The investigation on the workability of fibre cocktail reinforced self-compacting high performance concrete

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Abstract

The workability, the strength and the toughness are the significant factors for self-compacting-high performance concrete (SCHPC). The workability is a significant precondition for application of the Fibre Reinforced SCHPC. This paper presents research results on the workability of Monofibre and Fibre Cocktail (hybrid steel-polypropylene fibre) Reinforced SCHPC. Lots of mixtures made with steel fibres, PP-fibres and fibre cocktail of various dosages have been investigated. The mixtures were tested using various new methods for evaluating the flowability, filling ability and segregation risk of the fresh mortar/concrete. Based on the results of the workability, the suitable fibre types (steel fibres, PP-fibres and fibre cocktail) and the upper level of the fibre dosages for Fibre Reinforced SCHPC have been selected for study of the mechanical behaviour and the failure patterns in the next phase.

Keywords: Steel fibres; PP-fibres; Fibre cocktail; FRSCHPC; Workability; Rheological behaviour; Segregation resistance

1. Introduction

Workability of SCHPC is determined both by the superplasticizer (SP) dosage and by water/binder (w/b) value. Fibre Reinforced SCHPC (FRSCHPC) is a special SCC and remarkably sensitive not only to the w/b value and SP, but also to fibre type, fibre contents, aggregate property, etc. For the workability of SCHPC, there are some essential factors of great importance: *flowability, segregation resistance, passing ability through the steel bars, levelling ability and the time-dependent behaviour.*

The flow of fresh fibre reinforced SCHPC is an example of time-dependent rheology, and the benefit of traditional static measurements (normally slump and slump flow) is limited because some relevant parameters of workability (like viscosity and the ease of passing through the steel rebar cages) are not considered. Till now, there have been only a few systematic investigations of the influence of monofibre (only one type of fibre) and fibre cocktail on the workability.

There are numerous test methods available for measuring the rheological behaviour and the workability of SCHPC with or without fibre reinforcement. The rheometer test, flow-channel test and slump flow test appear to be adequate for mortar/fresh concrete with micro fibres. The slump flow test, *J*-Ring test and *L*-Box test are suitable for SCHPC with macro fibres. A series of tests were carried out to determine viable mixture proportions for fibre reinforced mortar and concrete of SCHPC.

2. Experiment of binder and fresh concrete

The workability of mortar and fresh concrete can be strongly influenced by adding fibres—both steel fibres and PP-fibres. The fresh concrete and mortar behave like Bingham liquid. The Bingham model requires two rheological

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parameters—yield stress τ_0 (N/mm^2) and plastic viscosity μ (Ns/mm^2)—to characterise the flow behaviour of fresh concrete.

Fresh concrete is a mixture from coarse and fine aggregates which are suspended in binder paste matrix. The viscosity of the mortar, the volumetric fraction of aggregate and the fibres control the flow behaviour of fresh fibre reinforced SCHPC. Rheological measurements of mortar and fresh concrete were conducted by using viscometer [1–3] as shown in Fig. 1a. The viscometer measured the torque T and speed N. For Bingham fluid: $T = g + hN$, where g is the intercept of the torque axis (liquid torque) and h is the slope of the T–N relation curves (relative viscosity) (Fig. 1b). The two Bingham parameters (τ_0 and μ) can be determined by using viscometer as follows: $\tau_0 = f(g)$ and $\mu = f(h)$.

To correlate and to investigate the workability of FRSCHPC, the mortar with maximum sand particle size of 4 mm, with or without fibres was firstly tested with rheometer, and then the concrete mixtures were tested by adding of 8 mm coarse aggregate with different pieces of equipments. A firm statement about the workability can be achieved by using the different testing methods as follows:

- a dynamic investigation/process (e.g. a continuous measuring of the workability during a time interval);
- a practice-orientated test equipment with steel reinforcement (e.g. through *J*-Ring or *L*-Box).

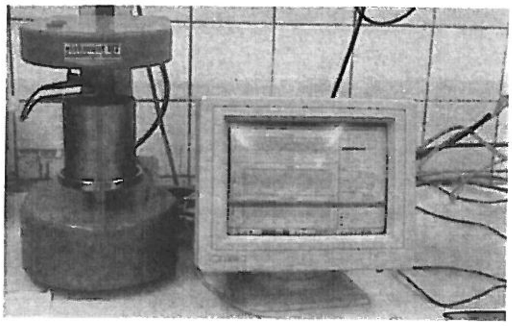

Fig. 1a. Rheometer for rheological test.

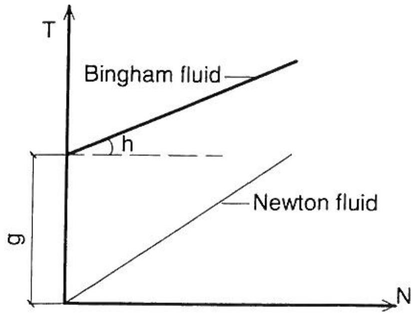

Fig. 1b. Rheometer for rheological test.

2.1. Materials

In this test program, the mix design of FRSCHPC was as follows: cement CEM I 42.5 400 kg/m^3, fly ash 200 kg/m^3; aggregate 55% 0–4 mm and 45% 4–8 mm, superplasticizer from 1% to 1.35%, water cement ratio 0.5. The investigated fibres can be divided into micro fibres ($l < 3$ cm) and macro fibres ($l \geqslant 3$ cm). The micro fibres are mainly used to reduce the shrinkage cracks, and the macro fibres will be used for structural purposes. Different widely used fibre types and fibre contents have been added into the mixture as follows (Fig. 2):

- PP-fibre A ($l = 14$ mm, $d = 0.075$ mm), ca. 9 million pieces/kg, content 1–2 kg/m^3;
- PP-fibre B ($l = 12$ mm, $d = 0.1$ mm), ca. 12 million pieces/kg, content 1–2 kg/m^3;
- PP-fibre C (structural synthetic fibres, $l = 52$–55 mm, equivalent diameter = 0.4–0.8 mm), ca. 160,000 pieces/kg; content 7 kg/m^3;
- PP-fibre D (synthetic structural fibres, $l = 40$ mm, $d = 1.1$ mm), 29,000 pieces/kg; content 7 kg/m^3;
- PP-fibre E (macro-structural fibres, $l = 54$ mm, equivalent diameter = 0.5 mm), content 7 kg/m^3;
- Steel fibre C ($l = 30$ mm, $d = 0.6$ mm), ca. 15,000 pieces/kg, fibre content 30 and 50 kg/m^3;
- Steel fibre F ($l = 6$ mm, $d = 0.16$ mm), ca. 1.1 million pieces/kg, content 10 kg/m^3.

2.2. Rheological parameter with rheometer

Generally, the flow behaviour is characterized through measurements of shear stress during a cycle of increasing and decreasing shear rate. A profile (Fig. 3a) of rotational speed has been developed for the measuring torque, where the speed achieved 120 rpm in 2 min in order to achieve the full breakdown of the mixture structure. Subsequently, the rotational speed is maintained by 120 rpm for 1 min, and then reduced to 2 rpm. After 10 s at this speed, the similar rising profile reaches the top speed in 2.5 min, which in

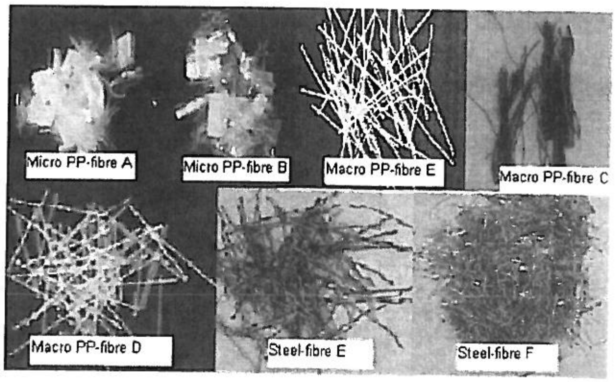

Fig. 2. Different fibres for experiment.

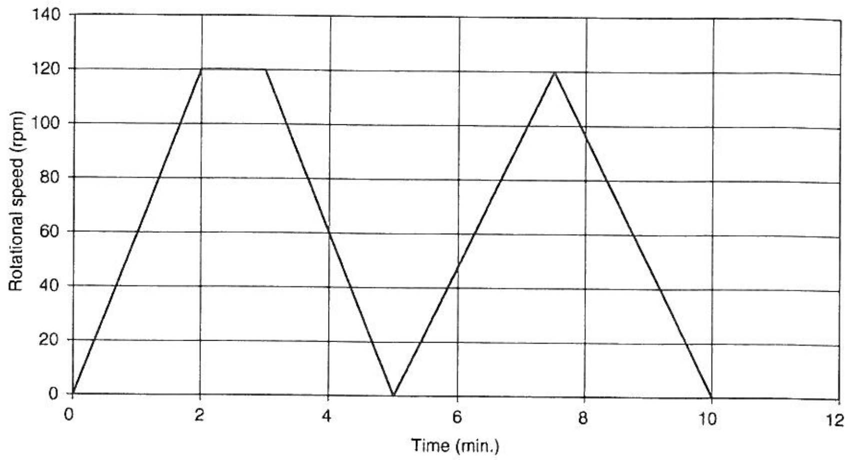

Fig. 3a. Rotational speed–time profile from 0 to 10 min.

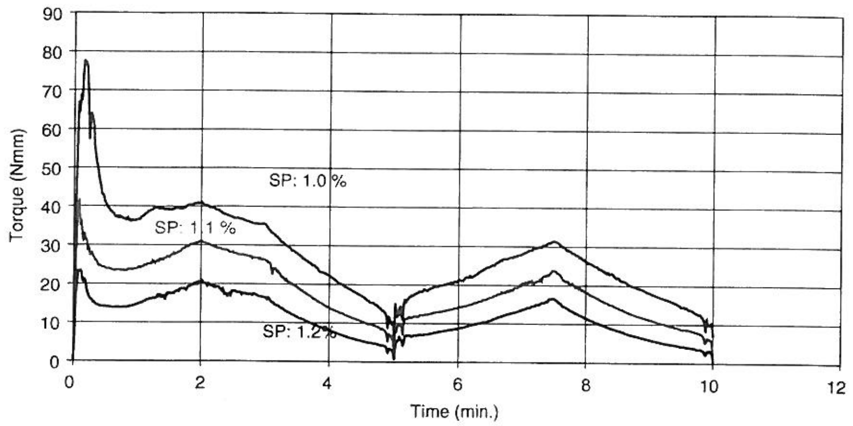

Fig. 3b. Comparison of the torque–time diagrams of the mortars with different SP dosage.

practice corresponds to the repeated mass motion during the concreting. The maximum torque T_m, the liquid torque (g) and the relative viscosity (h) with or without micro fibre (PP and steel fibres) should be investigated.

2.2.1. *Mortar with different SP dosages*

The basis of the evaluation for the workability of the mortar is the analysis of the rheological behaviour of mortar with different superplasticizer dosages and without fibres. The superplasticizers (SP) contents for the different mortars (M1, M2 and M3) were: 1.2% for M1, 1.1% for M2 and 1.0% for M3. Fig. 3b shows the comparison of the torque–time graphs of the mortars M1, M2 and M3 during a 10 min period. It can be seen that:

- The maximum torque (T_m) characterises the limit of the resistant shear torque of the mortar. That means that the T_m appears at the beginning of the rotation of fresh mixture and the corresponding rotational speed was only about 2 rpm.
- The mortar behaves in a linear elastic manner versus time up to T_m and behaves plastically after T_m.
- The mixture with 1% SP dosage shows the strongest resistant shear stress (T_m) of 77.8 N mm, the T_m decreases with the increasing of the SP dosage (Fig. 3b).

Fig. 4a illustrates the curve of torque–rotational speed and the trend line of this curve. The intercept of the trend line describes the liquid torque (g) of the mixture with SP dosage of 1.2%, and the gradient of the trend line corresponds to the relative viscosity (h). Fig. 4b shows the comparison of the rheological behaviour of M1, M2 and M3 during a 10 min period. It can be seen that:

- The liquid torque (g) demonstrates the resistant torque of a full breakdown of mixture structure and change the mixture structure from a stationary state into a motion state, the g corresponds to the top rotational speed around 120 rpm.
- The g decreases with increasing SP contents sharply.

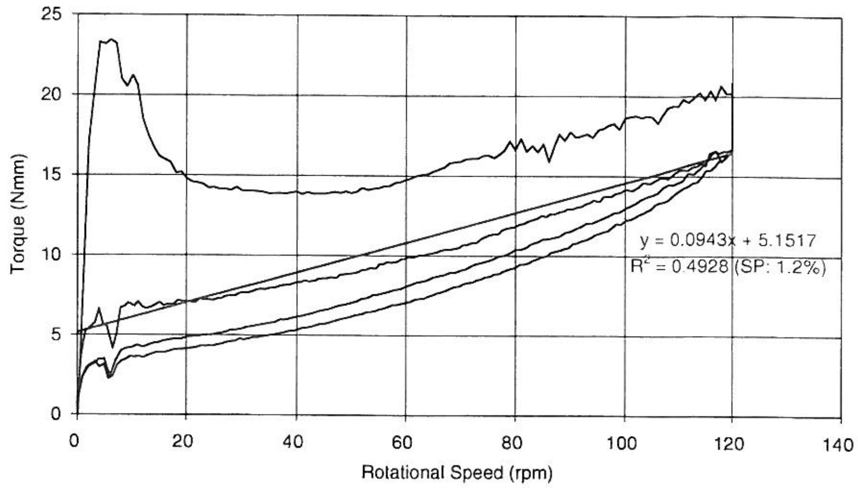

Fig. 4a. The curve of torque–rotational speed and its trend line.

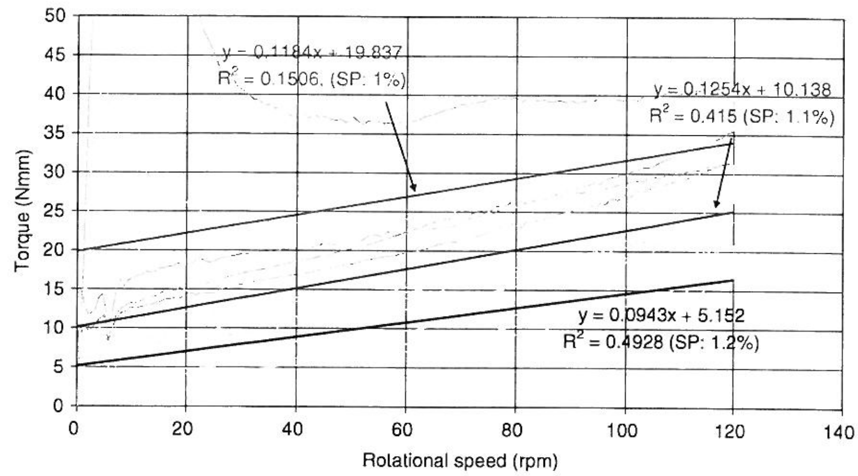

Fig. 4b. Comparison of the rheological behaviour of the mortars with different SP-dosage during a time period of 10 min.

2.2.2. *Mortar with micro fibres*

The experiments of PFRCA (PP-fibre reinforced concrete with fibre dosage of 1 and 2 kg/m^3 fibre A and fibre B) and CFC (fibre cocktail reinforced concrete) were performed, following a rotational speed profile over a period of 70 min as shown in Fig. 5. The flowability of mixture PFRCA 1 was better than mixture PFRCB 1. There was no segregation. Table 1 contains the comparison of the rheological parameters of PFRCA 1 (PP-fibre reinforced concrete with 1 kg/m^3 fibre A) during the periods of 0–10, 30–40 and 60–70 min.

After the successful experiment for mixture with 1 kg/m^3 PP-fibre A, the rheological behaviour of the mixture with 2 kg/m^3 PP-fibre A was investigated. It can be observed that there was obvious segregation and the ball formation. The mixture was segregated and harder after 30 min. The values of h, g and T_m of fresh PFRCA 2 were much higher than PFRCA 1 and T_m approached to the limit of the rheometer of 200 N mm. It was impossible to do a full measurement of torque from 60 to 70 min due to the segregated and hardened mixture. This means that the fibre dosage of 2 kg/m^2 PP-fibre A represents the upper level and is not suitable for SCHPC. Table 2 showed the comparison of the rheological parameters in the time intervals of 0–10 and 30–40 min. In contrast to Table 1, it can be seen that the values of T_m, h and g were much higher.

2.3. *Workability of fresh concrete with micro fibres*

In parallel with the viscosity test of rheometer, the flowability tests of fresh FRSCHPC have been carried out with a flow-channel [5]. Two litres of fresh concrete were put into the funnel (Fig. 6). After opening the lock ball valve in the funnel, the flow-time for the 750 mm long channel and the maximum flow-distance of the fresh concrete in the channel were measured. In order to investigate the time-dependent

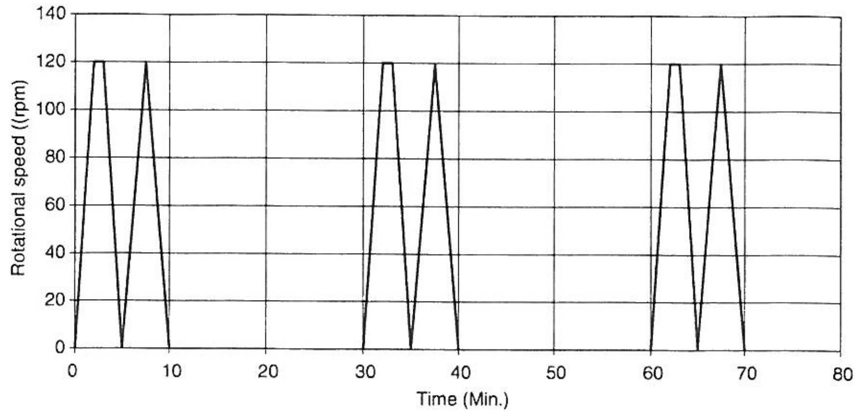

Fig. 5. Rotational speed–time profile from 0 to 70 min.

Table 1
Comparison of the rheological parameters of PFRCA 1 mixture

PFRCA 1, SP: 1.35% (min)	h (N mm/rpm)	g (N mm)	T_m (N mm)
0–10	0.28	7.02	53.0
30–40	0.21	10.46	56.7
60–70	0.29	17.92	69.2

Table 2
Comparison of the rheological parameters of PFRCA 2 mixture

PFRCA 2, SP: 1.35% (min)	h (N mm/rpm)	g (N mm)	T_m (N mm)
0–10	0.338	37.282	107.0
30–40	0.428	45.974	126.0

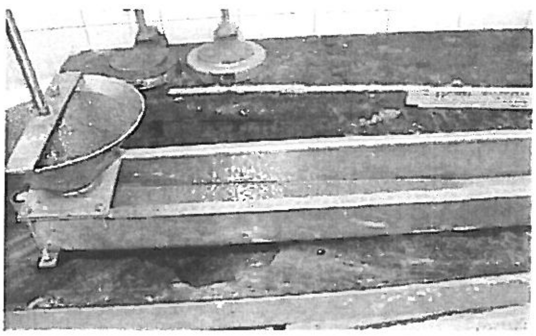

Fig. 6. Set-up for Flow-Channel Test.

dynamic behaviour of FRSCHPC, the experiment was performed immediately after the mixing and again 40 min after the mixing of the mixture with different fibre types and fibre contents (micro PP-fibre A: 1 kg/m^3 or 2 kg/m^3; micro steel fibre F: 10 kg/m^3 or 30 kg/m^3). Fig. 7a shows the comparison of the relations of flow-distance and the respective flow-speed as well as the maximum flow-distance of different mixtures with and without fibres just after mixing in the flow channel. It can be seen that immediately after the mixing, the flow behaviour of fresh concrete without fibres (OC), SFRCF 10 (fresh concrete with 10 kg/m^3 steel fibre F) and PFRCA 1 (PP-fibre reinforced concrete with 1 kg/m^3 fibre A) are similar. The fibre dosage of 1 kg/m^3 PP-fibre A and 10 kg/m^3 steel fibre F has no negative influence on the workability in comparison to the mixture without fibres, but the flowability of SFRCF 30 and PFRCA 2 was reduced sharply. Fig. 7b shows the comparison of different mixtures with and without fibres 40 min after mixing in the flow channel.

Because of the prolonged effect of SP, the flow behaviour after 40 min is similar to that of mixture immediately after the mixing [2,4]. The maximum flow-distance and flow-speed of PFRCA 2 decreased much more than SFRCF 30. This could be explained both by the larger number of fibre pieces/kg and by the fibre surface properties (e.g. the frictional coefficient of fibres).

2.4. Workability of fresh concrete with macro fibres

It is impossible to investigate the flow behaviour of fresh SCHPC with macro fibres using a flow-channel due to the small diameter of funnel outlet. Furthermore, it has been observed in the practice that the steel reinforcement can block the flow of fresh fibre reinforced concrete and has strong influence both on the flowability and on the segregation behaviour.

2.4.1. Slump flow test

The measurement of slump flow (Fig. 8) indicates the free deformability of the mixture for fibre cocktail reinforced concrete (CFC 305). Parallel to the slump flow spread, the air contents of the mixtures have been measured. Table 3 shows the average results of different mixtures with and without fibres immediately (Sf_0) and 45 min (Sf_{45}) after mixing.

From experience, it is known that the slump-flow spread of SCHPC should be not less than (⩾) 60 cm both for Sf_0 and for Sf_{45}. It can be seen that the flow behaviour of PFRCC 7 and PFRCE 7 (the mixture with 7 kg/m^3 macro PP-fibre C and PP-fibre E) was much less fluid than other

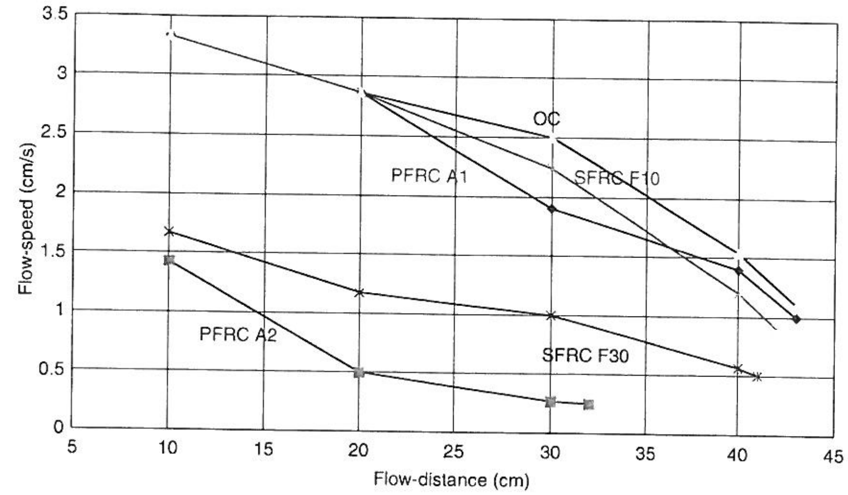

Fig. 7a. Flow-Channel Test.

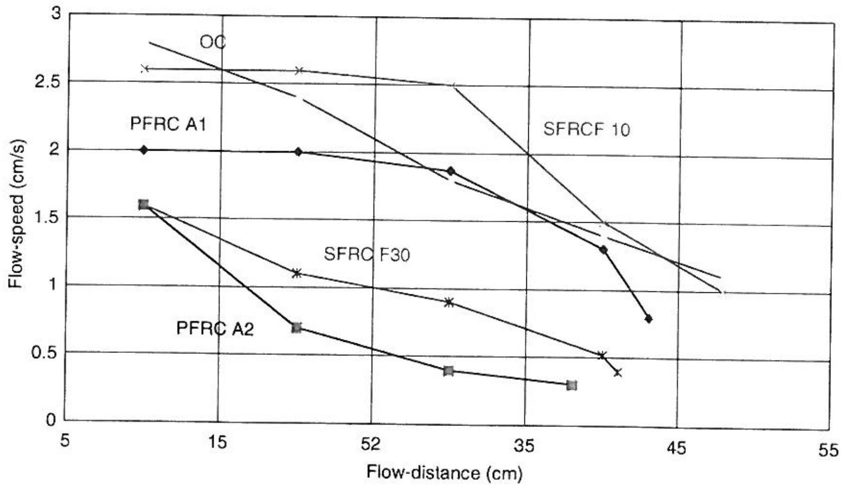

Fig. 7b. Flow-Channel Test after 40 min.

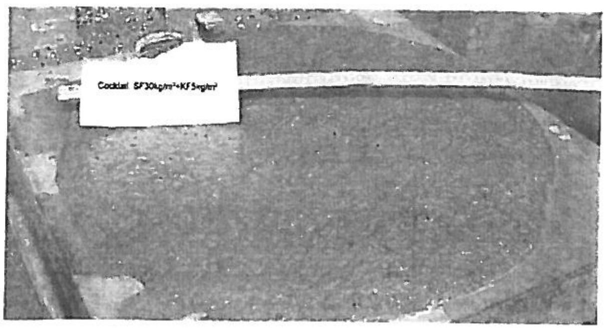

Fig. 8. Slump flow test.

Table 3
Comparison of the slump flow and the air contents of different mixtures

SCHPC	PFRCC 7	PFRCD 7	PFRCE 7	SFRCC 30	SFRCC 50	CFC 305
Sf_0	43	65	44	64	64	64
Sf_{45}	44	66	48	65	64	66
Air content (%)	4	5	4	4	4	4

mixtures. Besides, balls formed for PP-fibre C/E with concrete, therefore those two mixtures are not suitable for SCHPC. After 45 min, the slump-flow spread of PFRCD 7 (mixture with 7 kg/m^3 macro PP-fibre D), SFRCC 30, SFRCC 50 and CFC 305 increased due to the prolonged effect of SP. The series of PFRCD 7, SFRCC 30, SFRCC 50 and CFC 305 showed very good flowability both immediately and 45 min after the mixing. However, the slump-flow test cannot predict the segregation behaviour and the passing ability of the fresh fibre reinforced concrete through the steel bars.

2.4.2. *J-Ring*

In parallel with the slump flow test, the fibre reinforced mixture was investigated with a *J*-Ring test [2,4,6]. It was used to obtain an indication of flowability, segregation resistance, passing ability of FRSCHPC. In order to analyse the segregation resistance and passing ability of fibre reinforced fresh concrete, the following steel reinforcement was used: 15 steel bars (∅ = 15 mm), the bar spacing was 5 cm (Fig. 9). This test method represents a strongly reinforced column with a reinforcement ratio of $\mu = 2.7\%$. The difference of the mixtures inside and outside the *J*-Ring (L_J) and the slump flow spread of *J*-Ring (J_{sf}: cm) have to be measured. The average results of mixtures for different fibre types and fibre contents are shown in Table 4. The conditions for a successful FRSCHPC are as follows: $J_{sf} \geqslant 60$ cm and $L_J \leqslant 2.5$ cm. It can be seen that:

- The series of PFRCD 7, SFRCC 30, SFRCC 50 and CFC 305 show a remarkable passing ability (L_J), flowability (J_{sf}) and segregation resistance. They fulfilled the requirements for the two parameters of J_{sf} and L_J.
- The mixtures PFRCC 7 and PFRCE 7 show neither flowability nor passing ability.

2.4.3. *L-Box*

Additionally, the fibre reinforced mixture was investigated with an *L*-Box test [4]. The *L*-Box (Figs. 10–12) test can assess the flowability, segregation resistance, passing ability and levelling ability of concrete. FRSCHPC is poured into the vertical shaft and fills it up to 50 cm, and then the sliding shutter is opened and the mixture is allowed to fall and to flow under its own weight, passing through three steel bars (∅ = 15 mm) into the trough [4,5]. Similar to the flow-channel test, the flow-time T_L for the whole trough length, the maximum flow-distance L_f, and the respective flow-speed (V_L) of different mixtures with and without fibres are measured in the *L*-Box after mixture. Besides, the elevation difference L_s before and after opening the sliding shutter, the difference of mixture inside and outside steel bars L_L and the overflow height *H*2 and *H*1 have to be measured. The flow-speed is a function of the viscosity of the mixture. The flowability and segregation resistance, the passing ability and levelling ability of FRSCHPC can be described by the parameters of *H*2/*H*1, L_s and L_L (see Fig. 10).

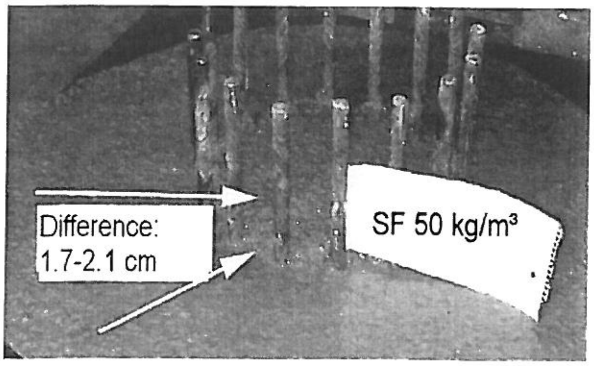

Fig. 9. Testing method with *J*-Ring.

Table 4
The average results for the investigated mixtures for FRSCHPC with *J*-Ring

SCHPC	J_{sf} (cm)	L_J (cm)
PFRCC 7	50.0	5.0
PFRCD 7	69.5	1.7
PFRCE 7	55.0	5.0
SFRCC 30	76.5	1.7
SFRCC 50	75.0	1.9
CFC 305	76.0	1.8

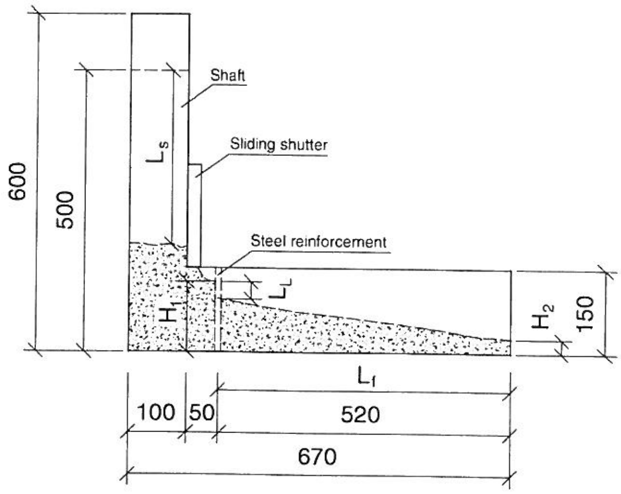

Fig. 10. *L*-Box with steel bars for workability.

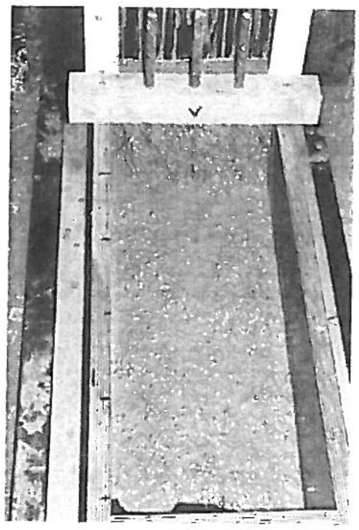

Fig. 11. PFRCC 7 mixtures with heavy congestion.

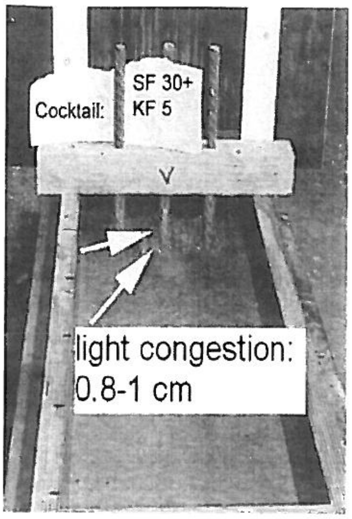

Fig. 12. CFC 305 mixtures with light congestion.

According to a series of experiments, an acceptable mix for FRSCHPC should have $L_s \geqslant 40$ cm and $L_L \leqslant 2$ cm. It is different to the requirement of EFNARC [8] on the normal SCC without fibres. The ratio of $H2/H1$ is not the only factor to evaluate the workability of fibre reinforced SCC. For FRSCHPC, $L_L \leqslant 2$ cm becomes an important parameter compared to the SCC without fibres because the fibres often cause congestion between in- and outside steel bars. Figs. 11 and 12 demonstrate the comparison of the mixtures of CFC 305 with acceptable light congestion and PFRCC 7 with heavy congestion by the steel bars in the *L*-Box. Fig. 13 shows the relationship between flow-distance and flow-speed determined with the *L*-Box. The average values of L_f, L_L, L_s and $H2/H1$ of different mixtures for FRSCHPC are listed in Table 5. It can be seen that:

- L_f, L_s and $H2/H1$ of PFRCC 7 and PFRCE 7 are much lower than those of other mixtures. Contrary to the above values, L_L of PFRCC 7 and PFRCE 7 are much higher than that of other mixtures. The most mixtures of PFRCC 7 and PFRCE 7 were stopped behind the steel bars, and they are not suitable for SCHPC.
- The series of CFC 305/307, PFRCD 7, SFRCC 30 and SFRCC 50 show very good segregation resistance, and passing ability through the steel bars under their own weight (L_L, L_f and L_s) and levelling ability over the whole trough under their own weight ($H2/H1$, L_L, L_f and L_s).

The *L*-Box experiments indicate that the fresh PFRCD 7 ran through the whole horizontal trough of 52 cm in 4.5 s, and the L_s of PFRCD 7 amounted to 42 cm. For PFRCE 7, most of the fresh fibre concrete was held back by steel bars. Both flowability and passing ability of PFRCE 7 were very low, and there was strong segregation in the mixture, and only 15% of all the fresh concrete flowed through the steel reinforcement. The fresh PFRCC 7 showed a similar workability to PFRCE 7. However, the series of fresh CFC 305/307, PFRCD 7, SFRCC 30 and SFRCC 50 showed excellent workability with properties as follows: (1) Excellent flowability and segregation resistance. (2) Satisfied passing ability and levelling ability under its own weight. (3) High flow speed ($\geqslant 10$ cm/s). The reason for the good workability for

Table 5
Average results of the parameters for FRSCHPC in the *L*-Box

SCHPC	PFRCC 7	PFRCD 7	PFRCE 7	SFRCC 30	SFRCC 50	CFC 305/307
L_f	40.0	52.0	40.0	52.0	52.0	52.0
L_s	23.0	42.0	22.0	42.0	42.0	43.0
L_L	6.0	1.1	6.5	1.2	1.4	0.9-1.0
$H2/H1$	0.1<	0.9	0.1<	0.9	0.85	0.85

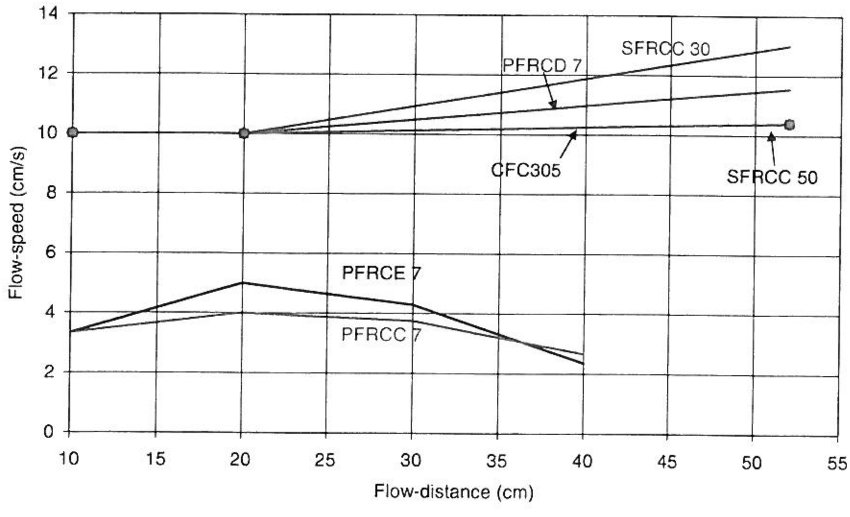

Fig. 13. Comparison of the flow-speed vs. flow-distance determined with the *L*-Box.

the fresh HFC 305, PFRCD 7, SFRCC 30 and SFRCC 50 can be explained both by the small frictional coefficient of fibre surface and by the smaller fibre length (*lf*) compared to the bar spacing (*ds*), normally, $lf \leqq 0.8$ ds.

3. Conclusion

The workability of the fresh concrete is an important precondition for using Fibre Reinforced Self-Compacting High Performance Concrete (FRSCHPC), and it is characterised mainly by the flowability, the segregation resistance, passing ability and levelling ability through the steel bars.

The investigation with micro fibres indicated:

- The dosage of 1 kg/m^3 micro PP-fibre and 10 kg/m^3 micro steel fibre do not have negative influence on the workability of fresh concrete; the dosage of 2 kg/m^3 micro PP-fibre has strong negative influence on the workability and is not suitable for reinforcing SCHPC.
- The flowability results with the rheometer agree with those from the flow channel. However, the rheometer alone cannot evaluate the segregation properties.

The workability of macro fibre reinforced SCHPC can be assessed better with *J*-Ring and *L*-Box than with slump-flow tests alone. The investigation with macro fibres indicated:

- The slump-flow test can analyse the flowability of fibre concrete without steel bars. However, it is impossible to investigate the passing ability and the segregation resistance through the steel rebar cages with this method.
- Compared to the slump-flow test, *J*-Ring and *L*-Box can assess both the flowability, the segregation resistance and passing ability, levelling ability and the time-dependent behaviour of fresh fibre reinforced concrete like flow-time and flow speed.
- The appropriate parameters of the workability with various test methods (like the difference of mixture inside and outside steel bars L_L, the ratio of fibre length (*lf*) to the bar spacing (*ds*)) for FRSCHPC have been recommended. They are useful both for evaluating the workability and for selecting the suitable fibres.
- The reason for the good workability for the fresh fibre reinforced self-compacting high performance concrete with mono or hybrid fibres could be traced back both to the properties of fibre surface (e.g. the frictional coefficient of fibres) and to the smaller fibre length compared to the bar spacing.
- For the flow behaviour and passing ability, the experiments with *J*-Ring demonstrated the similar results to the *L*-Box. Therefore, the macro PP-fibre of type C and E are not suitable for FRSCHPC.
- The investigation of the workability can assist in the good mix design for SCHPC in the practice.

Notation:

CFC	fibre cocktail reinforced concrete
CFC 305/307	fibre cocktail reinforced concrete with 30 kg/m^3 macro steel fibre C and 5 kg/m^3 macro PP-fibre D
HPC	high-performance-concrete
PFRCB 1	mixture of PP-fibre reinforced concrete with fibre dosage of 1 kg/m^3 fibre B
SFRCC 30	mixture of steel fibre reinforced concrete with fibre dosage of 30 kg/m^3 fibre C

Acknowledgements

The authors acknowledge the support from the Chinese National Science Foundation (Grant No. 50578026).

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