of physical property recovery [14]. It is clear from the figure that during the six months outdoor exposure, there is a general recovery in UPV, suggesting that the samples were able to successfully self-heal after two damaging events. It is also evident that self-healing activity is most active during two days of outdoor exposure following a loading event. After the first loading event, for example, average recoveries of 7% and 13% can be observed in samples damaged to 30% and 60% respectively, whereas the recoveries after the second loading were 9% and 12%, respectively. This finding suggests that the greater drop in UPV in samples tested to 60% of the strain capacity discussed above is likely due to the formation of a larger number of micro-cracks than the widening of individual micro-cracks. This can be explained by the fact that a greater number of small cracks provide a larger surface area, in the form of crack surfaces, than the equivalent elongation produced by the formation of a lower number of large cracks. As the crack width remains small, healing products can therefore precipitate simultaneously on the surfaces of these micro-cracks, leading to an apparent accelerated healing. Should the micro-cracks have widened significantly, the rate of healing would decrease significantly, resulting in a much slower recovery in UPV [14]. This finding confirms the ability of the developed mixture to exhibit controlled crack width.
From the results presented in Fig. 3(b), it is also noticeable that $R_n$ plateaus after only nine days of outdoor exposure. Thereafter, UPV recovery is much slower, with $R_n$ reaching their peak values on week 11 before the second tensile loading at values of 98% and 96% of pre-test value for samples tested to 30% and 60% strain capacity, respectively. Compared to the results after the first loading test, the duration that $R_n$ takes to reach a relatively constant value following the second loading event is much longer (about four weeks longer). This can be attributed to the prolonged dry period after the second tensile test (weeks 12–15) during which the self-healing is expected to be most active. The less pronounced rate of the healing can be due to the fact that the samples have undergone the self-healing process once and were cured for longer durations (97 days). Therefore, it can be expected that there were reduced numbers of unhydrated cement particles available for the healing process. Self-healing can also be hindered by the layer of hydration products lining the surfaces of healed micro-cracks that reopened, preventing water accessing the remaining unhydrated particles deposited on the original crack surface.

![Fig. 3](image_url)

**Fig. 3.** (a) The average UPV value and envelopes of the test data obtained from five control samples; (b) the average of the normalized UPV values and envelopes of the experimental results obtained from ten samples precracked at 30% and 60% ultimate tensile strain. The hourly rainfall data is also presented.

### 3.2. Self-sensing performance

Figs. 4(a)–(c) compare the tensile stress-strain responses of MC-ECC samples, which are shown in solid lines, to those of the control mix without MC fiber, which are shown in dashed lines. It is apparent that the inclusion of MC fibers up to 1.25% by volume has no appreciable influence on the tensile properties of ECC. The control mix (0% MC fiber) displayed an average tensile strain capacity of 3.7% and an average tensile strength of 4.1 MPa. The average tensile strain capacity for samples containing 0.25%, 0.75% and 1.25% MC fibers were 3.2%, 3.8% and
3.0%, respectively. The corresponding tensile strengths were 3.8MPa, 3.9MPa and 4.2MPa, respectively. Some variability between individuals response exist, but they are still within a reasonable range.

The piezo-resistive response of one control sample (0% MC fibers) is shown in Figs. 4(d)–(f). Fig. 4(d) presents the relationship between tensile stress and tensile strain and Fig. 4(d) presents the response from the same sample but between tensile stress and fractional change in resistivity (FCR) in place of strain. The FCR was computed using the following equation:

$$ FCR = \frac{\rho - \rho_0}{\rho_o} = \frac{\Delta \rho}{\rho_o} \tag{1} $$

where $\rho$ is the bulk resistivity during loading and $\rho_0$ is the bulk resistivity at zero strain. From the curves shown in Figs. 4(d) and 4(e), it is evident that the two take similar form, suggesting that the FCR can be used to obtain an indication of the strain. Further supporting evidence for this can be seen in Fig. 4(f) from which a strong relationship between strain and the FCR can be found. However, it should be noted that the use of FRC in place of strain can be done when the influence of non-mechanical loading such as moisture changes and hydration on the bulk resistivity is negligible. Fig. 4(f) presents the fractional change in resistivity per unit strain (known as the gauge factor). It is evident that gauge factor increases dramatically during early cracking; thereafter during the strain hardening phase, the gauge factor still increases, but at a much lower rate. The material sensitivity to crack formations is high, with gauge factors inclusive of the range 200–340 which are two orders of magnitude larger than that of an ordinary strain gauge.

![Fig. 4. Comparison of tensile stress-strain response between control mix and MC-ECC mix; (d)–(f) the piezo-resistive response of control mix; (g)–(i) the piezo-resistive response of ECC containing 0.75% MC fibers.](image-url)
Fig. 4(g)–(i) present the piezo-resistive response of one 0.75% MC fiber ECC sample. As before, Figs. 4(g) and (h) compare the relative differences between two approaches to obtain the tensile response of the sample: the first based on traditional stress-strain relationship and the other based on stress-FCR relationship. It is evident that the two responses are very similar, suggesting once again that FCR can be potentially used in lieu of strain, with the latter being more desirable for use due to the fact that it is non-destructive. It is evident from Fig. 4(i) that strain and FRC remain highly correlated and can be best represented by a quadratic equation, with a correlation coefficient of 0.99. It is also evident from Fig. 4(i) that the gauge factor remains high (two orders of magnitude larger than that of ordinary strain gauge) and that the addition of MC fibers reduces the variations in gauge factor during multiple cracking, with values ranging from 80 to 130 (approximately). From a practical point of view, this is advantageous as ideally it is desirable to use a constant value of gauge factor. However, it is also evident from Fig. 4(i) that the values of the gauge factor becomes smaller than that of the control mix, suggesting that some of the MC fibers were bridging the micro-cracks and transmitting electrical current. This problem will be addressed in a future work.

4. Concluding comments

The work highlights the potential of ECC for realizing the development of durable and intelligent infrastructure. It has been shown that the material is able to self-heal the micro-cracks under the natural environment following two extensive damage events. The mild, wet climate of UK has been particularly proven desirable in the exploitation of the self-healing attribute of the material. It is envisaged that the use of such a material in future infrastructure has the potential to reduce maintenance costs and as a result would offer economic advantages in the long term. The work also highlights the potential of electrical property measurements for determining the material’s state of health under service condition. The technique makes use of the fractional change in resistivity which is shown to respond to cracks and tensile strain without the need for an additional sensor. It was found that MC-ECCs show promise in the development of smart composites for intelligent infrastructure. Work is ongoing to further improve the sensing ability.

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