EXTRUSION OF ECC-MATERIAL

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Abstract

An extrusion process especially designed for extrusion of pipes made from fiber reinforced cementitious materials has been developed at Department of Structural Engineering and Materials at the Technical University of Denmark.

Engineered Cementitious Composite (ECC) materials have been developed in recent years at Department of Civil and Envirionmental Engineering, University of Michigan. These materials have been developed with the special aim of producing high performance, strain hardening materials with low volume concentrations of short fibers in a cementitious material.

ECC material specimens have until now been produced by traditional casting processes. In the present paper results from a recent collaborative research project are documented demonstrating that ECC materials can be extruded in the process referred to above.

The paper briefly describes the extrusion process, along with the engineering concepts of ECC materials. Typical mechanical properties of extruded ECC materials are presented, discussed and compared to properties of traditional ECC materials.

1 Introduction

Considerable attention has been paid recently to the use of extrusion in connection with production of FRC-elements, see e.g. [1] and [2]. The cylindrical shape of pipes obviously works favorably with the extrusion process, however, one of the inherent difficulties with using extrusion processes in connection with production of pipes are the conflicting requirements of on one hand the process itself: the material should be fluid enough to allow for mixing and passage through the die, and on the other hand the requirement of the extruded pipe specimen which should be stiff enough to allow for easy handling without change of shape.

Overall, the difficulties with using traditional extrusion in connection with cementitous materials can be summarized as follows:

- Extrude-ability and shape stability put contradicting demands on mix design
- Serious limitations are put on mix design
- The process results in high wear on machine parts due to the high internal friction in the cementitious materials
- Elaborate mixing is necessary before extrusion is possible
- The elaborate mixing involves danger of damaging of brittle fibers

In the last several years, the University of Michigan has been developing a fiber reinforced cementitious material known as Engineered Cementitious Composites (ECC) which is very different from commonly known FRC [3]. Its mechanical properties in terms of compressive strength are comparable to that of high strength concrete (70MPa) but its tensile ductility is significantly higher (4% to 6%). The strain-hardening behavior of ECC is accompanied by the formation of multiple, closely spaced cracks with crack widths in the sub-millimeter range. After the first cracking strength of the cementitious matrix is reached, the first crack will be bridged by fibers but will not increase in width as in the case of FRC, which tension-softens. Instead, many other fine cracks will develop along the specimen while the applied load at the composite is still being increased. Macroscopically, this strain-hardening behavior of ECC is akin to that associated with plastic yielding in steel.

Closely associated with the strain-hardening behavior is the high fracture toughness of ECC, reaching around 30 kJ/m^2, similar to those of aluminum alloys [4]. In addition, the material is extremely damage tolerant [5], and remains ductile even in severe shear loading conditions [6]. These behaviors appear to be scale invariant, confirmed by specimens with sizes ranging from cm to meters (maximum 1.5 m longest dimension) scale.

ECC [3] utilizes similar ingredients as those in FRC such as water, cement, sand, fiber and some common chemical additives but their combination is based on micromechanical principals in order to achieve ECC’s unique mechanical properties. Coarse aggregates are not used, as they tend to adversely affect the unique ductile behavior of the composite. Unlike some high-performance FRC, ECC does not utilize large amounts of fibers. In general, a fiber volume fraction of 2% or less is adequate to achieve the desired material properties and resulting structural performance. The material selection takes into account the properties of the fiber (length, diameter, strength, elastic modulus, etc.), the properties of the cementitious matrix (fracture toughness, elastic modulus and flaw size) and also the characteristics of the interface between fiber and matrix (chemical and frictional bond, slip-hardening behavior) as well as other fiber/matrix interactions (snubbing, fiber strength reduction due to bending). The micromechanics based design feature, the detailed analysis of the composite constituents and their proper combination in order to achieve multiple cracking and strain-hardening properties, and the resulting extreme tensile ductility make ECC very different from commonly known FRC composites and offer a wide variety of possible structural applications. ECC can be regarded as a new composite engineering concept as much as a new material.

The Objectives of the present investigation were two fold.

- Demonstrate that ECC materials can be extruded in the new extrusion process

- Assess the properties of the extruded ECC in comparison to properties of traditionally cast ECC materials

2 The new extrusion process

A new extrusion process especially designed for extrusion of pipes made from fiber reinforced cementitious materials has been developed at Department of Structural Engineering and Materials at the Technical University of Denmark. The properties of cementitious, polypropylene fiber reinforced extruded pipes have previously been described with special emphasis on the influence of the extrusion process [7].

The new extrusion process is characterized by the fact that the material is mixed with excess water which is later squeezed out during the extrusion process. This ensures easy mixing of the materials and good fiber distribution which is very important in order to achieve reliable mechanical properties. No pre-treatment other than traditional mixing of the fresh material is necessary. During the extrusion a consolidation process takes place where the fresh material is transformed from a fiber/particle suspension to a consolidated and compacted fiber reinforced material with a low water/cement ratio and low porosity. This transformation allows for good particle packing which - in turn - has been shown [7] to enhance the properties of the hardened material including the interfacial bonding parameters in a polypropylene fiber/cementitious system. The extrusion process is described in details in [8] and in [9]. Here a brief overview of the process will be given.

The principle is outlined in Figure 1. Consolidation pressure is applied to the fresh material by a piston and then let into the extrusion chamber. The fresh material is basically a fiber/particle suspension as explained above. The consolidation pressure can be decided according to the material composition and required extruding rate. The material is shaped between the core and the extruder pipe in the fresh state and flows to the draining section without further changes in dimensions. In the draining section, the core and the extruder pipe have a certain amount of holes that allow for the water to leave the material in a de-watering process with the consolidation pressure as the driving force. The consolidation pressure causes de-watering of the fresh material in a zone close to the draining section

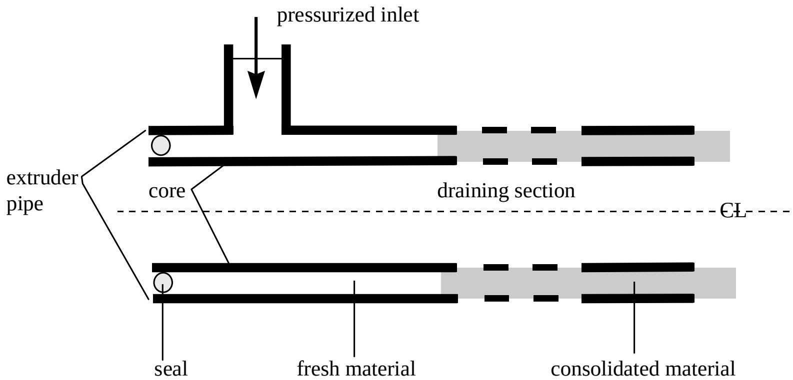

Figure 1. *An outline of the new extrusion principle, showing the key elements of the extrusion chamber.*

where the consolidated fiber reinforced composite material acts as a filter, which only permits water to pass. The length of the consolidated fiber reinforced composite pipes is increased as the water is squeezed out. In order to move the consolidated pipe a mechanical principle is applied.

The consolidated pipe is held back by the frictional stresses acting on the core and the extruder pipe. The core is moved backwards and immediately after forwards. When the core is moved backwards, the consolidation pressure of the fresh material on the cross section of the consolidated pipe combined with the frictional resistance between the consolidated pipe and the extruder pipe exceeds the frictional resistance between the consolidated pipe and the core. Thus, the consolidated pipe will not be moved backwards as the core is moved back. When the core is moved forwards, the consolidation pressure on the cross section of the consolidated pipe combined with the frictional resistance between the pipe and the core exceeds the frictional resistance between the consolidated pipe and the extruder pipe. Therefore, the consolidated pipe section will be moved forwards with the core. By this simple mechanical operation, the consolidated pipe can be moved out in front of the draining section and then more fresh material will flow forwards to the zone near the draining section. By applying suitable consolidation pressure and moving of the core at adequate intervals a continuous production process has been established.

The consolidated material is completely stable and self-supporting. This is clearly demonstrated in Figure 2, showing a 100 mm diameter ECC pipe with 10 mm wall thickness being extruded without any kind of support.

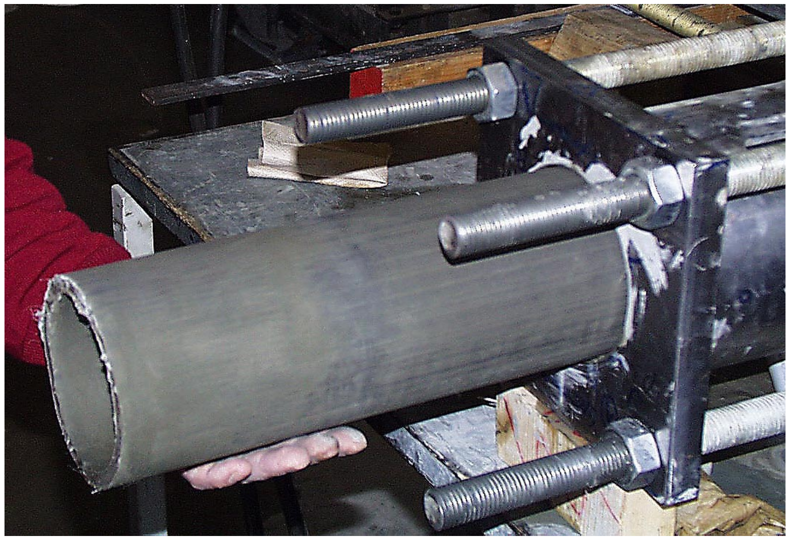

Figure 2. *The extrusion of a 100 mm ECC-pipe.*

3 Materials

3.1 The fibers

The fiber used in the present study of extrusion of ECC is a high modulus polyethylene fiber (Trade name Spectra 900) manufactured by Allied Signal Corporation (US). Fiber properties are listed in Table 1.

3.2 The matrix

The cement used in this study was ordinary rapid-hardening Portland cement delivered by Aaborg Portland (density 3.15 g/cm^3, median particle size 13μm*.)*. A silica fume slurry (solid density 2.17g/cm^3, water/solid silica ratio is equal to 1, median particle size 2.55 μm and quartz powder (density 2.63 g/cm^3, median particle size 9.7 μm) are used as fine particle fillers. Normal quartz sand (density 2.63 g/cm^3, approximate particle size: 0.1 to 0.3 mm) is used as aggregate. An optimization process based on optimum particle packing was carried out varying the mix proportions adopted for extrusion. In Table 1 the mix composition (before extrusion) resulting in optimum mechanical properties is shown.

Fiber Diameter (mm)	Fiber Length (mm)	Elastic Modulus (GPa)	Fiber Strength (MPa)	Fiber Density (g/cm^3)
0.038	19	120	2700	0.98

Table 1. *Polyethylene fiber dimensions and mechanical properties.*

Reactive Powder (C + SF)	Sand	Water	SP	MHEC	Fiber volume (%)
1 (0.975+0.025	0.5	0.365	0.01	0.0012	1.43

Table 2. *Mix proportions (by weight) used in extrusion. The following abbreviations are used: C: cement, SF: solid (dry) silica fume, SP: super plastiziser, MHEC: methylhydroxyethylcellulose. The water content refers to the fresh state, i.e. before extrusion.*

In the present study methylhydroxyethylcellulose (MHEC) is used to increase the viscosity of the fresh material and in this way control the consolidation rate (extrusion rate) during extrusion. The MHEC used in this study is produced by the German company Hoechst under the trade name Tylose FL15002. The content of Tylose FL15002 depends on the mix proportions and fiber content. The MHEC is an effective means of controlling the consolidation rate in the extrusion process which needs to be slowed down in the laboratory extruder since no indication of the position of the consolidation front is available. In this preliminary study a constant MHEC content was used.

3.3 Material structure

Examination of a polished section of the extruded ECC, see Figure 3, in SEM under secondary electron mode reveals a reasonably good distribution of the PE fibers (dark small particles). The section is a diametric cut showing that most fibers are aligned in the circumferential direction. No large pores can be observed, as are commonly found in cast specimens. The estimated porosity and density data before and after consolidation is given in Table 3.

Porosity before extrusion (cm^3/cm^3)	Porosity after extrusion (cm^3/cm^3)	Density before extrusion (g/cm^3)	Density after extrusion (g/cm^3)
0.41	0.28	2.12	2.35

Table 3. *Porosity and Density of a typical extruded ECC . The porosity is estimated as the volume of free water relative to the total volume of the material.*

3.4 Mechanical properties

The pipe is loaded in the typical crushing test configuration with line loads p per length along opposite generatrices in crushing load configuration.

The data from crushing tests can be represented as stress versus deformation data converting the line load on the pipe to stresses using a linear elastic analysis. Denoting the outer diameter of the pipe d_0 and the inner diameter d_i while the line load is denoted p, the stress f_{cr} can be expressed through:

$$f_{cr} = \frac{6}{\pi}\frac{p}{d_0}\frac{1+\frac{d_i}{d_0}}{\left(1-\frac{d_i}{d_0}\right)^2} \tag{1}$$

If the material behaves in a linear elastic perfectly brittle manner then, according to the beam theory of curved beams, f_{cr} coincides with the tensile strength f_t when p corresponds to the ultimate loading capacity of the pipe.

After an initial curing in 100% RH in room temperature for 24 hours, the tested specimens had been cured in water at 50^o C for 1 week before testing.

Applying the linear elastic interpretation a typical stress-deflection curve is shown in Figure 4 for the material described above with a fiber volume concentration of 1.43% which during consolidation is increased to about 1.75%. The stress-deformation curves typically show an initial linear part up to about 14 MPa at a deformation of 0.1 mm. Then follows a slight descending part down to about 10 MPa at about 0.4 mm deformation followed by a jagged part with an overall ascending trend. The maximum load carrying capacity is 22.5 MPa, which is reached over a defomation range of 2-8 mm. No overall descending trend was observed at the maximum deformation of 8 mm.

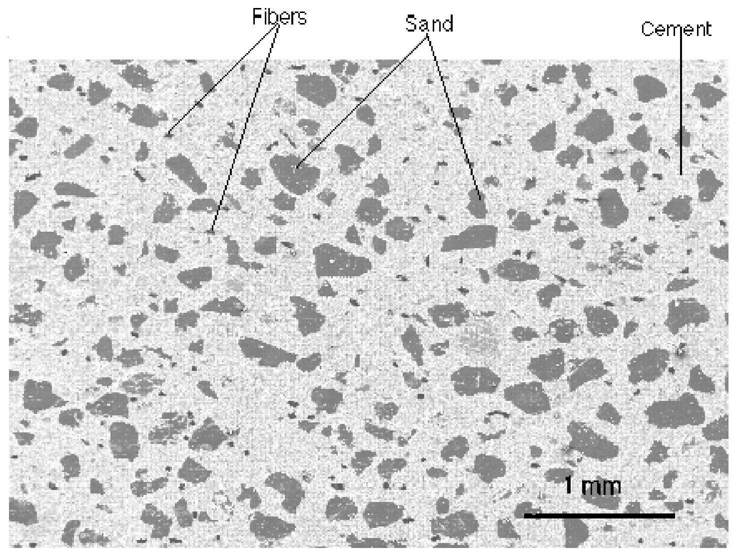

Figure 3. *SEM-picture showing micro-structure of extruded ECC-material.*

4 Discussion and conclusions

The extrusion of ECC pipes by a newly patented extrusion technique has been carried out. The experimental results show that the ECC material can work well with the present extrusion process. A number of different ECC mixes have been extruded demonstrating the robustness of the process. The specimens leaving the extruder are completely stable and easy to handle.

A partial optimization of the matrix has been carried out indicating that silica-fume can be added up to a content of 2.5% of the cement weight. Furthermore, sand and powders should be combined in order to obtain maximum packing density. Obtaining maximum packing density results in very low water/reactive powder ratios (down to 0.21) in the consolidated material. At the same time the material appears extremely homogeneous. This should result in extremely durable and impermeable materials even though these properties have not yet been tested. The results presented here seem to indicate that an even better packing density can be obtained by increasing the amount of sand compared to what have been used in the present investigation.

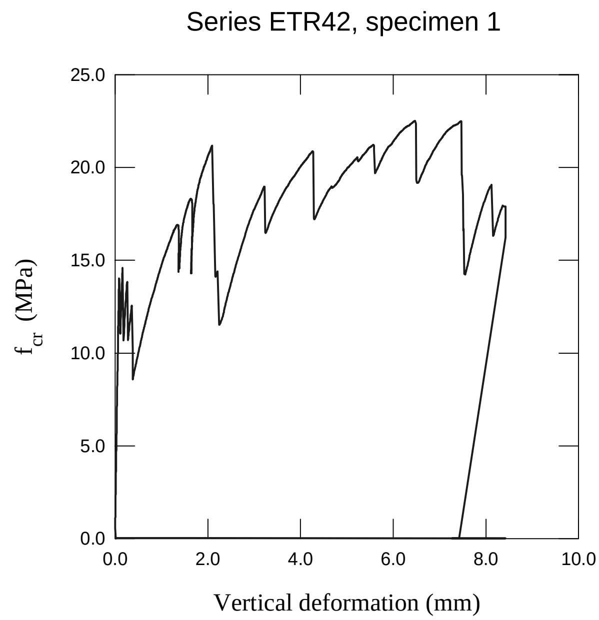

Figure 4. *Elastic stress versus total vertical deformation of pipe in crushing load configuration.*

Increasing fiber content results in improved mechanical properties without causing workability problems as long as the density of the consolidated material can be maintained. When compared with traditionally cast 2nd generation ECC materials comparable mechanical properties have been obtained with the best extruded ECC material: first crack strength between 10 and 15 MPa, and an ultimate MOR at 22.5 MPa. Note that this has been done only through mechanical densification without any chemical additives to improve the wettability of the PE fiber. Taking into account that the addition of such additives typically improves MOR by a factor 2 in traditionally cast ECC the effect of extruding ECC has been clearly demonstrated. Furthermore, it is possible to obtain much lower water/reactive powder ratios and possibly higher fiber volume concentrations with the extrusion process than with traditional casting processes. The extruded ECC pipes have higher load capacity and a much higher ductility and deformation capacity than any previously extruded FRC pipes.

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