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Relations between rheological and mechanical properties of fiber reinforced mortar

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Abstract. Fresh and hardened behaviors of a new hybrid fiber (steel fiber, polyvinyl alcohol fiber and calcium carbonate whisker) reinforced cementitious composites (HyFRCC) with admixtures (fly ash, silica fume and water reducer) have been studied. Within the limitations of the equipment and testing program, it is illustrated that the rheological properties of the new HyFRCC conform to the modified Bingham model. The relations between flow spread and yield stress as well as flow rate and plastic viscosity both conform well with negative exponent correlation, justifying that slump flow and flow rate test can be applied to replace the other two as simple rheology measurement and control method in jobsite. In addition, for the new HyFRCC with fly ash and water reducer, the mathematical model between the rheological and mechanical properties conform well with the quadratic function, and these quadratic function curves are always concave upward. Based on mathematical analysis, an optimal range of rheology/ flowability can be identified to achieve ideal mechanical properties. In addition, this optimization method can be extended to PVA fiber reinforced cement-based composites.

Keywords: whisker; hybrid fiber; Rheology; flowability; mechanical properties; mathematical model

1. Introduction

The crack and fracture of cementitious composites on loading is a gradual, multi-scale process: micro-crack usually preexists or first occurs in cement paste, then the propagation and coalescence of micro-cracks generate meso- and macro-cracks and eventually lead to the failure of cementitious composites (Banthia and Soleimani 2005, Bentz 2000, Nguyen *et al.* 2012). By introducing single type fiber into cementitious composites, cracks at certain scale can be restricted. But for the multi-scale nature of failure in cementitious composites, it is more logical than single type fiber to deal with cracks by the fiber hybridization on account of fiber dimensions and/or properties to attain promising performance (Arslan 2016, Banyhussan *et al.* 2016, Felekoglu and Keskinates 2016, Mastali *et al.* 2016, Perumal 2014, Wei and Meyer 2015). In this sense, the combination of fibers with different size, function and constitutive response is generally drawn into cement composites to restrict the growth of cracks at different stages and improve the strength, toughness and ductility of cement-based composites (Banthia and Soleimani 2005, Cao *et al.* 2015, Deng and Li 2007, Kandasamy and Akila 2015). Unfortunately, traditional hybrid fibers can hardly delay micro-crack initiation and propagation due to the relatively large length and diameter (Li *et al.* 2015, Parveen *et al.* 2013). Hence, micron calcium carbonate ($CaCO_3$) whisker with 20-30μm length and 0.5-2μm diameter is introduced to restrain the micro-cracks. In comparison with conventional hybrid fiber cementitious composites (HyFRCC) (with steel and polyvinyl alcohol (PVA) fiber) (Blunt and Ostertag 2009, Soe *et al.* 2013), the steel fiber and PVA fiber are partly replaced by cheap $CaCO_3$ whisker (approximately $236 per ton) to improve the mechanical performance as well as reduce the production cost of HyFRCC. The investigations reveal that the new HyFRCC can promote compressive and flexural performance efficiently by positive fiber synergy of the micro $CaCO_3$ whisker, meso- PVA fiber and macro- steel fiber (Cao *et al.* 2015).

In spite of the profits of the fibers and whiskers reinforcement, fibers and whiskers will reduce the flowability of fresh cementitious composites and further degrade fiber dispersion and orientation, this seems a obstruction for good compactness, porosity and density of harden cementitious composites (Cao *et al.* 2016, Gencel *et al.* 2011, Kuder *et al.* 2007). For effective utilization of fibers and whiskers, the flowability of fiber reinforced concrete must be regulated to construct easily in fresh state and the hardened properties are not negatively affected (Chung 2005, Kuder *et al.* 2007). But for HyFRCC, the quantitative correlations between rheology/ flowability and its mechanical properties have not been previously built up. Hence, the main objective of this manuscript is to build up these relationships demonstrably for the first time, depending on a systematic experimental investigation and mathematical analysis.

Rheology as a science assessing the fluid and deformation capacity of liquids under external shear stress,

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Table 1 Chemical constituents of raw materials (wt.%)

Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	CO_2	MgO	K_2O	SO_3	Na_2O	P_2O_5	MnO
Cement	61.13	21.45	5.24	2.89	2.37	2.08	0.81	2.50	0.77	0.07	0.06
Whisker	54.93	0.29	0.11	0.07	42.07	2.14	-	0.31	-	-	-
Fly ash	6.61	50.96	30.61	5.61	-	0.63	0.78	1.02	0.17	-	-
Silica fume	0.81	93.47	0.16	0.10	-	0.95	2.89	0.84	0.23	0.40	0.04

Table 2 Physical parameters of fibers

Fiber type	Length/mm	Diameter/μm	Tensile strength/MPa	E-modulus/GPa	Aspect ratio
Steel fiber	13	200	≥2 000	210	65
PVA fiber	6	35	1 472	32.3	171
$CaCO_3$ whisker	20-30μm	0.5-2	3 000-6 000	410-710	10-60

is more precision and impersonality than conventional workability test, which is largely based on feeling (Kuder *et al.* 2007, Wallevik and Wallevik 2011). The rheological parameters (yield stress and plastic viscosity) have been employed to evaluate the fresh properties of the new HyFRCC in present research. The mineral admixtures and water reducer have been introduced to optimize the rheological properties of the new HyFRCC. And the influences f mineral admixtures and water reducer on the rheological and mechanical properties of the new HyFRCC have also been studied.

In this investigation, several parameters of the new HyFRCC with various content of fly ash, silica fume and water reducer have been considered: (1) rheology (yield stress and plastic viscosity) and flowability(slump flow and flow rate); (2) the mechanical properties in terms of compressive strength and flexural behavior; (3) the quantitative relationship between rheology and flowability; (4) the quantitative correlations between rheological and mechanical properties.

2. Research significance

In this research, a new cost-effective HyFRCC with $CaCO_3$ whisker, PVA fiber and steel fiber, is developed. The influence of mineral admixtures and water reducer on the rheological and mechanical properties of the new HyFRCC is conducted. Moreover, the relationship between rheological and mechanical properties is established for the quality control and design optimization of the new HyFRCC.

The incorporation of fly ash and silica fume not only further reduces the unit cost of the new HyFRCC, but also optimizes rheological and mechanical properties as well as environmental friendliness (Ferrara *et al.* 2007, Gencel *et al.* 2011). Compared to conventional workability test (slump test, slump flow test, box test and so on), rheology test can give value of rheological parameters and is more precision and impersonality (Boulekbache *et al.* 2010). Hence, rheology test has been employed to obtain the rheological parameters, and the correlation between rheological parameters (yield stress and plastic viscosity) and flowability (slump flow and flow rate) of the new HyFRCC will be established, to justify the use of slump flow and flow rate as simple rheology measurement and control methods in jobsite (Kwan *et al.* 2010, Li and Li 2013).

The fresh state is a vital precondition for the application of fiber reinforced cementitious composites, and the plausible correlations between concrete flowability and mechanical properties have been authenticated by lots of researchers (Boulekbache *et al.* 2010, Ding *et al.* 2008, Ferrara *et al.* 2008, Ozyurt *et al.* 2007). But for HyFRCC, the quantitative correlations between rheology/flowability and its hardened state properties have not been previously built up. For the first time, this research systematically builds up the mathematical model between rheological parameters, flowability and compressive strength, flexural properties of the new HyFRCC. Based on these mathematical analysis, an optimal range of rheology/ flowability is identified for the first time to achieve ideal mechanical properties. And robust mechanical behaviors can be obtained through experiments, when the HyFRCC rheology/flowability is controlled to within this optimal scope (Li and Li 2013). This research tries to provide a reference in optimization of fresh and harden properties for applications of cement-based composites containing other hybrid fibers.

3. Experimental details

3.1 Materials

P.O 42.5R ordinary portland cement (Specific surface area=356 m^2/kg, 45μm sieve residue=14.60%, Dalian Onoda Cement Co. Ltd.), and quartz sand (Fineness modulus=2.51, Media sand, Dalian) were used as the major ingredients in matrix. Admixtures comprised of a high-range water-reducer (Polycarboxylic acid based, water reducing ratio 32%, Sika Co. Ltd.), fly ash (45μm sieve residue=23.72%, Dalian) and silica fume (diameter =0.01–0.3μm, Dalian) were used to modify the fluid properties and mechanical behaviors of mortars. Chemical constituents of cement, mineral admixtures and $CaCO_3$ whisker are shown in Table 1. Physical properties of fibers and whisker are tabulated in Table 2.

3.2 Mix proportion

Mix proportions of raw materials used in this study are shown in Table 3. As the water cement ratio and sand cement ratio adopted 0.3 and 0.5, respectively the new HyFRCC has demonstrated good mechanical behaviors in previous study (Cao *et al.* 2015). So in this research the water cement ratio and sand cement ratio were fixed at 0.3 and 0.5, respectively to maintain comparability. Mix proportion of standard hybrid fibers (SH) is 1.5% steel fiber + 0.4% PVA fiber +1.0% $CaCO_3$ whisker. Mortars without any fiber (Plain) and traditional fiber hybrid (TH) were used as control. The amount of the various mineral admixtures by mass as replacement of cement was changed to optimize the flowability of the HyFRCC. In addition, water reducers varied from 0.5% to 0.8% by mass were employed to study

Table 3 Dosage of raw materials in the combination

Groups	Volume fraction/vol.%			Binding materials/wt.%			Water reducer/wt.%
	Steel fiber	PVA fiber	$CaCO_3$ whisker	Cement	Fly ash	Silica fume	
Plain	0	0	0	100	0	0	0.5
TH	1.5	0.5	0	100	0	0	0.5
SH				100	0	0	0.5
FA5				95	5	0	0.5
FA10				90	10	0	0.5
FA15				85	15	0	0.5
FA20				80	20	0	0.5
SF5	1.5	0.4	1	95	0	5	0.5
SF8				92	0	8	0.5
SF11				89	0	11	0.5
SF14				86	0	14	0.5
WR0.6				100	0	0	0.6
WR0.7				100	0	0	0.7
WR0.8				100	0	0	0.8

Fig. 1 Equipment for rheological measurement

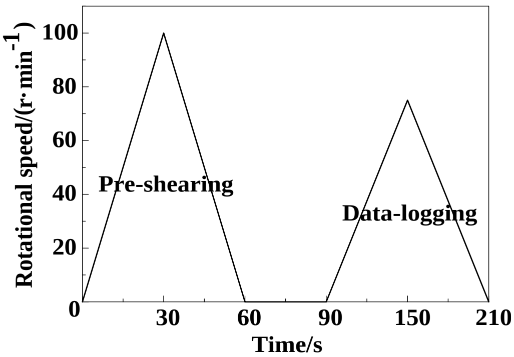

Fig. 2 Procedure of rheological testing

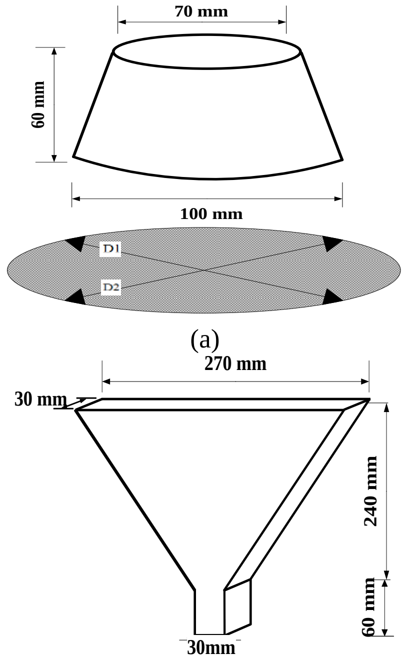

Fig. 3 Schematic graph of (a) slump cone and (b) V funnel (Okamura and Ouchi 2003)

the influence of water reducer on the HyFRCC.

3.3 Test methods

Rheological property of fresh HyFRCC was assessed by the Brookfield RST-SST rotational rheometer with a paddle rotator of VT60-30, as shown in Fig. 1. Rheological testing was conducted in two steps, as graphed in Fig. 2. To obtain the same shear history, each sample was subjected to a pre-shear cycle (first cycle) before the data-logging cycle (second cycle) for actual tests was conducted. And the data-logging interval is one second.

The fresh composites containing different dosage of admixtures were tested by V-funnel and slump flow cone to evaluate flow rate and flow spread (Okamura and Ouchi 2003), as illustrated in Fig. 3(a) and 3(b). Slump flow cone measurement, shown in Fig. 3(a): Firstly, the mini-slump cone was located on the center of a flat glass plate and filled up by the samples. Next, the mini-slump cone was carefully lifted up vertical within five seconds leaving the mortar spread freely. Two perpendicular diameters of the mortar patty formed after spread was measured and averaged after 3 minutes at least. Finally, the averaged diameter minus the cone bottom diameter was the spread value.

V-funnel measurement, shown in Fig. 3(b): Firstly, fresh composites were poured into the V-funnel until fully filled, during which the underneath outlet kept closed. After the top opening of V-funnel flatted, the underneath outlet was opened driving the mortar to fall out using self-weight. The time from the moment of flowing to the first light coming into the funnel from underneath outlet was defined as the flow time. Finally, the flow rate of mortars was calculated by the ratio between volume of mortar (1134 mL) and flow time with unit of mL/s.

40 mm×40 mm×40 mm cubes and 40 mm×40 mm×160 mm beams were used to investigate the compressive strength and flexural behaviors of harden HyFRCC at 28 d. A computer-controlled electro-hydraulic servo universal equipment (WDW-300) was employed with a crosshead speed of 0.5 mm/min and 0.05 mm/min for compressive and flexural test, respectively. During the four-point flexural experiments, beams were placed on support points 120 mm away from each other and loading was applied with 40 mm central spacing. Moreover, to acquire the

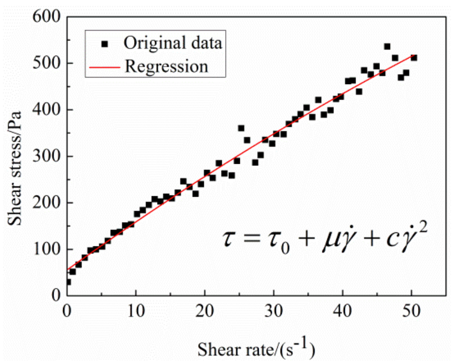

Fig. 4 A typical regression flow curve

midspan beam deflection data directly from the samples more precisely, linear variable displacement transducer (LVDT) contacting with the tensile region of the beams was employed and all data was acquired with the help of a computerized data collecting system (Banyhussan *et al.* 2016).

Table 4 Flowability and rheological parameters of each mortar

Group	Flow spread/mm	Flow rate/(ml/s)	Yield tress/Pa	Plastic viscosity/(Pa·s)
Plain	136.0	157.5	38.5	6.1
TH	87.5	108.7	48.4	7.6
SH	50.0	57.4	77.5	10.1
FA5	97.5	182.3	55.5	6.6
FA10	143.5	198.3	24.5	6.3
FA15	162.5	230.5	21.1	5.2
FA20	191.5	273.3	13.7	2.6
SF5	69.5	136.3	66.2	8.8
SF8	65.5	106.1	89.7	10.7
SF11	42.0	73.0	100.9	11.5
SF14	30.0	61.8	96.2	13.9
WR0.6	62.0	96.8	69.0	9.2
WR0.7	118.5	146.9	53.0	6.5
WR0.8	105.0	94.2	78.0	7.0

4. Results and discussion

4.1 Rheology and flowability

4.1.1 Influence of fly ash on rheology and flowability

Data extracted from the down curve of data logging cycle in rheology testing program is introduced to evaluate the rheological parameters of each mortar paste on account of its well dependability and reproducibility (Kwan *et al.* 2010, Vikan and Justnes 2007). Regression analysis is conducted to illustrate the best flow curve and the result shows that the data conform better with the modified Bingham model than the other generally rheological models. The typical regression flow curve is illustrated in Fig. 4 and the modified Bingham equation gives the relation of shear stress and shear rate by

$$\tau = \tau_0 + \mu\dot{\gamma} + c\dot{\gamma}^2 \qquad \tau \geq \tau_0 \tag{1}$$

Where τ is shear stress, Pa; τ_0 is yield stress, Pa; μ is plastic viscosity, Pa·s; $\dot{\gamma}$ is shear rate, s^{-1}; and c is regression coefficient. Rheological parameters of fresh cementitious composites are then acquired from the regression equations based on the modified Bingham model, as tabulated in the third and fourth columns of Table 4. And results of flow spread and flow rate of fresh HyFRCC are listed in the first two columns of Table 4.

Steel fiber, PVA fiber and $CaCO_3$ whisker increases the rheological parameters (yield stress and plastic viscosity) of the mortar paste as expected. As shown in Table 4, following the increase of fly ash, the yield stress and plastic viscosity decrease, whereas the flow spread and flow rate have a increasing tendency. Fly ash enhance the flowability of fresh HyFRCC. The definition of yield stress is the minimum shear stress needed to actuate the liquid from static state to flow, which is primarily influenced by the net structures within the cementitious composites. Network structures are mainly formed by the flocculation of cement hydration and the forces between cement particles caused by the combined effect of Van de Waals attraction, electronic repulsion and Zeta potential. The influence of mineral admixtures on the rheology of fresh hybrid fiber reinforced mortar can be explained in terms of the size, shape, surface feature and material texture of them. The flowability improvement caused by fly ash mainly attributes to its glassy surface and spherical particle. The glassy spherical particles easily roll over one another, reducing the friction between fibers, sands, cement particles and other ingredients in mortar paste, and the spherical shape also minimizes the particles' surface to volume ratio, leading to low fluid demands (Ferraris *et al.* 2001). Thus, the resistance for mortar to initiate flow is decreased and thereby the yield stress value of fresh HyFRCC decreases. Meanwhile, the flow spread increases because of the decrease of mortar resistance. Generally, the present study confirms to that a high yield stress correspond to a low spread values and vice versa (Artelt and Garcia 2008).

Plastic viscosity, the indicator of resistance within mortar when the materials are flowing, is influenced by the effect of particle shape, particle size distribution, particle concentration and the forces among particles. The hydration velocity of fly ash is much slower than that of cement, therefore the replacement of fly ash to cement leads to less hydration flocculation. And the less amount of flocculation means lower plastic viscosity and higher flow rate. It is deserved to note that the 45μm sieve residue of cement and fly ash used in the present research were 14.6% and 23.72%, respectively. And the bigger particle of fly ash than cement minimizes its surface to volume ratio, leading to low fluid demands of mortar paste. This is another reason for aforementioned phenomenon.

4.1.2 Influence of silica fume on rheology and flowability

As illustrate in Table 4, the yield stress and plastic viscosity initially decline but finally ascend, with the

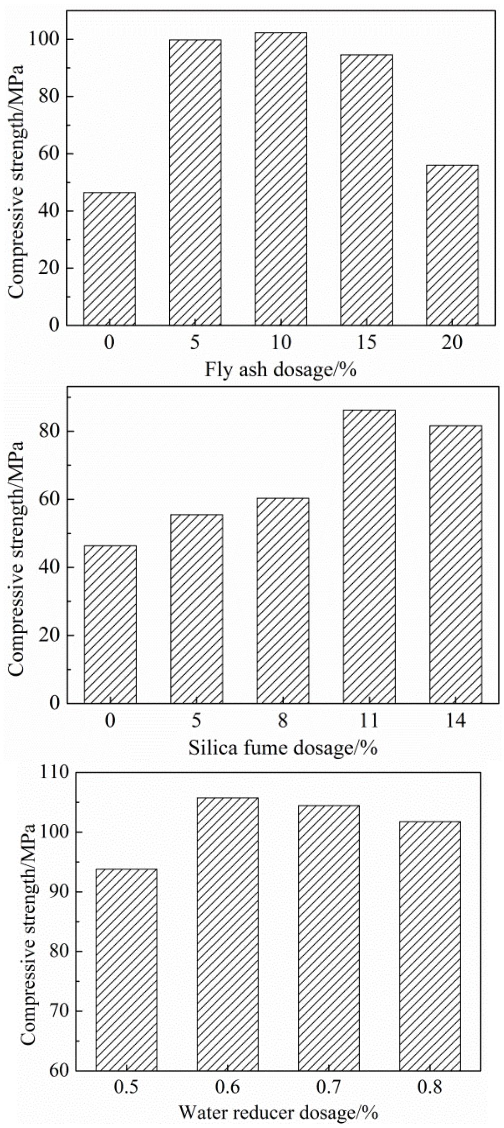

Fig. 5 Influence of fly ash, silica fume and water reducer on compressive strength of hybrid fiber reinforced mortars

increasing replacement of silica fume to cement. As replacement ratio of silica fume to cement is 5%, the fresh HyFRCC attain the least yield stress and plastic viscosity (66.2 Pa and 8.8 Pa.S, respectively). While replacement ratio of cement is 11% and 14%, the yield stress(100.9 Pa) and plastic viscosity (8.8 Pa.S) reach the greatest value, respectively. On the contrary, flow spread and flow rate initially increase but finally decrease, following the increasing replacement ratio of cement with silica fume, as shown in Table 4. As replacement ratio of cement is 5%, the fresh HyFRCC attain the greatest flow spread and flow rate (69.5 mm and 136.3 mL/s, respectively). About 5% replacement ratio of cement with silica fume is optimal for good flowability of the fresh HyFRCC.

With the ultrafine spherical particles, appropriate amount (about 5% herein) silica fume can fill the inter-space between sands, fibers and cement paste. And the filling effect increases the packing density of mixture, which promote the amount of free water and help the mortar to achieve better fluidity (Ferraris *et al.* 2001). Nonetheless, as the continue addition of silica fume (more than 8%), the ultrafine particle of silica fume augments its surface to volume ratio, bringing about high fluid demands of the mortar and worsening the flowability of the mortar paste. The worsen effect of silica fume is more critical than that of fly ash, e.g., as shown in Table 4 the smallest flow speed of new HyFRCC with silica fume is 30 mm, whereas that with fly ash is 97.5 mm, which is more than triple of 30 mm.

4.1.3 Influence of water reducer on rheology and flowability

As illustrate in Table 4, the yield stress and plastic viscosity initially decline but finally ascend, following the increasing of water reducer. With 0.7% water reducer, the fresh HyFRCC reaches the least yield stress and plastic viscosity (53.0 Pa and 6.5 Pa.S, respectively). On the contrary, flow spread and flow rate initially increase but finally decrease, along with the increasing dosage of water reducer, as shown in Table 4. With 0.7% water reducer, the fresh HyFRCC attains the greatest flow spread and flow rate (118.5 mm and 146.9 mL/s, respectively). About 0.7% water reducer is optimal for good liquidity of the fresh HyFRCC.

Water reducer can destroy the flocculation structure in cement mortar (Artelt and Garcia 2008, Wang *et al.* 2012)Therefore, in an optimum range (0.5%-0.7% herein), the more dense arrangement of the water reducer, the smaller and more evenly the dispersion of flocculation structure, and the better the flowability of fresh HyFRCC (Wang *et al.* 2012). Nonetheless, there is a saturated adsorption of cement particles to water reducer (Xu *et al.* 2014). Too much water reducer will make no contribution to flowability of mortar paste and even worsen its flowability for less free water.

4.2 Mechanical behaviors

4.2.1 Compressive strength

The 28-day compressive strength and the reinforced ratio of mixtures are illustrated in Fig. 5 and tabulated in the fourth column of Table 5, respectively. Compared to Plain, compressive strength of TH and SH shown 15.7% decrease and 1.3% increase, respectively. The increase of porosity caused by the loading of fibers may account for this strength decrease of TH (Chung 2005). Whereas, the replacement of $CaCO_3$ whisker to PVA fiber offsets the negative effect. This is likely resulting from the filling effect of $CaCO_3$ whisker in the cement mortar and a more compact HyFRCC is then obtained (Cao *et al.* 2014).

As shown in Fig. 5 and as expected, the compressive strength initially increases but finally decreases, along with the increase of fly ash, silica fume and water reducer, respectively. For compressive strength, the optimal proportions of fly ash, silica fume and water reducer are 10%, 11% and 0.6%, respectively. Note that the reasons for compressive strength enhancement of fly ash and silica fume vary a lot. The 45μm sieve residue of cement and fly ash used in the present research are 14.6% and 23.72%, respectively. And the diameter of silica fume is 0.01–0.3μm. The particle size of silica fume is much smaller than cement, hence the silica fume can strengthen the mortar by

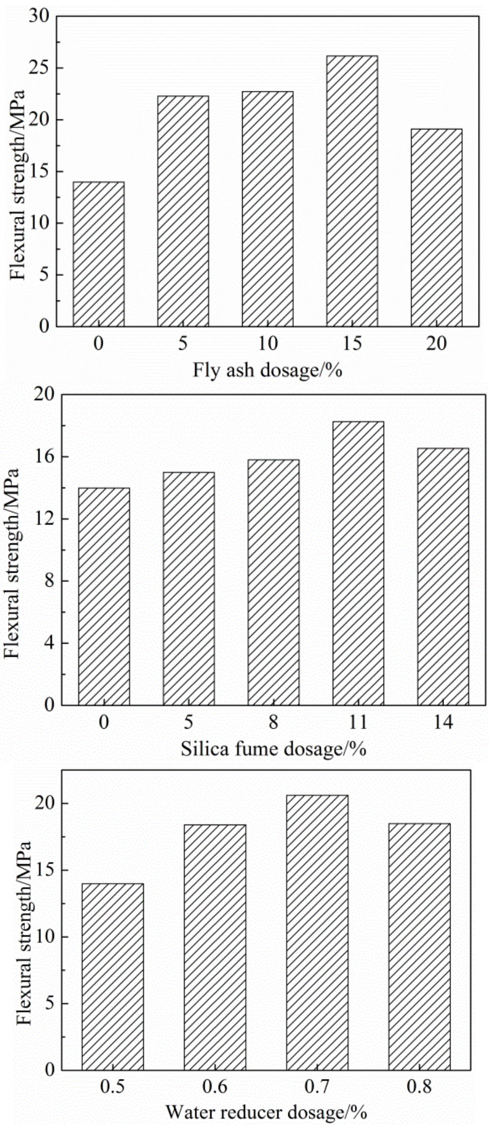

Fig. 6 Influence of fly ash, silica fume and water reducer on flexural strength of hybrid fiber reinforced mortars

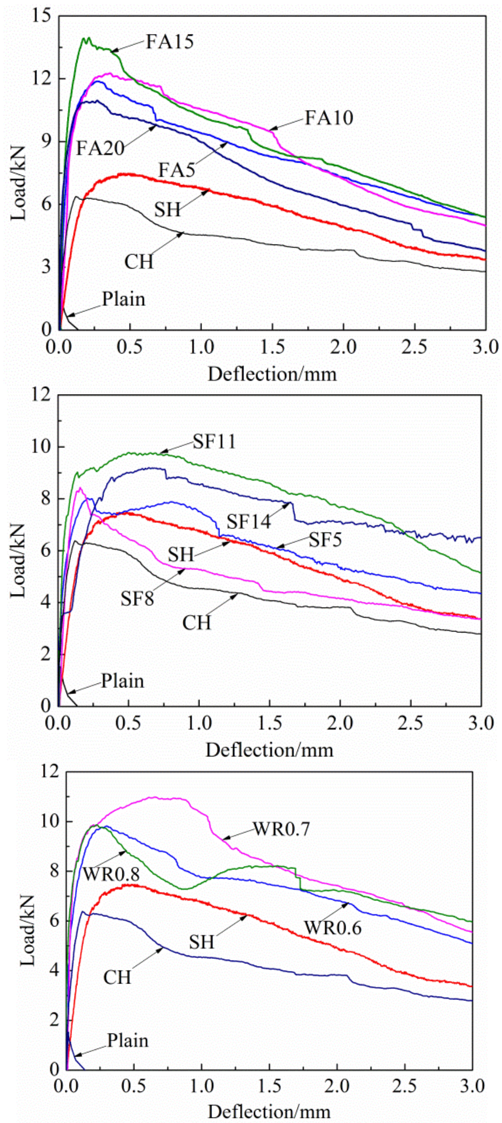

Fig. 7 Load-deflection curves of composites with various dosage of fly ash (FA), silica fume (SF) and water reducer (WR)

filling effect (Ferrara *et al.* 2007, Gencel *et al.* 2011). Whereas the bigger particle of fly ash than cement minimizes its surface to volume ratio, leading to low fluid demands of mortar paste, and then optimize the microstructure of matrix. Finally, compact matrix results in the improvement of compressive strength. In addition, the alkali-activated properties of fly ash and silica fume can optimize the interface between cement/sand and cement/fiber. And then the compressive strength of HyFRCC will be improved. However, too much replacement ratio of cement with fly ash and silica fume worsen the compressive strength account for their slower hydration velocity compare to cement. And the promotion of compressive strength by addition of water reducer also results from the flowability enhancement and vice versa.

4.2.2 Flexural strength

The flexural strength test results and the reinforced ratio of mixtures are illustrated in Fig. 6 and tabulated in the fifth column of Table 5, respectively. Compared to Plain, flexural strength of all HyFRCCs show significantly increase due to fiber hybrid. And the $CaCO_3$ whisker further improve the enhancement effect. The micro reinforcement of $CaCO_3$ whisker and the excellent fiber synergy of multi-scale fiber system may account for this phenomenon (Cao *et al.* 2015). It is deserved to notice that the enhancement of fibers to flexural strength is much more effective than that to compressive strength.

As shown in Fig. 6 and as expected, the flexural strength initially increases but finally decreases, along with the increase of fly ash, silica fume and water reducer, respectively. For flexural strength, the optimal proportions of fly ash, silica fume and water reducer are 15%, 11% and 0.7%, respectively. The reasons for the variation trend of flexural strength are similar to that of compressive strength.

4.2.3 Flexural response

The flexural responses of the HyFRCCs are compared based on the load-deflection curves. The load-deflection

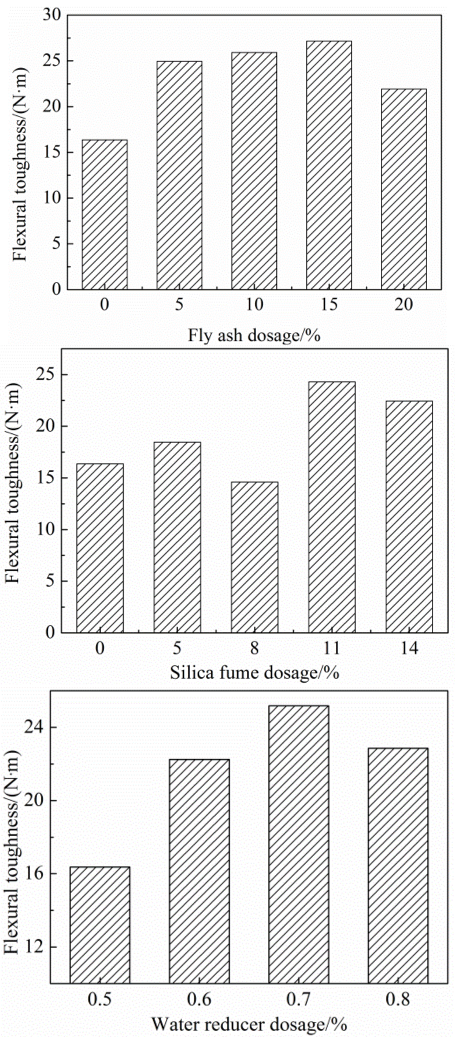

Fig. 8 Influence of fly ash, silica fume and water reducer on flexural toughness of hybrid fiber reinforced mortars

Table 5 Mechanical properties of each mortar

Group	Flexural toughness/(N·m)	Equivalent flexural strength/MPa	Compressive strength ratio*	Flexural strength ratio*
Plain	3.32	2.17	1	1
TH	15.79	8.20	0.84	5.27
SH	16.37	8.53	1.03	6.17
FA5	24.95	12.99	2.21	9.82
FA10	25.92	13.50	2.27	10.02
FA15	27.16	14.15	2.10	11.53
FA20	21.93	11.42	1.33	8.42
SF5	18.47	9.62	1.23	6.61
SF8	14.60	7.60	1.34	6.97
SF11	24.31	12.66	1.91	8.05
SF14	22.44	11.69	1.81	7.29
WR0.6	22.25	11.59	2.34	8.11
WR0.7	25.18	13.11	2.10	9.08
WR0.8	22.86	11.91	2.25	8.15

Note:*Compared to Plain

curves of composites are shown in Fig. 7. All of the HyFRCCs exhibit deflection-hardening response under flexural load. Whereas the deflection-hardening behaviors of mixtures incorporating $CaCO_3$ whisker are better than the one without whisker (CH) caused by the multi-scale fiber hybrid.

By bridging across cracks and delaying its developing, the hybrid fiber system remarkably improve the post-peak flexural softening behavior of the HyFRCCs (Yao *et al.* 2003). And SH presents better performance than CH in the descending branch of the load-deflection curve. Moreover, appropriate dosage of fly ash (FA), silica fume (SF) and water reducer (WR) showed more flatter softening branch. To some degree, admixtures have positive effects on the performance in softening branch of load-deflection curves. The enhancement of flowability and filling effect by admixtures may account for this phenomenon (Ferrara *et al.* 2007).

4.2.4 Flexural toughness

The flexural toughness and equivalent flexural strength of mixtures are illustrated in Fig. 8 and tabulated in the first and second column of Table 5, respectively. Compared to Plain, flexural toughness of all HyFRCCs show significantly increase due to fiber hybrid. And the $CaCO_3$ whisker further improves the enhancement effect. The micro reinforcement of $CaCO_3$ whisker can advance the bond strength between matrix and fibers and further improve the energy-dissipating capacity of HyFRCC (Cao *et al.* 2014). Moreover, the excellent fiber synergy of multi-scale fiber system also improve the toughness of HyFRCC (Cao *et al.* 2015). The degeneration of flexural toughness and equivalent flexural strength of SF8 may result from the unevenly fiber disperse caused by the bad flowability of HyFRCC with silica fume discussed in section 4.1.2.

As shown in Fig. 8 and as expected, the value of flexural toughness initially increase but finally decrease, along with the increase of fly ash, silica fume and water reducer, respectively. For flexural toughness, showing no difference with flexural strength, the optimal proportions of fly ash, silica fume and water reducer are 15%, 11% and 0.7%, respectively. The silica fume can strengthen the interface between cement/fiber by filling effect, and then the fibers can restrict the cracks efficiently and further improve the energy-dissipating capacity (Ferrara *et al.* 2007). Whereas fly ash can improve the flowability of HyFRCC, and optimize and fiber dispersion. Finally, good fiber dispersion result in efficient fiber synergy and energy-dissipating. In addition, the alkali-activated properties of fly ash and silica fume can optimize the interface between cement/fiber. And then the advanced bond strength between matrix and fibers can improve the energy-dissipating capacity of HyFRCC. However, too much replacement of fly ash and silica fume to cement worsens the flexural toughness due to their slower hydration velocity than cement. The improvement of flexural toughness by addition of water reducer also results from the flowability enhancement and vice versa.

4.3 Correlations between rheological properties and flowability

Due to the simple facility and effortless in jobsite, flow

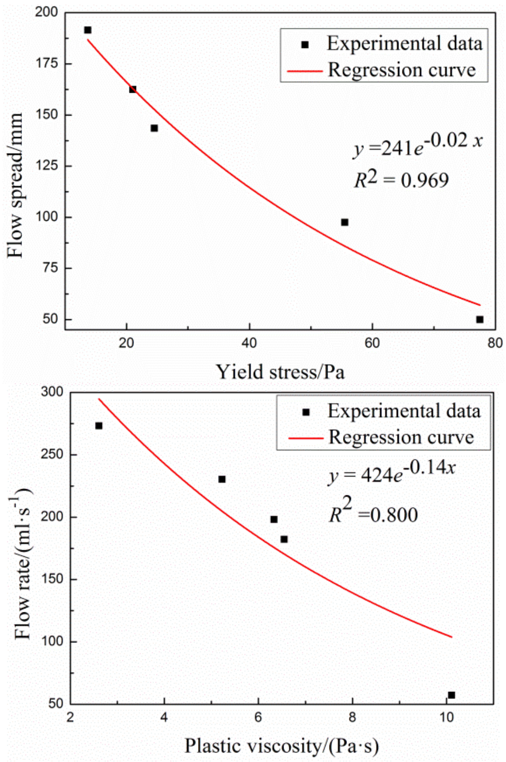

Fig. 9 Correlations between rheological properties and flowability of mortars with various dosage of fly ash

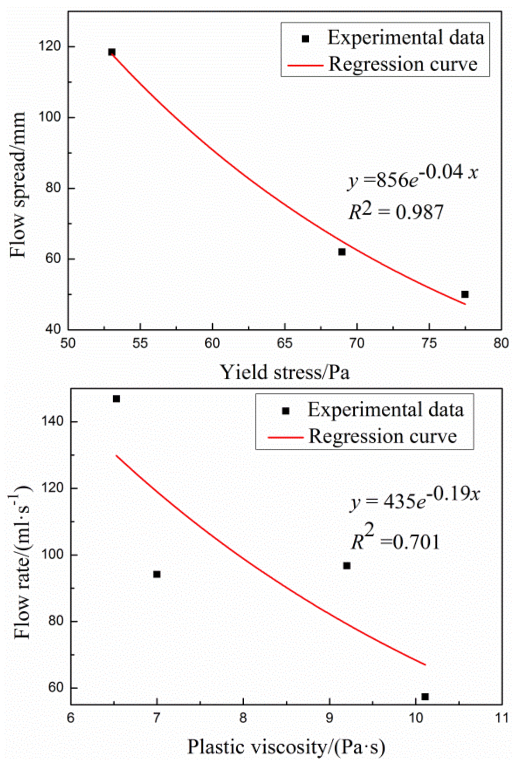

Fig. 10 Correlations between rheological properties and flowability of mortars with various dosage of water reducer. Note: The singular point yield stress=78.0 Pa is given up

spread and flow rate are simple measurement and control methods of fresh cementitious composites. Nonetheless, these conventional tests are strong subjective and easy to slip. Hence, once a correlation between the flowability and rheological parameters is built up, the flow spread and flow rate may parallelism the more accurate parameters of yield stress and plastic viscosity. Flow spread and flow rate are illustrated against yield stress and plastic viscosity and the best fit curves are obtained from the data plots, as shown in Fig. 9 and Fig. 10. For the new HyFRCC with fly ash and water reducer, there exist a negative exponent correlation between flow spread and yield stress as well as flow rate and plastic viscosity, with good correlation coefficients varied from 0.701 to 0.987 (Kwan *et al.* 2010). This means that the flow spread is mainly governed by yield stress and flow rate is governed by plastic viscosity. Through the correlations between rheology and flowability, the variation of micro-structures within mortar can be displayed by macro flowability.

Nonetheless, for the new HyFRCC with silica fume, the negative exponent correlation can't illustrate the relationship between rheological properties and flowability. As shown in Table 4, the flowability of new HyFRCC with silica fume is too bad to obtain accurate datas, e.g., the smallest flow speed value of the new HyFRCC with silica fume is 30 mm, whereas that with fly ash is 97.5 mm (which is more than triple of 30 mm). That is, the flow spread and flow rate can't reflect the micro-structures within mortar incorporation silica fume in this research. Hence, the accuracy of flowability test of new HyFRCC with silica fume need to be distinguished more carefully that with fly ash and water reducer.

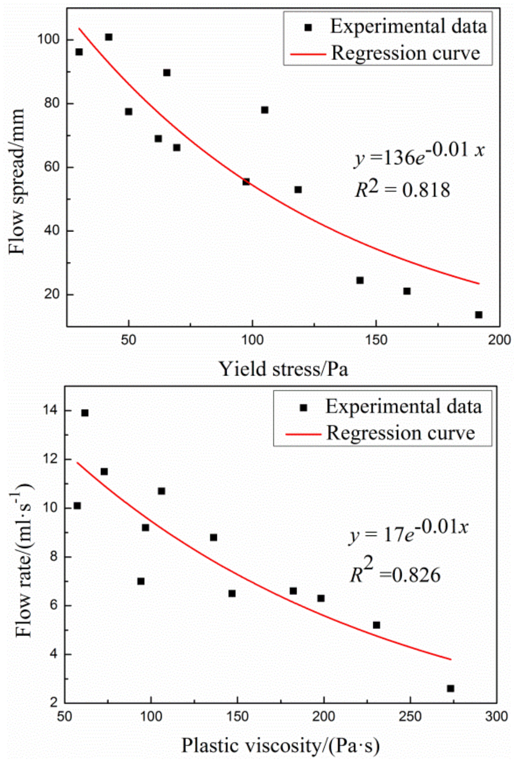

Fig. 11 Correlations between rheological properties and flowability of all composites

To improve the reliability of data fitting, the test results of all new HyFRCCs are employed to carry out regression analysis. There exists a negative exponent correlation

Table 6 Coefficients in $y = ax^2 + bx + c$ correlation between rheological and mechanical properties

Mortars	Mechanical parameter(y)	Rheological parameter(x)	a	b	c	R^2
New HyFRCC incorporation fly ash	Compressive strength/MPa	Yield stress/Pa	-0.06	4.9	10.6	0.94
		Plastic viscosity/(Pa·s)	-3.33	40.7	-24.0	0.99
		Flow spread/mm	-0.01	2.7	-61.7	1.00
		Flow rate/(ml/s)	-0.004	1.5	-24.9	0.99
	Flexural strength/MPa	Yield stress/Pa	-0.008	0.6	14.3	0.83
		Plastic viscosity/(Pa·s)	-0.5	5.5	8.5	0.91
		Flow spread/mm	-0.002	0.4	-2.4	0.87
		Flow rate/(ml/s)	-0.001	0.2	3.8	0.83
	Flexural toughness/(N·m)	Yield stress/Pa	-0.008	0.6	16.4	0.94
		Plastic viscosity/(Pa·s)	-0.5	5.3	11.5	0.98
		Flow spread/mm	-0.002	0.4	0.1	0.96
		Flow rate/(ml/s)	-0.001	0.2	6.2	0.93
New HyFRCC incorporation water reducer	Compressive strength/MPa	Yield stress/Pa	-0.3	38.9	-1089.4	1.00
		Plastic viscosity/(Pa·s)	-17.4	277.8	-984.2	0.95
		Flow spread/mm	-0.05	8.2	-238.1	0.78
		Flow rate/(ml/s)	-0.02	4.4	-143.4	1.00
	Flexural strength/MPa	Yield stress/Pa	-0.02	1.7	-28.5	1.00
		Plastic viscosity/(Pa·s)	-0.7	10.7	-19.1	0.82
		Flow spread/mm	-0.002	0.3	2.7	0.73
		Flow rate/(ml/s)	-0.0008	0.2	2.7	1.00
	Flexural toughness/(N·m)	Yield stress/Pa	-0.02	2.3	-40.6	1.00
		Plastic viscosity/(Pa·s)	-1.0	15.3	-31.8	0.86
		Flow spread/mm	-0.002	0.5	-1.2	0.78
		Flow rate/(ml/s)	-0.001	0.4	0.3	0.99
New HyFRCC incorporation silica fume	Compressive strength/MPa	Yield stress/Pa	0.004	-0.5	28.2	0.97
	Flexural strength/MPa	Yield stress/Pa	0.007	-1.0	52.9	0.97
	Flexural toughness/(N·m)	Yield stress/Pa	0.02	-3.5	156.3	0.84

Note: For HyFRCC with water reducer, the singular point yield stress=78.0 Pa is given up

between flow spread and yield stress also flow rate and plastic viscosity, with good correlation coefficients of 0.818 and 0.826, respectively as shown in Fig. 11. Generally, the use of slump flow and flow rate as simple rheology measurement and control method is feasible in jobsite.

4.4 Correlations between rheological and mechanical properties

In general, mechanical properties control of concrete around the world are conducted by standard specimens test at a standard age, e.g., the standard age of concrete for compressive strength test is 28 d in Chinese standard GB50107-2010. This widely used method is poor in time and economic efficiency. Once a correlation between the rheological and mechanical properties is built up, the rheological parameters (yield stress, plastic viscosity, flow spread and flow rate) are parallelism to the mechanical properties (compressive strength, flexural strength and flexural toughness). Then the mechanical properties of the new HyFRCC can be controlled by flowability optimization in fresh state, and the time, cost and resource consumption can be reduced remarkably. Regression analysis is executed to reveal the correlation between the rheological and mechanical properties. For the new HyFRCCs with fly ash and water reducer, the results show that data conform well with the quadratic function, with good correlation coefficients varied from 0.73 to 1.00, as shown in Table 6. The typical regression curve is illustrated in Fig. 12 and the quadratic function gives the relation of rheological and mechanical properties by

$$y = ax^2 + bx + c \tag{2}$$

Where y is mechanical parameter (compressive strength, MPa; flexural strength, MPa; and flexural toughness, N.m); x is rheological parameter(yield stress, Pa; plastic viscosity, Pa·s; flow spread, mm; and flow rate, ml/s) ; a, b and c are regression coefficients, as shown in Table 6.

As shown in Table 6, the numerical value of regression coefficient a is always negative for the new HyFRCC with fly ash and water reducer. That is to say the curves are concave upward, and the optimal mechanical property (=$(4ac-b^2)/4a$) and corresponding rheological parameter(=$-b/2a$) of new HyFRCCs (point A in Fig. 12) can be acquired based on the quadratic function. For example, for the compressive strength of HyFRCC incorporation fly ash, when independent variable is yield stress, based on the coefficients in Table 6, the optimal compressive strength can reach 110.6 MPa and corresponding yield stress equals to 40.8 Pa. In other words, if the yield stress of the fresh new HyFRCC incorporation fly ash is controlled about 40.8 Pa in construction, the optimal compressive strength nearly110.6 MPa can be obtained in harden state of the new HyFRCC. In addition, based on overall consideration of all mechanical parameters, rheological parameters can be controlled in certain range to achieve designed mechanical properties. That is, this systemative method can be employed for optimization design. As shown in Fig.12, the quadratic function also gives the limit range for the new HyFRCC to work normally, which is between point B and C ($\frac{-b-\sqrt{b^2-4ac}}{2a}$, $\frac{-b+\sqrt{b^2-4ac}}{2a}$). That is, falling outside this range the new HyFRCC will unable to work properly. Hence, the mechanical properties of the new HyFRCC with fly ash and water reducer are mainly controlled by rheological parameters.

For the new HyFRCC with silica fume, the correlations between yield stress and mechanical properties also conform to quadratic function. Nonetheless, this quadratic function with one unknown correlation can't illustrate the relationship between the other rheological parameters and mechanical properties, and function of third or fourth order is suitable for this situation. Significantly, the correlations between yield stress and mechanical properties also conform to $y = ax^2 + bx + c$ herein, but a is always positive and the curves are concave downward. The optimal mechanical properties can't be obtained only by yield stress and the other boundary conditions is needed. Analogously, due to the function of third or fourth order relationship

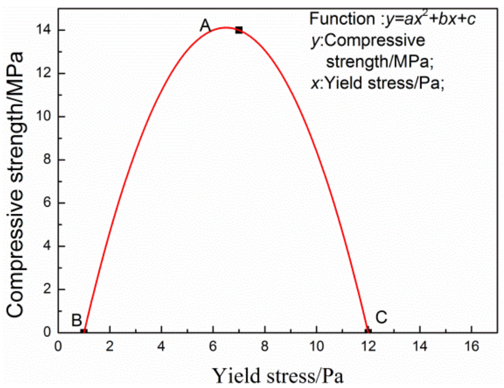

Fig. 12 Typical curve of the mathematical model between rheological and mechanical properties

Table 7 Coefficients in $y = ax^2 + bx + c$ correlation between flexural strength and flow spread of PVA fiber engineered cementitious composites

Mortars	Mechanical parameter(y)	Rheological parameter(x)	a	b	c	R^2
PVA fiber engineered cementitious composites (Şahmaran *et al.* 2010)	Flexural strength /MPa	Mix 1 flow spread/mm	-0.0003	0.098	3.54	0.93
		Mix 2 flow spread*/mm	-0.0006	0.17	0.32	0.61
		Mix 3 flow spread/mm	-0.0005	0.13	1.83	0.65
		Mix 4 flow spread/mm	-0.0005	0.12	2.42	0.83
		Mix 5 flow spread/mm	-0.0001	0.04	4.55	0.65
		Mix 6 Flow spread/mm	-0.00006	0.026	5.77	0.98

Note: *, the singular point flow spread=189.5 mm is given up

between the other rheological parameters and mechanical properties, the other boundary conditions is needed to achieve the optimal mechanical properties. As shown in Table 4, the flowability of the new HyFRCC with silica fume is too bad to obtain accurate data. That is, the rheological properties can't reflect the micro-structures within mortar incorporation silica fume accurately in this research. Hence, mechanical properties control of new HyFRCC with silica fume need to be distinguished more carefully in jobsite. Due to the ultrafine particle, more significant alkali-activated properties and filling effect of silica fume instead of rheological properties mainly control the mechanical behaviors of the new HyFRCC with silica fume. Consequently, besides rheological properties, more requirements is needed to control the mechanical behaviors of the new HyFRCC with silica fume than that with fly ash and water reducer.

The aforementioned mathematical model is identified from a limited number of experimental results. Therefore, regression analysis is carried out to further prove the validity of this model based on the date in pertinent literature (Şahmaran *et al.* 2010). As shown in Table 7, the relations between flexural strength and flow spread of PVA fiber engineered cementitious composites with various water reducer content conform with the quadratic function, with correlation coefficients varied from 0.61 to 0.98. Generally, the flexural strength of PVA fiber engineered cementitious can also be optimized by adjusting flow spread with the aforementioned method. That is, this optimization method can be extended to PVA fiber reinforced cement-based composites.

5. Conclusions

In this paper, the fresh and hardened properties of a new hybrid fiber (steel fiber, PVA fiber and $CaCO_3$ whisker) reinforced cementitious composites (HyFRCC) with admixtures(fly ash, silica fume and water reducer) are studied. Correlations between rheological properties and flowabilities are evaluated. And then, the relationships between rheological properties and mechanical properties are discussed. The following conclusions can be drawn from this research.

• Within the limitations of the equipment and testing program, it is illustrated that the rheological property of the new HyFRCC conforms to the modified Bingham model. Appropriate dosage of fly ash, silica fume and water reducer are beneficial to the liquidity of fresh HyFRCC. But too much admixtures will effect the liquidity negatively. And the negative influence of silica fume is more drastically than the other admixtures due to the ultrafine particle of silica fume.

• The new hybrid fiber system with $CaCO_3$ whisker can enhance the compressive strength, flexural strength, flexural response and flexural toughness of cement mortar more effectively than the conventional fiber hybrid. And appropriate dosage of admixtures can optimal the mechanical performance of the new HyFRCC in harden state.

• For the new HyFRCC with fly ash and water reducer, there exists a good negative exponent correlation between flow spread and yield stress as well as flow rate and plastic viscosity. The use of slump flow and flow rate as simple rheology measurement and control method is feasible in jobsite. Nonetheless, for the new HyFRCC with silica fume, the negative exponent correlation can't illustrate the relationship between rheological parameters and flowabilities due to its bad flowability. Hence, the accuracy of flowability test of new HyFRCC with silica fume need to be distinguished carefully in jobsite.

For the new HyFRCC with fly ash and water reducer, the correlations between the rheological and mechanical properties conform well with the quadratic function with one unknown, and the curves of the quadratic functions are always concave upward. Hence, the optimal mechanical property and corresponding rheological parameter can be acquired by mathematical calculation. In other words, if the rheological parameter of the fresh new HyFRCC with fly ash is controlled in construction, the optimal mechanical property can be obtained in harden state of the new HyFRCC. In addition, this optimization method can be extended to PVA fiber reinforced cement-based composites. However, for the new HyFRCC with silica fume, mechanical behaviors can't be controlled only by rheological properties due to the ultrafine particle, more significant alkali-activated properties and filling effect of silica fume than fly ash, and multi factors combination is needed.

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