Fresh behaviour of ultra-high performance concrete (UHPC) : an investigation of the effect of superplasticizers and steel fibres

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FRESH BEHAVIOUR OF ULTRA-HIGH PERFORMANCE CONCRETE (UHPC): AN INVESTIGATION ON THE EFFECT OF SUPERPLASTICIZERS AND STEEL FIBRES

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ABSTRACT: To decrease the porosity and increase the strength of Ultra-High Performance Concrete (UHPC), lower water-to-powder ratios and high contents of steel fibres are usually used, which lead to a reduced workability of fresh UHPC. In the present research, the effects of different superplasticizers and steel fibres on the fresh behaviour of UHPC were investigated. The initial and final setting times of the UHPC pastes containing 4 different superplasticizers (SP) were measured by Vicat needle tests. The effects of SP type and dosage on the spread flow were analysed for both paste and UHPC. The spread flows of UHPC with saturation dosages of SP were measured up to 2 hours to analyse the slump life and retention effect. Furthermore, the effects of 4 types steel fibres on the fresh behaviour of UHPC were investigated by using different fibre volume contents. The results show that the dispersing ability, retardation and retention effect of SP differed with different chemical constituents and structures, which greatly influenced the mixture's setting time, spread flow and slump life. The workability of UHPFRC was affected by the steel fibres' geometric characteristics and coating type, and it decreased continuously with the increase of the fibre content.

Keywords: Ultra-High Performance Concrete; Steel fibres; Superplasticizers; Fresh behaviour

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INTRODUCTION

Ultra-High Performance Concrete (UHPC) is a relatively new building material, which has been fabricated since 1990s. Compared to conventional concrete, it has superior mechanical strength, durability and impact resistance [1, 2, 3]. These excellent material properties can be achieved by certain methods, such as eliminating the coarse aggregate to increase the homogeneity, optimizing the grain-size distribution of the raw materials to improve compactness, utilizing a special heat curing and compressing treatments, etc. [4]. Besides those principles, adding high content of steel fibres and limiting the porosity by using low water-to-powder ratios for concretes are probably the mostly convenient and efficient ways to realize those superior material properties.

Superplasticizers (SP) are used to increase the fluidity of concrete with relatively low additions of water. Since their introduction in the 1930s, they have been used as critical chemical admixtures for modern concrete. The molecules are adsorbed onto particles, which are then physically separated by opposing their attractive forces with steric and/or electrostatic forces [5]. As the first generation water reducers, the Lignosulfonates (LS) can only limit the water content by about 10%. The polymelamine sulfonate (PMS) and sulfonated melamine formaldehyde condensate (PMS) have been produced as the second generation dispersant since 1960s, with a water-reduction ability of about 20-30%. The new generation of superplasticizers polycarboxylic ethers (PCEs), developed in 1980s, can achieve up to 40% water reduction. The properties of those PCE polymers are mainly determined by the following parameters: chemistry and length of the backbone, number and length of the side chains, amount of anionic and ionic groups, bond type between backbone and side chain, and overall charge density [5, 6, 7]. Therefore, different types of SP certainly show different effects on the fresh behaviour of UHPC.

The addition of steel fibres can significantly improve the performance of UHPC in the hardened state, especially the ductility, impact resistance, tensile strength and fatigue strength [8, 9, 10]. Nevertheless, steel fibres can also decrease the workability of UHPC to some extent at the same time. Nowadays, the available steel fibres in the market have various types with different length, diameter, coating category, as well as straight, twist and hook ended shapes. Those different characteristics of steel fibres have different degrees of influence on the workability reduction. Hence, it is necessary to investigate the effect of steel fibres on flowability of UHPC before their utilization.

The objective of this study was to investigate and understand the SP type and dosage effects on the setting times, spread flow of paste and UHPC, slump life and retention effect. Furthermore, the effects of steel fibres with different geometric and coating characteristics on the flowability were also investigated.

EXPERIMENTS

Materials

The raw materials used in this study were Portland Cement CEM I 52.5R (OPC), limestone powder (LP), nanosilica (nS), microsand 0-1 (MS), sand 0-2 (S), water (W), superplasticizers (SP) and steel fibres (SF). The specific densities of those ingredients are shown in Table 1. The particle size distributions of the used materials were measured by the sieve and laser diffraction analyses, shown in Figure 1.

Four PCE-type superplasticizers with different dispersing and retarding abilities were used in the pastes and UHPC. Steel fibres with different geometric and coating characteristics, with the tensile strength of 1100 MPa, were utilized to produce the Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). The detailed information of superplasticizers and steel fibres are shown in Tables 2 and 3, respectively.

Table 1 Specific densities of raw materials

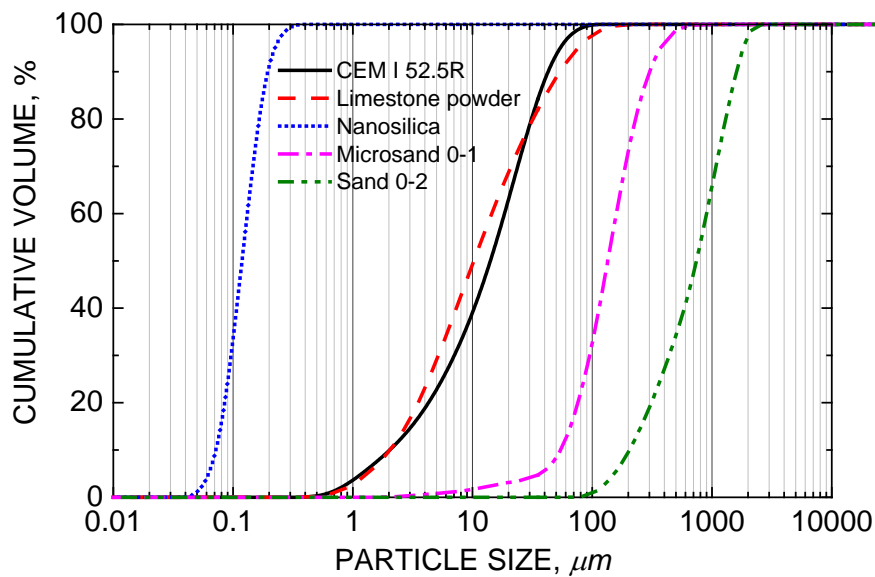| MATERIALS	OPC	LP	MS	S	nS	W	SP	SF
Specific density (g/cm³)	3.15	2.71	2.22	2.72	2.64	1.00	1.05-1.14	7.80

Figure 1 Particle size distribution of raw materials

Table 2 Product information of SP

NO.	DRY MATTER	SHAPE/COLOUR	DENSITY (g/ cm^3)	pH	CHLORIDE CONTENT	ALKALI CONTENT
SP1	35%	Amber liquid	1.082-1.142	7	$\leq 0.1\%$	$\leq 3\%$
SP2	25%	Light brown liquid	1.05	5 - 8	$\leq 0.1\%$	$\leq 1.5\%$
SP3	35%	Translucent yellowish liquid	1.07	5.0 ± 1.5	$\leq 0.1\%$	$\leq 0.5\%$
SP4	40%	Yellowish liquid	1.09	ca.4	$\leq 0.1\%$	$\leq 1\%$

Table 3 Characteristics of utilized steel fibres

NO.	FIBRE TYPE	LENGTH (mm)	DIAMETER (mm)	ASPECT RATIO	COATING
1	Short straight steel fibre (SSF)	6	0.16	38	Copper
2	Long straight steel fibre (LSF)	13	0.20	65	Copper
3	Short hook ended steel fibre (SHF)	29	0.65	45	Nickel
4	Long hook ended steel fibre (LHF)	31	0.45	69	Copper

Mixture Proportions

The nanosilica-to-binder ratio, limestone-to-powder ratio and water-to-powder ratio were fixed at 4%, 30% and 0.2, respectively, in all mixtures, following previous research [8]. The totally used water included the water in the nanosilica slurry and SP. In the setting time tests of pastes, the dosages of SP were at constant of 0.4%, 0.8% and 1.2%, dry matter by weight of powder. In the flow tests of pastes, the dosages of SP were varied from 0.4% to 2.0%, dry matter by weight of powder. In the flow tests of UHPC, the microsand-to-powder ratio and sand-to-powder ratio were fixed at 0.25 and 1.2, respectively, with the dosages of SP varying from 1.0% to 3.0%. After obtaining the relationship between the spread flow and SP dosages, the flow tests of UHPC were conducted at the saturation dosages of SP. In the flow tests of UHPFRC, the contents of steel fibres were from 0 to 3% by volume of mixture at the saturation dosages of each SP. The recipe of the UHPC reference admixture in this study is shown in Table 4.

The mixing of pastes lasted about 5 min using a 5-liter Hobart mixer, using the following procedure: dry mixing (cement and limestone) for 30s at the low speed, sequentially adding nanosilica slurry, 80% water, SP slurry, and remaining water for about 2 min at the low speed, followed by mixing the paste for 2 min at the low speed and 30 s at the medium speed. The adding order of components in mixing procedure of UHPC was similar to that of paste, whereas the total time is about 8 min (30 s for dry mixing, 180 s for adding slurries and water, another 150 s at the low speed and 120 s at the medium speed).

Table 4   Recipe of UHPC reference mixture

PRODUCTS	OPC kg/m^3	LP kg/m^3	MS kg/m^3	S kg/m^3	nS kg/m^3	W kg/m^3
Mass	611.3	272.9	227.4	1091.6	25.5	181.9

Testing Methods

The setting times of pastes were evaluated by using the manual Vicat apparatus based on EN 196-3: 2005. The spread flow of pastes and concretes were measured by using a truncated conical mould (Hägermann cone: height 60 mm, top diameter 70 mm, bottom diameter 100 mm), in accordance with EN 1015-3: 2007. To evaluate the slump life of the fresh UHPC, the spread flow of UHPC were also measured in 2 hours. The lab ambient temperature while mixing and testing was relatively constant, about 21°C.

RESULTS AND DISCUSSION

Setting Time and Flow of Paste

Figure 2 presents the initial and final setting times of pastes incorporating SP1, SP2, SP3 and SP4. From the figures it is obvious that the setting times are affected by both SP types and dosages. For all those 4 SPs, high dosages always increase the setting times. It indicates that those SPs have a retardation effect on the hydration of pastes, and the retardation effect is higher with the increase of SP dosages. It is also clear that pastes with SP1 have the longest setting times, reaching at about 7 h of initial and 8.9 h of final setting time at a dosage of 1.2%. It means that SP1 is not suitable to obtain a high early age strength for paste or concrete due to

the high retardation effect. The pastes with SP2 show the shortest setting times, which are approximately 1.42 h (2.67 h), 2.75 h (4.58 h) and 3.58 h (5.42 h) of initial (final) setting time respectively at the dosages of 0.4%, 0.8% and 1.2%. The low retardation effect of SP2 makes it possible to achieve a relatively high early age strength for paste or concrete. Compared with SP1 and SP2, medium setting times are observed for the pastes containing SP3 and SP4.
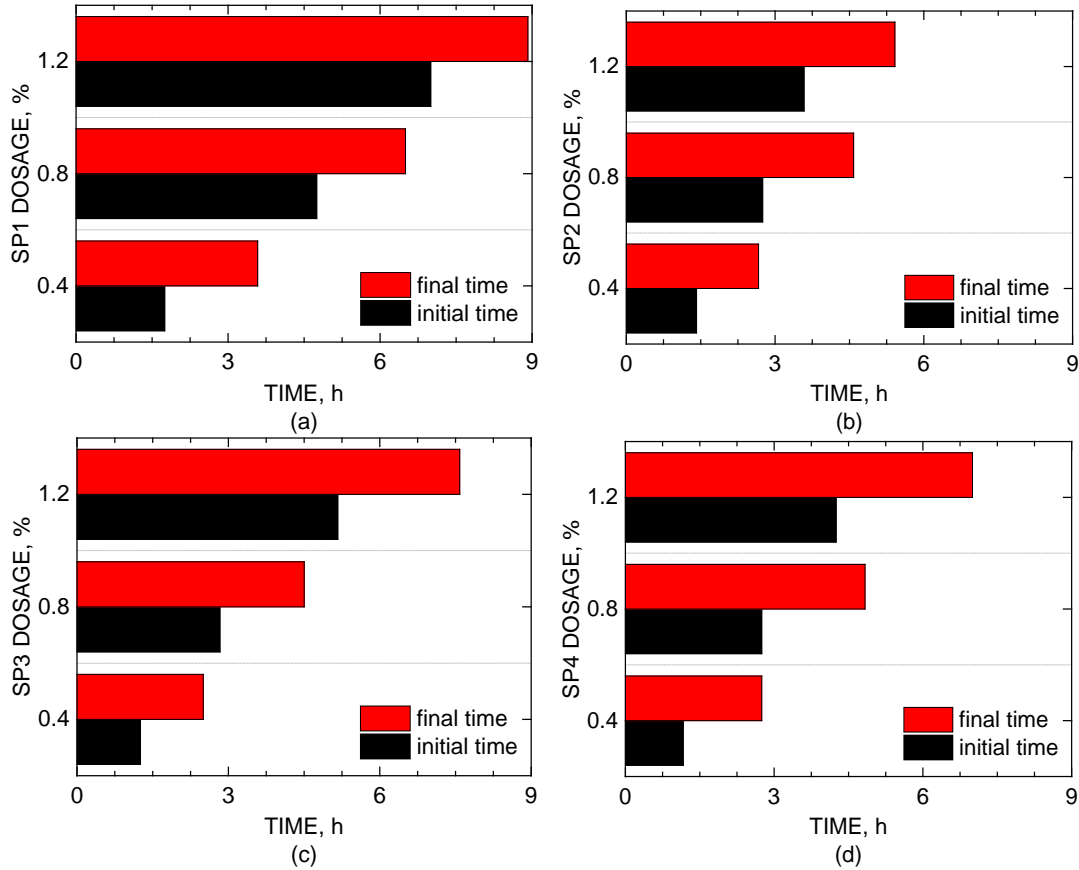

Figure 2   Setting times of pastes

Figure 3 shows the time differences between the initial and final settings at different SP dosages. The time differences of SP1 maintain at a stable level (approximately 75-175 min). SP2 shows a similar pattern at dosages of 0.8% and 1.2%, however it is shorter than that of SP1 at the dosage of 0.4%. The time difference of SP3 shows a nearly same increasing tendency with the increase of SP dosage to SP4, with about 20 min earlier than that of SP4.
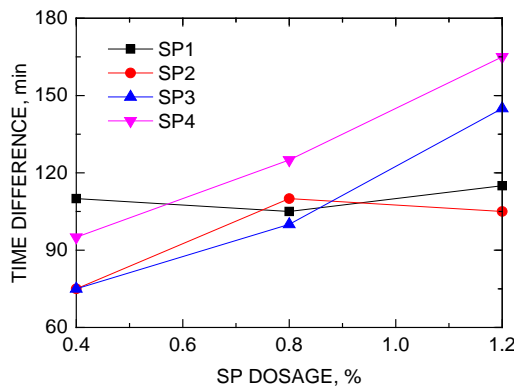

Figure 3   Time difference between initial and final settings

Figure 4 depicts the spread flow of pastes incorporating different types and dosages of SP. Generally, the flow diameters are increased with the increasing SP dosages at relatively low SP dosages. Nevertheless, the spread flows are kept at stable levels above the saturation dosages. This typical plateau at high dosages can be also observed from the relationships between SP adsorption on particles and SP dosages in some other researches [5, 7, 11]. It manifests that SP works only after the adsorption on the particles, which corresponds to surface coverage, similarly to the results in other studies [4, 12]. When the used SP exceeds the saturation dosage, a complete surface coverage will be obtained. Then the dispersing ability of SP will not increase anymore, which results in the occurrence of the typical plateau at high dosages.
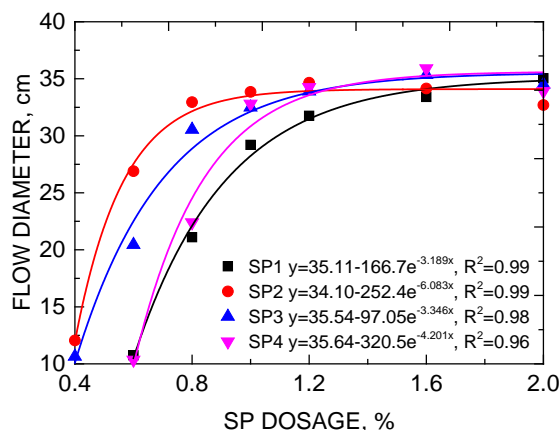

Figure 4 Spread flow of pastes

It is clear that the maximum flow diameters of pastes with different SP types are approximately 35 cm. The critical (saturation) dosages of SP1, SP2, SP3 and SP4 for paste are approximately 0.6% (1.4%), 0.4% (0.8%), 0.6% (1.2%) and 0.4% (1.2%), respectively. It can be concluded that SP2 and SP3 have a much higher dispersing ability for pastes with dosages ranging from 0.4% to 1.2%. However, with the increase of SP dosages, the dispersing ability of SP3 and SP4 are only a bit higher than that of SP2 and SP1. The following mathematical model is proposed to express the relationships between the spread flow and SP dosage:

$$y = y_0 - ae^{-bx} \tag{1}$$

where y is the flow diameters of pastes, x is the dosage of SP. y_0 is the maximum flow diameter (plateau). b represents the velocity to approach the plateau with the increase of SP dosage. a is related to the dispersing ability of SP, when b is fixed, a larger a means a higher increasing velocity of flow at a certain SP dosage.

Flow of UHPC

Figure 5 presents the spread flows of UHPC incorporating different types and dosages of SP. The spread flows of UHPC with SP2, SP3 and SP4 show a typical plateau at high dosages, which are similar to that of pastes. However, the SP1 presents a linear increase, which indicates that SP1 increases the flow ability very slowly at a relatively low dosage. All the critical dosages of SP2, SP3 and SP4 for UHPC are close to 1.0%, meanwhile all the saturation dosages are near to 2.2%. And the critical dosage of SP1 for UHPC is approximately 1.0%, but it does not show a clear saturation dosage till 3.0%. In conclusion, SP3 and SP4 have a higher dispersing ability than SP1 and SP2 for UHPC.

All relationships between the spread flow of UHPC and SP dosage can be also subjected to the exponential model $y = y_0 - ae^{-bx}$, which is similar to that of paste. It is worth to point out, the curve of SP1 is more likely to a linear model. In the case of SP1, the y_0 is just a 'theoretical' maximum flow diameter, which maybe not be possible in practice. It indicates that SP1 has a poor adsorption effect in UHPC, which may be incompatible with UHPC in this study.
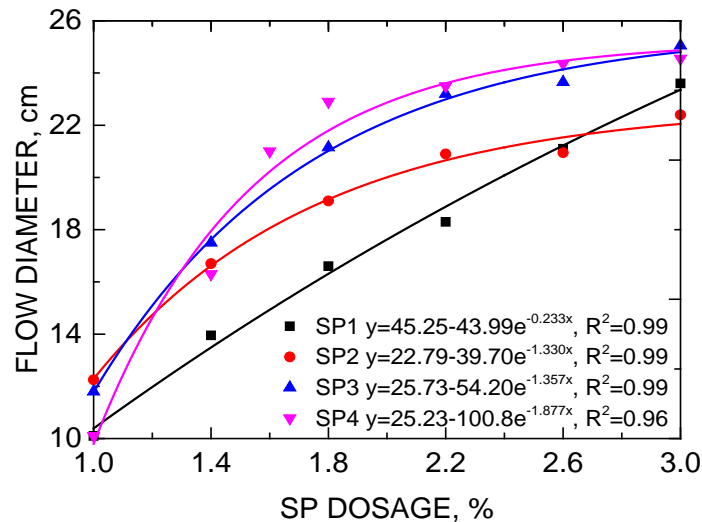

Figure 5   Spread flow of UHPC

SP1 $y=45.25-43.99e^{-0.233x}$, $R^2=0.99$
SP2 $y=22.79-39.70e^{-1.330x}$, $R^2=0.99$
SP3 $y=25.73-54.20e^{-1.357x}$, $R^2=0.99$
SP4 $y=25.23-100.8e^{-1.877x}$, $R^2=0.96$

Slump Life and Retention Effect

Figure 6 presents the slump life of fresh UHPC in 2 hours. Fresh concrete is well known to lose its workability with time, which is called 'slump loss' [4]. The previous researches imply that slump loss involves chemical and physical processes, which is mainly attributed to the physical coagulation of particles rather than to chemical processes [13]. Therefore, UHPC with SP1 has a shortest slump life, even though SP1 show the highest retardation effect on the paste setting. The possible reason is that SP1 has a low adsorption ability, which induces an uncompleted surface coverage. Uncompleted surface coverage (below saturation dosage) results in a rapid stiffening of the concrete [7]. UHPC with SP2 has a poor slump life probably due to its weak retardation effect on paste hydration and uncompleted surface coverage. UHPC with SP3 shows a perfect slump life in the whole testing time (2 h), which even has a slight increase of flow diameter before 80 min. UHPC with SP4 can maintain a good slump life before 40 min, which experiences a sharp decrease after that time.

Generally, UHPCs with SP1 and SP2 have a short slump life, which have a linear decrease relationship between the flow and elapsed time. UHPC with SP3 can just keep a good slump life within 40 min. UHPC with SP4 presents the best slump life, nearly without any slump flow loss in 2h.
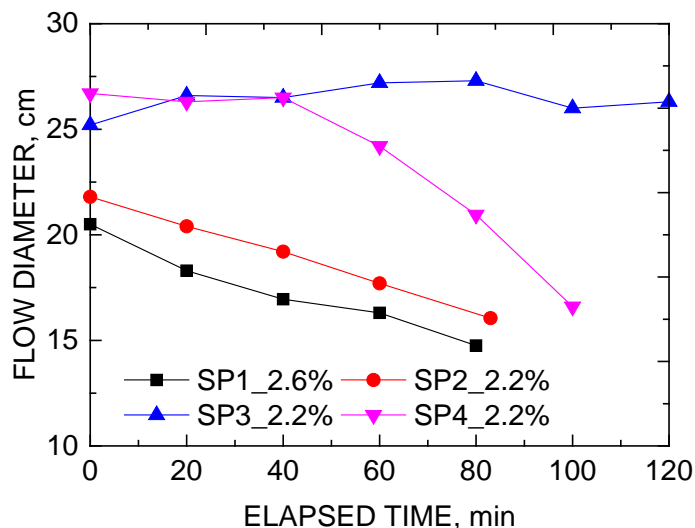
Figure 6   Slump life (2 h) of UHPC

Effect of Steel Fibres on Flowability

Figure 7 shows the effect of steel fibre on the spread flow of UHPFRC. Obviously, fibre types and contents affect the characteristics of UHPFRC in the fresh state. As needle-like particles, those steel fibres decrease the flow of UHPFRC due to two reasons: mechanical interaction (cohesive and anchoring forces) between fibres and grains, and interlock of fibres.
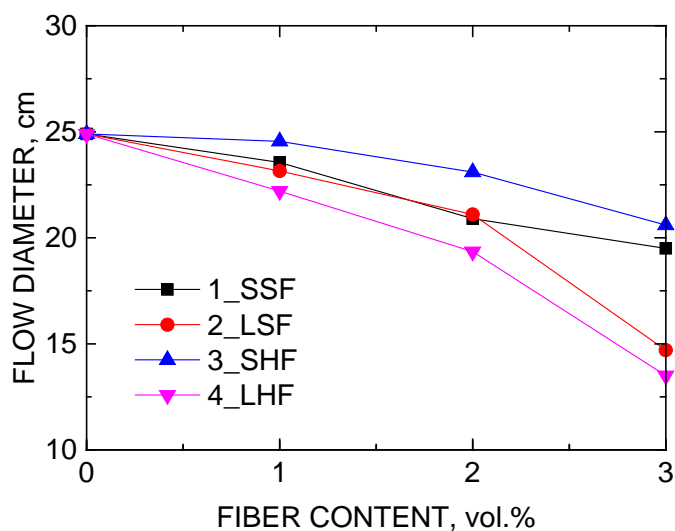

Figure 7   Spread flow with steel fibres

The characteristics of the utilized steel fibres are shown in Table 2. 1-SSF, 2-LSF and 4-LHF are copper coated steel fibres, while 3-SHF is coated with nickel. Compared to 1-SSF, the 2-LSF is more elongated, which contributes to a higher internal mechanical interaction in matrix, especially at high fibre contents. The hook ended characteristic of 4-LHF leads to a higher anchorage and interlock than 1-SSF and 2-LSF, which results in a larger resistance to the flow of UHPFRC. Even though, 3-LSF has a bigger anchoring and interlock effect than 1-SSF and 2-LSF, its cohesive forces are much less pronounced due to the minimum surface area per volume and unique coated surface.

CONCLUSIONS

This paper investigates the effect of superplasticizers and steel fibres on the fresh behaviour of UHPC. Both paste and concrete mixtures are designed to analyse the setting and flowability. Based on the obtained results, the following conclusions can be drawn:

- The type and dosage of SP have an obvious effect on the setting times which will be longer at higher dosages. The SP1 contributes to the longest setting times of pastes due to the largest retardation effect on the hydration, whereas the SP2 results in the shortest ones. The time differences between the initial and final settings are nearly to 75-175 min.
- The flowabilities of paste and UHPC are greatly influenced by the types and dosages of SP, which is related to the different adsorption abilities due to the different chemical constituents and structures. After obtaining a complete surface coverage of particles above the saturation dosage of SP, the dispersing ability of dosage will not increase anymore, which results in the occurrence of the typical plateau at high dosages. An exponential model $y = y_0 - ae^{-bx}$ is proposed to describe the relationships between the spread flow and SP dosage, which also presents that the SP3 and SP4 have a better dispersing ability than SP1 and SP2 for UHPC.
- The UHPCs with SP3 and SP4 have longer slump life, namely longer than 120 min and 40 min respectively. Whereas UHPCs with SP1 and SP2 present a poor slump life, with a linear decrease relationship between the flow and elapsed time. The slump loss and retention effect mainly depend on the physical coagulation of particles, as well as chemical processes to same extent.
- Geometric characteristic, coating type and volume content of steel fibres affect the flowability of UHPFRC. Generally, high volume content, elongated type, hooked ended type and copper-coated type of steel fibres contribute to a lower flow, due to the higher mechanical interaction and interlock.

ACKNOWLEDGEMENTS

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