Influence of Steel Fibres and Matrix Composition on The Properties of UHPFRC

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Abstract:

The influence of fibre length, volume fraction and composition of matrices on the self-flowing ability and the mechanical properties of ultra-high performance fibre reinforced concrete (UHPFRC) is reported. Four different self-compacting UHPC mixtures with different maximum grain size of 1 mm, 2.5 mm, 4 mm, 8 mm and compressive strength of 190 MPa were used. Two types of steel fibres with length-diameter ratios of 13mm/0.2mm and 20mm/0.2mm were employed to improve the ductility of these UHPCs. The investigations on the mechanical behaviours of the UHPFRCs using critical fibre volumes, which were experimentally determined to ensure the self-compacting properties of the fibres concrete, were carried out. There were no significant effects of the fibres on the compressive strength of the UHPFRCs. For UHPFRCs with maximum grain size up to 4 mm the concretes using the long fibre had a similar modulus of rupture and a better toughness in comparison to the concretes including twice higher volume fraction of the short fibre.

Keywords: ultra-high performance concrete (UHPC), ultra-high performance fibre reinforced concrete (UHPFRC), self-compacting concrete, steel fibre, fibre geometry

1. Introduction

In the previous work the authors developed four optimum self-compacting UHPCs with different maximum grain size of 1 mm, 2.5 mm, 4 mm, 8 mm and compressive strength of 190 MPa (Hoang et al., 2016). In this study two types of straight, smooth steel fibres with circular cross section of 0.2 mm diameter, having length of 13 mm (StF1) and 20 mm (StF2), were used to improve the ductility of these four UHPCs.

The objective of this study was to produce self-compacting UHPFRCs with maximum mechanical performance. First, the influence of the fibre types, volume and the matrices composition on the self-flowing ability of UHPFRCs were investigated. As a result, the critical fibre volumes, which are defined as the contents of the steel fibres above which fibres clumping (or balling) or spread flow less than 65 cm of UHPFRCs take place, were determined. The comparative investigations on the mechanical behaviour of the UHPFRCs were then carried out, the effectiveness of each fibre type in reinforcing UHPCs were analysed.

The materials what were used in this study are available on the Austrian and German market. The mix design of UHPCs are described in detail in Hoang et al. (2016). Mix-proportions and properties of the used UHPCs are shown in Table 1. Cement CEM I 52.5 N – no C_3A with a Blaine fineness of 4500 (cm^2/g), a grain size distribution d50 of 7.7 (µm), a density of 3.1 (g/cm^3) and a compressive strength of 61 (MPa) at 28 days, was used. Undensified silica fume with a grain size without agglomeration of 1 (µm), a density of 2.2 (g/cm^3) was used as ultra-fine filler and highly reactive powder. Quartz powder with a grain size distribution of 1-84 (µm), a density of 2.63 (g/cm^3) was used as fine filler. Fine aggregates include three quartz sands with different grain size, such as QS1 (1323 – 2533 µm), QS2 (515 – 1081 µm), QS3 (103 – 283 µm), their densities are 2.63 g/cm^3. Two coarse aggregates (CrB1 and CrB2) were basalt with grain size distribution of 4 mm to 8mm, and 2 mm to 4 mm, their densities are 2.95 g/cm^3. The applied superplasticizer (SP) is in liquid form with 30 wt.% solid content, its density is 1.05 g/cm^3.

Table 1: Mix-proportions and properties of the used UHPCs in this study.

	UHPC_1mm	**UHPC_2.5mm**	**UHPC_4mm**	**UHPC_8mm**
Maximum grain size (mm)	1	2.5	4	8
Cement (kg/m^{3}concrete)	720	720	720	640
Water / Cement (wt. ratio) [(a)]	0.25	0.25	0.25	0.25
Vol. of paste (lit/m^3 concrete)	539.1	539.1	539.1	479.2
	Proportions by weight			
Cement	1	1	1	1
Quartz Powder (QP)	0.3	0.3	0.3	0.3
Silica fume (SF)	0.12	0.12	0.12	0.12
Water_add [(a)]	0.229	0.229	0.229	0.229
Superplasticizer (SP)	0.03	0.03	0.03	0.03
Crushed basalt 1 (CrB1)	-	-	-	0.6049
Crushed basalt 2 (CrB2)	-	-	0.4532	-
Quartz sand 1 (QS1)	-	0.9091	-	0.8090
Quartz sand 2 (QS2)	1.3468	0.6061	0.9428	0.5778
Quartz sand 3 (QS3)	0.3367	0.1684	0.3367	0.2140
	Properties in fresh and hardened states (mean value)			
T_{500} (sec.)	12	7	8	11
Slump-flow (mm)	800	875	840	805
Comp. Strength (MPa) (12 cubes 100 mm) (28d)	193.5	196.5	197.4	191.2
Comp. Strength (MPa) Modulus of Elasticity (GPa) (3 cylinders D100 H200) (28d)	183.3 53.4	189.8 54.9	188.1 53.8	185.6 57.0

[(a)] Water = Water_add + Water of SP, where Water of SP = 70 wt.% SP

2. Background

Many UHPC projects used 1-2.5 Vol.-% of straight and smooth (or twisted) steel fibres with a length of 9-30 mm and an aspect ratio of 50-100 to strengthen UHPC matrix having high paste volume fraction of 0.6-0.65 (Richard and Cheyrezy, 1995; Resplendino, 2011; Fröhlich and Schmidt, 2014; Graybeal and Baby, 2013; Wille et al., 2012). Most researches on steel fibre reinforced concrete indicate that although the increasing of fibre factor, which is defined as the product of the fibre aspect ratio and the fibre volume fraction, $(L_f/d_f)*V_f$, leads to the improving of mechanical properties of hardened fibre concrete, the workability of fibre concrete is decreased and fibres tend to form clumps or balls. Furthermore, with a certain fibre geometry, the increase of aggregate volume as well as aggregate size leads to a decrease of volume fraction of fibre and a negative effect on fibres distribution (Bentur and Mindess, 2007; Kooiman, 2000; Bui et al., 2003; Grünewald, 2004; Martinie et al., 2010). Therefore, this study is absolutely necessary to select the proper UHPFRCs for individual applications as the matrices have a low paste volume fraction of 0.48-0.54.

3. Testing Methods

3.1. Mixing procedure

The homogeneous UHPFRCs were produced by using Eirich intensive mixers. The mixers have a driven, rotating mixing pan, a mixing tool which rotates eccentrically and a fixed wall scraper cleans the wall of the mixing pan. The mixing procedure was as follow: The dry powders including cement, quartz powder, silica fume were added to the mixer first, then mixed for 30 seconds at the speed of 150 rpm of mixing tool and lowest speed of mixing pan. The speed of mixing pan was constant during mixing. Premixed water with superplasticizer was then introduced for 60 seconds at a mixing tool speed of 150 rpm. Next, the paste was homogenized for 240 seconds at the speed of 450 rpm of mixing tool. The aggregate was added to the paste at a mixing tool speed of 150 rpm for 240 seconds. The speed of mixing tool was decreased down to 84 rpm, the UHPCs without fibres were mixed for a further 60 seconds, in case of fibres addition, the further mixing time at this stage was 180 seconds.

3.2. Slump-flow test

The slump-flow test according to DIN EN 12350-8 was applied to assess the self-flowability of UHPCs with and without fibres. Two minutes after cone lifting, from the spread-flow of the concrete, two diameters perpendicular to each other were determined and their mean was reported, the T_{500}-time was also recorded in the test. The slump-flow test is illustrated in Fig. 1.

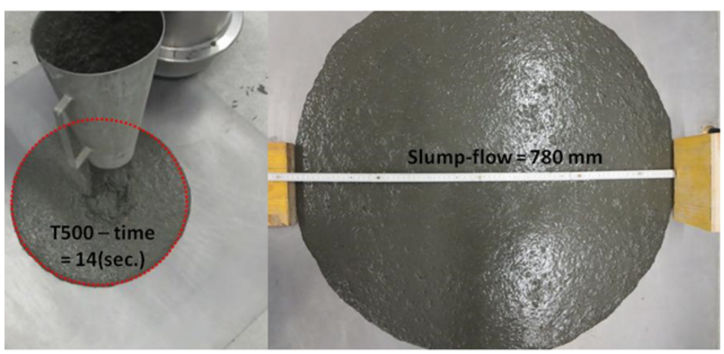


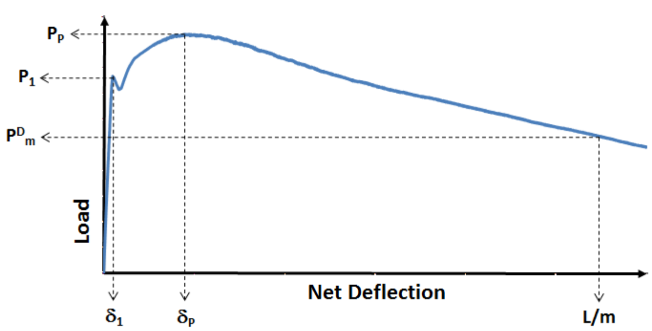
Figure 1: The slump-flow test of UHPFRC_4mm with 1.5 Vol.-% StF1 (L_{f1}/D_{f1} = 13mm/0.2mm). The results of T_{500} – time = 14 seconds (left), and slump-flow = 780 mm (right).

3.3. Specimen preparation and compression test

The compression test was carried out according to DIN EN 12390-3. For each UHPFRC mixture, six cube specimens of 100 mm were produced to determine the compressive strength. All specimens were casted without any compaction. After casting, the specimens were covered with plastic sheet and stored at room temperature for 24 hours. Then the specimens were removed from their moulds and cured in water at 20^{o}C for 6 days. They were then stored at ambient laboratory conditions for additional 21 days. The compression test was carried out at the concrete age of 28 days. Both loading faces of all specimens were ground before testing. A hydraulic servo-controlled compression machine 5000 kN capacity was used, the loading rate was 0.6 MPa/s. The mean values were reported.

3.4. Specimen preparation and bending test

For each UHPFRC mixture, six square cross-section beams of 140 x 140 x 560 (mm^3) (which represent 3D orientation of fibres) were produced to investigate the effectiveness of fibres in improving the ductility and toughness of UHPC. 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 parameter calculations when Peak Load (Modulus of Rupture) greater than First-Peak Load in accordance with this standard is shown in Figure 2. However, in most case of this study the UHPFRCs showed stable deflection-hardening, the First-Peak Load could not be determined. Besides the Peak Load point, four other points corresponding to the deflections of 0.42 mm, 0.7 mm, 2.8 mm, 4.2 mm were considered for the comparative calculating. Self-compacting UHPFRC was poured at one end of the mold and left to spread into place. There was no vibration. After casting, the specimens were covered with plastic sheet and stored at room temperature for 24 hours. Then the specimens were removed from their moulds and stored at ambient laboratory conditions for additional 27 days. The bending test was carried out at 28 days age of the specimens. A servo-controlled bending machine with changeable load-cells of 100-1000 kN capacity was used, the rate of displacement of the loading head was constant 0.2 mm/min during testing. The test setup for the beam is illustrated in Figure 3. The top surface of specimen in casting is the side surface of specimen in bending test.



L = Span length
P_1 = First-Peak Load
P_P = Peak Load
δ_1 = Net deflection at First-Peak Load
δ_P = Net deflection at Peak Load
f_1 = First-Peak Strength
f_P = Peak Strength
P^D_m = Residual load at net deflection of L/m
f^D_m = Residual strength at net deflection of L/m
f = $(P*L)/(b*d^2)$
b and d are the width and the depth of the specimen
m = 1000, 600, 150, 100 (in this study)
The total area under the load - deflection curve up to a net deflection of L/m is the toughness T^D_m

Figure 2: Example of parameter calculations when Peak Load greater than First-Peak Load according to the ASTM C1609/C1609M.

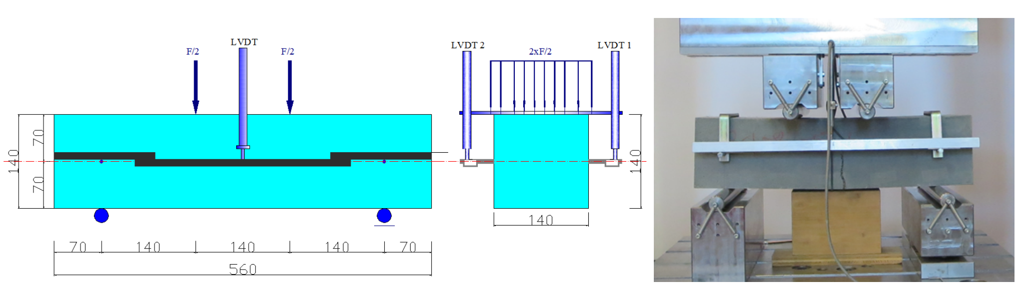


Figure 3: Four-point bending tests on unnotched beam of 140x140x560 mm^3 according to the ASTM C1609/C1609M.

4. Results

Table 2: The critical volumes of StF1 and StF2 and the equivalent fibre factors for the four UHPC matrices.

Fibre		**UHPC_1mm**	**UHPC_2.5mm**	**UHPC_4mm**	**UHPC_8mm**
StF1 (13/0.2)	Critical vol. (%)	1.75	1.5	1.5	1
	Fibre factor $(L_{f1}/d_{f1})*V_{f1}$	1.138	0.975	0.975	0.65
StF2 (20/0.2)	Critical vol. (%)	1	0.75	0.75	0.5
	Fibre factor $(L_{f2}/d_{f2})*V_{f2}$	1	0.75	0.75	0.50

The critical volumes of the short fibre StF1 and of the long fibre StF2 for the four UHPC matrices were experimentally determined and the results are shown in Table 2. Figure 4 shows the results of slump-flow and T_{500}-time of the UHPFRCs with a fibre volume no higher than critical values. The Figure 5 shows UHPFRCs with fibres clumps (and balls) when the critical fibre volumes were exceeded.

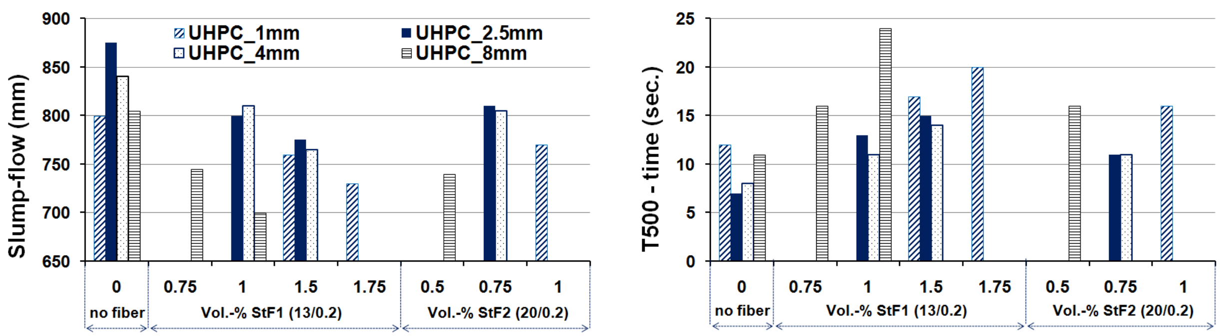


Figure 4: The slump-flow (left) and T_{500} – time (right) of UHPCs with and without fibres, the fibre contents were less than or equal to the critical volume fraction.

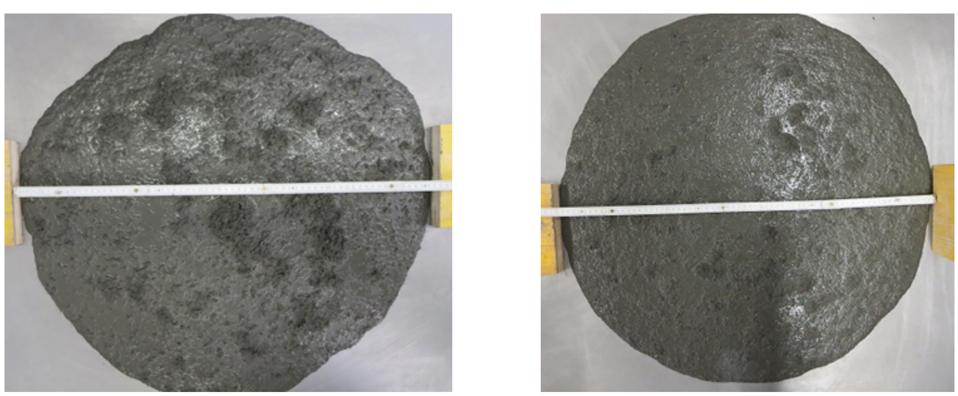


Figure 5: Fibres clumping (and balling) in the UHPC_8mm – 0.75 Vol.-% StF2 (left) and in the UHPC_2.5mm – 1.75 Vol.-% StF1 (right). Although these fibre concretes have the slump-flow of 650 mm and 700 mm, respectively, they cannot be used in practice.

The results of the UHPFRCs compressive strength are shown in Table 3. The Fig. 6a, 6b, 6c, 6d shows the flexural behaviour of the UHPFRCs. Each curve was the average of 6 test beams. The measurements of the peak strength (f_P), the residual strength (f^D_m) and the toughness (T^D_m) at the specified points of the load-deflection curve are also presented in Table 3.

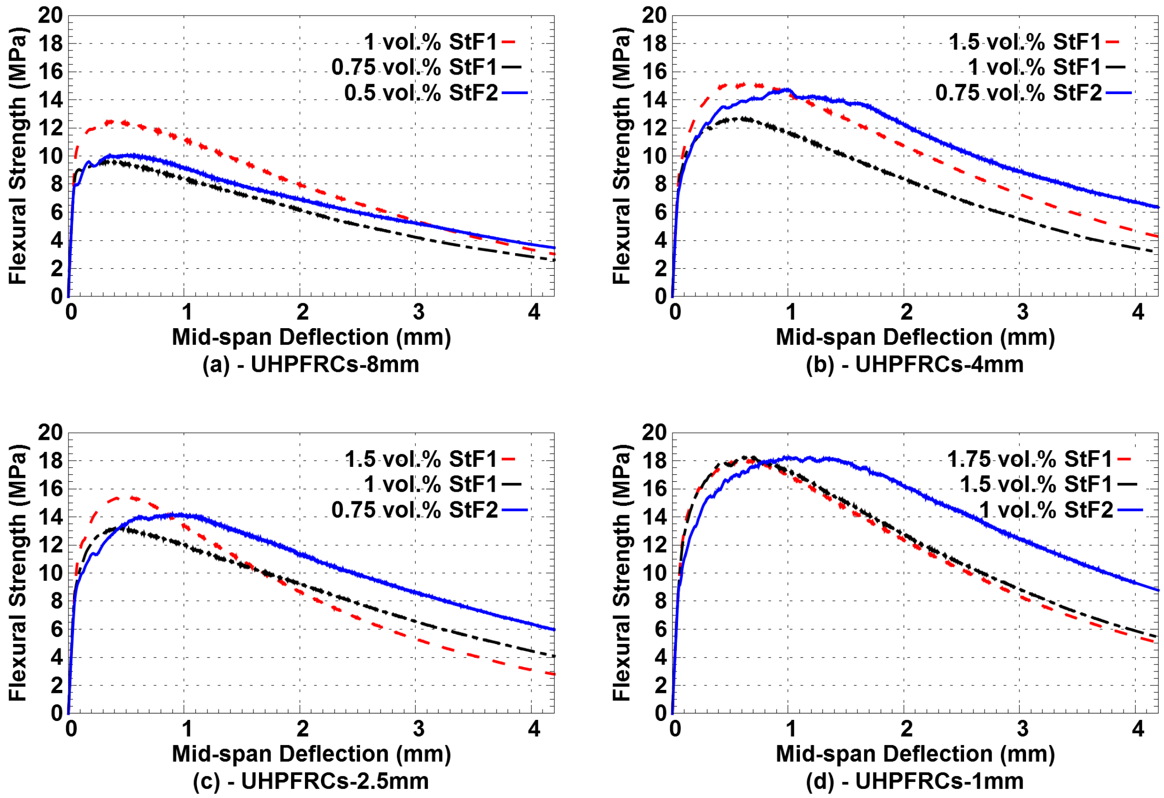


Figure 6: Flexural behaviour of the UHPFRCs based on four-point bending tests using beam of 14x14x56 cm^3.

Table 3: The compressive strength and the average flexural properties of UHPFRCs.

Matrix	**Fibre** vol.-%	**Comp. strength** MPa	**Flexural strength**-MPa **and toughness**(*) -N.m **at the Peak points and the specified points of the Load-Deflection curves**					
			Peak		**Specified deflections** - mm			
			Deflection mm		**0.42**	**0.7**	**2.8**	**4.2**
UHPC_8mm	0.5-StF2	193.8	0.511	10.04 (29.95)	9.93 (24.01)	9.81 (42.24)	5.52 (145.1)	3.47 (185.8)
	0.75-StF1	194.2	0.358	9.6 (20.10)	9.54 (23.97)	9.07 (41.02)	4.58 (133.4)	2.61 (165.6)
	1-StF1	193.3	0.388	12.47 (27.41)	12.40 (30.00)	11.95 (52.34)	5.90 (173.5)	3.02 (213.0)
UHPC_4mm	0.75-StF2	200.8	0.992	14.72 (81.01)	13.04 (28.49)	14.09 (53.59)	9.45 (227.2)	6.34 (298.4)
	1-StF1	199.7	0.561	12.65 (39.80)	12.43 (28.22)	12.51 (51.24)	6.04 (177.7)	3.15 (218.3)
	1.5-StF1	199.2	0.646	15.11 (50.95)	14.88 (32.33)	15.01 (59.78)	7.92 (219.6)	4.27 (274.0)
UHPC_2.5mm	0.75-StF2	199.1	0.899	14.16 (71.77)	13.08 (28.48)	13.82 (53.53)	9.13 (218.4)	5.97 (286.7)
	1-StF1	199.8	0.459	13.17 (33.64)	13.16 (30.29)	12.72 (54.02)	7.06 (189.8)	4.08 (240)
	1.5-StF1	198.3	0.551	15.33 (47.33)	15.32 (34.23)	14.93 (62.11)	5.85 (198.8)	2.79 (237.0)

UHPC_ 1mm	1-StF2	196.1	1.181	18.23 (121.88)	16.02 (34.32)	17.56 (65.32)	13.12 (292)	8.77 (391.2)
	1.5-StF1	195.6	0.615	18.23 (61.22)	17.82 (38.43)	18.22 (71.34)	9.54 (262.2)	5.43 (329.1)
	1.75-StF1	195.9	0.679	17.98 (68.55)	17.36 (38.46)	17.96 (71.01)	9.11 (256.8)	5.04 (319.6)

(*) the toughness values are put in parentheses

The short fibre StF1 is much more suitable than the long fibre StF2 in reinforcing UHPC_8mm when the same workability is required. The highest flexural strength of UHPC_8mm with critical volume of 1% StF1 was 12.5 MPa. For the strengthening of UHPC_4mm, UHPC_2.5mm and UHPC_1mm the long fibre StF2 is the best fibre regarding the highest flexural behaviour of fibre concrete and the lowest fibre content. At the critical volume of 0.75% StF2 the UHPFRC_2.5mm and UHPFRC_4mm obtained the highest flexural strength of about 14.5 MPa. The optimum UHPFRC_1mm was achieved by using the critical volume of 1% StF2, the modulus of rupture was 18.2 MPa.

5. Discussion

A homogenous fibres distribution and a good self-flowability of UHPFRCs were observed as the fibre contents were less than or equal to the critical volumes. The slump-flow test results indicate that the critical fibre volumes increased at increasing the paste volume and the content of the smaller 1 mm aggregate. Indeed, the three UHPCs with maximum grain size of 1 mm, 2.5 mm and 4 mm had the same paste (characteristics and volume fraction) but the maximum fibre contents of both fibres of UHPC_1mm was the highest. Further, compared with these three matrices, UHPC_8mm with a higher aggregate volume fraction and a high content of the larger 1 mm aggregate had the lowest critical fibre volumes. The higher the fibre factor $(L_f/d_f)*V_f$, the more the slump flow decreased. However, there is a strong interaction between long fibres and aggregates, leading to a lower flowability of long fibre concrete compared with short fibre concrete as the same fibre factor.

The compression test results show that the addition of steel fibres up to the critical volume influenced negligibly on the compressive strength of UHPFRCs (less than 2% increasing).

During the beam casting the fibres tended to orient in the direction of flow, which is also the direction of applied stress, resulting in a good improvement in bending behaviour, but this effect decreased as the grain size of aggregate increased. Indeed, the bending test results show that using the same volume of 1% StF1, the flexural strength and the toughness at the peak points reduced with the increasing of aggregate size of UHPC_2.5mm, UHPC_4mm and UHPC_8mm. Also, a similar phenomenon can be observed for the comparison of UHPC_1mm, UHPC_2.5mm and UHPC_4mm at 1.5 vol.% StF1.

6. Conclusions

An experimental study performed to obtain insight into the fibres-matrix interactions that influence the self-compacting properties and the mechanical properties of UHPFRCs. It verifies convincingly that the determination and utilization of the critical fibre volume for a specific UHPC matrix are significant to achieve the highest performance for self-compacting fibre concrete.

For UHPFRCs with maximum grain size up to 4 mm, the long fibre StF2 was much more effective than the short fibre StF1 in term of cost saving and toughness improving, the concretes using the long fibre had a similar modulus of rupture and a better toughness in comparison to the concretes having twice higher short fibre volume fraction. Fibre factors of long fibre StF2 were 1, 0.75, 0.75 for UHPCs_1, 2.5, 4 mm respectively. Short fibre with fibre factor of 1 is the best for UHPC_8mm.

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Acknowledgements

The presented work has been a part of the research project "Substitution von Stahl durch UHPC", 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.