

SUSTAINABLE DEVELOPMENT OF AN ULTRA-HIGH PERFORMANCE FIBRES REINFORCED CONCRETE (UHPFRC): TOWARDS AN EFFICIENT UTILIZATION OF FIBRES

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Abstract

This paper addresses a sustainable development of an Ultra-High Performance Fibres Reinforced Concrete (UHPFRC), focusing on an efficient utilization of fibres. The design of the concrete mixtures is based on the aim to achieve a densely compacted cementitious matrix, employing the modified Andreasen & Andersen particle packing model. The binary and ternary fibres hybridization is designed to reinforce the concrete matrix. Then, the flexural behaviour and toughness of the developed UHPFRC are measured and analysed. The results show that the UHPFRC with hybrid fibres has much better flexural behaviour than the mixture with a single type of fibre. Nevertheless, the flexural toughness of UHPFRC is dominated by the hooked steel fibres. Due to the specific characteristics of UHPFRC, the JSCE SF-4 standard is found more suitable than ASTM C1018-97 to be used to evaluate the flexural toughness property of the sustainable UHPFRC.

1. INTRODUCTION

Ultra-high performance fibre-reinforced concrete (UHPFRC) is a relatively new construction material, which has superior mechanical properties, durability and energy absorption capacity [1-4]. However, as the sustainable development is currently a crucial global issue and various industries are striving in saving energy and lowering environmental impact, the high material cost, high energy consumption and embedded CO₂ for UHPFRC are the typical disadvantages that restrict its wider application [5-7]. Hence, how to efficiently develop UHPFRC still needs further investigation.

Until now, the most common measures pursued to reduce the economic and environmental disadvantages of UHPFRC are mainly limited to the inclusion of industrial by-products or sometimes waste materials, without sacrificing the superior mechanical properties of UHPFRC [1-3, 8-9]. However, in the design of UHPFRC, all of these above mentioned methods did not consider the effect of particle packing on the properties of concrete. In most cases, the recipes of UHPFRC are given directly, without any detailed explanation or theoretical support. Hence, it is questionable whether the concrete matrix is optimal and the

binders are used efficiently. To optimized design UHPFRC matrix, the modified Andreasen & Andersen particle packing model was utilized to produce a dense and homogeneous skeleton of UHPFRC with a relatively low binder amount (about 650 kg/m^3) [10]. Additionally, beside the appropriate design of the concrete matrix, the efficient application of steel fibres is also vital in reducing the materials' cost, energy consumption and embedded CO_2 , since the cost of 1% volume content of fibre applied in UHPFRC is generally higher than that of the matrix (of the same volume) [11]. Nevertheless, in many literature positions investigating UHPFRC, the steel fibres are added directly (sometimes with large volumetric amounts, e.g. more than 5% Vol. [12]), without considering the efficiency of the used fibres.

As commonly known, in most cases, the hybrid fibres reinforced concretes show better hardened properties than the concretes with only a single type of fibres [13-16]. The application of different types of fibres combined in one concrete mixture was firstly proposed by Rossi in 1987 [17], as the so-called multi-modal fibre reinforced concrete (MMFRC). Due to the fact that the short fibres can bridge the microcracks, while the long fibres are more efficient in preventing the development of macrocracks, the stress in the hybrid fibres reinforced concrete can be well distributed and its mechanical properties can be improved [18]. Hence, an appropriate hybridization design of the used steel fibres in the production of UHPFRC can be treated as a potential method to enhance the fibre efficiency.

Based on these premises mentioned above, the objective of this study is to efficiently develop UHPFRC, and clarify the influence of hybrid or ternary fibres on its properties.

2. MATERIALS AND METHODOLOGY

2.1 Materials

The cement used in this study is Ordinary Portland Cement (OPC) CEM I 52.5 R, provided by ENCI HeidelbergCement Benelux (the Netherlands). A polycarboxylic ether based superplasticizer is used to adjust the workability of concrete. The limestone is used as a filler to replace cement. A commercially available nano-silica in a slurry is applied as pozzolanic material. Two types of sand are used, one is normal sand in the fraction of 0-2 mm and the other one is a microsand in the 0-1 mm size range (Graniet-Import Benelux, the Netherlands). Additionally, three types of steel fibres are utilized, as shown in Figure 1: 1) long straight fibre (LSF), length = 13 mm, diameter = 0.2 mm; 2) short straight fibre (SSF), length = 6 mm, fibre diameter = 0.16 mm and 3) hooked fibre (HF) length = 35 mm, diameter = 0.55 mm.



Figure 1 Steel fibres used in this study

2.2 Methodology

The UHPFRC mixtures developed in this study based on the modified Andreasen & Andersen particle packing model [10, 19-21] are listed in Table 1. One example of the resulting integral grading curve of the composite mixes is shown in Figure 2. In this study, only about 620 kg/m^3 of binders are used to produce the UHPFRC matrix. In addition, the steel fibres are added into the designed concrete matrix with different hybridizations and proportions (as shown in Table 1). In all the mixtures, the total fibre amount is 2% by the volume of concrete. Based on the previous authors' investigations [22], to obtain the best mechanical properties, the added fibres amount ratio between long and short fibres is 3/1 in this study.

Table 1: Composition of developed UHPFRC mixtures

No.	OPC kg/m ³	LP kg/m ³	M-S kg/m ³	N-S kg/m ³	nS kg/m ³	W kg/m ³	SP kg/m ³	LSF vol. %	SSF vol. %	HF vol. %
1	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0	0	0
2	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0	0	2
3	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0.125	0.375	1.5
4	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0.5	0	1.5
5	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0	0.5	1.5

(OPC: CEM I 52.5 R, LP: Limestone powder, M-S: Microsand, N-S: Normal sand, nS: Nanosilica, W: Water, SP: Superplasticizer, LSF: Long straight fibre, SSF: Short straight fibre, HF: Hooked fibre)

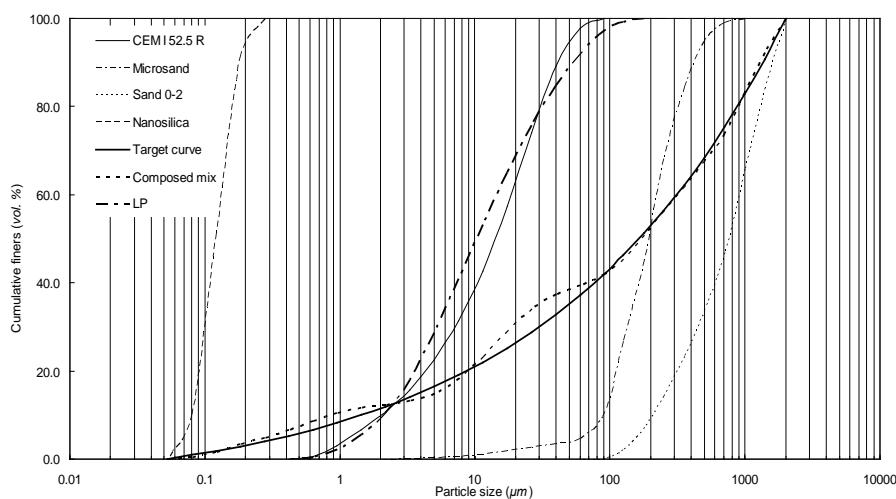


Figure 2 PSDs of the involved ingredients, the target and optimized grading curves of the developed UHPFRC matrix

After mixing, the fresh UHPFRC mixtures are cast in moulds with the size of 100 mm × 100 mm × 500 mm. The beams are demoulded approximately 24 h after casting and subsequently cured in water at about 21 °C. After curing for 28 days, the beams are subjected to the 4-point bending test as described in EN 12390-5 [23]. For the 4-point bending test, the span between the two supported points at the bottom is 400 mm. To obtain flexural load over the middle deflection curve, a Linear Variable Differential Transformer (LVDT) mounted on the surface of the tested samples is utilized to record the mid-deflection. During the test, the set-up is running in a displacement control mode, which is set at 0.1 mm/min. Before the test, the calibration of the used LVDT is done.

Based on available literature, two standards are mainly used to evaluate the flexural toughness of fibre reinforced concrete, which are ASTM C1018-97 [24] and JSCE SF-4 [25]. In this study, both of these standards are utilized to calculate the flexural toughness of UHPFRC.

3. RESULTS AND DISCUSSIONS

3.1 Flexural behaviour

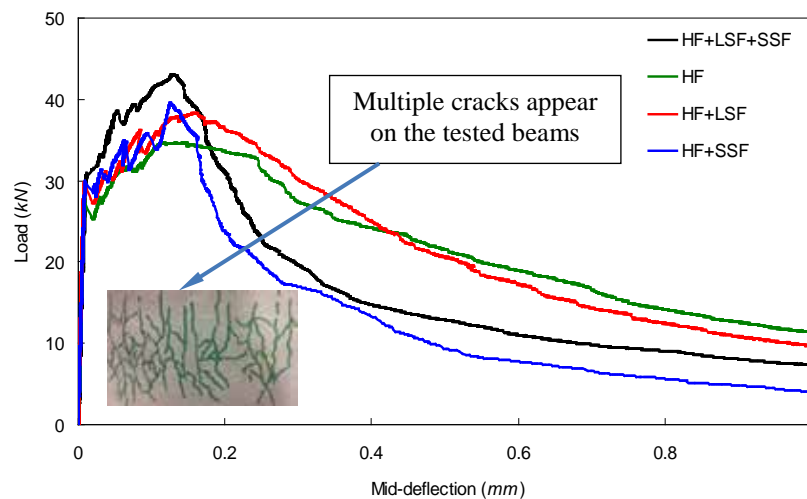


Figure 3 4-point bending test results of the developed UHPFRC with hooked fibres

Figure 3 presents the 4-point bending test results of the developed UHPFRC. The load/mid-deflection curves can be mainly divided into three parts: elastic section, strain hardening section and strain softening section. From the beginning of the test until the moment when the first crack appears, the linear section part of the curve can be observed. Due to the fact that the tested UHPFRC is very stiff, very small mid-deflections of the samples can be noticed. In this study, the first crack deflections of all the samples fluctuate around 0.01 mm. After the first crack appears, the strain hardening section starts, and a number of small cracks will generate in the tested beam, as shown in Figure 3. In this process, the fibres in the concrete mixtures will mainly endure the load and limit the growth of the generated cracks, until the peak force appears. When the fibres in concrete can not restrain the further growth of the small cracks, the fibres will be pulled out and the endurable force of the test beam will decrease, which reflects the initiation of the strain softening section. Nevertheless, due to the different characteristics of the fibres and the binding force between the fibres and concrete

matrix, the strain softening behaviour of reinforced concrete can be very different. In this study, it is important to notice that the endurable force of the mixtures with SSF (e.g. HF+LSF+SSF and HF+LSF) sharply decreases after reaching the peak force, while for concrete with only HF or HF+LSF a relatively slow decreasing trends are observed. The decreasing rates of the residual load of the tested UHPFRCs follow the order: HF < HF+LSF < HF+LSF+SSF < HF+SSF, which implies that the addition of SSF may significantly reduce the flexural toughness of UHPFRC.

3.2 Flexural toughness

Figure 4 shows the flexural toughness of UHPFRC calculated based on ASTM C1018-97. It can be noticed that the first crack flexural toughness of the tested UHPFRC are very small and similar to each other, and fluctuate around 0.2 Nžm (therefore, $\delta=0.2$ Nžm). After that, with an increase of deflection, a difference of the post crack flexural toughnesses between the UHPFRC with different fibres can be observed. Especially at the deflection of 10.5 δ , the mixture with ternary fibres has the largest post crack flexural toughness (4.1 Nžm), which is followed by the HF+SSF (3.3 Nžm), HF+LSF (3.2 Nžm) and HF (3.1 Nžm), respectively. Hence, based on the ASTM C1018-97, the flexural toughness of the mixture with ternary fibres is the highest, while the flexural toughness of the mixture with only HF is the smallest.

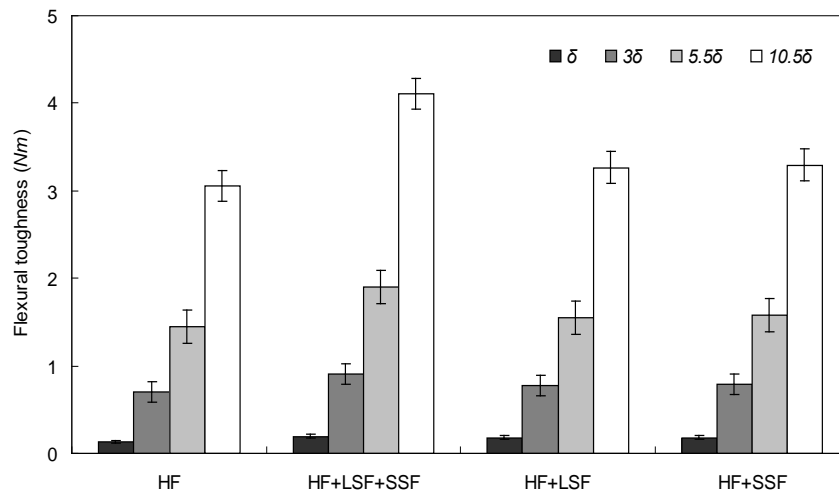


Figure 4 Flexural toughness of the developed UHPFRC based on ASTM C1018-97

In addition, the flexural toughness indices of all the mixtures are calculated based on ASTM C1018-97, and are presented in Figure 5. It can be noticed that the I5 for all the mixtures are similar to each other. Moreover, the indices I10 and I20 show that the toughness indices of the tested concretes with different fibres follow the order: HF > HF+LSF+SSF > HF+LSF > HF +SSF. Hence, it can be summarized that the concrete mixture with only HF has the largest flexural toughness, which is closely followed by the mixture with ternary fibres. However, it is important to notice that the calculated flexural toughness and flexural toughness indices are conflicting each other, which implies that the standard ASTM C1018-97 is not very suitable to evaluate the flexural toughness of UHPFRC.

To clarify the conflicting results of flexural toughness found based on ASTM C1018-97, the JSCE SF-4 is employed to further evaluate the flexural toughness of UHPFRC. The

calculated flexural toughness and flexural toughness factors of UHPFRC based on JSCE SF-4 are shown in Figure 6. It is obvious that the calculated flexural toughnesses presented in Figure 6 are all in the range from 25 to 35 Nžm, and are much larger than those calculated based on ASTM C1018-97 (shown in Figure 4). In addition, according to the literature, the flexural toughness of UHPFRC calculated based on JSCE SF-4 is similar to the results of other fibre reinforced concrete, as shown in [25-26]. Moreover, the calculated flexural toughnesses and flexural toughness factors shown in Figure 6 follow the order: HF > HF+LSF > HF+LSF+SSF > HF+SSF, which is in line with the obtained 4-point bending test results (Figure 3). Hence, it is demonstrated that the HF can significantly increase the flexural toughness of UHPFRC, while that the additional SSF is less effective in improving the flexural toughness.

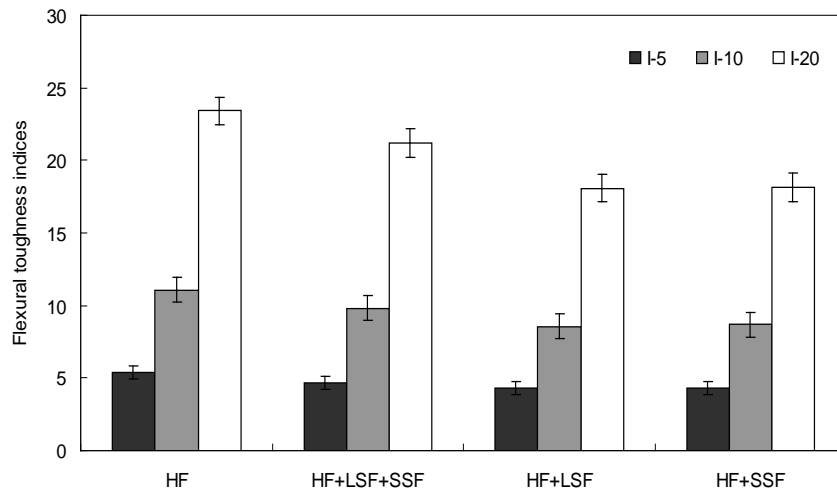


Figure 5 Flexural toughness indices of the developed UHPFRC based on ASTM C1018-97

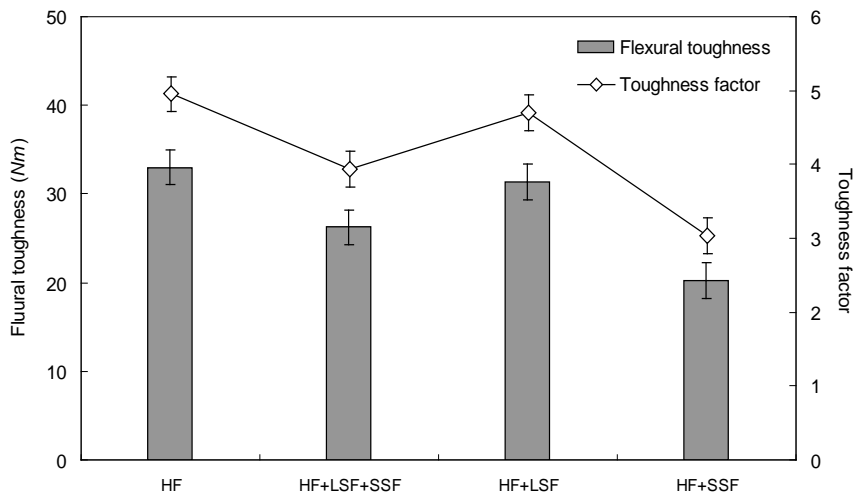


Figure 6 Calculated flexural toughness and flexural toughness factor of the developed UHPFRC based on JSCE SF-4

4. CONCLUSIONS

This paper presents a method to efficiently develop Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). Towards an efficient application of fibres in UHPFRC, the hybridization design of fibres is utilized. Particularly, the ternary fibres reinforced UHPFRC is produced, tested and analysed. The obtained experimental results show that the ternary hybrid fibres are beneficial in increasing the peak force of UHPFRC in the 4-point bending test, while the hooked fibres are the dominant factor to improve the flexural toughness of UHPFRC. Hence, based on different requirements on the properties of UHPFRC, various hybridization designs of the fibres can be executed, which can significantly improve the fibre efficiency. Moreover, due to the specific characteristics of UHPFRC, it is found that the JSCE SF-4 guideline is more suitable to be used to evaluate the flexural toughness property of UHPFRC than ASTM C1018-97.

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REFERENCES

- [1] Tuan N.V., Ye G., Breugel K., Copuroglu O., Hydration and microstructure of ultra-high performance concrete incorporating rice husk ash. *Cem Concr Res* 2011; 41: 1104-1111.
- [2] Tuan N.V., Ye G., Breugel K., Fraaij A.L.A., Dai B. D., The study of using rice husk ash to produce ultra-high performance concrete. *Constr Build Mater* 2011; 25: 2030-2035.
- [3] Yang S.L., Millard S.G., Soutsos M.N., Barnett S.J., Le T.T., Influence of aggregate and curing regime on the mechanical properties of ultra-high performance fibre reinforced concrete (UHPFRC). *Constr Build Mater* 2009, 23: 2291-2298.
- [4] Toledo Filho R.D., Koenders E.A.B., Formagini S., Fairbairn E.M.R., Performance assessment of Ultra High Performance Fiber Reinforced Cementitious Composites in view of sustainability. *Mater Design* 2012; 36: 880-888.
- [5] UNSTATS. Greenhouse gas emissions by sector (absolute values). United Nation Statistical Division: Springer; 2010.
- [6] Friedlingstein P, Houghton RA, Marland G, Hackler J, Boden TA, Conway TJ, et al. Uptake on CO₂ emissions. *Nat Geosci* 2010; 3:811-2.
- [7] Habert G., Denarié E., Šajna A., Rossi P., Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes. *Cem Concr Comp* 2013; 38: 1-11.
- [8] Hassan A.M.T., Jones S.W., Mahmud G.H., Experimental test methods to determine the uniaxial tensile and compressive behaviour of ultra-high performance fibre reinforced concrete (UHPFRC). *Constr Build Mater* 2012; 37:874-882.

- [9] Tayeh B.A., Abu Bakar B.H., Megat Johari M.A., Voo Y.L., Mechanical and permeability properties of the interface between normal concrete substrate and ultra-high performance fibre concrete overlay. *Constr Build Mater* 2012; 36: 538-548.
- [10] Yu R., Spiesz P., Brouwers H.J.H., Mix design and properties assessment of Ultra-High Performance Fibre Reinforced Concrete (UHPRFC). *Cem Concr Res* 2014, 56: 29-39.
- [11] Kim D.J., Park S.H., Ryu G.S., Koh K.T., Comparative flexural behavior of Hybrid Ultra-High Performance Fiber Reinforced Concrete with different macro fibers. *Constr Build Mater* 2011; 25: 4144-4155.
- [12] Habel K., Viviani M., Denarié E., Brühwiler E., Development of the mechanical properties of an Ultra-High Performance Fiber Reinforced Concrete (UHPRFC). *Cem Concr Res* 2006; 36(7): 1362-1370.
- [13] Banthia N., Majdzadeh F., Wu J., Bindiganavile V., Fiber synergy in Hybrid Fiber Reinforced Concrete (HyFRC) in flexure and direct shear. *Cem Concr Comp* 2014; 48: 91-97.
- [14] Ganesan N., Indira P.V., Sabeena M.V., Bond stress slip response of bars embedded in hybrid fibre reinforced high performance concrete. *Constr Build Mater* 2014; 50: 108-115.
- [15] Yap S.P., Bu C.H., Alengaram U.J., Mo K. H., Jumaat M.Z., Flexural toughness characteristics of steel-polypropylene hybrid fibre-reinforced oil palm shell concrete. *Mater Design* 2014; 57: 652-659.
- [16] Banthia N., Gupta R., Hybrid fiber reinforced concrete (HyFRC): fiber synergy in high strength matrices. *Mater Struct* 2004, 37(10):707-16.
- [17] Rossi P., Acker P., Malier Y., Effect of steel fibres at two stages: the material and the structure. *Mater Struct* 1987, 20: 436-439.
- [18] Markovic I., High-performance hybrid-fibre concrete – development and utilisation. Technische Universität Delft, Ph.D. thesis; 2006.
- [19] Brouwers H.J.H., Radix H.J., Self-compacting concrete: theoretical and experimental study. *Cem Concr Res* 2005; 35: 2116-2136.
- [20] Hüsken G., Brouwers H.J.H., Earth-moist concrete: application of a new mix design concept, *Cem Concr Res* 2008; 38: 1246-1259.
- [21] Hunger M., Entrop A.G., Mandilaras I., Brouwers H.J.H., Founti M., The behavior of a microencapsulated phase change material in concrete, *Cem Concr Comp* 2009; 31: 731-743.
- [22] Yu R., Spiesz P., Brouwers H.J.H., Static properties and impact resistance of a green Ultra-High Performance Hybrid Fibre Reinforced Concrete (UHPHFRC): experiments and modeling. *Constr Build Mater* 2014, 68: 158-171.
- [23] BS EN 12390-5. Testing hardened concrete - Part 5: Flexural strength of test specimens. British Standards Institution-BSI and CEN European Committee for Standardization (2009).
- [24] ASTM C 1018-97. Standard test methods for flexural toughness and first crack strength of fibre reinforced concrete. American Society for Testing and Materials (ASTM), 1998, 04(02): 506-513.
- [25] JSCE Standard SF-4. Method of test for flexural strength and flexural toughness of fibre reinforced concrete. Japan Society of Civil Engineers (JSCE), 1984.
- [26] Nataraja M.C., Dhang N., Gupta A.P., Toughness characterization of steel fibre reinforced concrete by JSCE approach. *Cem Concr Res* 2000, 30: 593-597.
- [27] Sukontasukkul P., Toughness evaluation of steel and polypropylene fibre reinforced concrete beams under bending. *Thammasat Int. J. Sc. Tech.* 2004, 9(3): 35-41.