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DUCTILITY AND DURABILITY OF STRAIN HARDENING CEMENTITIOUS COMPOSITES IN THE MARINE ENVIRONMENT

Bárbara Ferreira[1, a], Eduardo Pereira[1, b], Vítor Cunha[1, c], João Almeida[1, d]

[1]ISISE – Dep. of Civil Engineering, University of Minho, Portugal

[a]a61824@alumni.uminho.pt, [b]epereira@civil.uminho.pt, [c]vcunha@civil.uminho.pt, [d]j.almeida@civil.uminho.pt

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ABSTRACT

Modern structures are being exposed to severe environments and the lack of durability is one of the most serious problems in concrete infrastructures. Structural concrete exposed to marine environment deserves special attention as the sea salts chemically react with the cement matrix and the steel reinforcement which results in loss of strength, cracking, spalling, etc. The challenges of Civil Engineering, especially within the structures in extreme environments, pose considerable expectations with regards to the development of fibre reinforced materials for the development of more resistant and durable solutions.

In the present work, the behaviour of an Engineered Cementitious Composite (ECC) was studied. All the specimens prepared were cured in 4 types of environments: exposed to air (20ºC of temperature and 60% of humidity) immersed in tap water, immersed in salted water and immersed in seawater, all at an average temperature of 18ºC. A series of experiments, including compressive and direct tension tests were carried out to characterize the mechanical properties of the ECC materials while exposed to different environments.

The most important characteristic of ECC, which include multiple-cracking behaviour at increasing tensile strains when subjected to increasing tensile loading, was confirmed in all types of curing environments. In all cases the cementitious composites performed well with regards to the strain hardening behaviour typically observed in these materials, although the cracking processes have shown different characteristics. Due to the ability of the material to control crack opening below extremely low values, typically under 100 µm, the durability of structures can be significantly improved when ECC materials are used in the in marine environments. It was shown also that the salted water does not represent well the effect of seawater while characterising ECC mechanical characteristics in the laboratory.

1. Introduction

Concrete, that is the most ubiquitous construction material, is known to be a tension-weak material, with a tensile strength much lower than the compressive strength (typically 10%) and very limited tensile strain capacity [1]. In the marine environment, the structures are exposed to a serious number of physical and chemical interactions that affect the strength and stiffness of the concrete causing cracking, leading to other types of concrete deterioration such as corrosion, alkali-silica reaction and sulphate attack, resulting in further cracking and disintegration [2] [3].

Synthetic composite materials are a recent alternative to the most traditional materials. These materials are designed to perform better in harsh environments, while subjected to the various corrosive and erosive actions of the sea, under dynamic, cyclic and impact loading conditions over a wide range of temperatures.

Strain hardening cementitious composites represent a class of fibre reinforced cementitious composites which have been developed with the aim of withstanding extreme tensile strains at moderate tensile stresses, departing from the typical behaviour of cementitious materials. Due to the complexity of the cracking processes established in these materials under tension, the presence of the fibres and the integral design of the material considering both the mechanical properties of the fibres, of the cementitious matrix and of the fibre-matrix interaction are essential to attainthe so-called pseudo-strain hardening in tension [4] [5]. Engineered Cementitious Composites (ECC) is a class of this type of cement-based materials typically reinforced with Polyvinyl Alcohol (PVA) fibres developed for applications in the large material volume usage. One of its first predecessors was developed in 1960 by Romauldi and co-workers, that used short steel fibres in concrete to reduce the brittleness [6]. In 1980 began the interest in fibre reinforced concrete materials with tensile ductility, as a measure of tensile deformation (strain) capacity typically associated with ductility in steel.

Pseudo-strain hardening behaviour in tension exhibited by ECC is associated with the development of multiple cracks during tensile loading. ECCs display significantly higher ductility and a more reliable crack width control when compared with reinforced concrete [7]. Considering this type of behaviour, the present research is dedicated to the assessment of the effect of the curing environment on the tensile and compressive properties of Strain Hardening Cementitious Composites. This research addresses this topic by carrying out two types of mechanical tests: compression tests for assessing the deformability and compressive strength and direct tension tests to assess the tensile behaviour and multiple crack formation potential of the material while subjected to different curing environments.

2. Experimental procedure

Materials and procedures. The following materials were used to prepare the ECC mixture: cement CEM 42.5N type I, fly ash, tap water, viscosity modifying agent (VMA), sand, limestone filler and super-plasticizer (SP). The mass proportions of all materials used in the preparation of the ECC mixture are presented in Table 1~~Table 1~~. The density of the fly ash used in the composition was 2420 kg/m^3, as characterized by Reis et al. [8]. Polyvinyl Alcohol (PVA) fibres 8 mm long and with a diameter of 40 µm were added to the mixture at a volume fraction of 2%. According to the supplier, the tensile strength of the PVA fibres is 1600 MPa, the Young's modulus is 41 GPa and the density is 1300 kg/m^3.

Table 1. Mass proportions of all ingredients used in the mixture.

Materials	***CEM***	***Fly Ash***	***Sand***	***Filler***	***Tap water***	***SP***	***VMA***	***PVA Fibres***
Weight (g)	836.9	1653.7	292.9	292.9	657.9	31.6	2.5	52

A mortar mixer with 3 L of capacity was used to prepare all the ECC mixtures. Firstly all the materials were collected and weighted. Solid ingredients, including cement, fly ash, sand, limestone filler and VMA were put in the bowl and mixed for one minute in slow speed. Water and super-plasticizer were then added into the bowl while mixing for another 5 minutes. After that, the mixer was stopped in order to obtain the fresh properties of the mortar.

The mixer was restarted and the fibres were added into the mortar and mixed until a good fibre distribution was obtained, about 2 minutes later. Subsequently the fresh properties were determined in the flow table. The specimens were cast in different moulds and then vibrated in the shaking table, in order to reduce the air entrapped in the mixture. After one day in the mould the specimens were demoulded and moved into the climatic chamber. The temperature and relative humidity (RH) in the climatic chamber were kept constant during curing, respectively at 20ºC and 60%.

All the specimens prepared in this work were cured in 4 types of environments: in air (20ºC of temperature and 60% of humidity), immersed in tap water, immersed in salted water (NaCl) and immersed in seawater collected from the Atlantic Ocean, near Porto. The average temperature of tap water, salted water and seawater was 18ºC +/- 1ºC. Tensile and compressive tests were carried out 28 days after.

Compression testing. Compressive tests were carried out using cubes with 50 x 50 x 50 mm^3. In this study, one actuator with 200 kN load cell and one LVDT (Linear Variable Differential Transformer) were used. The compressive tests were carried out at a constant compressive displacement increment of 0.02 mm/sec. Fig. 1Fig. 1 shows the setup used in the compression test.

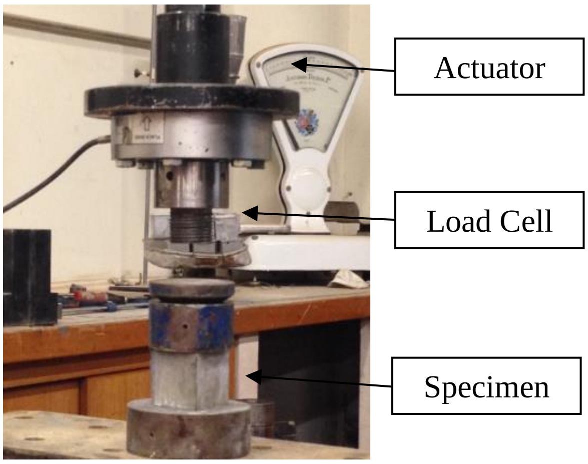

Fig. 1- Setup used for the compression tests.

Tensile testing. The specimens for direct tension testing and for characterizing the tensile stress-strain responses were cast using dogbone-shaped moulds. These moulds were 20 mm thick, 370 mm long and 100 mm wide (the straight central part was 50 mm wide and 110 mm long). One actuator with a 200 kN load cell, two grips (one grip was connected with the actuator and the other was fixed in the reaction frame) and 3 LVDT's were used in this test, see Fig. 2Fig. 2. Further details about the experimental procedure may be found elsewhere [9]. During testing the specimens were subjected to an increasing tensile displacement imposed at a constant rate of 0.010 mm/s.

Fig. 2-Test setup used for the tensile tests.

3. Results and discussion

Compressive behaviour. Three specimens for each type of curing environment were tested. The results showed that the compressive strength of the ECC mixture investigated was moderately influenced by the type of curing. As shown in Table 2~~Table 2~~, the compressive strength ranged between 37 and 44 MPa and the coefficients of variation obtained were quite low.

Form

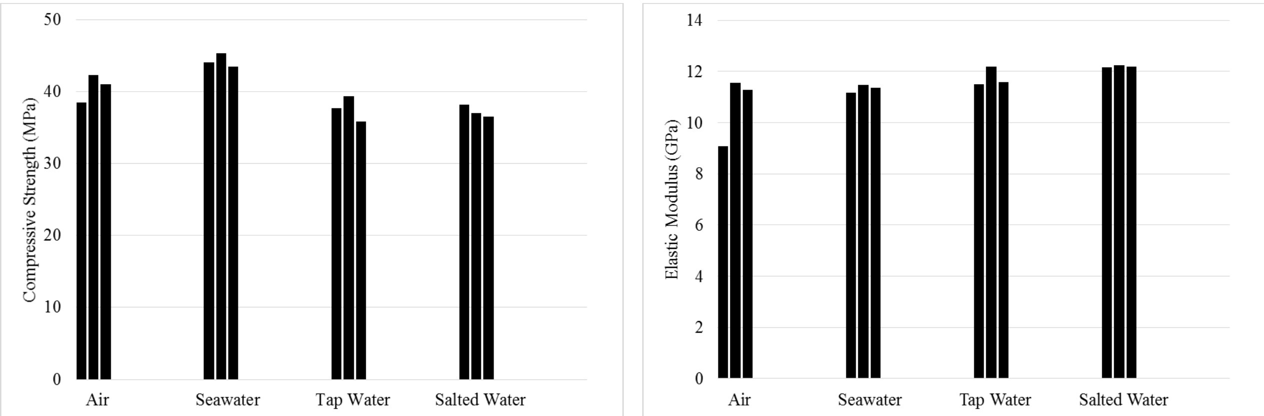

Fig. 3- Results of compression tests on ECC mixtures.

In Fig. 3~~Fig. 3~~ the results obtained for the nominal elasticity modulus of each specimen are also presented. The nominal elasticity modulus ranged between 8.7 and 10.8 GPa. These values may not be compared with the ones typically found in the literature for cementitious materials because cubic specimens have been used, which lead to significantly higher deformations for the same load levels when compared to the standardized procedure based on cylindrical specimens. However, this procedure is adequate to establish a relative comparison between the results obtained in this research, and in such a way evaluate the effect of the curing conditions on the deformability of the ECC. Fig. 4 depicts the damage pattern of specimen Ma_01 after completion of the compression test.

Table 2- Compression characteristics obtained in each type of curing environment.

Curing	*Average Compressive Strength* **(MPa)**	*Standard Deviation* **(MPa)**	*Coefficient of Variation* **(%)**
Air	40.64	1.60	3.9
Seawater	44.33	0.79	1.8
Tap Water	37.66	1.40	3.7
Salted Water	37.27	0.68	1.8

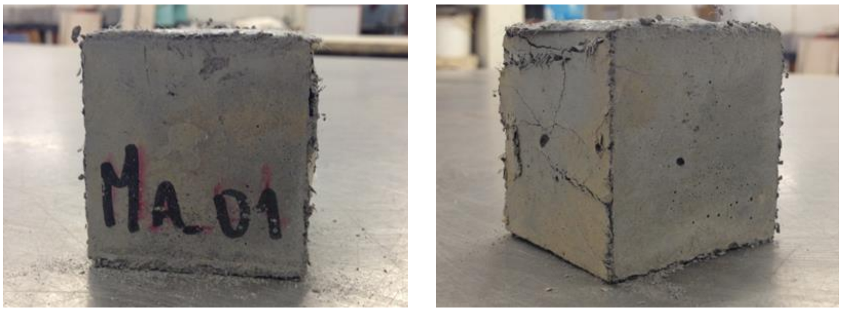

Fig. 4- ECC specimen after compression testing.

Tensile behaviour. Three specimens were tested for each curing environment. The tensile stress-strain results obtained after 28 days of curing are represented in Fig. 6~~Fig. 5~~. All the specimens showed the typical strain hardening behaviour of ECC materials.

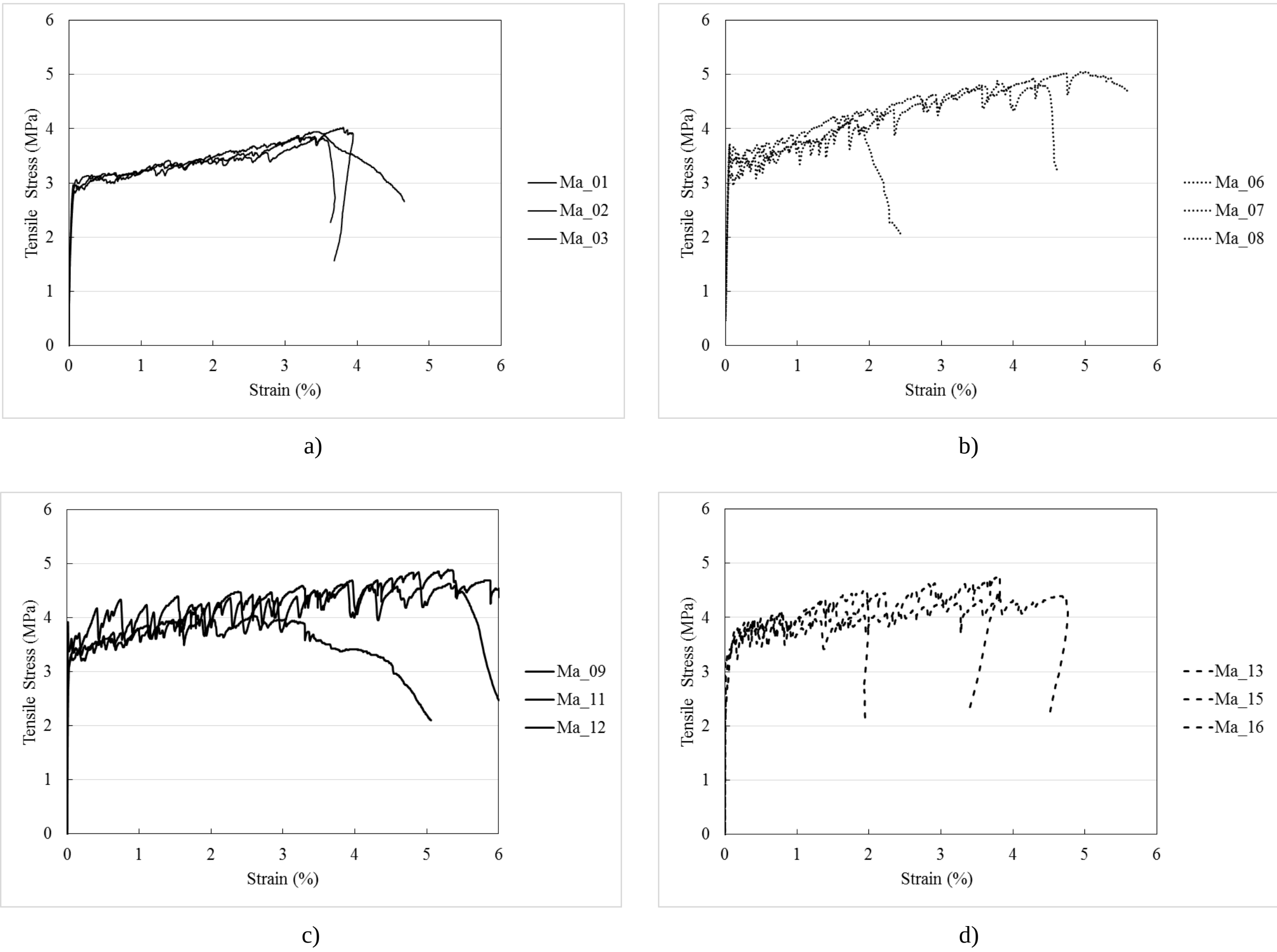

Fig. 5- Tensile test results at 28 days of specimens: a) cured in air; b) cured in seawater; c) cured in tap water; d) cured in salted water.

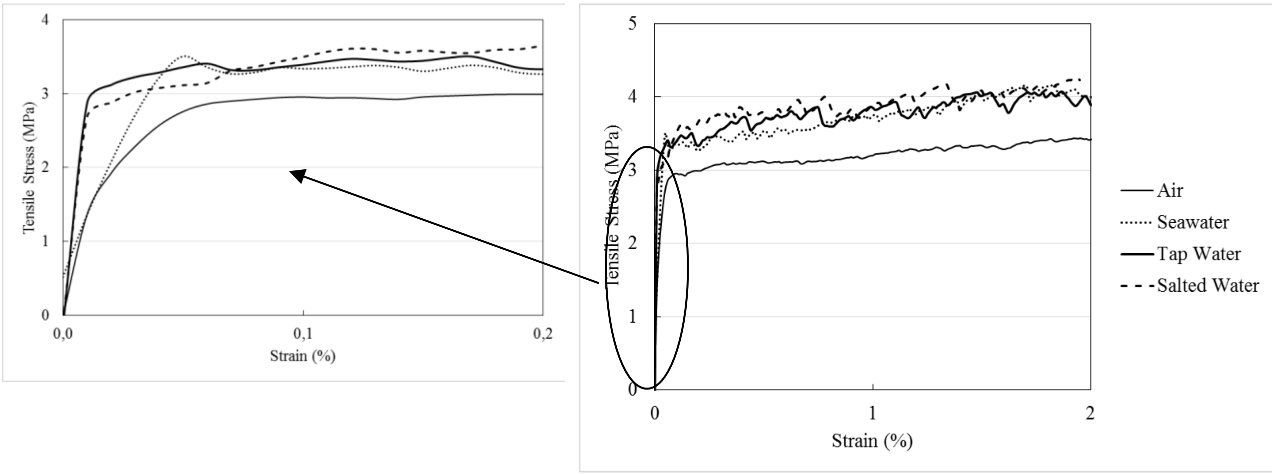

Fig. 6- Average tensile responses obtained for specimens cured in all environments.

The first cracking tensile stress ranged between 3 and 4 MPa. The main results obtained for each specimen are presented in Table 3~~Table 3~~, including: the first crack stress, σ_c; the strain at first cracking stress, $\mathcal{E}_c$; the ultimate tensile stress, σ_u and the ultimate tensile strain, $\mathcal{E}_u$.

The specimens cured in tap water have reached, in general, higher values of the ultimate tensile strain. During the strain hardening stage of the tensile stress-strain response, the different curing environments have resulted in different behaviours. The sudden tensile stress drops during this stage of the tensile stress-strain response correspond to the formation of cracks with larger crack widths, and assume different features depending on the curing environment considered.

Fig. 6~~Fig. 6~~ shows that the behaviour of the different specimens is different even prior at the formation of the first crack. The tap water and sated water curing have higher high stiffness phase when compared with the other types of cure.

The different crack patterns obtained from the four different curing environments are presented in Fig. 7~~Fig. 7~~. The specimens cured under sea water showed a tight crack pattern which was visually imperceptible, with promising characteristics for durability improvement and water tightness preservation in harsh environments

Table 3- Summary of the tensile results obtained for all curing environments

Cure	***Specimen***	σ_c (MPa)	$\mathcal{E}_c$ (%)	σ_u (MPa)	$\mathcal{E}_u$ (%)
Air	Ma_01	3.06	0.10	3.94	3.47
	Ma_02	3.15	0.32	3.83	3.53
	Ma_03	2.97	0.06	4.02	3.81
Sea Water	Ma_06	3.69	0.05	4.89	3.78
	Ma_07	3.19	0.09	4.13	1.71
	Ma_08	3.71	0.06	5.05	5.00
Tap Water	Ma_09	3.92	0.01	4.03	2.60
	Ma_11	3.42	0.13	4.69	5.88
	Ma_12	3.32	0.06	4.89	5.30
Salted Water	Ma_13	3.31	0.06	4.40	4.69
	Ma_15	373	0.13	4.50	1.94
	Ma_16	3.21	0.01	4.77	3.82

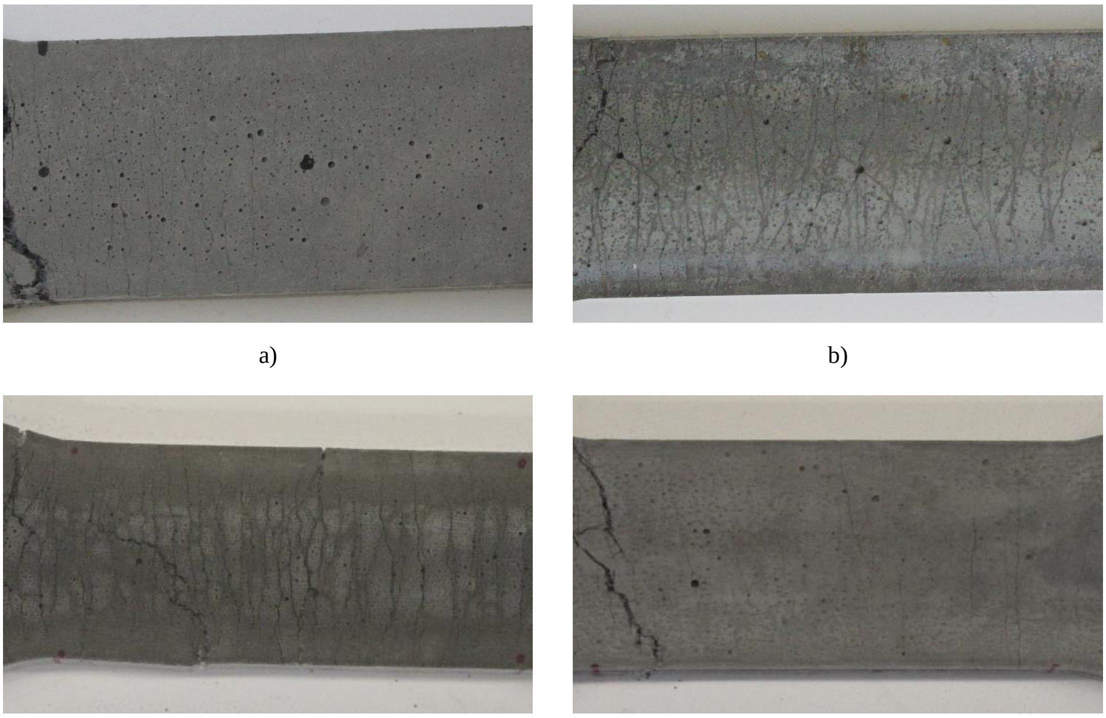

Fig. 7- Images of the dogbone specimens after testing: a) cured in air; b) cured in seawater; c) cured in tap water; d) cured in salted water.

4. Conclusions

The present investigation concerning the mechanical behaviour of Engineered Cementitious Composites showed that the main properties of ECC materials, including multiple cracking behaviour at increasing tensile strains when subjected to direct tension, is sensitive to variations of the curing environment. However, although the differences in the tensile behaviour are clearly distinguishable, the tensile properties including tensile strain hardening or multiple cracking were never compromised. The results obtained from the compressive and tensile testing showed also that the curing in salted water does not represent well the effect of the seawater environment on ECC mechanical characteristics.

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