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ABSTRACT: High performance, fibre-reinforced, cement-based composites (HPFRC), distinguished from standard FRC by its superior tensile response, are currently being developed all over the world. However, these composites remain expensive, requiring specialist application and reliance on long-term maintenance cost reduction for acceptance by industry. In order to reduce the cost, the requirement of super fine grading of the aggregate, as well as the total aggregate content, are addressed in this paper.

An experimental programme is reported, which aims to quantify the effects of these variables on the tensile behaviour of a particular HPFRC.

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Technical Paper

The Role of Aggregate in High Performance Fibre Reinforced Cement-based Composites

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Biography

Gideon van Zijl (PrEng) is Professor of Civil Engineering and Head of the Division for Structural Engineering of the University of Stellenbosch and part-time research fellow at the Delft University of Technology, The Netherlands. He obtained a BEng and MEng (Civil Eng, 1990) degree at the University of Stellenbosch, and a PhD (Civil Eng, 2000) at the Delft University of Technology. His research group develops and models advanced cement-based materials, in co-operation with several consulting, construction, supplying and manufacturing companies from the local Civil Engineering industry.

Abstract: *High performance fibre reinforced cement-based composites (HPFRC), distinguished from standard FRC by its superior tensile response, are currently being developed all over the world. However, these composites remain expensive, requiring specialist application, and reliance on long-term maintenance cost reduction for acceptance by industry. In order to reduce the cost, the requirement of super fine grading of the aggregate, as well as the total aggregate content, are addressed in this paper. An experimental program is reported, which aims to quantify the effects of these variables on the tensile behaviour of a particular HPFRC.*

Keywords: *Fibre reinforcement; tensile response; strain hardening; engineered cement-based composites*

Introduction

In the development of high performance fibre reinforced cement-based composites (HPFRC), in particular engineered cement-based composites (ECC), which exhibit strain hardening and tough tensile response, spanning over tensile strains beyond 5%, it has become usual to use extremely fine aggregate. Analogous to high (compressive) strength concrete (HSC), where a significant reduction in the water: binder ratio (W/B) must be supplemented with a careful choice of aggregate, both these parameters play a governing role in ECC, as shown recently by Van Zijl and Boshoff (2005). Through their influence on the fibre-matrix interfacial bond strength, the W/B and aggregate: binder ratio (A/B) strongly influence the ultimate tensile strength of FRC, including ECC.

Super fine silica sand, with an ASTM grading of F50-F70 (ASTM C 50-70) was used by research groups at Michigan University (Li et al., 1995), as well as at Cornell University (Kesner et al., 2003). In a recent research project at the University of Stellenbosch, the ASTM sand grading F95 was used (Van Zijl and Boshoff, 2005). While such fine sand can be ordered in the USA as a standard aggregate, it must be specially graded in South Africa, with significant cost implication. In addition, the total aggregate content, which is usually in the order of 70-75% in concrete, lies in the range 30-50% by mass in ECC. It is, therefore, not surprising that these materials are expensive, intended for special applications only up to now.

Lower aggregate proportion is known to lead to higher levels of shrinkage and creep in concrete. This has been confirmed through shrinkage and compressive creep measurement (Van Zijl et al., 2002) for ECC. For shrinkage, however, another mechanism acts in ECC in addition to the lower aggregate content, namely the prevention, or control of shrinkage cracks to narrow widths by fibres. Through such crack control, the real free shrinkage is realised, as opposed to apparently lower shrinkage of unreinforced mortar or concrete, measurement of which includes the cracks.

In this paper a systematic study of the influence of sand grading, as well as the amount of sand used in ECC is reported. The influence is measured and quantified in terms of mechanical response to direct and indirect tensile testing. The current study is restricted to the single fibre volume of Vf = 2% of polyvinyl alcohol fibres (PVA) of length 12mm and diameter 40 μm, and a single W/B ratio of 0.4. These proportions have been shown to produce strain hardening tensile response, with ultimate strains ranging up to and beyond 5%.

Local sand for ECC

As well-graded natural sands diminish in South Africa, in particular in the Western Cape, dune sands, of which vast amounts are available, become an option

Technical Paper *(cont.)* - High performance fibre reinforced cement-based composites

for use as fine aggregate in concrete, despite their poor grading. Improvement is possible by blending these sands (Loedolff and Van Zijl, 2005) with sands from other sources, leading to greater compactability and better quality concrete. Fine sands are required for combination with super fine fibres, with diameters in the range 10-40 μm. To study the possibility of using natural sand like that from Phillippi, two gradings of this sand were prepared. Firstly the super fine F95 grading, according to the USA Silica ISO 9002 Certified Quality System test, was prepared. This grading produces a fineness modulus (FM) of 0.39. Secondly, a fine sand was prepared from Phillippi sand by sieving off all particles of 0.3mm and larger. This produced a sand with an FM of 0.80, from the natural Phillippi sand with an FM of 1.48. The gradings of these sands are shown in Figure 1.

While fine silica sand is available, the abundance of Phillippi sand made it a pragmatic choice for the current study, considering cost. Another reason is the well-rounded nature of the sand grains in Phillippi sand. The F-series sands used in research programs in the USA comprised rounded to sub-angular grains used in the USA Silica ISO 9002 Certified Quality System. With these sands, superior strain hardening ECC's were developed, as well as superior casting finishes. Finally, by using only Philippi sand, the aggregate characteristic particle shape and roughness are kept constant, enabling the influence of the sand grading and quantity to be studied objectively.

Experimental program

A previously designed and tested ECC mix (Van Zijl and Boshoff, 2005), known to produce strain hardening, was used. This mix is given in Table 1. Note that the proportions can be found by division of the indicated masses, for instance the water: binder ratio is 0.40 : (0.45+0.50+0.05) = 0.40 by mass. To study the

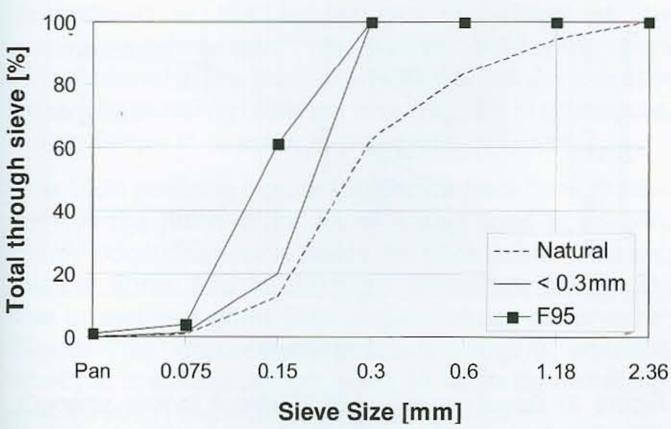

Figure 1: Gradings of Phillippi sand used in test program

influence of both grading and proportion of sand, two series of specimens were prepared, as summarized in Tables 2 and 3. Firstly, the sand grading was varied, but keeping the constant A/B = 0.5. Secondly, the F95 grading was used to prepare mixes of increasing A/B in the range $0.3 \leq A/B \leq 1.5$. Four specimens of each mix were made. Note that this represents a minimum number of specimens of each type from which trends can be derived with confidence.

Direct tensile testing was performed, requiring dog bone shaped specimens, as shown in Figure 2. The nominal thickness was 15mm. Note that such small thickness relative to the fibre length implies that the results are applicable to thinwalled applications, in which two-dimensional orientation of the fibres is likely to be enforced by the boundaries.

The specimens were tested under displacement control in a Zwick Z250 Materials Testing Machine, at the fixed displacement rate of 0.15mm/minute.

Table 1 Mix design for specimens

Constituent	Mass
Water	0.40
Binder:	
Cement	0.45
Fly Ash	0.50
Slagment	0.05
Aggregate	0.5
Fibres (by portion of total volume)	2%

Table 2 Test series 1: Aggregate grading

Set	A/B	Sand Grading
1.1	0.5	Phillippi
1.2	0.5	0.3mm
1.3	0.5	F95

Table 3 Test series 2: Aggregate content

Set	A/B	Sand Grading
2.1	0.3	F95
2.2	0.5	F95
2.3	0.7	F95
2.4	1.0	F95
2.5	1.5	F95

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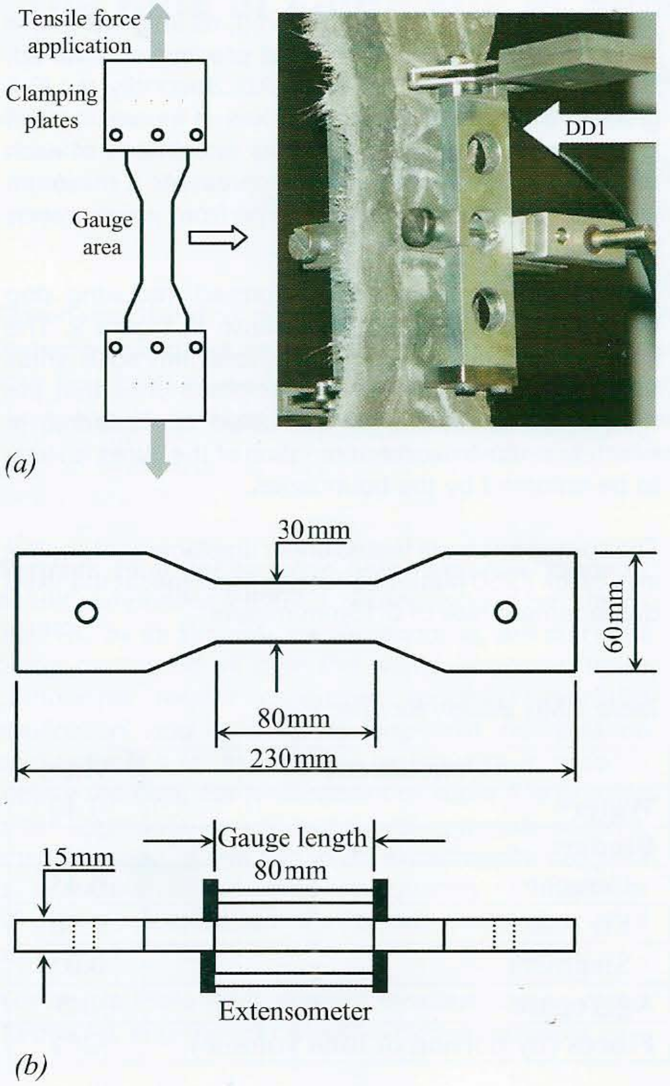

Figure 2: (a) Direct tensile testing of (b) dog bone shape specimen.

Strength evolution in ECC

To investigate an appropriate testing age, a separate experimental study was performed on the rate of gain of direct tensile, as well as compressive strength. For this experimental test series 3, as summarised in Table 4, the mix as indicated in Table 1 and set 1.1 (Table 2) was used to prepare a total of 16 dog bone specimens (4 of each set), as well as 9 (3 of each set) small cubes (50mm x 50mm x 50mm). The compressive specimen size was restricted to enable testing in the same materials testing machine (Z250) as used for the tensile tests. Thereby, the full compressive load-deformation response could be monitored, as opposed to only the peak resistance registered by standard compressive testing equipment. The small grain sizes used in these materials justify the use of such small specimens. All the specimens were cured in water at 23°C until the testing age indicated in Table 4, at which stage they were tested directly after being taken out of the water.

Table 4 Test series 3: Strength evolution

Set	Age at testing (days)	A/B	Sand Grading
3.1	7	0.5	F95
3.2	14	0.5	F95
3.3	21	0.5	F95
3.4	28	0.5	F95

Detailed description of these tests and the results are described by Stander (2004). The results are shown graphically in Figures 3-5. The well-known slow hydration process of high fly ash (FA) content concrete/mortar is reflected in the matrix cracking stress (σ_M) development, the tensile elastic modulus (E_M), as well as the compressive strength (σ_{cu}) development. However, a clear trend of earlier development of the ultimate strength is apparent. This is in agreement of fibre pull-out studies performed by Chan and Li (1997). The interface zone between fibres and the matrix, which governs the frictional bond between these two constituents, develops at a faster rate, reaching maturity at or before 14 days. Based on these results a testing age of 14 days was chosen for the series 1 and 2 specimens.

Results: the role of aggregate in ECC tensile response

Stress-strain results for all the specimens of sets 2.1 and 2.2 in Table 3 are shown in Figure 6 (a) and (b) respectively. Strain hardening tensile response was indeed achieved for these sets, as was the case for all other sets, although to a lower degree of ductility. Reasonable repeatability is apparent for three of

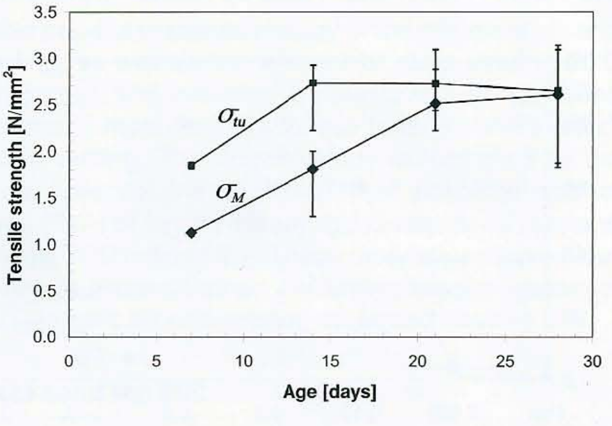

Figure 3: Development of ECC direct tensile strength, showing first matrix crack stress and ultimate tensile stress.

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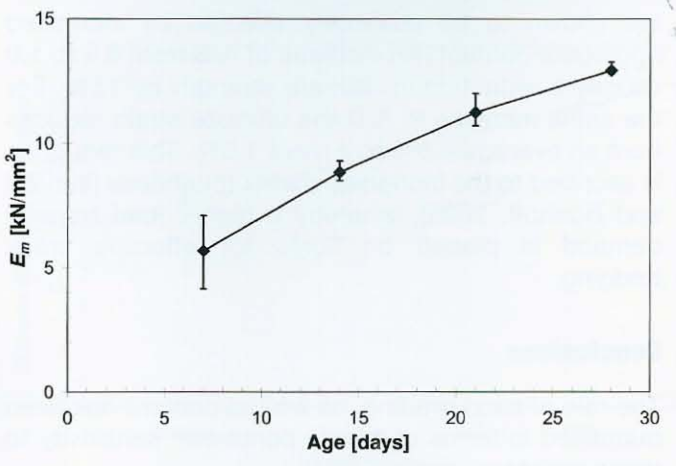


Figure 4: Development of ECC tensile elastic modulus.

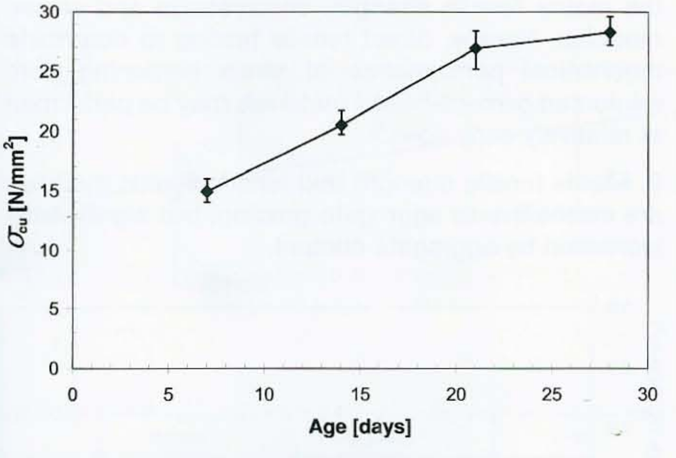


Figure 5: Development of ECC compressive strength.

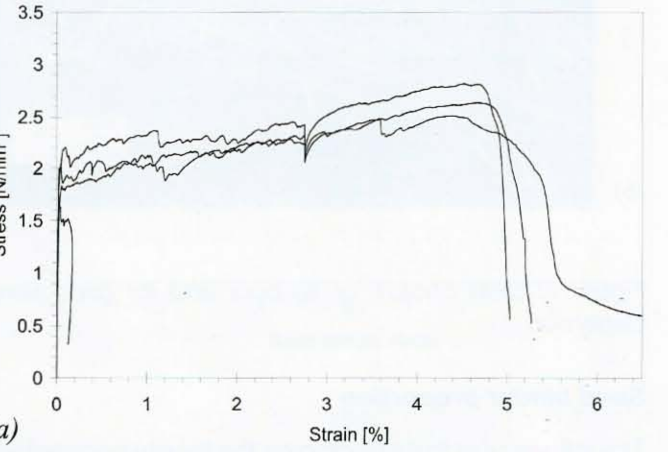
the four specimens of each of these sets. Note that close inspection of the fourth specimen of series 2.1 (Figure 6(a)) revealed a combination of a large void and extreme bundling of fibres in the failing section. This result was considered as an out-layer and not considered in the subsequent evaluation of the experimental results. No further out-layers were encountered in the total experimental set. An example of severe bundling of fibres, which results in premature, brittle failure in tension, is presented in Figure 7.

The SEM photo in Figure 7(a) shows poor fibre dispersion in the plane of failure of a dog bone specimen. Such poor dispersion leads to poor crack bridging by the fibres and subsequent premature failure. On the other hand good fibre dispersion, as observed in Figure 7(b), ensures good crack bridging, enabling multiple cracking, which leads to large deformability before strain localisation and failure occurs.

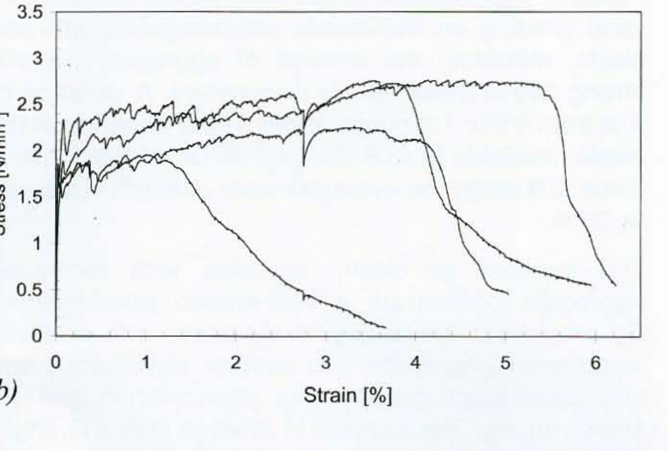
In Figure 8 all the direct tensile results of both series 1 and 2 are shown graphically in terms of minimum, average, and maximum values of first cracking stress, elastic modulus and the ultimate tensile strain. Note that the ultimate tensile strain is taken in this study as the strain coinciding with 80% of the ultimate stress on the descending stress-strain branch. Detailed descriptions of all the results are given in Van Dyk (2005).

Sand grading

From the left hand column of graphs in Figure 8 it is apparent that the matrix strength and, yet to a lesser degree, the elastic modulus are insensitive to the sand gradings employed in this study. However, a significant improvement in both ultimate tensile strength and strain is achieved by using finer graded sand. It is postulated that the fibre-matrix frictional bond is improved by better packing of well-graded, fine aggregate particles. Crack bridging by fibres is thus enhanced, leading to higher ultimate tensile resistance of the composite, as well as increased ultimate strain.



(a)



(b)

Figure 6: ECC tensile response for (a) A/B=0.3 and (b) A/B=0.5 of F95 graded Phillippi sand.

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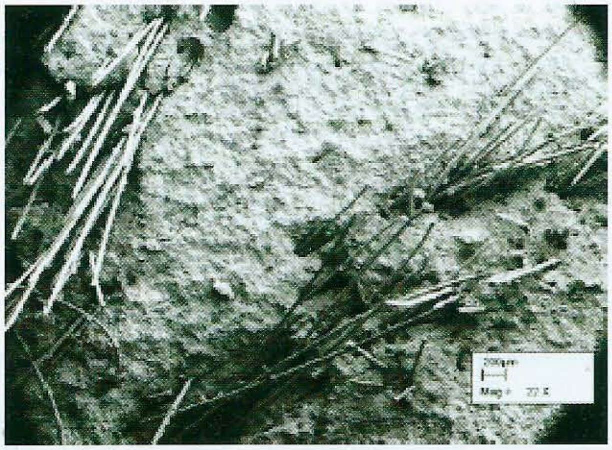
(a)



(b)

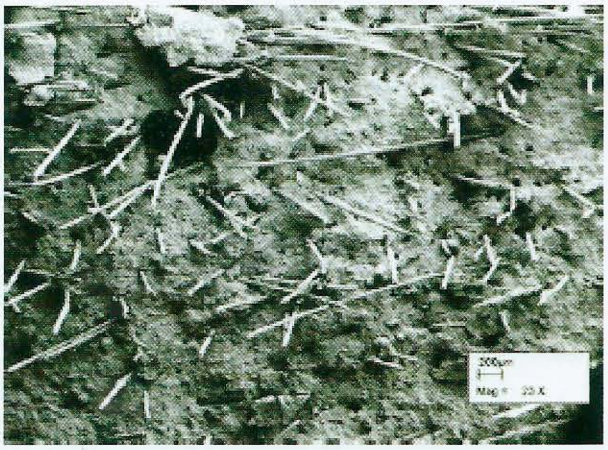


Figure 7: SEM photo's of (a) poor and (b) good fibre dispersion.

Sand binder proportion

The influence of the A/B ratio on the tensile parameters of the tested ECC is shown in the right hand side of Figure 8. As opposed to the insignificant influence of sand grading on the matrix (cracking) strength and elastic modulus, the amount of aggregate plays a strong role in these tensile parameters. A variation of A/B from 0.3 to 1.0 brings about a near doubling of the elastic modulus from 8 kN/mm^2 to 15 kN/mm^2. In the same A/B range the average matrix strength increases by 31%.

The increase in elastic modulus with increased aggregate content is a well-known phenomenon. By employing the theory of mixtures, with one stiff constituent (aggregate) and another, significantly less stiff constituent (paste), this phenomenon can be shown clearly. The increase in average matrix strength is ascribed to the greater tortuosity in the crack path upon increased aggregate content.

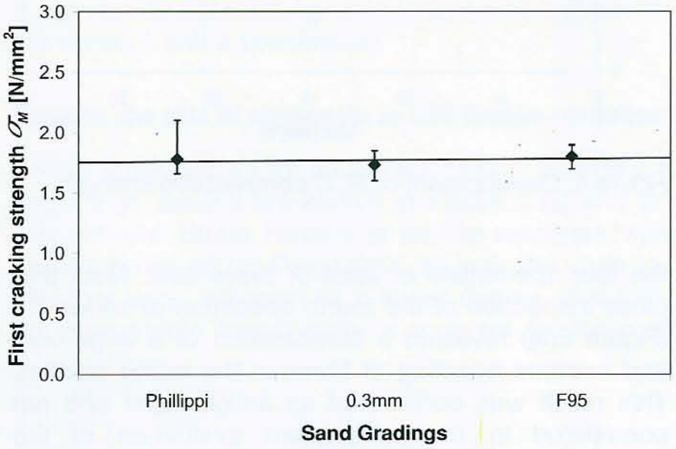
The ultimate tensile strength and strain of ECC are shown to be adversely affected by increased aggregate content. An increase of A/B from 0.3 to 1.0 causes a reduction in ultimate strength by 15%. For the same increase in A/B the ultimate strain reduces from an average 4.8% to a mere 1.5%. This reduction is ascribed to the increased matrix toughness (Van Zijl and Boshoff, 2005), whereby a higher load transfer demand is placed on fibres for effective crack bridging.

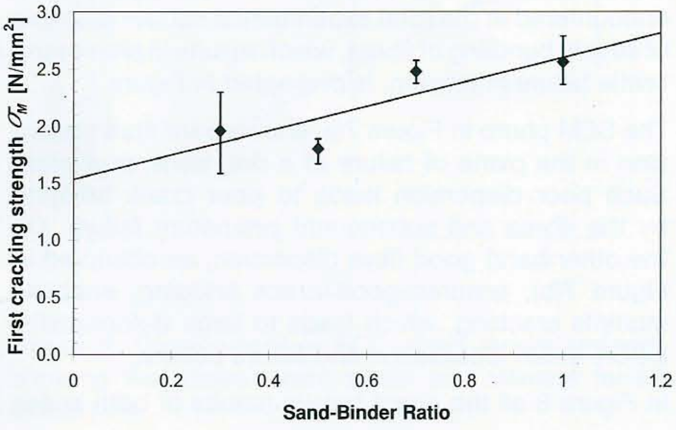
Conclusions

The role of sand grading, as well as content has been quantified in terms of tensile parameter sensitivity to these variables.

1. Under the condition of wet curing, the ultimate tensile strength of ECC develops within 14 days, as opposed to the longer hydration time required for the matrix tensile strength, compressive and elastic modulus. Hereby, direct tensile testing to determine mechanical performance of strain hardening fibre reinforced cement-based materials may be performed at relatively early ages.

2. Matrix tensile strength and tensile elastic modulus are insensitive to aggregate grading, but significantly increased by aggregate content.





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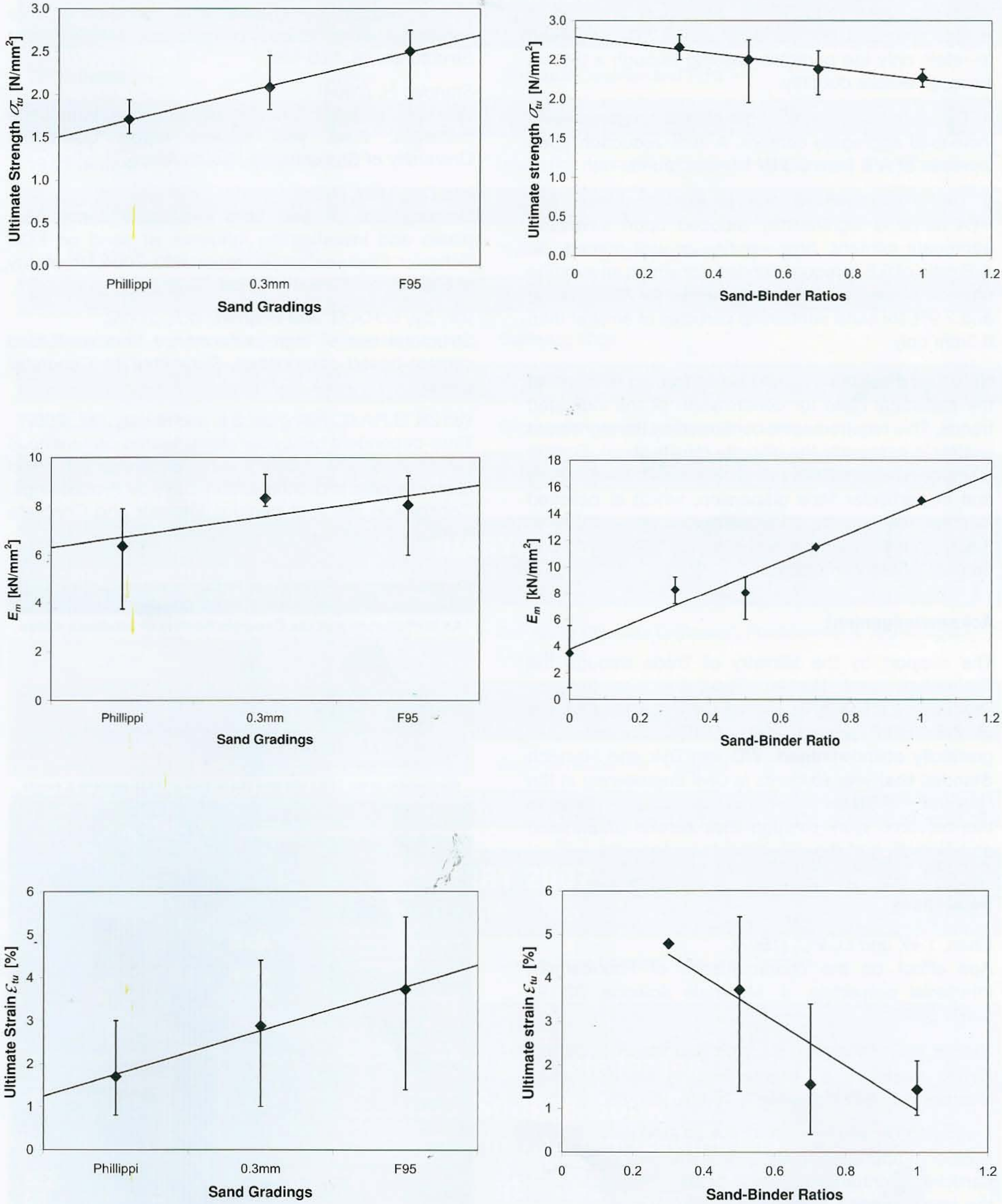

Figure 8: Influence of aggregate grading (left) and A/B (right) on ECC tensile parameters.

Technical Paper *(cont.)* - High performance fibre reinforced cement-based composites

3. Ultimate tensile strength and strain are significantly increased upon reduction in aggregate fineness. It is recommended that sand for use in ECC is sieved to retain only the particles passing through a 0.3mm sieve, to ensure ductility.

4. The ultimate tensile strength of ECC is reduced with increased aggregate content. A 30% reduction upon increase of A/B from 0.3 to 1.0 was found.

5. The ultimate tensile strain of ECC containing fine PVA fibres is significantly reduced upon increased aggregate content, however fine or well-graded. An A/B ratio of 0.5 is recommended, for which an average ultimate strain of 3.7% was obtained for F95 grading and 2.9% for sand containing particles of smaller than 0.3mm only.

Note that more tests should be performed to increase the statistical base for confirmation of the indicated trends. This requirement is confirmed by the significant scatter in especially the ultimate tensile strain. Further research is required to improve the material composition and in particular fibre dispersion, which is believed to play a dominating role in ensuring repeatability of the tensile mechanical response of fibre reinforced cement-based composites.

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