Comparative Flexural and Tensile Behaviours of Ultra-High Performance Fibre Reinforced Concrete with Different Steel Fibres

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Abstract. This research work focuses on the optimization of tensile strength and ductility of ultra-high performance fibre reinforced concrete (UHPFRC) using low steel fibre content. A fine grain ultra-high performance concrete (UHPC) matrix with a compressive strength of 190 MPa was developed. Six different high strength steel fibres were employed to improve the ductility of the matrix. Four micro steel fibres were two types of smooth straight fibres and two types of crimped fibres while two indented macro steel fibres were hooked ends fibre and straight fibre. Pull-out tests were carried out to determine the average fibre-matrix bond strength. The flexural and tensile performances of UHPFRC with six different steel fibres were investigated. The enhancements in flexural/tensile strengths, deflection/strain capacities, energy absorption capacity were significantly depended on the fibre types and fibre factor (V_f*L_f/D_f). The experimental and estimated results indicate that the use of 1.5 vol.% of the most effective fibre with L_f/D_f of 20 mm/0.2 mm guarantees to achieve a strain-hardening UHPFRC with an ultimate tensile strength of higher than 10 MPa.

Keywords: Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) · Steel fibre · Compressive strength · Tensile strength · Strain-hardening · Toughness

1 Introduction

The improvement of packing density of granular composition in combination with highly effective superplasticizer together with fibre reinforcing generates a new class of concrete called Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). The characteristic key properties of UHPFRC are (i) its self-flow ability, (ii) its ultra-high compressive strength of 150–200 MPa, (iii) its high ductility and toughness, and (iv) its extremely high durability. Due to its outstanding characteristics, many innovative applications of UHPC were developed for sustainable and elegant structures.

High-strength steel fibre is the most effective fibre in the very brittle UHPC matrix because the tensile strength, ductility and elastic modulus of steel fibre is significant higher than that of UHPC matrix (Naaman 2003a; Fehling et al. 2013). UHPFRC with a strain-hardening behaviour is expected for structural application. The behaviour of strain-hardening UHPFRC under uniaxial loading is characteristic by the following regimes (Naaman 2003b):

V. Mechtcherine et al. (eds.), *Strain-Hardening Cement-Based Composites*,
RILEM Bookseries 15, DOI 10.1007/978-94-024-1194-2_57

- linear-elastic behaviour up to the first cracking tensile stress σ_{cc} which is estimated according to Eq. (1).
- Strain-hardening behaviour with multi-microcracking, the maximum post-cracking tensile stress σ_{pc} is calculated using Eq. (2) and $\sigma_{pc} \geq \sigma_{cc}$.
- Strain-softening behaviour.

$$\sigma_{cc} = \sigma_{mu}\left[1 + \left(\frac{E_f}{E_m} - 1\right)V_f\right] \tag{1}$$

$$\sigma_{pc} = \omega\tau_f \frac{L_f}{D_f} V_f \tag{2}$$

where: $\sigma_{mu,}$ the tensile strength of matrix; V_f, the fibre volume fraction; L_f, the fibre length; D_f, the fibre diameter; E_f/E_m, the ratio of the elastic moduli of fibre and matrix; ω, the product of several coefficients considering the influence of embedded length, fibre orientation effect, group reduction effect; τ_f, the average fibre-matrix bond strength.

Equation (1) indicates that the first cracking tensile stress σ_{cc} of UHPFRC and the tensile strength of matrix σ_{mu} are nearly same if a low steel fibre content is used. Based on the working mechanism of the cementitious composite described by Eq. (2), various approaches have been proposed in order to improve the maximum post-cracking tensile stress σ_{pc}: (i) the use of high fibre content, (ii) the increase of fibre aspect ratio (L_f/D_f), (iii) the improvement of fibre-matrix bond strength τ_f by the densification of the transition zone between fibre and matrix, (iv) the use of deformed fibre for achieving a high mechanical bond between fibre and matrix. It should be noted that the use of high fibre content allows to increase σ_{pc} but the material cost increases significantly. Furthermore, the content of a given fibre type is limited for a sufficient concrete workability (Martinie et al. 2010). The mixing, casting of high volume steel fibre concrete are difficult and a special mixing technique may be required.

Various researches indicated that the very high dense microstructure of UHPFRC increases significantly the average fibre-matrix bond strength τ_f. Therefore, strain-hardening UHPFRC with low steel fibre content could be achieved. Graybeal and Baby (2013) developed a direct tension test method for UHPFRC and reported that strain-hardening UHPFRC with straight smooth steel fibres of 2–2.5 vol.% (L_f/D_f = 13 mm/0.2 mm and 20 mm/0.3 mm) and a compressive strength of 200 MPa exhibited σ_{pc} of 11.6 MPa and the corresponding tensile strain ε_{pc} of 0.58%. Wille et al. (2011) used a matrix with a compressive strength of 200 MPa in the company of 2 vol.% hooked ends steel fibre (L_f/D_f = 30 mm/0.38 mm) or 2.5 vol.% straight smooth steel fibre (L_f/D_f = 13 mm/0.2 mm) or 2 vol.% twisted polygonal fibre (L_f/D_f = 30 mm/0.3 mm), and reported that σ_{pc} and ε_{pc} of UHPFRC were 14.2 MPa and 0.24%, 14 MPa and 0.45%, 14.9 MPa and 0.61% respectively. Bastien-Masse et al. (2016) presented that UHPFRC with a compressive strength of 151 MPa and steel fibre content of 3 vol.% (L_f/D_f = 13 mm/0.16 mm) possessed σ_{pc} of 13.4 MPa and ε_{pc} of 0.28%.

This paper presents a research that focuses on the optimization of tensile strength and ductility of self-compacting UHPFRC using no higher than 2 vol.% steel fibres.

A systematic experimental investigation was carried out for six different steel fibre types, starting with determination of the fibre-matrix bond strength, to examination of the flexural and direct tensile behaviours of UHPFRC. Therefore, the most effective fibre was established regarding tensile performance improving and material saving.

2 Materials and UHPFRC Mixture Designs

The used materials in this research are available on the Austrian and German market. The mix design of the used UHPC matrix with a maximum grain size of 1 mm is described in detail by Hoang et al. (2016a). For 1 m^3 UHPC matrix, 750 kg cement Cem I 52.5 N (C_3A < 2.5 wt.%) and Water/Cement of 25 wt.% were used. Silica fume, quartz powder, superplasticizer, with respect to cement, were 12 wt.%, 30 wt.% and 3 wt.% respectively. Volume ratio of fine quartz sand 0.1–0.3 mm to coarse quartz sand 0.3–1 mm were 20/80. This UHPC matrix ensured a high self-flowability (test acc. to DIN EN 12350-8) for UHPFRC having fibre factor (V_f*D_f/L_f) up to 1.5 (Hoang et al. 2016b).

Six different high strength steel fibre types were employed to improve the ductility of UHPC matrix. Four micro steel fibres were two types of smooth straight fibres (F1: L_1/D_1 = 13 mm/0.2 mm; F2: L_2/D_2 = 20 mm/0.2 mm) and two types of crimped fibres (F3: L_3/D_3 = 9 mm/0.12 mm; F4: L_4/D_4 = 12 mm/0.18 mm) while two indented macro steel fibres were hooked ends fibre (F5: L_5/D_5 = 30 mm/0.55 mm) and straight fibre (F6: L_6/D_6 = 25 mm/0.3 mm). Fibre F1 was OL 13/0.20 steel fibre type from Bekaert, its tensile strength was 2600 MPa. Fibres F2, F5, F6 with tensile strength of 2200 MPa were supplied by Stratec Abrasive and Fibre Technology GmbH having trade names of FM 20/0.2, FE 30/0.55 and FG 25/0.3 respectively. Fibres F3 and F4 having tensile strength of 3300 MPa were produced by Voestalpine Special Wire GmbH.

Table 1 shows the fibre contents for the direct tensile test and four-point bending test. All fibre concretes showed good self-flowing properties with the slump-flow of no less than 750 mm and no fibre clumps. Within the fibre contents of no higher than 2 vol.% there was no influence of fibre types on the 28 days compressive strength of UHPFRC.

Table 1. Sets of test specimens and UHPFRC properties.

Group	Fibre type	Fibre volume (%)	Aspect ratio	Fibre factor	28d-f_c (MPa)
UHPC-2F1	F1	2	65	1.3	194.6
UHPC-1.5F2	F2	1.5	100	1.5	193.5
UHPC-1.5F3	F3	1.5	75	1.125	195.1
UHPC-1.5F4	F4	1.5	66.7	1	194.8
UHPC-2F5	F5	2	54.5	1.091	196.3
UHPC-1.75F6	F6	1.75	83.3	1.458	196.7

3 Testing Program

3.1 Curing

All specimens were casted without any compaction. After casting, the specimens were covered with plastic sheet and stored at room temperature for 24 h. The specimens were then removed from their moulds and stored at ambient laboratory conditions for additional 27 days. All tests was carried out at 28 days age of concrete.

3.2 Single Fibre Pull-Out Test

Single-sided specimens were applied for pull-out test, as shown in Fig. 1. For each kind of fibre fifteen separated fibres were stuck vertically into three base made of Styropor®, each base with size of 20 × 40 × 160 mm^3 included five fibres. The styropor bases with fibres were put into a three-gang mould 40 × 40 × 160 mm^3. The fresh UHPC with maximum grains of 1 mm was then filled into the mould. Thus, the protruding part of the fibre from the styropor base was the embedded length of the fibre in UHPC matrix. The fibre embedded length was equal to a half fibre length. A servo-controlled universal testing machine with a capacity of 1000 kN was used. In order to obtain a high precise of the load values, a HBM® load cell with a capacity of 2 kN was attached to the machine test frame. The rate of displacement of the loading head was 0.05 mm/min during testing. The data of pullout force and crosshead displacement were recorded.

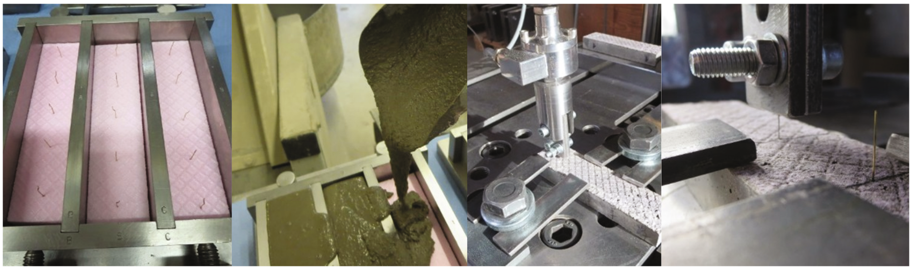

Fig. 1. Specimens preparation and configuration of the single fibre pull-out test.

3.3 Four-Point Bending Test

For each UHPFRC mixture, six square cross-section beams of 140 × 140 × 560 mm^3 were produced to investigate the influence of fibre types, contents on the flexural behaviour of UHPFRC. Four-point bending test on unnotched specimen according to the ASTM C1609/C1609M – Standard test method for Flexural Performance of Fiber Reinforced Concrete was applied. The toughness and the residual strength at the Peak Load and at the specified points corresponding to the deflections of L/1000 mm, L/600 mm, L/150 mm were considered. The servo-controlled universal testing

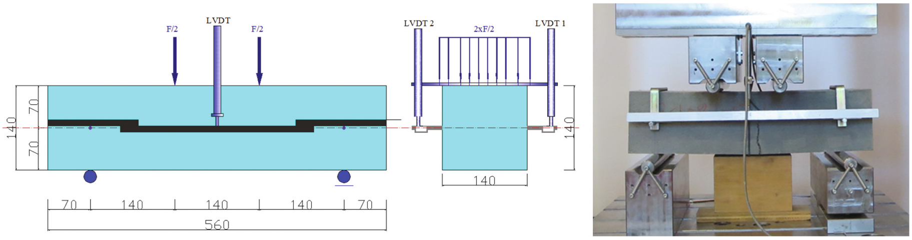

Fig. 2. Four-point bending test according to the ASTM C1609/C1609M.

machine with a capacity of 1000 kN was used, the rate of displacement of the loading head was 0.0025 mm/s during testing. The test setup is illustrated in Fig. 2.

3.4 Direct Tensile Test

Dog-bone shape specimens with a circular bay, which reduces stress concentration and allows the failure occur at the weakest spot in the material (Vliet and Mier 2000), were used, as depicted in Fig. 3. The cross-section area (50 mm × 150 mm) at the middle of the specimen is 40% smaller than that of the specimen ends. The lower end of the specimen was fixed on the bedplate of test machine and the upper end of the specimen was connected to an adapter having a pin to create rotating boundary condition. The strain was captured with a parallel ring extensometer containing four linear variable differential transformers (LVDT), the gage length was 320 mm. The servo-controlled universal testing machine with a capacity of 1000 kN was used. Tests were performed under displacement control with a constant displacement rate of 0.0025 mm/s. Three specimens were tested for each UHPFRC group.

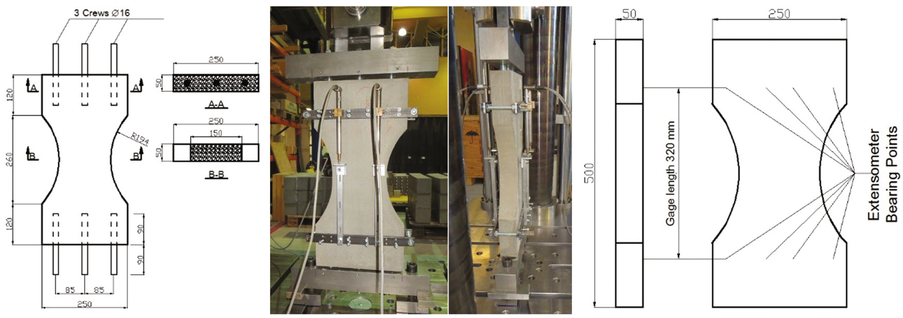

Fig. 3. Specimen preparation and direct tension test setup.

4 Results and Discussion

4.1 The Effect of Fibre Types on Fibre Pull-Out Resistance

The pull-out test results are represented in Table 2. The pull-out resistances of the deformed fibres F3, F4, F5 in UHPC matrix were much higher than that of the smooth straight fibres F1, F2 and of the indented straight fibre F6 due to their good mechanical anchorage. A very high bond between crimped fibre F3 and the UHPC matrix led to a very high tensile stress in the fibre. The failure of 40% number of tested fibres implied

Table 2. Fibre pull-out resistance.

	F1	F2	F3	F4	F5	F6
τ_f (MPa)	5.59	4.71	21.78	16.28	18.58	6.77
St. Dev. (MPa)	1.37	1.88	1.17	2.21	1.54	1.47
Number of fibre failure	0/15	0/15	6/15	0/15	3/15	0/15

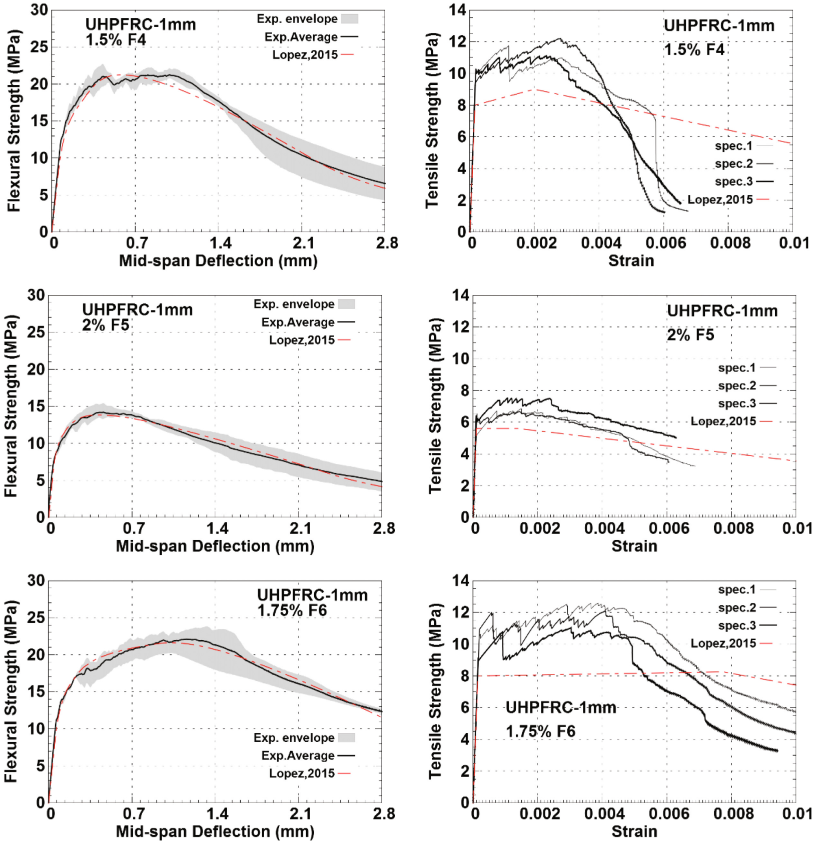

Fig. 4. (*continued*)

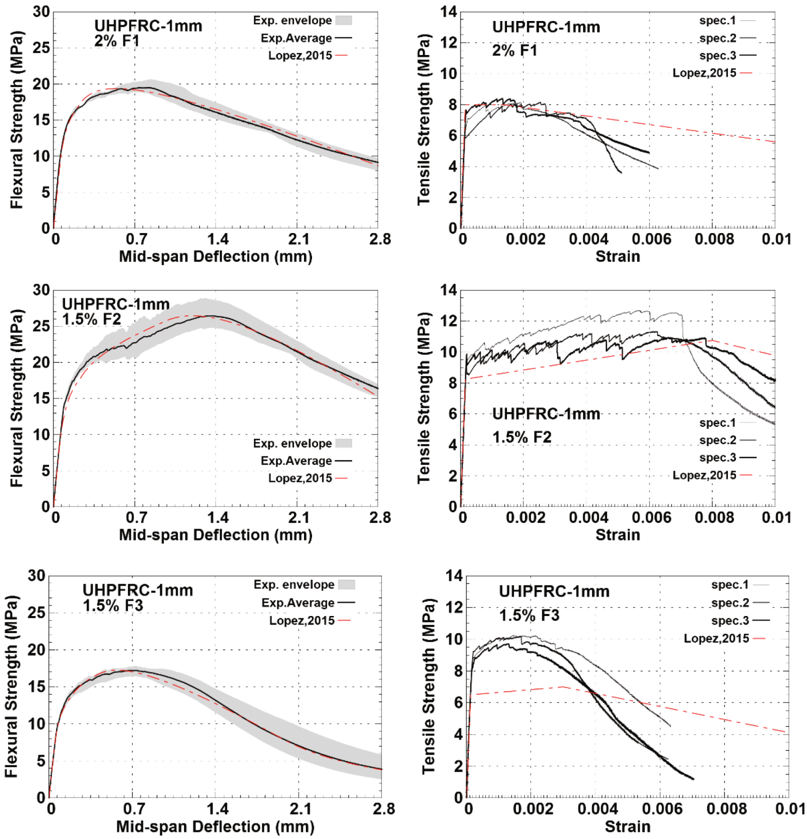

Fig. 4. Influence of fibre types, contents on the flexural and direct tensile behaviours of UHPFRC, experimental and estimated results.

the disadvantage of fibre F3 in the UHPC matrix having 190 MPa compressive strength. A shorter fibre length of fibre F3 is required to against the fibre failure but the efficiency in strengthening is reduced. A longer wavelength or a decrease of the wave height could be a suitable solution for fibre F3. Fibre modification, however, is not discussed in this research. Fibre F4 was quite good, fibre-matrix bond strength was high but the tensile stress in the fibre was relative lower than the fibre failure tensile strength. The results of fibres F5 and F6 indicated that the effect of the hooked ends on improving pull-out resistance was much higher than that of the indented surface. However, a high risk of fibre failure of fibre F5 was recognized. Fibre F6 with indented surface had a better bond with the UHPC matrix in comparison to the smooth straight fibres F1 and F2.

4.2 Influence of Fibre Types, Contents on Flexural and Direct Tensile Behaviour of UHPFRC

Kanakubo (2006) indicated that specimen geometry, size and boundary conditions have a significant influence on results of the direct tensile tests. Therefore, in this research an inverse analysis based on four-point bending test was carried out to estimate the tensile constitutive properties of UHPFRC. The inverse analysis method developed by Lopez et al. (2015) was used.

The deflection-hardening and strain-hardening behaviours were observed for all UHPFRC groups in both experiment and inverse analysis, as shown in Fig. 4. The average test results and estimated results are presented in Table 3.

Table 3. Experimental and estimated results of the flexural and tensile properties of UHPFRC.

Group	Specimen no.	Flexural strength (MPa)	Tensile strength (MPa) and Strain (‰)				
			σ_{cc}	ε_{cc}	σ_{pc}	ε_{pc}	$\varepsilon_{t,max}$
UHPC-2F1	Exp-average	19.48	5.73	0.113	8.23	1.927	–
	Estimation	–	8.00	0.145	8.00	1.400	30
UHPC-1.5F2	Exp-average	26.45	9.61	0.190	11.64	6.175	–
	Estimation	–	8.25	0.150	10.75	8.000	30
UHPC-1.5F3	Exp-average	17.22	8.45	0.183	10.05	1.479	–
	Estimation	–	6.50	0.130	7.00	3.000	20
UHPC-1.5F4	Exp-average	21.22	9.80	0.178	11.69	2.129	–
	Estimation	–	8.00	0.160	9.00	2.000	23
UHPC-2F5	Exp-average	14.19	6.06	0.110	7.02	1.336	–
	Estimation	–	5.60	0.102	5.60	1.400	25
UHPC-1.75F5	Exp-average	22.09	10.31	0.185	11.90	3.594	–
	Estimation	–	8.0	0.151	8.25	7.750	30

4.3 Discussion

The experimental results of bending and direct tensile tests are in good agreement. Surprisingly, UHPC-2F5 with 2 vol.% F5 possessed the weakest flexural and tensile behaviours in comparison to others although the single fibre pull-out resistance of fibre F5 was much higher than that of fibres F1 and F2. This may be attributed to the lowest density of fibre crossing, the lowest fibre aspect ratio of fibre F5 and the low fibre factor of UHPC-2F5. In addition, the real fibre-matrix bond strength of fibres F1 and F2 in the specimens of flexural and tensile tests, that formed by a homogeneous mixing process of UHPC matrix and fibres, may be much higher than the results of single fibre pull-out test, it could be a suitable reason for the observed phenomenon.

The estimation of the tensile properties based on four-point bending test showed that the first cracking tensile stress σ_{cc} of fibre concrete (which approximate to the matrix tensile strength) was in range of 6–8 MPa. However, the very high scattering of σ_{cc} (5.7–10.3 MPa) was observed in the experiment, and has not explained yet.

Comparing the experimental and estimated tensile strength of a UHPFRC group pointed out that fibres in the thin dog-bone specimen might have a 2-D distribution and tended to orient in the direction of applied stress leading to higher results of the experiment.

The experimental results showed that the flexural deflection-hardening response, the modulus of rupture of UHPC-2F1 were better than that of UHPC-1.5F3. However, the experimental σ_{pc} of UHPC-1.5F3 was higher than that of UHPC-2F1. The higher density of fibre crossing, the greater fibre pull-out resistance of fibre F3 in comparison with fibre F1 and the good fibre orientation in the thin dog-bone specimen of fibre F3 could be the reason.

The results indicate that fibre F4 was much more advantage than fibre F1 because such fibres had nearly same length, fibre aspect ratios, density of fibre crossing but the flexural stress deflection-hardening response and tensile stress strain-hardening response of UHPC-1.5F4 was better than that of UHPC-2F1.

The longer length of fibre F6 in comparison to the length of fibre F2 led to a better fibre orientation in the direction of applied stress in the thin dog-bone specimen and resulted in the same ultimate tensile strength of UHPC-1.75F6 and UHPC-1.5F2. However, in 3-D fibres distribution of the bending specimens the experimental flexural results and the estimated tensile properties showed that the ductility and toughness of UHPC-1.5F2 was better than that of UHPC-1.75F6.

5 Conclusions

An in depth experimental investigation was done of the flexural and tensile behaviours of UHPFRC with different steel fibres. In addition, for a good analysis and interpretation of the experimental results a back calculation based on four-point bending test for estimation of the tensile properties was performed. Both experiment and estimation demonstrated the highest effectiveness of fibre F2 in improving ductility and toughness of UHPFRC. The use of 1.5 vol.% of fibre F2 guarantees to achieve a strain-hardening UHPFRC with an ultimate tensile strength of higher than 10 MPa.

The very high fibre-matrix bond strengths of micro fibres F3 and F4 due to the mechanical effect indicate that micro fibres F3 and F4 are very suitable for high/ultra-high performance concrete with a compressive strength up to 150 MPa.

Fibre-matrix bond strength in specimens of bending and tensile tests that formed by a homogeneous mixing process of fibre and matrix may be higher than result of single fibre pull-out test.

The modification of direct tensile test using a specimen with a sufficiently large size for a 3-D fibre distribution and a universal joint for reducing bending effect is needed for a good description of UHPFRC tensile behaviour.

Acknowledgement. The presented work has been a part of the research project "Substitution of Steel with UHPFRC", No. 846023, supported by the Austrian Research Promotion Agency (FFG), Kirchdorfer and Voestalpine companies. The authors would like to express their gratitude to these organizations for the financial support.

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