Engineered Cement Composite Materials Characterization for Tunneling Applications

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Abstract—Cements, which are intrinsically brittle materials, can exhibit a degree of pseudo-ductility when reinforced with a sufficient volume fraction of a fibrous phase. This class of materials, called Engineered Cement Composites (ECC) has the potential to be used in future tunneling applications where a level of pseudo-ductility is required to avoid brittle failures. However uncertainties remain regarding mechanical performance. Previous work has focused on comparatively thin specimens; however for future civil engineering applications, it is imperative that the behavior in tension of thicker specimens is understood. In the present work, specimens containing cement powder and admixtures have been manufactured following two different processes and tested in tension. Multiple matrix cracking has been observed during tensile testing, leading to a "strain-hardening" behavior, confirming the possible suitability of ECC material when used as thick sections (greater than 50mm) in tunneling applications.

Keywords—Cement composite, polymeric fibers, pseudo-ductility, test-geometry.

I. INTRODUCTION

ENGINEERED Cement Composites (ECC) materials, typically consisting of a cementitious matrix reinforced with a low volume fraction of small diameter fibers, can exhibit a degree of pseudo-ductility under stress, instead of failing in a brittle manner. Previous work has demonstrated the potential of this particular family of materials [1]. According to this and related studies, specimens with a thickness of 12.7mm have exhibited a pseudo-ductility due to a process of multiple cracking when loaded in tension [2]-[3]. Based on such results, it would appear that these materials have the potential to be used in civil engineering applications where a level of pseudo-ductility is required to avoid brittle failure. Of particular interest is the possibility of the elimination of steel reinforcing bars from concrete structures ensuring that no long-term corrosion exists, which is especially relevant for underground water-retaining structures such as hydraulic tunnels.

Deterioration arises from corrosion, especially when the steel reinforcement becomes exposed with time due to cracking. The pseudo-ductility of the ECC material associated with matrix cracking gives enhanced strain capacity before damage localization. The material, being able to exhibit pseudo-ductility under tensile stress, could be used in tunnel lining technology for repair of existing tunnels and also in new tunnel construction.

Fig. 1 illustrates a case where ECC is used as a repair material to the intrados of the original pre-cast concrete lining (PCC lining). In the case where the primary lining is considered impermeable, PCC sustains the ground load (including ground water), and in the case where the primary lining is very permeable (worst case scenario), the ECC lining will have to withstand both internal and external water pressure. The reinforcement material is also considered for the extension of the design life of existing tunnels, where there is internal water pressure.
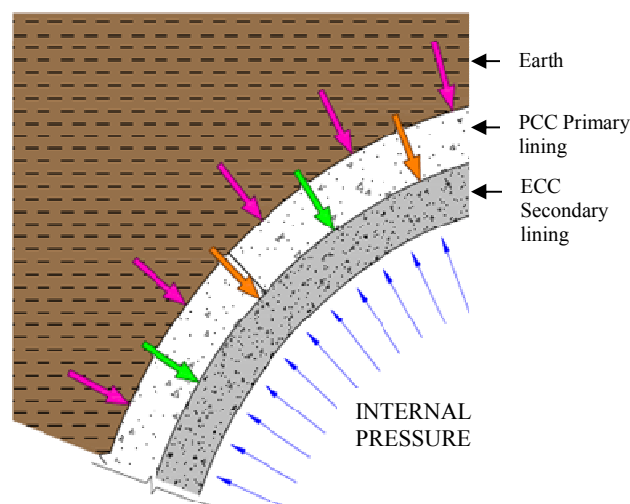

Fig. 1 ECC tunnel lining for repair

Most of the current water tunnels operate as gravity pipelines, whereas future operational requirements will demand the water to be pumped and distributed to the other reservoirs, and therefore a high internal pressure (often up to 6 bars in the UK) will be applied. The majority of current hydraulic tunnels in the UK are inadequate to cope with the internal pressure as many of them are built as wedge-block linings and therefore a high water pressure can blow out the segments if there is not adequate ground support. The use of a permanent lining with fiber reinforced cement composite could also be an alternative for tunnels where a high internal water pressure is anticipated.

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The presence of multiple fine cracks (as opposed to a low number of wider crack openings) helps to maintain the water tightness of the water-pressurized structures in service conditions and allows self-healing to take place. The ECC mixture could be suitable for both sprayed and cast-in-place (behind a shutter) applications.

II. CONTEXT OF THE STUDY

Previous studies focused on thin specimens. For example, the Japanese Society of Civil Engineers (JSCE) reporting on High Performance Fiber Reinforced Cement Composites (ECC being a typical example of this type of material), specifies the use of a thin dog-bone shape specimen 13mm thick (Fig. 2), with an angled shoulder between the grip region and the gauge (length of 80mm) for testing the ECC materials in tension [4].

In practice, ECC materials might be used in structures of thicknesses of the order 50-150mm (and potentially greater). Hence, the need to move from initial work focusing on comparatively thin sections to thicker sections is essential.
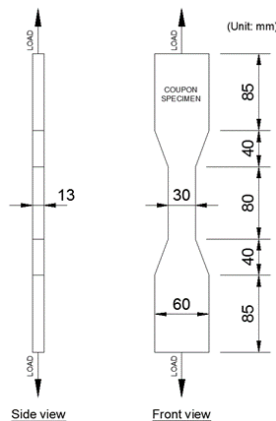
Fig. 2 Schematic of unconfined tensile test based on the Japanese Standard [4]

Thicker sections have been tested more recently, these were 20mm [5], the thickest found in the literature for this type of material. The initial tensile testing results found a maximum strain of 4%, lower than found in thinner section specimens showing a tensile strain above 5% [2].

In the current work, the Japanese Standard for testing the material in tension has been followed regarding the "dog-bone" shape of the specimen, but it was considered necessary to increase the thickness specified in the Standard, to 30mm. Additionally, it was noted that the geometry presented in the standard gives a very sharp transfer between the shoulder and the gauge. The current work has used specimens where the transfer has been made less sharp by giving the shoulder a radius of curvature of 185mm (Fig. 3).

Therefore, the specimen thickness is almost four times the fiber length (8mm) compared with thinner sections, and when casting it is more likely that fibers will be randomly distributed in all directions: this may affect the mechanical performance of the ECC in tension.
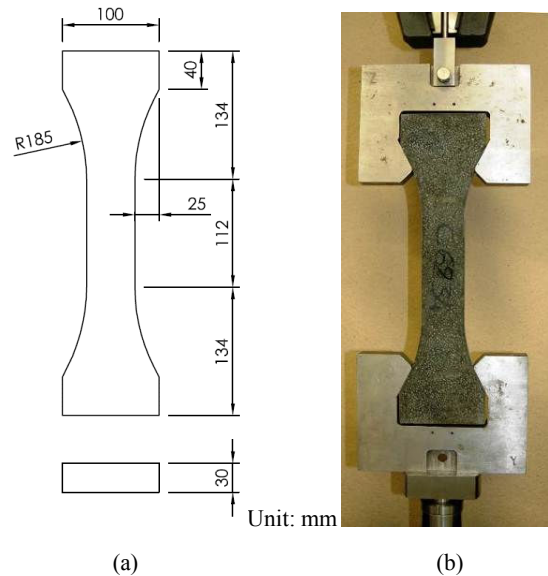
Fig. 3 Tensile test arrangement for the original standard dog-bone geometry following the Japanese Standard

Before this material can be used in a commercial context for applications with thick sections, the mechanical performance of the ECC material, especially in tension, must be demonstrated. In addition, there is capacity for optimizing material design and manufacturing routes (with reference to composition, fiber volume fraction and distribution). The link with processing and composition must also be evaluated.

The specific aim of the present study is to contribute to the understanding of these issues in order to facilitate the implementation of these materials in civil engineering applications.

III. MATERIALS AND MANUFACTURE

A. Mixture Composition

Previous work specified a mix containing cement powder, water, aggregates, admixtures and polymeric fibers at 2% by volume [2]. In the current work, polymeric fibers have a nominal diameter of 40μm and a length of 8mm. Two types are used: Type 1 (T1) and Type 2 (T2). T2 is resin-bundled, whereas T1 is not resin-bundled.

B. Processing

Small specimens were made with a Hobart commercial small-scale mixer (6 liter capacity). The different components were added successively, mixing until a homogeneous distribution was 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 cycle when the fibers are added has an effect on their eventual distribution in the cured ECC. In Process 1 (P1), fibers were added to the dry ingredients prior to the addition of water whilst in Process 2 (P2), water was added to the mix before the fibers.

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C. Casting

A study conducted on polypropylene fibers in a cementitious matrix demonstrated a clear link between the casting method, on which depend the fibers orientation and the mechanical performance [6]. It appeared that extruded specimens with approximately 80% of the fiber content aligned with respect to the extrusion direction exhibit enhanced mechanical performance compared with cast specimens having a broader distribution of fiber orientations.

In the current study, the fresh mixture is poured into a mold producing dog-bone shaped specimens 30mm in thickness. As a comparison, plaques of similar thickness to the dog-bones were also cast and from which dog-bone specimens were subsequently cut, using a water-jet cutting process (Fig. 4). The cutter was a Global Cutting Technologies YC-L1212 using Naiky, NcStudio[TM]-V9 control software; cutting parameters were 150mm/min and 100 Mesh Garnet sand.

Fig. 4 Cutting of a test sample from a 30mm thick plaque using a water-jet cutter

IV. EXPERIMENTAL METHODS

A. Introduction

The fundamental attraction of this material is its pseudo-ductility, which means that structural failure by catastrophic fracture is less likely to happen. Tensile testing is the most severe test case for the material, whereas flexural testing is more likely to promote a graceful failure. Consequently, the tensile testing is more likely to demonstrate the performance of the ECC material and has been used for the current work.

In order to understand the variability in mechanical properties, it is also important to appreciate the fiber 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 fibers, clustering of pores and variation in pore size.

B. Tensile Testing Method

The dog-bone shaped specimens were loaded in tension, using a Universal Testing Machine (Instron 4505 5500R with a load cell of 10kN capacity and using Bluehill 2 Instron's proprietary software for control and data acquisition) in displacement control at a rate of 0.05mm/min. 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. Load and cross-head displacement data were used to produce stress-strain plots.

V. RESULTS

A. Introduction

Three specimens were manufactured per fiber and process type; specimens were tested at 27 days.

First, both fiber types were tested with specimens made using Process 1. Then, as Process 2 found an advantage over Process 1 in terms of workability (the ease of placement and the resistance to segregation [7]), it was decided to test the best fiber obtained previously with both Processes to confirm the selection. An acceptable workability is very relevant when placing this material in construction. Workability is measured following BS EN 1015-3 [8]. Table I presents values of workability measured for each batch manufactured.

TABLE I
WORKABILITY OF MIXES PRODUCED AND TENSILE TEST DATA FOR COUPONS
MANUFACTURED (ALL SAMPLES TESTED AT 27 DAYS) – CASTING MEDIUM:
MOLD

Specimen	Fibre/ Process	Workability (mm)	σ at FC (MPa)[a]	σ_{max} (MPa)[a]	ε frm FC (%)[a]
C6256	T2/P1		4.3	4.3	0.37
C6257	T2/P1	175	4.3	4.4	0.95
C6258	T2/P1		3.7	3.9	0.53
C6522	T1/P2		4.3	4.3	0.3
C6523	T1/P2	208.5	4.5	4.9	2.17
C6524	T1/P2		3.9	4.7	1.41
C6541	T1/P1		3.9	4.3	1.04
C6542	T1/P1	175	3.7	3.8	0.33
C6543	T1/P1		3.3	3.9	2.24

[a]σ at FC = stress at first crack, σ_{max} = maximum stress, ε frm FC = strain from first crack, MPa = megapascal.

The effect of the casting process (specimens cast in molds and cut from a plaque) on the mechanical performance is also considered.

B. Influence of Fiber Type and Process

Fig. 5 and Fig. 6 show an improved performance (a strain from first crack of almost 2.5%), associated with multiple fine cracks within the gauge length. Variations within similar specimens remain; this is not unexpected and is typical behavior of a ceramic. It seems also plausible that this is in part a consequence of the variability in the microstructure linked with the manufacturing process.

Comparing results (Fig. 5), it would appear that when Process 1 was used, specimens manufactured using fiber T2 exhibit a stiffer response associated with a higher maximum stress (σ_{max}) whereas fiber T1 specimens present a higher ultimate strain. Possibly, fiber T2 promotes enhanced matrix strength due to the resin-bundling, whereas fiber T1 specimens exhibiting first cracking at low stresses enable a higher strain after first crack. These initial results demonstrate that fiber T1 would have an advantage over fiber T2 when using Process 1.

Looking at Fig. 6, specimens containing fiber T1 and manufactured with Process 2 seem to present the highest ultimate strain associated with an even higher maximum stress (up to 5 MPa) compared with specimens manufactured with

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Process 1. It seems that fiber T1, as in Fig. 5, promotes a higher strain and the use of Process 2 enables a higher stress. Process 2 enables, perhaps, a better fiber dispersion and therefore better mechanical performance.
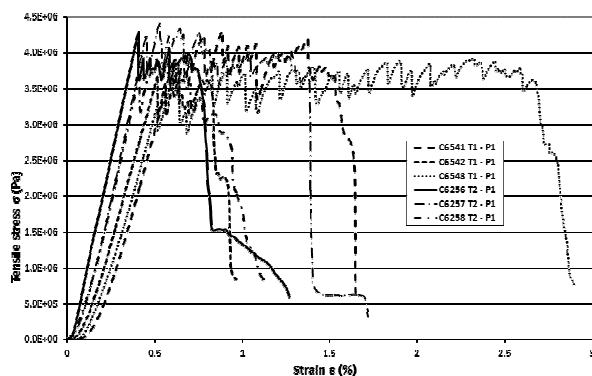

Fig. 5 Stress-strain results for specimens tested in tension: effect of fiber type (Process 1)
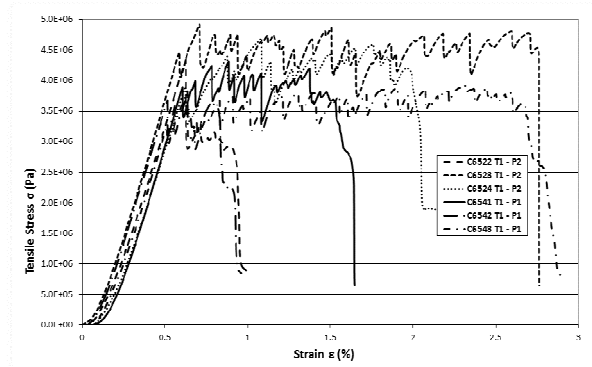

Fig. 6 Stress-strain results for specimens tested in tension: effect of process type (Fiber type 1)

However, it should also be noted that there is still variability in mechanical performance within batches (similar fiber type and process) and understanding these variations is also part of the study.

C. Influence of Casting in a Mold or in a Plaque

It is possible that the casting method would have an influence in physical properties and fiber dispersion and orientation, where the mold, due to its smaller size compared with the plaque, would align the fibers following the tensile axis and promote better tensile performance. The difference in mechanical performance between samples cast in molds and the ones cast in plaques are currently under investigation. The idea is to also reproduce high performance specimens, even when the specimens are cut from a plaque where they are cast.

To have a better understanding of this, a study of the physical properties, fiber dispersion/orientation will also be undertaken.

VI. Concluding Remarks

A. Summary

The pseudo-ductility of ECCs under stress is associated with the formation of multiple fine cracks in the specimen, instead of a single crack leading to brittle failure.

Based on the literature review, a specific composition, containing polymeric fibers of a diameter of 40μm, has been selected for the study. Initial methodologies are established for characterizing the ECC material as well as for testing in tension, based on a Japanese Standard.

Mechanical testing of specimens with a thickness of 30mm reveals promising results in tension as the pseudo-ductility associated with multiple cracks under stress is demonstrated in most of the specimens tested. These results have enabled the evaluation of specific parameters such as fiber type and process, as enhancing the mechanical performance. The casting method would play a role in the mechanical performance. However, more data, along with statistical analysis are required to support these conclusions.

Further work will concentrate on acquiring more data from specimens tested in tension, so as to validate the hypotheses regarding the difference in mechanical performances obtained when using a specific fiber type and process, the influence of the casting method and ways to optimize the mechanical performance.

B. Key-Findings for Tunneling Applications

The current paper has provided an overview and the important parameters to consider before using ECC in future tunneling applications. The study revealed:

(1) ECC material could be used in large thicknesses in structures and still perform well under tensile stresses: a pseudo-ductile behavior associated with the formation of multiple cracks, sustaining a tensile stress of up to 5MPa (typical of a high performance concrete)

(2) Process 2, where the fibers (T1) are added to the mixture after the water addition and at the end, is preferred as offering a better workability of the ECC material in its fresh state, and therefore a better ease of placement.

(3) The casting method or the method of placing the ECC material in structures should be carefully chosen, as it could play an important role in the mechanical performance of the material by controlling the fiber dispersion and most probably the fiber orientation.

(4) Variability in mechanical performance remains and reducing this variability should be a future priority.

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