

ENGINEERED CEMENT COMPOSITES PROPERTIES FOR CIVIL ENGINEERING APPLICATIONS

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Abstract

Engineered Cement Composites (ECC) materials have the potential to be used in civil engineering applications where a level of ductility is required to avoid brittle failures. However uncertainties remain regarding mechanical performance, physical properties, shrinkage and durability. In the present work, specimens containing cement powder and admixtures have been manufactured following two different processes and tested mechanically. Multiple matrix cracking has been observed in both tensile and flexural tests and this leads to “strain-hardening” behaviour. The results have been correlated with sample density and porosity and it is suggested that higher levels of porosity do not necessarily lead to a loss of the strain hardening capacity. Shrinkage has been investigated and it is shown, consistent with the literature, that shrinkage can be reduced both by controlling the initial environment to which the material is exposed and by the use of additives. Durability was assessed by flexure testing of beams specimens aged for different times. Initial testing (up to one year) indicates that the specimen retain ductility, although the initial cracking threshold increases with time – which may have implications for longer aging times.

1 Introduction

Cements, which are intrinsically brittle materials, can exhibit a degree of ductility when reinforced with a sufficient volume fraction of a fibrous phase. Recent work [1] has demonstrated the potential of a particular family of these materials comprising polymer fibre reinforcement and a cementitious matrix. According to this and related studies, this ECC material (containing polymeric micro-fibres in a cement matrix) exhibits ductility under stress, instead of failing in a brittle manner. In particular, it was shown that cast, flat specimens exhibit strain-hardening, when loaded in tension, as a result of multiple-cracking of the matrix. Based on such results, it would appear that these materials have the potential to be used in civil engineering applications.

Of particular interest is the possibility of the elimination of steel from reinforced concrete ensuring that no long-term corrosion exists: this is especially relevant for structures designed to contain water.

Before this material can be used in a commercial structural context, there are a number of issues that must be addressed. These include: optimising material design and manufacturing routes (with reference to composition, fibre volume fraction and distribution, and shrinkage behaviour); demonstrating that the ductility can be achieved in different design geometries (including different length scales) and the long term durability of the structure, with particular reference to the role of the fibre-matrix interface.

The aim of the present study is to contribute to the understanding of these issues in order to facilitate the implementation of these materials. The current paper presents initial results relating to mechanical behaviour, physical properties, shrinkage and durability.

2 Materials and Manufacture

2.1 Raw materials

The constituent materials for the ECC used in the present work are cement powder, fine aggregates, water, admixtures and polymeric fibres (the latter at 2% by volume). The polymeric fibres have a nominal diameter of 40 µm and a length of 8 mm. Two types are used: Type 1 (T1) and Type 2 (T2). T2 is resin-bundled, whereas T1 is not resin-bundled.

2.2 Manufacture and Process

Small specimens were made with a Hobart commercial kitchen mixer whilst larger mixes were prepared using a concrete mixer. The different components are added successively, mixing until a homogeneous distribution is achieved before adding the next component. The order of the incorporation of a component has, in general, little effect. However, the point in the manufacturing cycles when the fibres are added has an effect on the

eventual distribution of the fibres in the cured ECC. In Process 1 (P1), fibres are added to the dry ingredients prior to the addition of water whilst in Process 2 (P2), water is added to the mix before the fibres.

3 Experimental methods

3.1 Introduction

The interesting feature of this material is its ductility, which means that structural failure by catastrophic fracture is less likely to happen. Consequently, while (cube) compression tests have been carried out on the material, the resulting values are not particularly helpful in evaluating structural performance. Therefore, flexure and tensile testing are more appropriate to demonstrate the performance of the ECC material.

In order to understand the variability in mechanical properties, it is important to appreciate the fibre dispersion and to understand the relationship between this and the density and porosity of manufactured samples. Manufactured test samples can potentially lead to preferential alignment of fibres, clustering of pores and variation in pore size. Density measurement and the other characterisation techniques used are also discussed in this section.

3.2 Tensile Testing

Thin dog-bone shaped specimens (Fig. 1) are loaded in tension using a testing machine (Instron, 5500R 4505 with a load cell of 100 kN) in a displacement control at a rate of 0.05 mm/min.

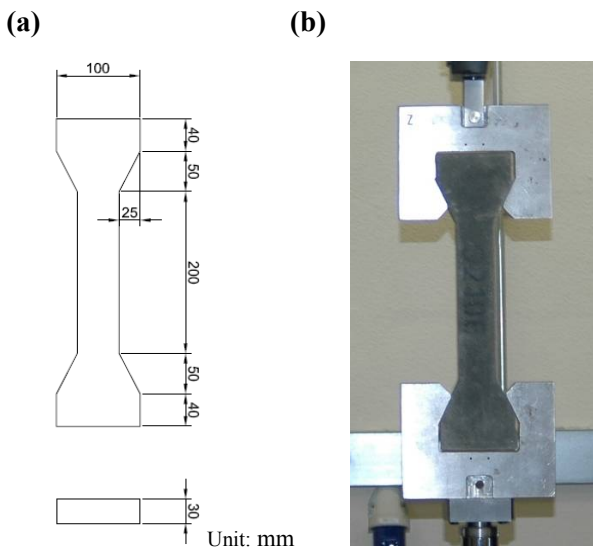


Fig.1. Tensile test arrangement for (a) Test specimen geometry and (b) Gripping arrangement

The flexibility to correct for imperfections in the specimen geometry and misalignment in the test machine is given by the pin situated at the top grip.

3.3 Flexure Testing

Flexural testing has been carried out based on one of the published concrete standards [2].

Beams (500 mm x 100 mm x 100 mm) were loaded in four point bending (4PB) using a testing machine (Controls, Triaxial tester T400 Digital with a load capacity of 50 kN) in displacement control at a rate of 0.2 mm/min. Fig. 2 shows the geometry and load application points [3].

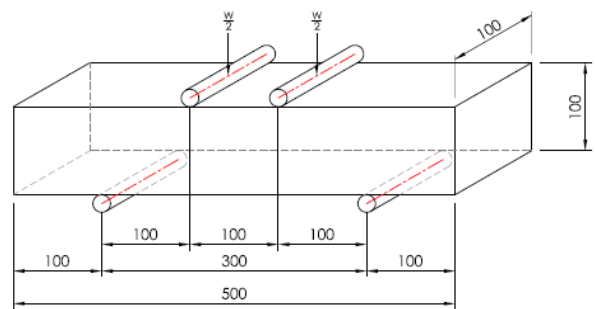


Fig.2. Schematic diagram of the flexure test specimen

Load and strain data were used to produce Moment-Curvature plots. The curvature, κ , gives a measure of the degree of (uniform) bending in the sample and may be determined using eq. 1:

$$\kappa = \frac{\epsilon_t - \epsilon_c}{t} \quad (1)$$

In equation (1), the terms ϵ_t and ϵ_c denote the tensile and compressive surface strains and t is the sample thickness.

Flexural testing is carried out on a range of beam specimens to evaluate the effect of process and fibre type on mechanical behaviour.

To be used in civil engineering application, the ECC material should be able to maintain its ductility with time (aging), and this is dependent on the ability of the fibres to slip in the cementitious matrix under stress. To investigate this phenomenon, flexural tests were carried out on aged samples.

The autogenous healing ability of the ECC material is also evaluated by flexural testing. Beam specimens are tested until the appearance of first cracks. They are then placed in an aqueous environment for the opportunity to heal and then re-tested in flexure. It will be assumed that if the

material exhibits an enhanced mechanical response on retesting (for instance a higher load at the onset of non-linearity in the load-displacement response) then the cracks have experienced some degree of healing.

3.4 Scanning Electron Microscopy (SEM)

Fractured surfaces from the tensile dog-bone samples were examined using a Scanning Electron Microscope (SEM). In this way, the matrix porosity could be visualized and preliminary observations regarding the fibre distribution and the fibre-matrix interface could be made. A Hitachi, S3200N SEM was used. Small samples were cut from the cracked faces of the tension specimens and gold coated (two 6 nm coatings of 60 % gold and 40 % palladium) to make them conductive for SEM examination.

3.5 Density and porosity measurements

Density and porosity measurements were made using samples cut from both tensile and flexural specimens.

The samples are weighed to determine their mass. The volume is measured using a water displacement technique for the samples from the specimens tested in flexure and by direct measurement of dimensions for the samples tested in tension.

Porosity P is determined as follows. Samples are placed in the kiln for 24 hours at 50 °C to dry and are then weighed (m_{dry}). The sample is then placed in vacuum to eliminate as much of the air present as possible prior to the introduction of water to occupy the volume left empty by the air. The samples are weighed again to determine m_{water} . The porosity is given by:

$$P(\%) = \left(\frac{(m_{water} - m_{dry}) / \rho_{water}}{V} \right) \times 100 \quad (2)$$

In equation (2), ρ_{water} denotes the density of water.

3.6 Shrinkage

To be used in civil engineering applications, the ECC material may require a design life of more than 100 years, during which time it should preserve its ductility. The long-term durability of the composite material is associated with the ageing process at the fibre/cement interface and the effect that this may have on the ability of the fibre to slip in the matrix. Another important aspect of the durability/aging of the ECC is the drying shrinkage [4], and this has also been investigated here.

Shrinkage is evaluated using beam specimens (500 mm x 100 mm x 100 mm) (Fig. 3) and taking measurements along the 500 mm length. Two metallic studs are embedded in the specimen and are used to record the change in length. Shrinkage beams are manufactured by pouring mixes into a mould and demoulding after 23 hours. The beam is then placed in water for an hour. The first measurement is taken at 24 hours.

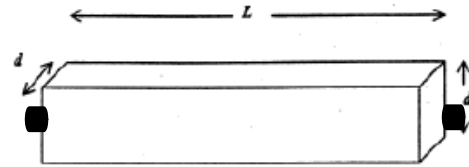


Fig.3. Shrinkage beam specimen

4 Results and discussion

4.1 Effect of process and fibre type on mechanical performance

4.1.1. Flexure test results

Fig. 4 illustrates typical moment-curvature behaviour for an ECC specimen tested in flexure: an elastic region until the appearance of the first crack followed by a region of “strain-hardening”, associated with the formation of multiple cracks, leading up to the failure of the specimen.

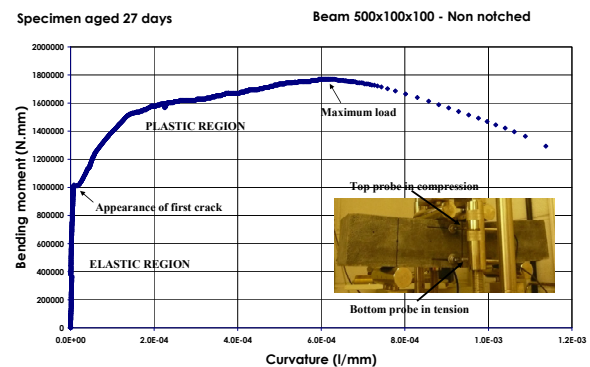


Fig.4. Typical bending moment – curvature response for a beam specimen tested in four-point bending

Comparing results for the different fibres and different manufacturing routes (Fig. 5), when Process 1 was used, there was a higher deflection at failure and maximum load for the specimens made with Type 2 fibres. Similar results were found when Process 2 was used; suggesting that Type 2 gives improved performance.

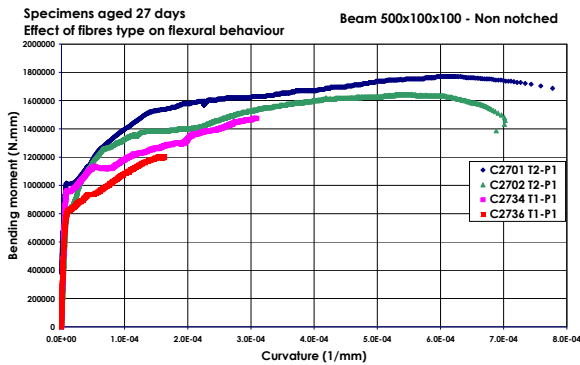


Fig.5. Bending moment-curvature data for specimens tested in four point bending: effect of fibre type (using Process 1)

The results obtained with specimens made using fibres T2 (Fig. 6) show that the specimens made with Process 1 exhibit improved mechanical behaviour compared to Process 2 (strain-deflection associated with a good maximum load), perhaps suggesting a better dispersion of fibres when they are added to the dry components rather than added to the wet mix.

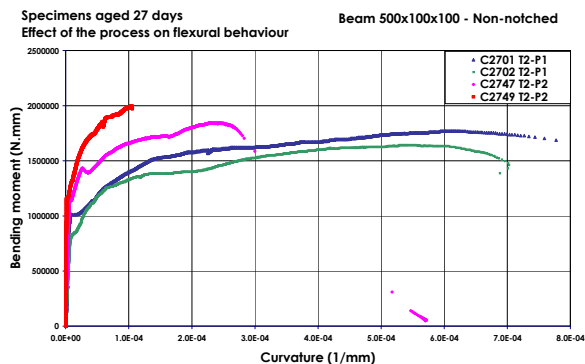


Fig.6. Bending moment-curvature data for specimens tested in four point bending: effect of process type (using Fibres Type 2)

4.1.2 Tensile test results

The tests carried out on thin dog-bones showed more variability than the flexure tests (Fig. 7). It seems plausible that this is in part a consequence of the greater difficulties in achieving multiple cracking in tensile tests (the samples are more sensitive to misalignment and initial cracking at the shoulder of the specimen that may lead to premature failure). Aged specimens tend to exhibit a higher maximum load and a lower displacement at failure. Similarly aged specimens present different performances. On average, specimens made with fibres T2 show a similar failure load to specimens made with fibres T1 (around 6000 N in each case) but a higher

displacement to failure (around 1.0 mm compared to 0.5 mm).

Hence these tests also suggest that T2 fibres give an enhanced mechanical performance – possibly the resin-bundling gives enhanced dispersion.

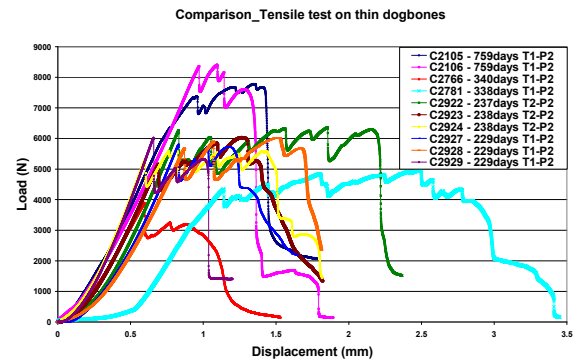


Fig.7. Load-displacement results for specimens tested in tension: effect of fibres type and age

Figure 8 shows SEM photomicrographs of the fracture surface of sample C2105 (Fibre Type 1, Process P2). Porosity in the matrix is apparent and it is apparent that there are regions where the fibres are bundled and regions of better dispersion. These images also suggested that there was some deposit on the surface of the fibres confirming some level of interaction (mechanical or chemical) at the fibre-cement interface. From images such as these it is possible to make simple estimates of the volume fraction of fibre, which was consistent with the known levels of addition, and porosity.

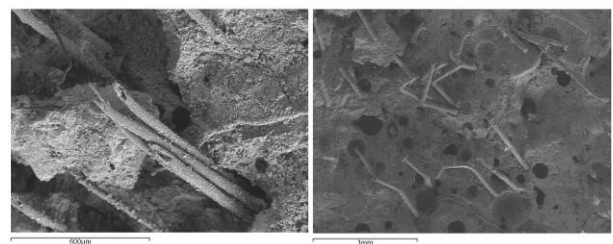


Fig.8. SEM images of specimen C2105

4.2 Physical properties

In this section, values of density and porosity are reported for a range of samples and compared with the mechanical properties. Table 1 shows the data for the flexural test specimens. The average density measured on eight specimens was 1862 kg.m^{-3} with a standard deviation of 37 kg.m^{-3} . The porosity values measured on 4 samples were reasonably consistent, in the range 1.1 – 1.6 %; although there is no measure of scale (large number of small pores or

small number of larger pores) or distribution (clustered, predominantly found at faces, evenly dispersed). Overall there is not sufficient variation in the parameters to draw any meaningful conclusions at this stage, other perhaps than that further testing is required.

Specimen	Description (Fibre type/Process)	Maximum load (ML) (kN)	Curvature at ML ($\times 10^{-4} \text{ mm}^{-1}$)	Density (kg/m ³)	Porosity (%)
C2701	T2/P1	35.4	6.3	1887	1.5
C2702	T2/P1	32.9	5.6	1838	1.5
C2734	T1/P1	29.4	3.1	1848	/
C2736	T1/P1	27.8	1	1820	/
C2747	T2/P2	36.8	2.3	1905	1.6
C2749	T2/P2	39.9	1	1918	1.1
C2788	T1/P2	35.4	1.6	1857	/
C2790	T1/P2	20.9	0.5	1826	/

Table 1: Important flexural test parameters associated with the values of density and porosity

Table 2 shows the corresponding data for the tensile samples. The lowest porosity samples appear to have the highest failure loads, but this does not correspond to the highest displacement. The largest displacements are actually associated with the highest porosity. It is perhaps possible that higher levels of porosity may promote first cracking and subsequently multiple cracking at lower loads but that when first cracking occurs at higher loads it is more likely to lead to specimen failure with reduced associated displacement. Further experimental work is needed to test these hypotheses but it appears that the ECC material can still operate effectively (at least on a short term basis) despite the presence of significant porosity.

Specimens	Description (Fibre type/Process)	Maximum load (ML) (kN)	Displacement after first crack (mm)	Density (kg/m ³)	Porosity (%)
C2105	T1/P2	7.7	0.47	1935	1.7
C2106	T1/P2	8.4	0.34	1925	1.8
C2766	T1/P2	3.9	0.29	2014	4.9
C2781	T1/P2	5	1.64	1926	8.0
C2922	T2/P2	6.4	1.33	1850	6.6
C2923	T2/P2	6	0.69	1872	5.1
C2924	T2/P2	5.6	0.84	1865	5.7
C2927	T1/P2	5.8	0.36	1886	6.5
C2928	T1/P2	6	0.81	1889	6.9
C2929	T1/P2	6	0.36	1900	6.9

Table 2: Important tensile test parameters associated with the values of density and porosity

4.3 Shrinkage (unrestrained)

4.3.1 Effect of the environment

The results from the shrinkage investigation confirm the possibility of reducing shrinkage by controlling the environment of the material in its early age. Fig. 9 shows the shrinkage as a function of time for specimens aged in two different ways. The specimen cured in water prior to being placed in air exhibits shrinkage of 730 $\mu\epsilon$ at 57 days compared with a shrinkage of 1500 $\mu\epsilon$ for the specimen placed immediately in air. It is also apparent from Fig. 9 that the specimen placed immediately in water almost returns to its original dimensions.

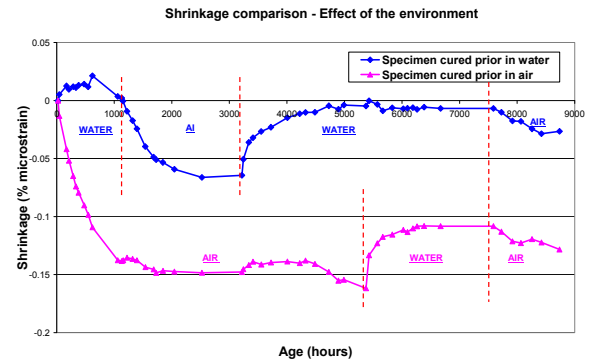


Fig.9. Comparison of shrinkage of a specimen cured in water prior to being placed in air with a specimen directly cured in air

These results are important for civil engineering applications, as the reduction in drying shrinkage results in a significant reduction of the risk of cracking of structures.

4.3.2 Effect of additives

Additives can also reduce shrinkage; an ECC mix which incorporated micro-silica powder resulted in a reduction of drying shrinkage by approximately 500 $\mu\epsilon$ (composition C in Fig. 10).

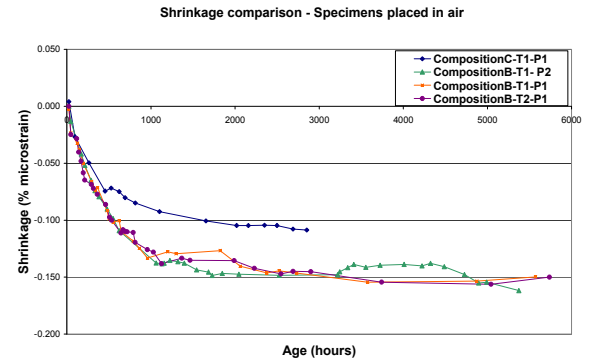


Fig.10. Shrinkage comparison on specimens with and without incorporation of a specific admixture

Further work in this area will inform investigation into specific applications of this modified material.

4.4 Durability

4.4.1 Time effect on ductility

The results revealed a higher maximum load at failure when specimen is aged 307 days than when aged 28 days (Fig. 11). The curvature value at maximum load is also higher at 307 days, even though the overall ductility is reduced.

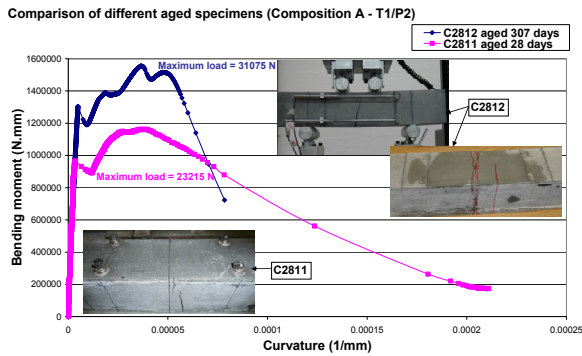


Fig.11. Bending moment-curvature graph of beam specimens tested at different ages

4.4.2 Self-healing

Cracks appear routinely during the life of cementitious materials under a combination of shrinkage and stress. The experiments undertaken reveal the possibility of the ECC material to exhibit ductility with time even when subject to a prior stress causing the formation of cracks in the specimen (Fig. 12). It appears possible that the increase of performance when re-loaded is due to the (partial) healing of cracks in the material.

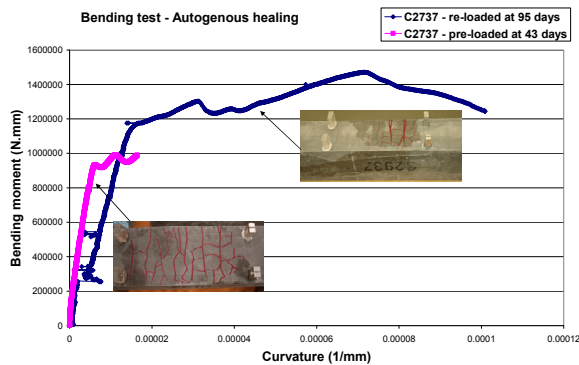


Fig.12. Preloading and reloading bending moment – curvature of ECC specimen

5 Concluding Remarks

This paper has provided an overview and an initial experimental investigation of a number of factors that influence the performance of ECC materials. Multiple cracking phenomena have been observed in tensile samples of a greater scale than tested by most researchers. Further work is needed to understand in more detail the roles of the manufacturing route, fibre type and fibre distribution and porosity. Control of the environment has been confirmed to be important in influencing shrinkage behaviour and there is evidence that the system can show healing after aging. With regard to understanding the aging phenomena of ECC materials in greater details, it

will also be necessary to consider the surface chemistry of the fibres and the behaviour of the fibre-matrix interface with time.

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