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ENGINEERED CEMENTITIOUS COMPOSITE WITH BLAST FURNACE SLAG AND LIMESTONE POWDER

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Abstract

This paper presents a research on developing Engineered Cementitious Composite (ECC) with locally available materials in the Netherlands, i.e. Portland cement, blast furnace slag (BFS) and limestone powder. Considering the advantage of the replacement of Portland cement by BFS and limestone powder, it can be expected that the use of BFS and limestone powder in ECC not only reduces the cost and enhances the sustainability, but also enhances the workability, mechanical properties and durability of ECC. In order to optimize the mix proportion, four mixtures with different limestone powder content were investigated with compressive test, four-point bending test and uniaxial tensile test. The mixture M3, with the Portland cement to BFS to limestone powder ratio of 1:1.2:2 by weight, exhibits the best deformation capacity at 28 days. It was also found that there is a strong correlation between the tensile strain capacity of ECC and the margin between ultimate tensile strength.

Keywords: Engineered Cementitious Composites, optimizing mix proportion, blast furnace slag, limestone powder, uniaxial tensile capacity.

1. INTRODUCTION

ECC, short for Engineered Cementitious Composites, is a class of ultra ductile fibre reinforced cementitious composites originally developed at the University of Michigan in the early 1990s [1]. It is a micromechanically designed cement-based material taking into account the mechanical interactions between fibre, matrix and interface and minimizing the fibre content to 2% by volume. Unlike conventional cement-based materials, ECC shows tensile strain-hardening behaviour with the strain capacity in the range of 3-7%, which is several hundred times of the strain capacity of conventional cement-based materials. The high ductility of ECC is achieved by multiple cracking with crack width self-limited to about 60 μm. Fig. 1 shows a typical tensile stress-strain curve of ECC and the tight crack width control.

Under the same pre-tension load up to 1.5% deformation, the crack width of ECC is much smaller than that of reinforced mortar and ECC exhibits a water permeability several orders of magnitude lower than reinforced mortar [2]. ECC can significantly enhance the durability of structures exposed to aggressive environments, such as freeze-thaw cycles, hot-wet cycles, chloride immersion, deicing-salt exposure and alkali-silicate reaction [3]. ECC has been successfully employed in coupling beams in high-rise buildings to enhance their seismic resistance, in link slabs on bridge decks and in concrete repairs.

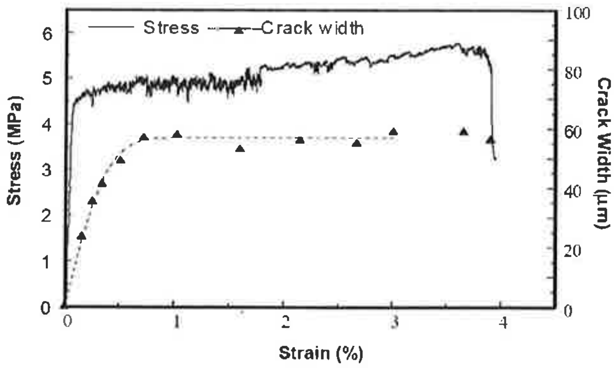

Figure 1: Tensile stress-strain curve and tight crack width control of ECC [7].

This paper presents a research on the development of ECC with locally available materials, i.e. Portland cement, blast furnace slag (BFS) and limestone powder, performed at the Delft University of Technology. BFS is a by-product from the manufacture of pig iron, and limestone powder is produced by finely ground limestone. The replacement, up to 70%, of Portland cement by BFS does not have much effect on compressive strength of concrete after 28 days but results in a reduction of tensile strength [4], which is conducive to producing ECC achieving high compressive strength and maintaining high ductility. The finely ground BFS with small particle size can improve the particle packing surrounding fibres and can, therefore, result in good fibre/matrix interface. The addition of BFS and limestone powder also improves the fresh properties and durability of concrete [5, 6]. It can be expected that the use of BFS and limestone powder in ECC not only reduces the cost and enhances the long term performance, but also enhances workability, mechanical properties and durability of ECC. The mechanical properties of ECC with BFS and limestone powder were investigated by means of compressive, four-point bending and uniaxial tensile tests, and the results are reported here.

2. MATERIALS AND METHODS

Portland cement CEM I 42.5 N was used. Fig. 2 shows the particle size distribution curves of CEM I 42.4 N, BFS and limestone powder, which were measured with laser-diffraction technique. The minimum particle size, which this method can detect, is 1.8 µm. the average particle sizes of CEM I 42.4 N, BFS and limestone powder were 16.18 µm, 10.55 µm and 13.41 µm, respectively. The mix proportion of ECC is listed in Table 1. From mixture M1 to M4 limestone powder content increased, in order to find out the optimum limestone powder content. The water-to-powder ratio and superplasticizer content decreased slightly in order to get good workability. The polyvinyl alcohol (PVA) fibre with a length of 8 mm and a diameter of 40 μm was used in the content of 2% by volume.

The solid materials, i.e. CEM I 42.5, BFS and limestone powder were first mixed with a HOBART® mixer for 1 minute. Then water and superplasticizer were added. The sample was mixed at low speed for 1 minute and then at high speed for 2 minutes. After that, fibres were added at low speed and the sample was mixed at high speed for another 2 minutes. The fresh ECC was cast into a beam with the dimension of 160 mm × 40 mm × 40 mm for compressive test. Coupon specimens with the dimension of 240 mm × 60 mm × 10 mm were cast for four-point bending and uniaxial tensile tests. After 1 day curing in moulds covered with plastic paper, the specimens were cured under sealed condition at a temperature of 20 °C for another 27 days.

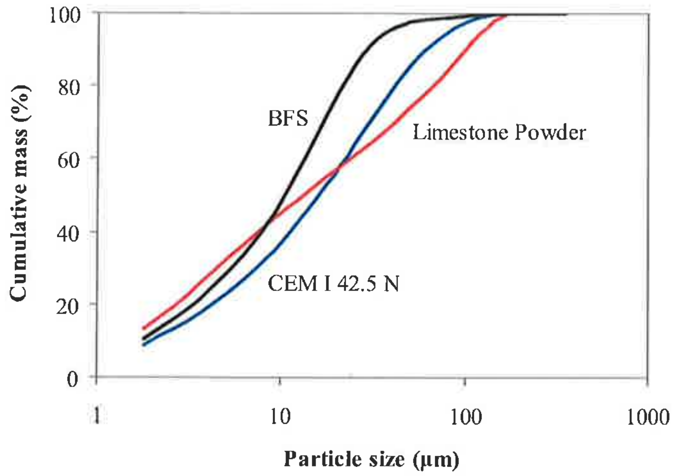

Figure 2: Particle size distribution of CEM I 42.5 N, BFS and limestone powder, measured with laser-diffraction technique.

Table 1: Mix proportion of ECC.

Mix Number	CEM I 42.5 N (g)	BFS (g)	Limestone Powder (g)	Water/Powder ratio	Super-plasticizer (g)
M1	1000	1200	800	0.270	25
M2	1000	1200	1500	0.265	23
M3	1000	1200	2000	0.260	18
M4	1000	1200	3000	0.256	18

After 28 days curing, the beam specimens were cut into 3 cubes with the dimension of 40 × 40 × 40 mm^3 used for compressive tests. The compressive strength was obtained by averaging the results of three measurements. The coupon specimens were evenly cut into 4 pieces with the dimension of 120 mm × 30 mm × 10 mm. These specimens were used in four-point bending test. The support span of four-point bending test set-up was 110 mm and the load span was 30 mm. The flexural strength and deflection were calculated with the results of three measurements. The uniaxial tensile tests were carried out on the coupon specimens. The testing gauge length was 70 mm and the deformation of specimens was measured with LVDTs. The tensile load was applied on the ends of coupon specimens at the speed of 0.001 mm/s. More than four specimens were tested for each mixture.

3. RESULTS AND DISCUSSION

Under four-point bending load or uniaxial tensile load, all specimens exhibited multiple-cracking behaviour as shown in Fig. 3. Among the four mixtures M3 exhibits the best deformation capacity. Fig. 4 shows flexural load-deflection curves and tensile stress-strain curves of M3. In the flexural load-deflection curves, the maximum flexural stress was defined as flexural strength and the corresponding deflection was defined as flexural deflection capacity. In the tensile stress-strain curves, the stress at the first drop associated with the first crack was defined as first cracking strength. Similarly, the maximum stress was defined as ultimate tensile strength and the corresponding strain was defined as tensile strain capacity. By averaging the results of three four-point bending measurements and four uniaxial tensile measurements, the flexural deflection capacity and tensile strain capacity of M3 can be calculated and they are 3.8 mm and 3.1 %, respectively. The comparison of flexural deflection capacity and tensile strain capacity of four mixtures are plotted in Fig. 5. The results of four-point bending test and uniaxial tensile test agree with each other in terms of deformation capacity, and the flexural deflection capacity and tensile strain capacity are in the same order from large to small: M3, M4, M2 and M1. Even though M1 exhibits the smallest deformation capacity, M1 has a tensile strain capacity of 1.7%, which is much higher than that of conventional concrete (about 0.01%).

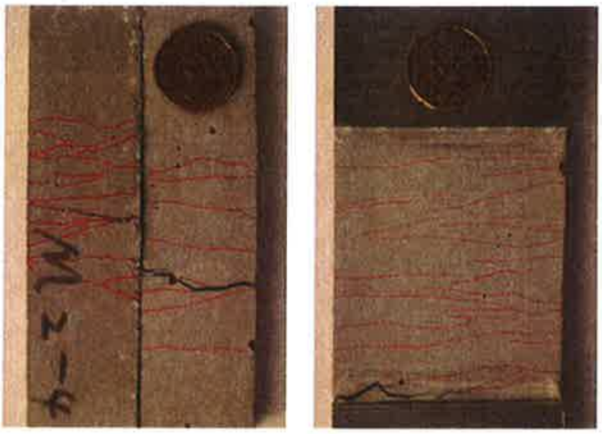

Figure 3: Multiple-cracking behaviour of specimens under four-point bending load (left) or uniaxial tensile load (right).

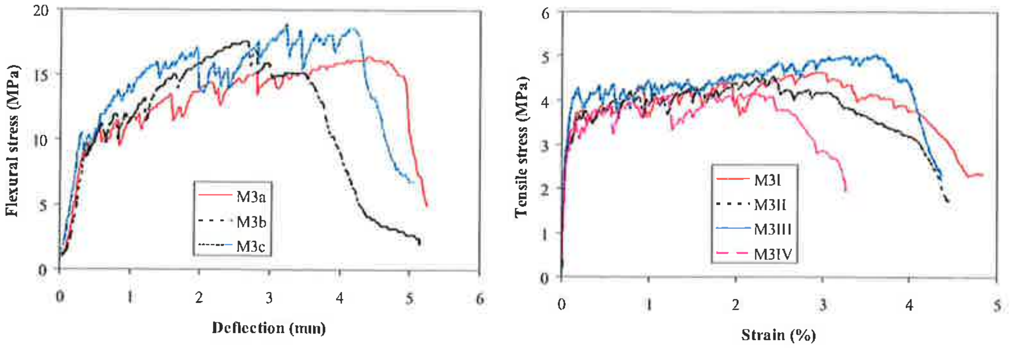

Figure 4: Flexural load-deflection curves (left) and tensile stress-strain curves (right) of M1 with the average flexural deflection capacity of 3.8 mm and the average tensile strain capacity of 3.1%.

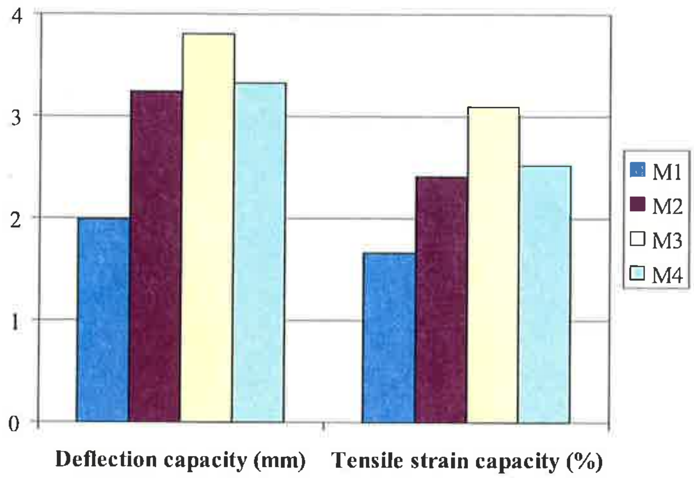

Figure 5: Flexural deflection capacity and tensile strain capacity of four mixtures.

Fig. 6 displays the results of compressive, flexural, first cracking and ultimate tensile strengths of four mixtures. From M2 to M4, as the limestone powder content increases, the compressive strength decreases. The compressive strength of M1 is not available, and it can be expected that M1 might have a compressive strength higher than the other mixtures, since it has less limestone powder addition. The flexural strength and first cracking strength of four mixtures have the same trend as the compressive strength, and range from 21.8 MPa to 16.5 MPa and from 3.5 MPa to 3.0 MPa, respectively. The ultimate tensile strength behaves differently. M3 exhibits the highest ultimate tensile strength of 4.4 MPa, which is tightly followed by M2. M1 has the lowest ultimate tensile strength of 3.7 MPa.

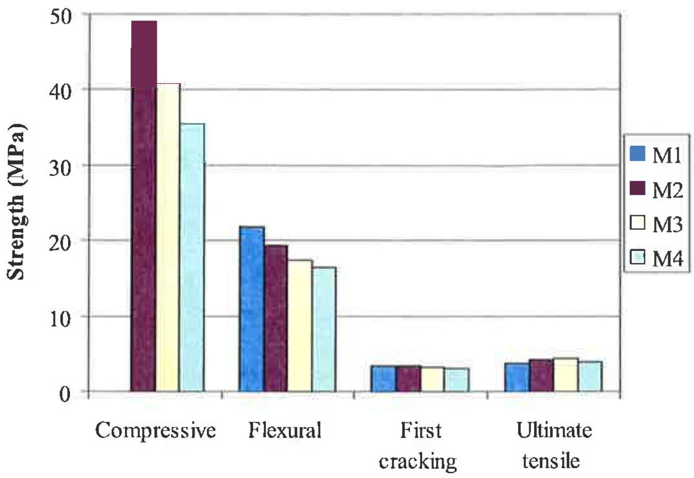

Figure 6: Compressive, flexural, first cracking and ultimate tensile strengths of four mixtures (The compressive strength of M1 is not available).

The multiple-cracking behaviour of ECC results from the interaction between fibre and matrix. One of the criteria for multiple cracking is that the matrix tensile strength must be lower than the bridging strength between fibres and matrix in this cross-section [8]. Once the matrix cracks, tensile load is transferred to fibres. As the crack opens, fibres start to slip inside the matrix. Due to the slipping-hardening property of the fibre/matrix interface, fibres can hold increasing tensile load, which causes further cracking. Repeating the above process results in multiple cracking and large tensile strain. Finally, ECC fails when the tensile stress exceeds the bridging strength of a cracking plane. From M1 to M4, as the tensile strength of the matrix decreases reflected by the first cracking strength, the matrix becomes easier to crack. On the other hand, the increasing addition of limestone powder working as an inert filler leads to a weak fibre/matrix interface. Li [8] suggested that both too weak and too strong interfaces are not conducive to the strain-hardening behaviour of ECC. Too weak interface with bad fibre bridging properties results in the pull-out of fibres from matrix and a low fibre/matrix bridging strength. As a result, ECC fails shortly after matrix cracks. Too strong interface results in the rupture of fibres instead of slipping and a small crack opening. Even though a lot of cracks form, the cracks with small opening can not contribute much to the deformation of ECC. The experimental results in this study conform this, and reveal that M3 has the optimum limestone powder content in terms of deformation capacity.

According to the discussion in the last paragraph, there seems to be a strong relation between tensile strain capacity of ECC and the margin between the ultimate tensile strength and first cracking strength, which is plotted in Fig. 7. A larger margin between ultimate tensile strength and first cracking strength gives the matrix more chances to crack. Therefore, in ECC mix design in the future, the emphasis will be placed on enlarging the margin between ultimate tensile strength and first cracking strength. A good linear relation between the tensile strain capacity and the flexural deflection capacity is also found as shown in Fig. 8. This relation was already reported and employed in predicting the tensile strain capacity of ECC with the flexural deflection capacity [9].

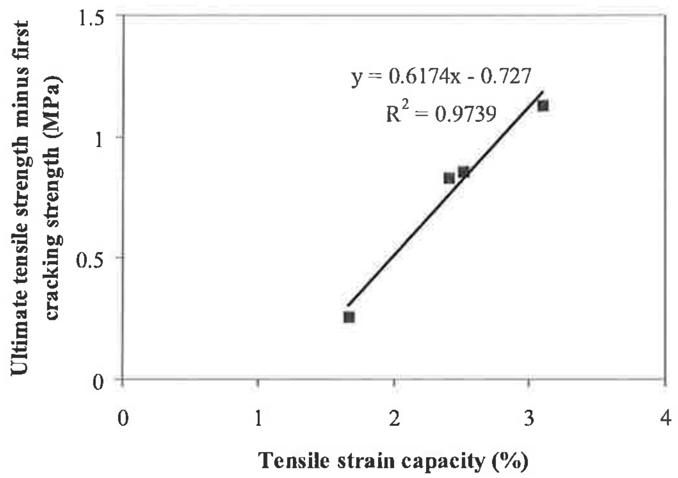

Figure 7: Relation between the tensile strain capacity and the margin between ultimate tensile strength and first cracking strength.

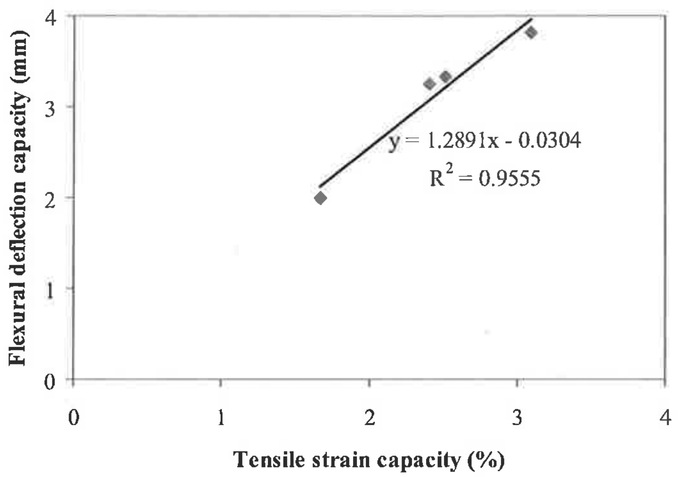

Figure 8: Relation between the tensile strain capacity and the flexural deflection capacity.

4. CONCLUSIONS

- Under four-point bending load or uniaxial tensile load, all specimens exhibit multiple-cracking behaviour. Among the four mixtures M3, with the Portland cement to BFS to limestone powder ratio of 1:1.2:2 by weight, has the best deformation capacity and its flexural deflection capacity and tensile strain capacity are 3.8 mm and 3.1 %, respectively.
- From M1 to M4, as the limestone powder content increases, the compressive strength, flexural strength and first cracking strength decrease. While, M3 exhibits the highest

ultimate tensile strength of 4.4 MPa, and M1 has the lowest ultimate tensile strength of 3.7 MPa.

- From experimental study, it is found that there is a strong correlation between the tensile strain capacity and the margin between ultimate tensile strength.

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