A STUDY ABOUT THE INFLUENCE OF FIBRE TYPE AND CONTENT ON PROPERTIES OF STEEL BAR REINFORCED HIGH-STRENGTH STEEL FIBRE REINFORCED CONCRETE

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Abstract

The effect of fibres in combination with steel bar reinforcement is still widely unexplored. For this reason a research program was started, focused on the influence of steel fibre types and amounts as well as different bar reinforcements on flexural tensile strength, fracture behaviour and workability of steel bar reinforced high-strength steel fibre reinforced concrete (HSSFRC). The parameters which were investigated are in detail the influence of fibre geometry (straight with end hooks, corrugated), tensile strength of fibres (1000 N/mm², 1900 N/mm²) and different steel bar reinforcements in combination with diverse fibre contents (20, 30, 40 and 60 kg/m³).

Keywords: Beam; steel fibre; high-strength concrete; post cracking behaviour; fibre reinforced concrete; longitudinal reinforcement.

1 Introduction

High-strength concrete (HSC) or also called high performance concrete (HPC) is a construction material whose cube compressive strength according to the German regulations ranges between 67 N/mm² and 115 N/mm². HSC is predominantly utilized in structural elements loaded by high compressive forces such as columns in building or bridge constructions. In comparison to normal performance concrete (NPC) HPC has a lot of advantages. Among other things this concrete type is characterised by a high density and strength as well as a good workability. The existing disadvantages like the rising shrinkage of concrete or the increasing brittleness can be improved by the addition of steel fibres. Compared to conventional HSC the most important benefits of HSSFRC are the hindrance of the development of macrocracks, the delay of the propagation of microcracks to macroscopic cracks and the better ductility after microcracks. HSSFRC is also tougher and demonstrates higher residual strengths.

2 Test Program

The experimental investigations were carried out according to the German regulations [1] for steel fibre reinforced concrete. The test program was divided into

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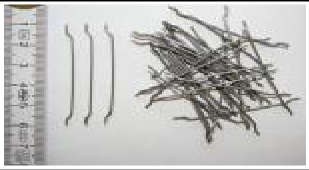
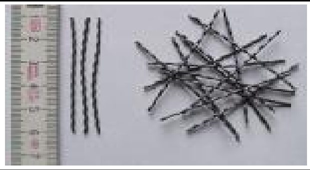
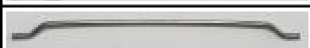
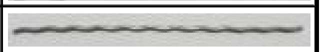
separate parts in which each one of them was studied in detail: influences of geometry and tensile strength of 4 steel fibres as well as the effects of different bar reinforcements. The applied fibre contents were 20, 30, 40 and 60 kg/m³. Based on the large number of test results only three of four fibre types with the fibre contents of 20, 40 and 60 kg/m³ are presented in this paper.

2.1 Materials and mixture proportions

The properties of three selected steel fibre types used for the HSSFRC mixtures are shown in Table 1. In total 4 steel fibres were tested.

Tab. 1 Overview of investigated steel fibre

Description	Fibre type F1	Fibre type F2	Fibre type F3
Depiction			
			
Geometry			
Shape	straight	straight	corrugated
Surface	plane	plane	plane
Cross-section	circular	circular	circular
Anchorage	hooked ends	hooked ends	continuous
Variables			
l_f [mm]	50	50	50
d_f [mm]	1	1	1
λ [mm]	50	50	50
f_t [N/mm²]	1100	1900	1100
f_t [1)] [N/mm²]	1222	1762	925
n_f [kg^{-1}]	3150	3100	2850

[1)] determined fibre tensile strength (quantity of samples: 10 fibres)

The illustrated fibre types above have a length (l_f) of 50 mm, a diameter (d_f) of 1.0 mm and an aspect-ratio ($\lambda = l_f/d_f$) of 50. These fibre types mainly differ in their shape (straight and corrugated) as well as in their tensile strength (f_t). Fibre types F1 and F3 are normal-strength fibres with a tensile strength of circa 1100 N/mm². F2 is a high-strength fibre with a tensile strength of approximately 1900 N/mm². The value n_f represents the number of fibres per kg. In all cases the modulus of elasticity averages 200000 N/mm².

The following materials were used:

- Cement CEM II/A-M(S-LL) 42,5R with conformity with EN 197-1 from CEMEX OstZement GmbH
- Fly ash EFA-Füller S-B/F from BauMineral GmbH
- Superplasticizer ISOLA BV/FM11 based on polycarboxylic ether (PCE) produced by CEMEX Admixtures GmbH

- Retarder ISOLA VZ 1 based on phosphate from CEMEX Admixtures GmbH
- Aggregates: 0/2 mm sand as well as 2/8 mm and 8/16 mm gravel

Table 2 shows the different concrete compositions of various HSC and HSSFRC mixtures. The mixture design R^0 (reference concrete) represents a fibreless concrete composition. Based on this mixture for different fibre amounts (20, 40, 60 kg/m³) HSSFRC compositions were produced with the fibres types F1, F2 and F3. The HSSFRC mixtures were essentially the same apart from the usage of different amounts of steel fibres in comparison with the HSC composition R^0. A slightly higher proportion of PCE was used as well as the addition of a retarder was required to maintain the workability with increasing fibre dosage over the working period. All concrete mixtures were mixed in a 0.5 m³ single-shaft compulsory mixer. The yield for each mixture was 0.380 m³. In order to reduce the influence of the moist aggregates for all concrete compositions dried aggregates were used.

Tab. 2 Concrete Compositions

Components		Concrete Compositions				Unit
		R^0	$F1^{20/40/60}$	$F2^{20/40/60}$	$F3^{20/40/60}$	
Cement	c	400.0	400.0	400.0	400.0	kg/m³
Total Water	w	132.0	132.0	132.0	132.0	kg/m³
	w/c ratio	0.330	0.330	0.330	0.330	-
Additives	Steel Fibres	0	20 / 40 / 60	20 / 40 / 60	20 / 40 / 60	kg/m³
	Fly Ash	100.0	100.0	100.0	100.0	kg/m³
	w/(c+FA) ratio	0.264	0.264	0.264	0.264	-
Admixtures	Superplasticizer	2.5	10.4/11.6/12.4	10.4/11.6/11.6	10.4/11.6/11.6	kg/m³
	Retarder	0.2	0.8 / 2.0 / 2.4	2.0 / 2.0 / 2.4	2.0 / 2.0 / 2.4	kg/m³
Aggregates	0/2 Sand	39.0	39.0	39.0	39.0	%
	2/8 Gravel	25.0	25.0	25.0	25.0	%
	8/16 Gravel	36.0	36.0	36.0	36.0	%

2.2 Fresh properties tests

One workability test, as mentioned, was carried out for HSC and HSSFRC mixtures in accordance with the German standard DIN EN 12350-5. The test was carried out in the lapse of 5-10 minutes after emptying the concrete mixer. The *flow table test* consists of the determination of the mean diameter in the horizontal concrete spread on a table after lifting the cone-shaped mould with compaction. Hence the table top is raised until it meets the stop and then dropped freely 15 times. In this test the workability of the produced mixtures was investigated. The table flow test also gives an indication of the cohesion of the fresh concrete. That results in a possible determination of segregation or bleeding. The target slump for the investigations should have a range between 56 and 62 cm.

2.3 Hardened properties tests

The concrete compressive and splitting tensile strength was measured on three cubes with an edge length of 150 mm in each instance. The modulus of elasticity was investigated on three cylinders with a height of 30 cm and a diameter of 15 cm. Furthermore four-point bending tests were carried out for determining the post cracking behaviour. For this purpose HSC and HSSFRC beams with a cross section of

150 x 150 mm and a length of 700 mm were used as specimens (Fig. 1). The casting of the specimens, the curing procedure and the test set-up were chosen according to the German regulations [1] which are similar to those of RILEM. The beams were loaded orthogonal to the casting direction. The load was applied using displacement controlled method with a rate of 0.2 mm/min. The deflection was recorded by using one LVDT on each side of the beam.

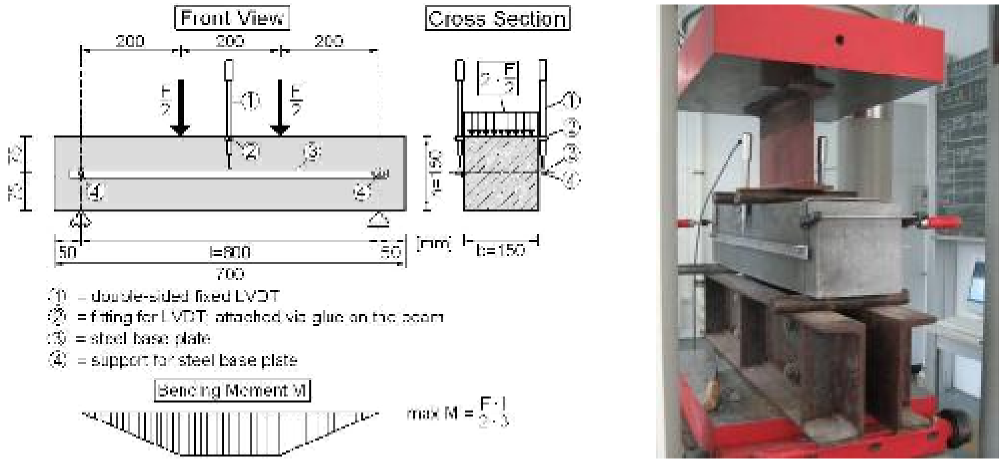


Fig. 1 Experimental Set-up of the four point bending test

Altogether 18 beams per test series were produced. In each case 6 beams with two different grades of steel bar reinforcements and 6 beams without reinforcing steel were investigated, as shown in Fig. 2.

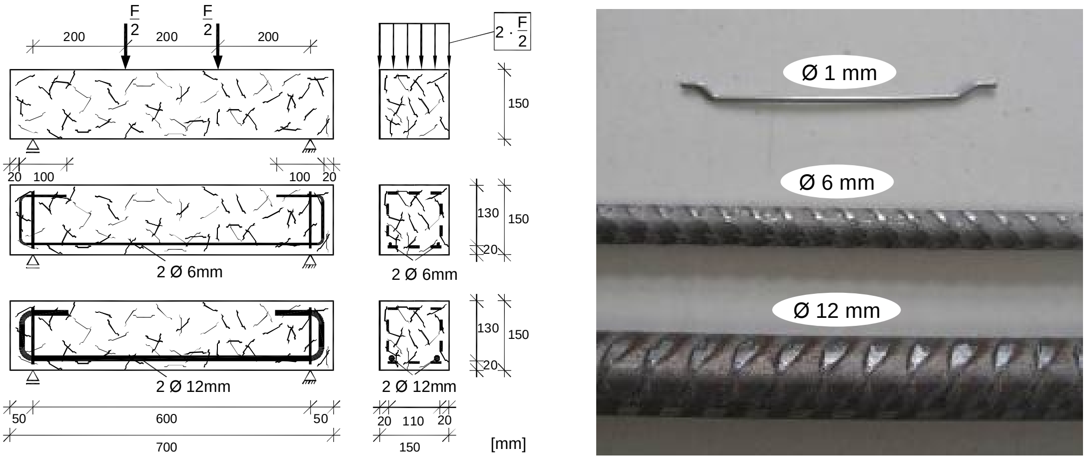


Fig. 2 Test specimens: a) no bar reinforcement; b) 2 Ø 6 mm; c) 2 Ø 12 mm

The distance between the bottom edge of the reinforcing steel and the concrete surface was 2 cm. Longitudinal tensile reinforcement had hooks at the beam ends to ensure adequate anchorage. Deformed steel bars with a diameter of 6 and 12 mm and specified yield strength of 500 N/mm² (BSt 500) were used as bottom longitudinal reinforcement. The hardened properties of the mixtures were tested 28 days after casting.

3 Experimental Results

3.1 Properties of fresh concrete

Due to the low water/binder-ratio the concrete compositions were characterised by a high viscosity that results in an aggravated workability. However during and after the tests a uniform distribution and a random orientation of fibres without any signs of balling or clustering were observed. Table 3 presents the workability test results and concrete temperatures of different HSC and HSSFRC mixtures.

Tab. 3 Properties of fresh concrete

Properties of fresh concrete		Concrete composition										
		R^{0}	$F1^{20}$	$F1^{40}$	$F1^{60}$	$F2^{20}$	$F2^{40}$	$F2^{60}$	$F3^{20}$	$F3^{20*}$	$F3^{40}$	$F3^{60}$
Flow table test	[cm]	62.5	63.0	55.5	57.3	57.0	56.0	62.8	62.0	58.0	64.5	61.5
Concrete temperature	[°C]	22.1	20.1	21.9	19.8	21.3	20.5	22.3	25.2	26.6	33.6	29.0
Ambient temperature	[°C]	7.2	3.5	6.5	2.5	6.3	4.8	11.0	18.5	18.8	26.8	23.0

$F3^{20*}$ repetition of the mixture with a bar reinforcement of 2 Ø 12 mm

3.2 Properties of hardened concrete

In all cases the failed surfaces of HSC and HSSFRC mixtures revealed uniform distribution of aggregates, confirming segregation resistance and stability of the mixtures produced. To evaluate the degree of the fibre segregation, the specimen's fracture surface was discretized in four rows and four columns of cells, presented in Fig. 3. Generally there was a steady increase of the percentage of fibres in the casting direction related to the complete fibre distribution that was observed. In this connection similar fibre distributions under varying longitudinal reinforcement were obtained.

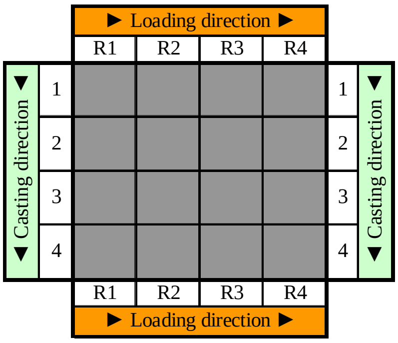
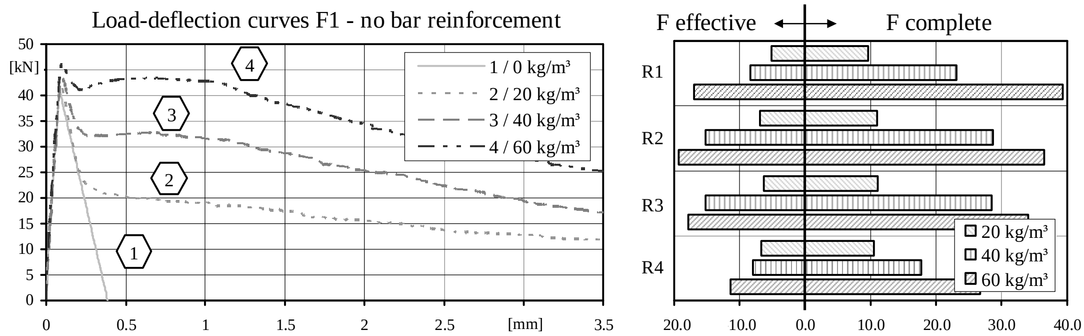


Fig. 3 Discretization in cells of specimen's fracture surface

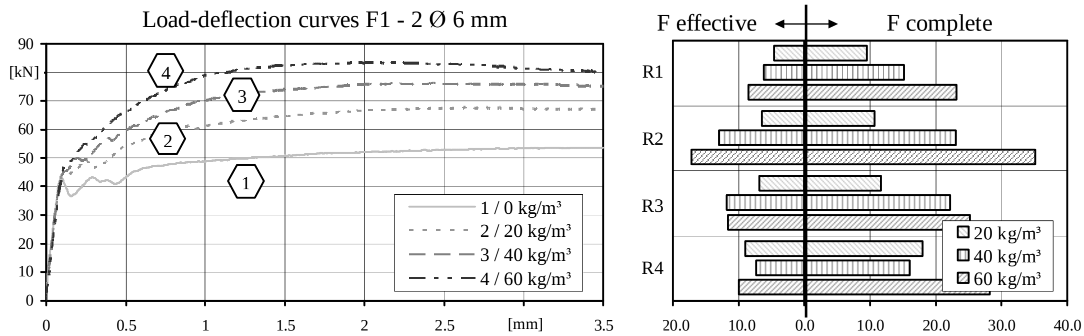
In Fig. 4 to 6 it is exemplary shown the influence of fibre dosage (20, 40 and 60 kg/m³) for diverse reinforcement ratios (0.25 % with 2 Ø 6 mm and 1.0 % with 2 Ø 12 mm) on the pre- and post cracking behaviour of HSC and HSSFRC of fibre type F1. The plotted load-deflection curves were determined in four-point bending tests. Each curve is the average relationship of three to six test beams (n_{beams}) as it is shown in the table under the graphs. In addition to the presented load-deflection curves the average number of complete and effective fibres (F complete, F effective) of the failed cross section is given in the opposite diagram. The abbreviation ΣF_c refer to the number of fibres in the complete cross section of the fractured surface. The number of effective fibres is characterized with an additional indices e (ΣF_{ce},). Effective fibres are those that are not located directly at an edge, are not orientated almost parallel to the failed cross-section and stick out more than

5 mm. Additionally the standard deviation (s) of the number of fibres is shown. An overview of selected material properties and average number of fibres in the failed cross-section is given in the table under the load-deflection curves. The strength values (cube compressive strength $f_{cm,cube}$, splitting tensile strength $f_{ct,sp}$ and the modulus of elasticity E_{cm}) the load values (initial crack load $F_{ic,m}$, load corresponding to 0.5 mm and 3.5 mm deflection $F_{0.5,m}$, $F_{3.5,m}$) based on test series as well as and the load differences between $F_{0.5,m}$ and $F_{ic,m}$ (ΔF_1) as well as between $F_{3.5,m}$ and $F_{0.5,m}$ (ΔF_2) as percentage were stated. Apart from that the average concrete cover (c_l) of the longitudinal reinforcement is listed in the last column.



Fibre content	$f_{cm,cube}$	$f_{ct,sp}$	E_{cm}	$F_{ic,m}$	$F_{0.5,m}$	$F_{3.5,m}$	ΔF_1	ΔF_2	ΣF_c	s_c	ΣF_{ce}	s_{ce}	n_{beams}	c_l
	[N/mm²]			[kN]			[%]		[-]				[-]	[cm]
0 kg/m³	86.15	4.16	35438	41.20	-	-	-	-	-	-	-	-	6	-
20 kg/m³	86.82	5.09	43106	40.92	20.28	11.72	-50.44	-42.21	42.3	7.63	25.0	4.69	6	-
40 kg/m³	91.06	5.60	41238	42.59	32.45	17.12	-23.81	-47.24	98.0	30.50	46.7	17.83	6	-
60 kg/m³	88.16	6.14	40307	45.78	43.14	25.22	-5.77	-41.54	136.5	23.50	65.5	11.81	6	-

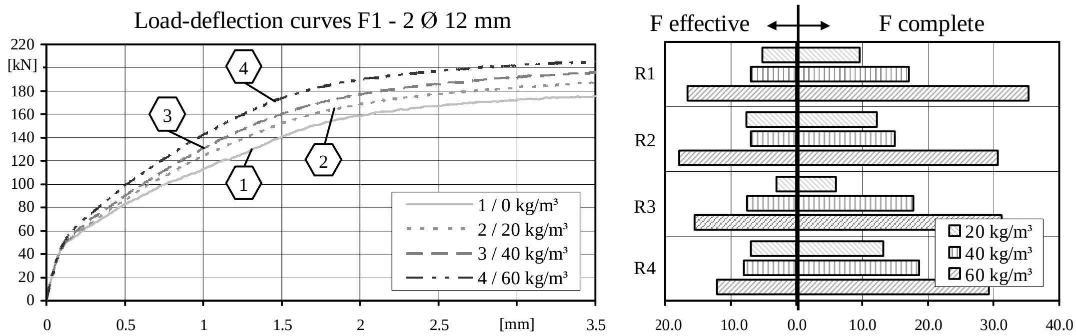
Fig. 4 Average load-deflection curves for different fibre contents and distribution of effective and complete fibres in the loading direction without bar reinforcement (F1)



Fibre content	$f_{cm,cube}$	$f_{ct,sp}$	E_{cm}	$F_{ic,m}$	$F_{0.5,m}$	$F_{3.5,m}$	ΔF_1	ΔF_2	ΣF_c	s_c	ΣF_{ce}	s_{ce}	n_{beams}	c_l
	[N/mm²]			[kN]			[%]		[-]				[-]	[cm]
0 kg/m³	86.15	4.16	35438	41.23	43.21	53.53	4.80	23.88	-	-	-	-	6	2.23
20 kg/m³	86.82	5.09	43106	43.68	54.31	66.86	24.35	23.09	49.8	14.16	27.0	8.51	6	1.87
40 kg/m³	91.06	5.60	41238	41.92	59.74	75.11	42.49	25.74	76.3	14.04	38.3	4.68	6	1.98
60 kg/m³	88.16	6.14	40307	45.01	66.43	79.95	47.59	20.36	111.7	17.82	47.3	7.81	6	2.02

Fig. 5 Average load-deflection curves for different fibre contents and distribution of effective and complete fibres in the loading direction with 2 Ø 6 mm (F1)

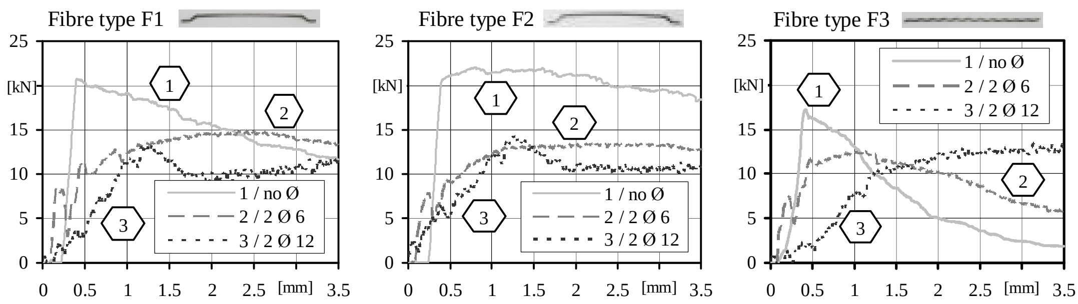
The load bearing capacity was generally improved by increasing fibre content. In general a reduced number of broken fibres in the failed cross-section were counted in combination with steel bar reinforcement. For all tested beams with a bar reinforcement of 2 Ø 6 mm flexural tensile failures was observed independent of the fibre content. For fibre volumes greater than 40 kg/m³ a failing in shear of the high-strength concrete beams with a longitudinal reinforcement of 2 Ø 12 mm was not obtained.



Fibre content	$f_{cm,cube}$	$f_{ct,sp}$	E_{cm}	$F_{ic,m}$	$F_{0.5,m}$	$F_{3.5,m}$	ΔF_1	ΔF_2	ΣF_c	s_c	ΣF_{ce}	s_{ce}	n_{beams}	c_l
	[N/mm²]			[kN]			[%]		[-]				[-]	[cm]
0 kg/m³	86.15	4.16	35438	42.57	82.58	175.48	93.97	112.49	-	-	-	-	3	1.74
20 kg/m³	86.82	5.09	43106	41.57	85.85	187.20	106.55	118.05	41.0	9.92	22.8	6.06	5	1.72
40 kg/m³	91.06	5.60	41238	42.76	89.80	195.85	109.99	118.11	68.7	17.57	29.5	7.61	6	1.93
60 kg/m³	88.16	6.14	40307	43.91	98.53	205.41	124.40	108.47	126.5	16.97	62.2	9.06	6	1.95

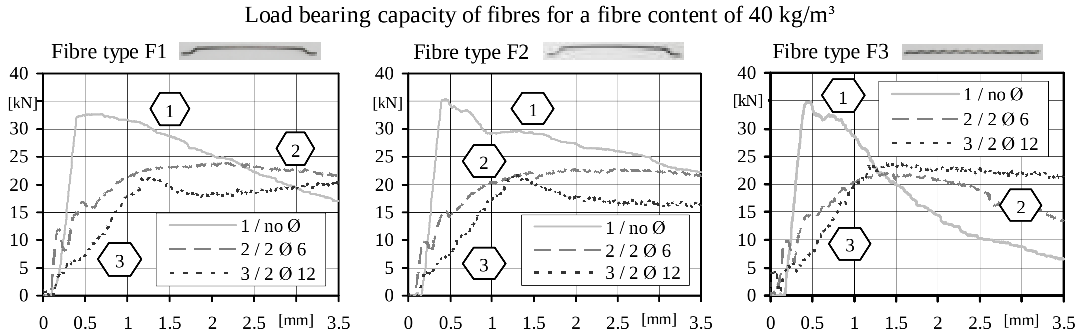
Fig. 6 Average load-deflection curves for different fibre contents and distribution of effective and complete fibres in the loading direction with 2 Ø 12 mm (F1)

Fig. 7 to 9 presents the contrast of load-deflection curves generated by the fibre part in interaction with diverse bar reinforcements for the respective fibre concentrations. Curve number 1 demonstrated the percentage of fibres obtained without bar reinforcement. Thereby the working capacity of concrete (assumed according to [1]) was subtracted from the curves without bar reinforcement. The curves number 2 and 3 represent the percentage of fibres achieved with two different variations of bar reinforcement (2 Ø 6 mm and 2 Ø 12 mm). These load-deflection curves were generated by the subtraction of loads determined with fibres and longitudinal reinforcement and loads based on tests with reinforcing steel but without fibres. In addition to the illustrated fibre number the average difference of concrete cover of the bar reinforcements (Δc_l) are given.



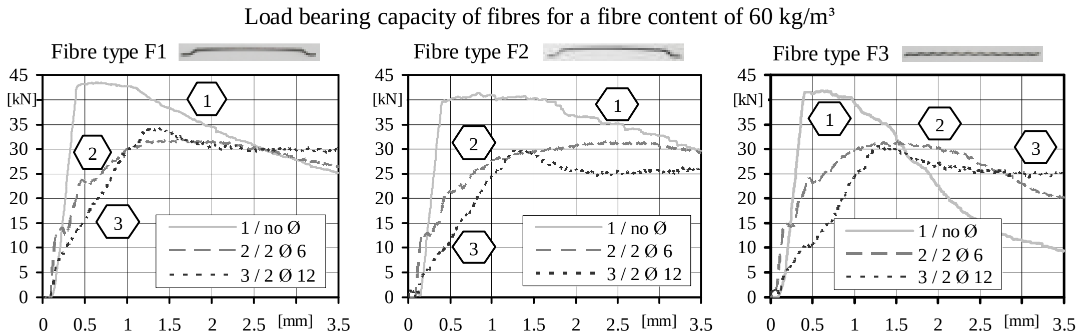
Bar reinforcement	F1 ΣF_c	F1 s_c	F1 ΣF_{ce}	F1 s_{ce}	F1 Δc_l	F2 ΣF_c	F2 s_c	F2 ΣF_{ce}	F2 s_{ce}	F2 Δc_l	F3 ΣF_c	F3 s_c	F3 ΣF_{ce}	F3 s_{ce}	F3 Δc_l
	[-]				[cm]	[-]				[cm]	[-]				[cm]
no Ø	42.3	7.63	25.0	4.69	-	43.8	6.34	23.8	6.27	-	32.0	8.20	18.0	6.13	-
2 Ø 6	49.8	14.16	27.0	8.51	-0.37	31.8	3.31	17.0	2.76	-0.33	31.8	7.65	19.2	5.95	-0.29
2 Ø 12	41.0	9.92	22.8	6.06	-0.03	41.5	10.48	19.5	4.59	0.18	42.7	11.24	22.3	3.90	0.10

Fig. 7 Comparison of load bearing capacity of fibre types F1, F2 and F3 for different bar reinforcements (fibre content 20 kg/m³)



Bar reinforcement	Fibre type F1					Fibre type F2					Fibre type F3				
	ΣF_c	s_c	ΣF_{ce}	s_{ce}	Δc_1	ΣF_c	s_c	ΣF_{ce}	s_{ce}	Δc_1	ΣF_c	s_c	ΣF_{ce}	s_{ce}	Δc_1
	[-]				[cm]	[-]				[cm]	[-]				[cm]
no Ø	98.0	30.50	46.7	17.83	-	83.3	11.79	34.3	5.16	-	85.3	8.29	43.2	4.31	-
2 Ø 6	76.3	14.04	38.3	4.68	-0.25	76.5	10.71	32.2	9.81	-0.28	71.0	12.25	39.5	7.23	-0.50
2 Ø 12	68.7	17.57	29.5	7.61	0.16	81.2	20.57	34.8	8.80	0.23	82.3	9.50	45.0	12.77	0.35

Fig. 8 Comparison of load bearing capacity of fibre types F1, F2 and F3 for different bar reinforcements (fibre content 40 kg/m³)



Bar	Fibre type F1					Fibre type F2					Fibre type F3				
	ΣF_c	s_c	ΣF_{ce}	s_{ce}	Δc_1	ΣF_c	s_c	ΣF_{ce}	s_{ce}	Δc_1	ΣF_c	s_c	ΣF_{ce}	s_{ce}	Δc_1
	[-]				[cm]	[-]				[cm]	[-]				[cm]
no Ø	136.5	23.50	65.5	11.81	-	116.8	13.57	49.5	6.92	-	122.8	12.86	61.8	5.04	-
2 Ø 6	111.7	17.82	47.3	7.81	-0.21	123.5	24.01	46.5	7.92	-0.12	112.3	17.47	59.0	10.92	-0.40
2 Ø 12	126.5	16.97	62.2	9.06	0.18	119.8	14.06	42.8	4.54	0.25	111.0	13.25	45.2	11.21	0.27

Fig. 9 Comparison of load bearing capacity of fibre types F1, F2 and F3 for different bar reinforcements (fibre content 60 kg/m³)

4 Conclusions

The application of straight hooked high-strength steel fibres (F2) in steel bar reinforced HSC seems to be unnecessary because an increase of the load bearing capacity compared to normal-strength steel fibres (F1) was not observed. For the design of steel bar reinforced HSSFRC constructions, the load bearing capacity in the range of low deformations (0.5 mm) is overestimated if the residual loads based on the test results of the HSSFRC beams without bar reinforcement will be accepted. Also in the range of high deflections (3.5 mm) especially for the high-strength fibre F2 an overestimation is possible.

References

[1] Deutscher Beton- und Bautechnik-Verein e.V., *DBV-Merkblatt Stahlfaserbeton*, Wiesbaden, October 2001