The investigation on strength and flexural toughness of fibre cocktail reinforced self-compacting high performance concrete

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Abstract

Based on the experimental results of the workability, the suitable fibre types (steel fibres, PP-fibres and fibre cocktail) and fibre dosages for fibre-reinforced-self-compacting-high-performance-concrete (FRSCHPC) were selected. To assess the influences of different fibres on the compressive strength, flexural toughness and failure patterns of beams and slabs, a series of experiments has been carried out and evaluated. The results show that the fibre cocktail – a combination of steel fibres and PP-fibres – can represent an optimal fibre reinforcement for self-compacting-high-performance-concrete.

Keywords: Fibre cocktail; FRSCHPC, Compressive strength; Flexural toughness; Failure pattern

1. Introduction

Fibre-reinforced-self-compacting-high-performance-concrete (FRSCHPC) has great potential significance for construction (e.g., for smart structures, concrete repair, bridge construction, etc.). The fibres could improve the ductility and stress distribution of HPC, replace the steel reinforcement partly, reduce the crack width, enhance the bar spacing and decrease the labour costs. Several approaches have been developed to improve the properties of SCHPC. One approach is to optimise the fibre combination for the workability, strength and flexural toughness and cost benefit.

Developing FRSCHPC requires careful control of some factors to ensure the high performance of concrete such as high strength, high toughness and improved failure patterns. The fibre types, contents and different fibre cocktail (combinations of steel- and PP-fibres) are important factors affecting both the workability, and the toughness and failure patterns of SCHPC.

The research results for fibres reinforced SCHPC are limited. It is unclear whether there are differences [1–4] between fibre cocktail samples and mono-fibre samples in terms of the toughness, and if a fibre cocktail should be used for producing SCHPC. Based on the investigation of the workability of FRSCHPC [7,8] this paper presents the research results of different fibre influences on the strength, the flexural toughness and on the failure patterns of FRSCHPC with different mono-fibres and fibre cocktails.

2. Experiments

2.1. Materials

The base mix of the plain SCHPC without fibre reinforcement from the investigations on the workability is illustrated in Table 1a.

The micro fibres are mainly used to reduce the shrinkage cracks, and the central point of this work is to investigate

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Nomenclature

CFC fibre cocktail reinforced concrete
CFC 305/307 fibre cocktail reinforced concrete with 30 kg/m^3 steel fibre C and 5 or 7 kg/m^3 PP-fibre D
FRSCHPC fibre-reinforced-self-compacting-high-performance-concrete
HPC high-performance-concrete
NC mixture of concrete without fibre
SFRCC 30 mixture of steel fibre reinforced concrete with fibre dosage of 30 kg/m^3 fibre C,
SCHPC self-compacting-high-performance-concrete
SP superplaticizer
F_u maximum value of the load in the interval of 0.1 mm (kN)
δ_1 deflection corresponds to the F_u (mm)
D^b_{BZ} energy absorption of the unbroken concrete (kN mm)
D^f_{BZ2} $D_{BZ2} - D^b_{BZ}$(kN mm) by $\delta_2 = \delta_1 + 0.65$ (mm)
D^f_{BZ3} $D_{BZ3} - D^b_{BZ}$(kN mm) by $\delta_3 = \delta_1 + 3.15$ (mm)
D_{BZ} energy absorption of the fibre reinforced concrete (kN mm) $= D^b_{BZ} + D^f_{BZ}$
equ β_{BZ2} equivalent flexural tensile strength (MPa) by δ_2,
equ β_{BZ3} equivalent flexural tensile strength (MPa) by δ_3
δr increasing rate.

Table 1a
Base mixture proportion of SCHPC without fibre reinforcement

Materials	Cem I B42.5 (kg/m^3)	Fly ash (kg/m^3)	Aggregate (kg/m^3)	SP (kg/m^3)	W/C ratio	W/B ratio
Content	400	210	0–4 mm (55%):776 4–8 mm (45%):660	6.1 (1% of binder)	0.5	0.33

Table 1b
Designation of specimens and properties of different fibres

Specimen	Fibre type	Content (kg/m^3)		Length (mm)	Diameter or equivalent diameter (mm)	Pieces/kg
		Steel fibre	PP-fibre			
PFRCC7	PP-fibre C	–	7	52–55	0.4–0.8	160,000
PFRCD7	PP-fibre D	–	7	40	1.1	29,000
PFRCE7	PP-fibre E	–	7	54	0.5	–
SFPCC30	Steel fibre C	20	–	30	0.6	15,000
SFRCC50		50	–			
CFC305	Steel fibre C and PP-fibre D	30	5	–	–	–
CFC307		30	7			

load-carrying capacity of FRSCHPC after the peak-load. Therefore only macro fibres with different fibre contents have been added into the samples of SCHPC as shown in Table 1b.

2.2. Test methods

In accordance with the German guideline for fibre reinforced concrete/shotcrete [5], tests regarding the fibre influence on the flexural toughness have been carried out. The beam size is B (width) $\times$ H (depth) $\times$ L (length) $= 150 \times 150 \times 700$ mm, tested on a span $L_s = 600$ mm. The deformation rate is 0.2 mm/min (Fig. 1). The energy absorption of FRC is determined in accordance with the following expression:Energy absorption

$$D_{BZ} = \int_0^{\delta u} F(\delta)\mathrm{d}\delta \quad (1)$$

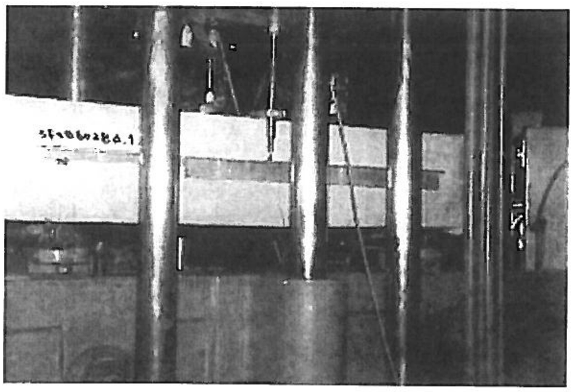

Fig. 1. Set-up of bending test for FRSCHPC beams.

Additional to the beam test, round panel (diameter $\times$ thickness: 60×7.5 cm) tests of FRSCHPC with different fibre types and fibre contents have been carried out related to ASTM [6]. The panels (Fig. 4) are subjected to a central point load with a deformation rate of 0.4 mm/min, and the panel is supported on three symmetrically arranged pivots. Such a test panel experiences bi-axial bending in response to a central point load and exhibits a mode of failure related to the in situ behaviour of structures such as concrete slabs-on-grade, shotcrete tunnel linings.

3. Results

3.1. Development of the compressive strength

Table 2 shows the development of compressive strength of SCHPC with and without fibre reinforcement in 1, 7 and 28 days. The addition of fibres aids in converting the brittle properties of concrete into a ductile material, but no significant trend of improving compressive strength was observed. The compressive strength of all the samples exceeded 50 N/mm^2 after 7 days, and 70 N/mm^2 after 28 days. Therefore, the proposed mix design has produced concrete that meets satisfactorily the strength requirement of SCHPC [7].

3.2. Flexural properties

3.2.1. Flexural beam test

The flexural strength and toughness of beams with different fibre types and fibre contents has been investigated according to [5] as shown in Fig. 1. Fig. 2 shows the comparison of the load-deflection curves of SFRCC 30 (beams with 30 kg/m^3 steel fibre C), PFRCC/D/E 7 (concrete with 7 kg/m^3 macro PP-fibre C, D and E) at the age of 28 days [7]. It can be seen:

- Compared to post-crack behaviour of samples with PP-fibres, the beams of SFRCC 30 behave much better than PFRCC/D/E 7 over the entire deflection range. After a deflection of 1.5 mm, the load bearing capacity of SFRCC 30 sloped down faster than PFRCC 7, PFRCD 7 and PFRCE 7 because the short steel fibres (3 cm) are pulled out with the increasing of the beam deflection. This shows an important advantage of longer PP-fibres.
- PFRCC 7 and PFRCE 7 indicate better post-crack behaviour than that of PFRCD 7. The reason could trace back to the high surface frictional coefficient of fibre C and E. However, the workability of PFRCC 7 and PFRCE 7 was very low [7,8].
- PFRCD 7 shows a relative low energy absorption ability after the first crack, but excellent workability [7,8]. This points a possible advantage of the fibre combination

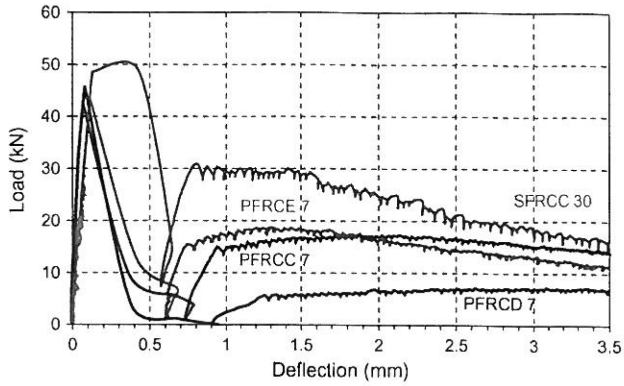

Fig. 2. Comparison of the load-deflection curves of the PP-fibre and steel fibre reinforced SCHPC beams.

from steel fibre C and PP-fibre D, which may have both good workability and high post-crack behaviour. Therefore, the mechanic properties of fibre cocktail (hybrid PP-steel fibre) reinforced SCHPC were investigated mainly.

Table 3 shows the comparison of the mean values of the peak-load, flexural strength and post-crack parameters for SFRCC 30, SFRCC 50 and CFC 305 (fibre cocktail of 30 kg/m^3 steel fibre C and 5 kg/m^3 PP-fibre D) according to the German guideline [5] after 28 days.

PFRCC 7 and PFRCE 7 have not been taken into account for the further investigation because the mixtures of SCHPC with PP-fibre C and E did not achieve sufficient workability [8]. Table 4 shows the increase rate (δr) of the toughness parameters (the energy absorption and the equivalent flexural strength) and the fibre contents of various fibre reinforced concrete at the age of 28 days.

Tables 3 and 4 show that (1) Compared to CFC 305, flexural strength changed about 6%, the toughness parameters (energy absorption: D^{f}_{BZ2}, D^{f}_{BZ3}, and the equivalent flexural strength equ β_{BZ2}, equ β_{BZ3}) of SFRCC 50 were similar, the difference was smaller than 3.25% when the total fibre dosage in SFRCC 50 increased more than 40%. 2) The post-crack behaviour of CFC 305 is much better than SFRCC 30. Compared to SFRCC 30, the energy absorption (D^{f}_{BZ3}) and equivalent flexural strength (equ β_{BZ3}) of CFC 305 increased by about 30%, although the total fibre dosage increased by only about 17%.

Furthermore, it has been observed that flexural failure pattern of the beams changed from only one main crack for SFRCC 30 into a multiple crack pattern of CFC 305 (Fig. 3) which occurs in steel fibre reinforced beams only

Table 2
Comparison of the compressive strength (N/mm^2) from 1 to 28 days

Concrete age (d)	NC	PFRCE 7	PFRCC 7	PFRCD 7	SFRCC 30	SFRCC 50	CFC305
1	30	38.4	29.5	40	32.54	28.35	30.65
7	50	54.78	50.22	52.11	64.86	56.54	59.1
28	77	72.2	70	76	75.2	81.2	74.27

Table 3
Comparison of the flexural strength, the equivalent flexural strength and energy absorption of beams with different fibre types and fibre contents

Samples	F_u (kN)	β_{BZ} (N/mm^2)	D^f_{BZ2} (kN mm)	equ β_{BZ2} (N/mm^2)	D^f_{BZ3} (kN mm)	equ β_{BZ3} (N/mm^2)
PFRCD 7	45.67	8.12	–	–	34.84	2.06
SFRCC 30	44.7	7.95	20.27	7.21	83.66	4.96
SFRCC 50	39.15	6.96	22.59	8.26	110.24	6.53
CFC 305	41.7	7.41	22.48	8	109.22	6.47

Table 4
Comparison of the increase rate (δr) of the strength and toughness parameter

	β_{BZ}	D^f_{BZ2}	equ β_{BZ2}	D^f_{BZ3}	equ β_{BZ3}	Total fibre dosage
δr (SFRCC 50–30)	12.42%	11.45%	14.49%	31.77%	31.65%	66.67%
δr (SFRCC 50–CFC 305)	6.12%	0.49%	3.25%	0.93%	0.93%	42.86%
δr (CFC 305-SFRCC 30)	6.7%	10.9%	10.96%	30.55%	30.44%	16.67%

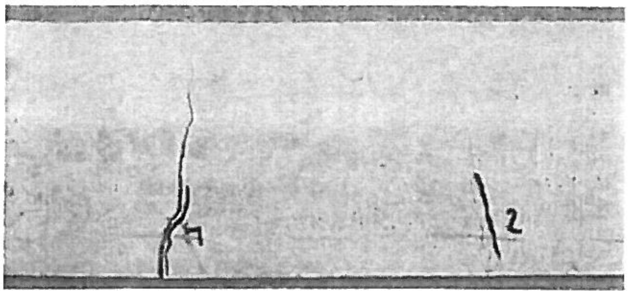

Fig. 3. Multi-crack failure pattern of SCHPC beam with fibre cocktail reinforcement.

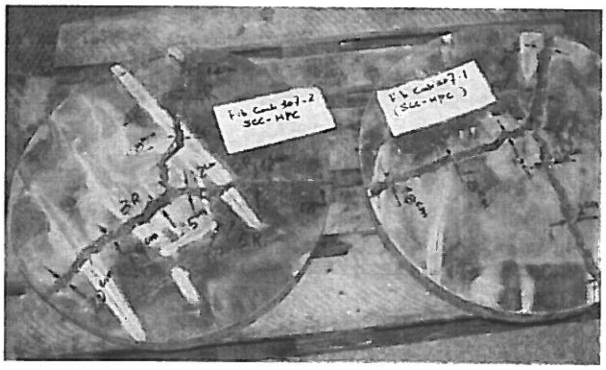

Fig. 4. Failure pattern of round panels of CFC 307.

if the steel fibre content is more than 50 kg/m^3 [7]. This means that the tensile stress distributed more uniformly in the beam with fibre cocktail than in the beam with only steel fibres. After the steel fibres are pulled out, the longer PP-fibres continue to transmit tensile stresses across the crack in the concrete and prevent the further spread of cracks and this leads to an improvement in tensile strength and ductility of concrete. Due to the multi-crack formation, the maximum crack width was reduced about 15%. It has positive effect both on the serviceability and on the durability of SCHPC in practice.

3.2.2. *Flexural panel test*

Fig. 4 shows the typical failure mode of hybrid fibre reinforced panel after testing according to [6]. The panel tests indicate that the failure patterns of the fibre combination are very different between steel fibre and PP-fibres. As the most steel fibres are pulled out, the PP-fibres are partly broken down and partly pulled out. This observation supports the use of fibre cocktail in SCHPC because the tensile capacity of PP-fibres can be better exploited, and a fibre cocktail can better prevent the further pulling out of the steel fibres from the concrete matrix after the cracking.

Table 5 indicates the comparison [7] of the mean values of the energy absorption in the deflection of 5, 10, 15, 20, 25, 30, 35 and 40 mm of the flexural panel test for steel fibre

Table 5
Comparison of the mean value of the energy absorption for SFRCC50 and CFC 307 after the round panel tests

	Energy absorption (J)							
Deflection (mm)	5	10	15	20	25	30	35	40
SFRCC 50	226	368	426	456	472	480	484	487
CFC 307	184	336	429	490	531	560	579	594

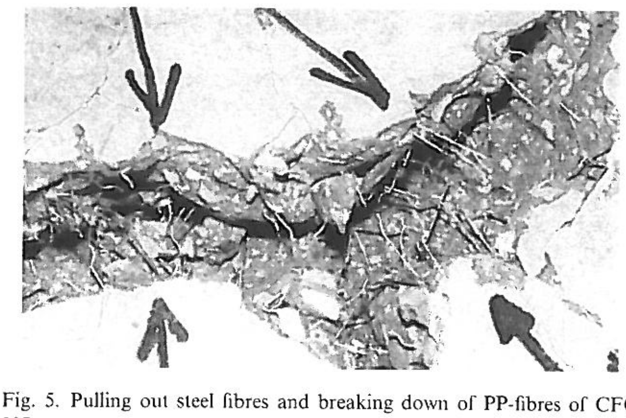

Fig. 5. Pulling out steel fibres and breaking down of PP-fibres of CFC 307.

reinforced SCHPC with fibre dosage of 50 kg/m^3 (SFRCC 50) and fibre cocktail reinforced SCHPC with 30 kg/m^3 steel fibre C and 7 kg/m^3 PP-fibre D (CFC 307). It can be seen that after a defined deflection the energy absorption of CFC 307 is higher than that of SFRCC 50. It means that the PP-fibres demonstrated their benefits in the post-crack behaviour by increasing of the deflection ($\geqslant$15 mm) and the pulling out of the steel fibres. (see Fig. 5).

4. Conclusion

In addition to the workability of fresh SCC, fibre reinforced SCHPC has to show good load-carrying capacities, such as post-crack properties, failure patterns and compressive strength. This work investigated the optimisation of fibre type, fibre combinations and fibre dosage in term of the behaviours above mentioned. Significant benefits in toughness properties, failure patterns and cost may be achieved by fibre cocktail reinforced SCHPC. The investigation with macro fibres indicated:

- The addition of fibres aids in converting the brittle properties of concrete into a ductile material, but no significant trend of improving compressive and flexural strength was found.
- The analysis of the increase rate (δr) of the toughness parameter demonstrates the possible cost benefit of using fibre cocktail. Compared to SFRCC 30, the flexural toughness of CFC 305 increased about 30%, although the total fibre dosage gained only about 17%. Compared to CFC 305, the flexural toughness of SFRCC 50 increased very slightly, while the total fibre content increased by 43%.
- The beam failure pattern changed from only one main crack for SFRCC 30 into a multiple crack pattern for CFC 305. This normally occurs in steel fibre reinforced beams only if the steel fibre content is more than 50 kg/m^3. Due to the multi-crack formation, the maximum crack width decreased.
- The failure patterns of various fibres in the fibre cocktail reinforced SCHPC are different: the steel fibres are pulled out, and the PP-fibres are partly broken down and partly pulled out. This observation supports the use of fibre cocktail in SCHPC because the tensile capacity of PP-fibres can be better exploited, and fibre cocktail can better prevent the further pulling out of the steel fibres from the concrete matrix after the cracking.
- In the bi-axial bending panel test, the round panels of CFC 307 absorbed more energy than the panels of SFRCC 50 from a relative large central deflection ($\geqslant$15 mm), although the total fibre content of SFRCC 50 is 26% more than that of CFC 307.

The results above mentioned have concluded that the fibre cocktail – a combination of steel fibres and PP-fibres with very positive hybrid effect – can represent an optimal fibre reinforcement for SCHPC.

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