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The micromechanics model analysis of the viscosity regulation of ultra-high strength concrete with low viscosity

M Zhu[1,a], F G Wang[2,b], F Z Wang[1,c], Y P Liu[1,d]

[1]State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan, Hubei 430070, China；

[2].Jiangsu Subote New Material Co., Ltd., Nanjing, Jiangsu 211013, China

E-mail:[a]mingz99@163.com, [b]337698651@qq.com,[c] fazhwang@whut.edu.cn, [d]420426327@qq.com

Abstract: The plastic viscosity of mortar and concrete with different binder content, sand ratio, water-binder ratio, microbead dosage and different class and dosage of fly ash were tested and calculated according tomicromechanics model proposed by A.Ghanbari and B.L.Karihaloo, The correlations between these parameters and fresh concrete workability were also investigated, which showed i. high consistence with the objective reality. When binder content, microbead dosage, fly ash dosage or the water-binder ratio was increased or sand ratio was reduced, the fresh concrete viscosity would decrease correspondingly. However their effects were not that same. The relationships between T50 a, V-funnel and inverted slump time with fresh concrete viscosity were established, respectively.

1. Introduction

Ultra-high strength concrete (UHSC), with the advantages of remarkably decreasing the construction weight and effectively improving the concrete durability, can reduce the energy consumption and construction cost. However, due to its low water consumption and low water-binder ratio, the fresh concrete viscosity is relatively high, which . frequently results in pumping accidents.

Fresh concrete can be regarded as a particle suspending system, comprised of liquid phase and solid phase (particle phase) with particle dimension from submicron size to millimeter size. Therefore, the rheological properties of fresh concrete are affected by several bonds or forces from different constituents [1]. Generally, in mortar system the cement grout is regarded as liquid phase and the fine aggregate is regarded as particle phase, while in concrete system the mortar is regarded as liquid phase and the coarse aggregate is regarded as particle phase. In fact, this classification of phase is simplified. On sub-microcosmic level, cement grout can be regarded as a particle suspending fluid and its rheology is dependent on the suspending fluid with other equivalent size fine particles. When rheological properties of fresh concrete are characterized by Bingham body model (τ=τ0+ηu) [2], yield shear stress (τ0) is the maximum stress to prevent plastic deformation. With application of external force, fresh concrete will flow if the internal shear stress (τ) is greater than or equal to the yield shear stress (τ0). Plastic viscosity (η) is a parameter to show the flowing property of fresh concrete. The less the viscosity value is, the faster the fresh concrete flows under the same external force. This shows that yield shear stress (τ0) and plastic viscosity (η) are two main rheological parameters to reflect the workability of fresh concrete. BML Viscometer, invented by Wallevik [4], can be used to test the rheological parameters (τ0 and η) of slurry containing fine powders [3]. However, this viscometer is not suitable to test complicated concrete system, which comprised of liquid phase and varied solid particles with a tremendous size difference, from fine aggregate and coarse aggregate to cement and ultrafine additions. So far there has not been an instrument that can be used to correctly and precisely test the rheological property of fresh concrete. Based on the plastic viscosity values of cement slurry or slurry with mineral fillers, A.Ghanbari and B.L.Karihaloo [5] proposed micromechanics model and estimated the plastic viscosity of steel fiber and non-steel fiber self-compacting concrete (SCC). And the calculated results had relatively good consistence with the objective reality. In this paper, this method was employed to evaluate rheological properties of UHSC with low viscosity. The effect of binder content, sand ratio, water-binder ratio, microbead dosage and different class and dosage of fly ash on concrete rheological performances were studied. the plastic viscosity of mortar and concrete with different. And the correlations between these parameters and concrete workability were also investigated.

2. Experimental programs

2.1 Materials

P·I52.5 Portland cement (C) provided by Huaxin Cement Co,. Ltd., Wuhan, China, a Class I fly ash (FA) by Hubei Guodian Qingshan Co-generation Co.Ltd.，Wuhan, China, a Grade S95 class ground granulated blast furnace slag (GGBS) by Wuhan Ganghua Co,. Ltd., Wuhan, China, silica fume (SF) by Guizhou Haitian Ferroalloy Abrasive Co., Ltd.，Guizhou, China, microbead (M) by Shenzhen Tongcheng New Material Co. Ltd., Shenzhen, China, and ViscoCrete3301 C100 polycarboxylates superplasticizer with a 24% solid content by Sika were used in this study. Taken from Dongting Lake, Hunan, China, medium sand with an apparent density of 2.62g/cm^3 and a fineness module of 2.8 was used as fine aggregate. The medium sand contained less than 1% material finer than 75 μm in natural sand. Continuously graded crushed basalt stone with minimum particle size of 5mm, maximum particle size of 16mm, apparent density of 2.72g/cm^3 and crush value of 2.7% was used as coarse aggregate. The crushed stone, with less than 5% elongated and flaky particles content by weight, contained less than 0.2% material finer than 75 μm in natural sand. The chemical composition and physical properties of materials are presented in tables 1 and 2, respectively.

2.2 Experimental method

The viscosity and yield stress of binder slurry were tested by BROOKFIELD R/S Plus Rotating Rheometer. Then linear regression equation of rheological curve was derived from linear regression method. According to Chinese Code JGJ/T281-2012, T and CECS203-2006, the workability of fresh concrete were tested, such as slump-flow, time to reach 19.68in.(500mm) diameter (T50)，V-funnel，inverted slump time and air content. According to micromechanics model proposed by A.Ghanbari and B.L.Karihaloo, the plastic viscosity of mortar and concrete were calculated, respectively..

Table 1 Physical properties of cement

Fineness (〉80μm)%	Setting time (min)		Soundness	Flexural strength (MPa)		Compressive strength (MPa)		Density (g/cm^3)	Water requirement of normal consistency (g)	Blaine specific area (m^2/kg)
	Initial	Final		7d	28d	7d	28d			
1.7	130	185	Qualified	8.8	9.2	50.1	59.5	3.14	135	350

Table 2 Physical properties of mineral fillers

Mineral fillers names	Flexural strength (MPa)		Compressive strength (MPa)		Index of activity (%)		Blaine specific area (m^2/kg)	Density (g/cm^3)	Ratio of water demand (%)	Fineness (%)
	7d	28d	7d	28d	7d	28d				
FA(I)	5.4	8.3	24.8	37.4	67	78	559	2.25	92	5.5
FA(II)	4.7	7.0	24.0	34.7	61	68	460	2.46	102	27.7
GGBS	6.3	8.9	29.6	53.9	76	106	535	2.87	-	-
SF	9.2	10.2	57.8	75	115	126	20000	2.07	-	-
M	7.8	8.8	49.2	65.5	98	110	3300	2.43	85	-

2.3 Experimental theory

The raw material particles are regarded as rigid spheres in the micromechanics model proposed by A.Ghanbari and B.L.Karihaloo [5-7],. The calculation process is given in figure.1: Firstly, the paste is regarded as liquid-solid phase suspension system, among which the cement grout is the liquid phase and the cement replacement material (CRM) is the solid phase, then its viscosity was tested. Secondly, the mortar slurry and concrete is regarded as liquid-solid phase suspension system, respectively.

Their viscosity could be calculated by Eq. (1) to (4).

Note: CRM stands for cement replacement material, namely mineral fillers, such as GGBS and SF.

The plastic viscosity of liquid-solid suspension phase system is obtained by Eq. (1) to (2).

$$\eta_{Ci+1} = \eta_{Ci} f_{i+1}(\phi_{i+1}) \quad (1)$$

$$\phi_i = \frac{v_i}{v_i + v_0} \quad (2)$$

where (η_{C1}) is the plastic viscosity (Pa.s) of slurry mixed with mineral fillers, ϕ_i is the volume fraction of solid phase, v_i is the volume of solid phase (m^3), v_0 is the continuous matrix volume (m^3), and $f_i(\phi_i)$is a function. Depending on the volume fraction value, the value can be obtained by Eq. (3) or (4).

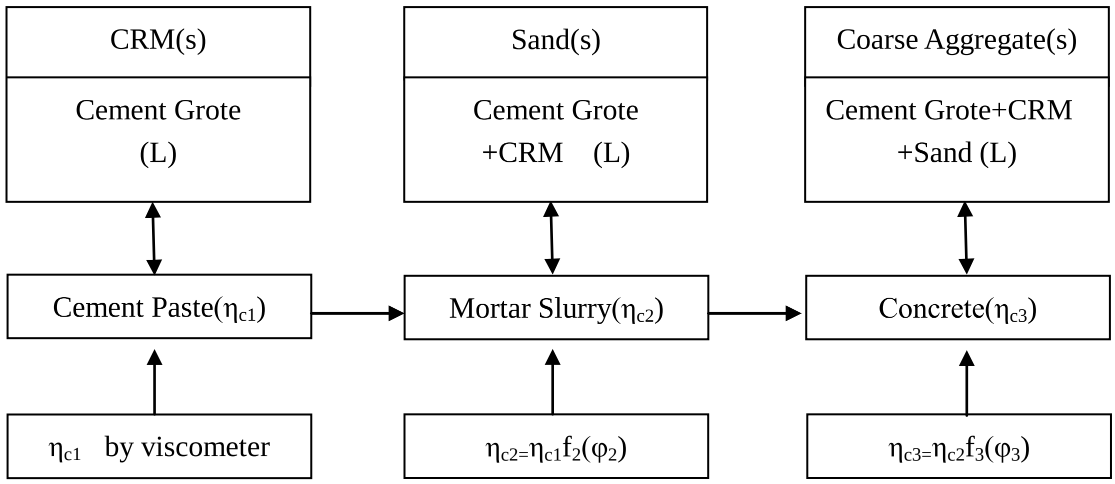


Figure.1. Process of viscosity calculation of fresh concrete

1）When volume fraction of solid phase (ϕ_i)is less than 10%, function $f_i(\phi_i)$ ismerely related to the volume fraction(ϕ_i) and can be obtained by Einstein equation, namely Eq. (3).

$$f_i(\phi_i) = 1 + [\eta]\phi_i \tag{3}$$

where $[\eta]$ is a dimensionless inherent viscosity, a tested value [8] representing the effect of a single particle on viscosity. When the particles are regarded as rigid dense spheres, and the distance among the particles are far more than the mean particle diameter, $[\eta]$ value equals to 2.5.

2）When volume fraction of solid phase (ϕ_i) is more than 10% but less than the probable maximum volume fraction (ϕ_i), function $f_i(\phi_i)$ is not only related to the volume fraction but also to the dispersion degree and morphology of the solid phase in the fluid. And the function $f_i(\phi_i)$ can be obtained by Eq. (4) proposed by Krieger and Dougherty [9].

$$f_i(\phi_i) = (1 - \frac{\phi_i}{\phi_m})^{-[\eta]\phi_m} \tag{4}$$

where ϕ_m is the probable maximum volume fraction, representing the minimal separating distance among particles, namely the conditions with the minimum void ratio and the exceedingly high viscosity.

Both $[\eta]$ and ϕ_m are dependent on the shear rate. With the increase of shear rate, the $[\eta]$ decreases while the ϕ_m increases. When either parameter increases, the other will decrease correspondingly. For rigid dense sphere, $[\eta]\phi_m$ value equals to 2.5.

3. Results and discussion

3.1 Mix proportion design and viscosity calculation of UHSC with low viscosity

With different binder content, sand ratio, water-binder ratio, microbead dosage and different fly ash class and dosage, the corresponding mix proportion design and workability results are presented in table 3.

Table 3 Mix proportions and workability of UHSC with low viscosity

No.	Binder (kg/m^3)	Binder proportions (%)						w/b	Water (kg/m^3)	Superplasticizer (SP/Binder)	Sand ratio (%)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Workability（s）		
		C	GGBS	FA (I)	FA (II)	M	SF							T50	V-funnel	Inverted slump time
1	580	63.5	20	10	0	0	6.5	0.21	121.8	0.03	40	685	1027	9	60	9.5
2	630	63.5	20	10	0	0	6.5	0.21	132.3	0.03	40	665	995	8	45	8.5
3	680	63.5	20	10	0	0	6.5	0.21	142.8	0.03	40	645	967	7	35	7
4	730	63.5	20	10	0	0	6.5	0.21	153.3	0.03	40	625	935	6.5	30	7
5	630	63.5	20	10	0	0	6.5	0.21	132.3	0.03	37	615	1047	8.5	46	9
6	630	63.5	20	10	0	0	6.5	0.21	132.3	0.03	43	713	945	8	42	8
7	630	63.5	20	10	0	0	6.5	0.21	132.3	0.03	46	762	894	8	48	8.5
8	630	63.5	20	10	0	0	6.5	0.19	119.7	0.03	40	665	995	15	80	15
9	630	63.5	20	10	0	0	6.5	0.20	126	0.03	40	665	995	8	45	8.5
10	630	63.5	20	10	0	0	6.5	0.22	138.6	0.03	40	665	995	6	35	5.5
11	630	73.5	20	0	0	0	6.5	0.21	132.3	0.03	40	665	995	12	70	12.5
12	630	68.5	20	0	5	0	6.5	0.21	132.3	0.03	40	665	995	9.5	57	9.5
13	630	68.5	20	5	0	0	6.5	0.21	132.3	0.03	40	665	995	9	53	9
14	630	63.5	20	0	10	0	6.5	0.21	132.3	0.03	40	665	995	8.5	45	8.5
15	630	58.5	20	15	0	0	6.5	0.21	132.3	0.03	40	665	995	7	40	7.5
16	630	63.5	20	7.5	0	2.5	6.5	0.21	132.3	0.03	40	665	995	7	41	8
17	630	63.5	20	5	0	5	6.5	0.21	132.3	0.03	40	665	995	6.5	35	7
18	630	63.5	20	2.5	0	7.5	6.5	0.21	132.3	0.03	40	665	995	5	31	6.5
19	630	63.5	20	0	0	10	6.5	0.21	132.3	0.03	40	665	995	4.5	26	5

According to the experimental theory in Part 2.3, relevant parameters and viscosity values of concrete specimens in table 3 are given in table 4.

Table 4 Tested viscosity values of grout and calculated viscosity values of UHSC

No.	η_{C1} (Pas)	ϕ_2	$f_2(\phi_2)$	η_{C2} (Pas)	ϕ_3	$f_3(\phi_3)$	η_{C3} (Pas)
1	1.60	0.4471	5.3988	8.64	0.3924	3.9747	34.33
2	1.60	0.4196	4.6000	7.36	0.3768	3.6733	27.04
3	1.60	0.3938	4.0030	6.40	0.3625	3.4265	21.95
4	1.60	0.3696	3.5453	5.67	0.3475	3.1940	18.12
5	1.60	0.4007	4.1506	6.64	0.3965	4.0604	26.96
6	1.60	0.4366	5.0710	8.11	0.3579	3.3518	27.20
7	1.60	0.4530	5.5986	8.96	0.3386	3.0661	27.47
8	3.55	0.4285	4.8372	17.17	0.3818	3.7650	64.65

9	2.45	0.4240	4.7153	11.55	0.3793	3.7194	42.97
10	1.35	0.4152	4.4908	6.04	0.3744	3.6294	21.92
11	2.90	0.4250	4.7418	13.75	0.3798	3.7293	51.28
12	2.40	0.4230	4.6891	11.25	0.3787	3.7081	41.73
13	2.20	0.4222	4.6691	10.27	0.3783	3.7011	38.02
14	1.80	0.4211	4.6373	8.35	0.3777	3.6886	30.79
15	1.40	0.4169	4.5325	6.35	0.3753	3.6472	23.14
16	1.50	0.4199	4.6078	6.91	0.3770	3.6774	25.42
17	1.35	0.4202	4.6156	6.23	0.3772	3.6802	22.93
18	1.15	0.4205	4.6235	5.32	0.3774	3.6830	19.58
19	1.05	0.4208	4.6314	4.86	0.3775	3.6872	17.93

3.2 Experimental results analysis of viscosity of UHSC with low viscosity

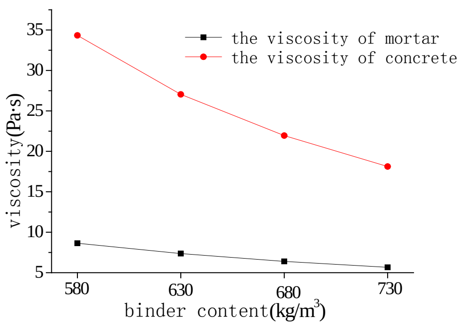


Figure.2. Effect of binder content on viscosity of mortar and concrete

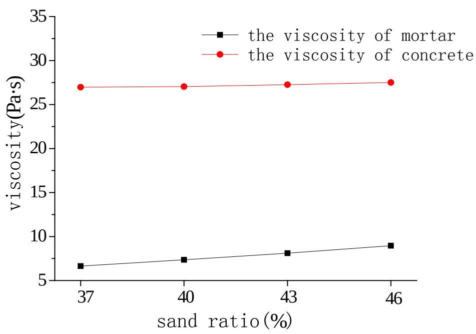


Figure.3. Effect of sand ratio on viscosity of mortar and concrete

3.2.1 Effect of binder content on viscosity of mortar and concrete.Based on the tested paste viscosity value (η_{C1}) of specimen 1, 2, 3 and 4, effects of different binder content on calculated mortar viscosity (η_{C2}) and concrete viscosity (η_{C3}) are given in figure.2 respectively. figure.2 shows that when binder content increased, both (η_{C2}) and (η_{C3}) decreased remarkably. The (η_{C2}) decreased from 8.64Pas to 5.67Pas, while the (η_{C3}) decreased from 34.33Pas to 18.12Pas. The decrease of concrete viscosity was far more than that of mortar viscosity. There are two reasons to explain this trend : the first one is that slurry quantity of mortar and fresh concrete increase with the increase of binder content, When both superplasticizer dosage and water-binder ratio are constant, the real superplasticizer dosage and real water consumption in unit volume fresh concrete will increase. The former increase sufficiently releases the water wrapped in flocculating constituent, while the latter increase makes the particles water film thicker, which result in declined viscosity. The other reason is that aggregate (sand and stone) volume in unit volume of fresh concrete will gradually decrease with the binder content increase, which decreased water absorption quantity and increased slurry quantity on the aggregate particles surfaces.

3.2.2 Effect of sand ratio on viscosity of mortar and concrete.Based on the tested paste viscosity values (η_{C1})of specimen 5, 2, 7 and 8, effect of sand ratio on calculated mortar viscosity (η_{C2}) and concrete viscosity (η_{C3}) are given in figure.3 respectively. figure.3 shows that (η_{C2}) and (η_{C3}) slightly increased with increase of sand ratio: (η_{C2}) increased from 6.64Pas to 8.96Pas, while (η_{C3}) increased from 26.97Pas to 27.5Pas. The increased (η_{C2}) is due to the fact that when the sand ratio increases, the sand quantity in unit volume concrete also increases while the binder ratio and dosage remain unchanged. Therefore, the slurry film covering on the aggregate particles surface was thinner, resulting in the mortar viscosity increase . For the increase of (η_{C3}), it is due to the fact that the sand water absorption is higher than that of coarse aggregate (basalt). With the increase of sand ratio, the fine sand quantity increases and the real water quantity in unit volume decreases, resulting in the increased viscosity. Meanwhile, compared with coarse aggregate, fine aggregate has a relatively higher Blaine specific surface, and all the aggregate surface are required to be covered or wrapped by slurry. Hence when the sand ratio increases, the required slurry quantity will increase. With the same slurry quantity in unit volume, the slurry film covering on the aggregate surface becomes thinner, resulting in the increased viscosity.

3.2.3 Effect of water-binder ratio on viscosity of mortar and concrete.Based on the tested paste viscosity value (η_{C1}) of specimen 8, 9, 2, and 10, effect of water-binder ratio on calculated mortar viscosity (η_{C2}) and concrete viscosity (η_{C3}) is given in figure.4 respectively. figure.4 shows that when the water-binder ratio increased, both (η_{C2}) and (η_{C3}) declined remarkably. The (η_{C2}) decreased from 17.17Pas to 6.04Pas, while the (η_{C3}) decreased from 64.63Pas to 21.92Pas. The variation trend is due to the fact that the solid particles themselves are not characterized by the viscosity, and the (η_{C2}) and (η_{C3}) depend on the particle surface's water film thickness, which then depends on the initial water consumption and the water quantity wrapped in the flocculating constituent. With the constant superplasticizer dosage , the water quantity wrapped in the flocculating constituent will maintain the same. Therefore, with increase of initial water consumption, the water volume in unit volume increases. Consequently, the water film on the particle surface in unit volume mortar/concrete becomes thicker, resulting in the decrease of (η_{C2}) and (η_{C3}).

3.2.4 Effect of class and dosage of FA on viscosity of mortar and concrete.Based on the tested paste viscosity value (η_{C1}) of specimen 11, 13, 2, and 15 mixed with FA (I) and that of specimen 11, 12 and 14 mixed with FA (II), effects of different FA class and dosage on calculated mortar viscosity (η_{C2}) and concrete viscosity (η_{C3}) are given in figure.5 respectively. figure.5 shows that when the FA dosage increased both (η_{C2}) and (η_{C3}) declined remarkably. With the same FA class, when FA dosage increased, both mortar viscosity and concrete viscosity decreased further. With the different FA class and the same FA dosage, the viscosity of mortar and concrete mixed with FA (I) decreased more than that mixed with FA (II). This could be attributed to the "ball-bearing" and water-reducing effects of FA Meanwhile, the FA density is less than that of cement, which resulted in an increased volume slurry and slurry film thickness on the particles surface when the cement is replaced by FA with equivalent weight of cement. The smaller density of FA (I) contribute to the better viscosity reducing effect. Meanwhile, the particle size of FA (I) is smaller than that of FA (II). Hence FA (I) can better fill in the space among the cement particles, which obtains denser packing. Due to the same reason, FA (I) can also replace more water from the space among relatively bigger particles. Therefore, the water film on the surface of slurry becomes thicker, resulting in the viscosity decrease.

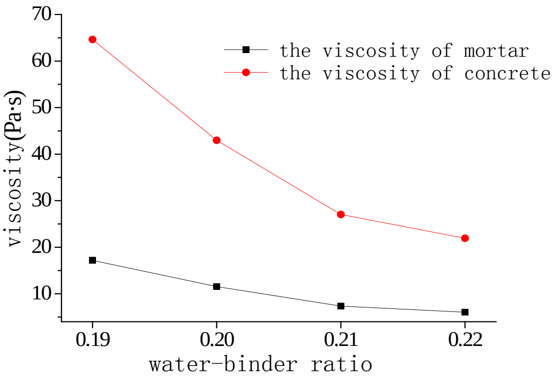


Figure.4. Effect of water-binder ratio on viscosity of mortar and concrete

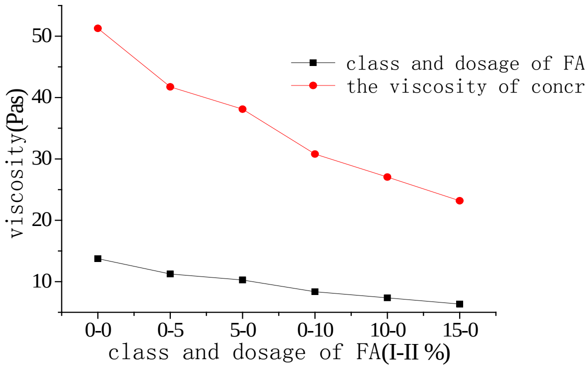


Figure.5. Effect of class and dosage of FA on viscosity of mortar and concrete

3.2.5 Effect of microbead dosage on viscosity of mortar and concrete.Based on the tested paste

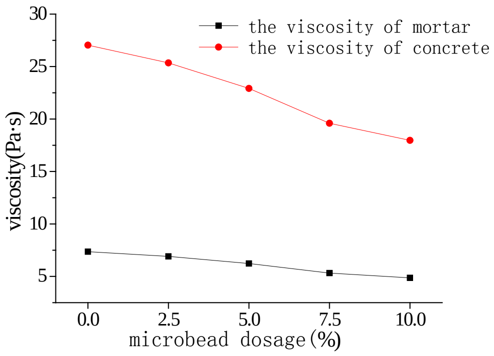


Figure.6. Effect of Microbead dosage on viscosity of mortar and concrete

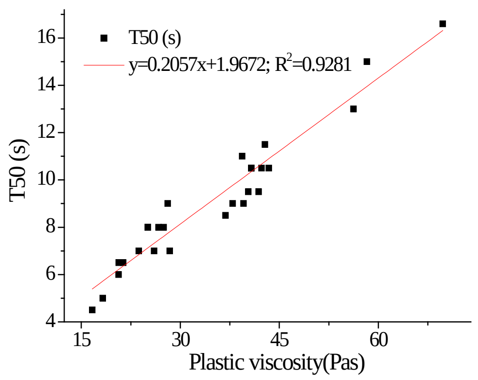
viscosity value (η_{C1})of specimen 2, 16, 17, 18 and 19, effects of different microbead dosage on calculated mortar viscosity (η_{C2})and concrete viscosity(η_{C3})are given in figure.6 respectively. figure.6 shows that with the increase of microbeadreplacing percentage, both (η_{C2})and (η_{C3}) declined remarkably. The(η_{C2})decreased from 7.36Pas to 4.86Pas, while the (η_{C3}) decreased from 27.04Pas to 17.97Pas. Furthermore, the viscosity reducing effect of microbead is better than that of FA. One reason is due to their different particle morphology. Although most FA particles are spheres, all microbead particles are perfect spheres, with smooth surface. Therefore, the “ball-bearing” effect of microbead, filling in the space of cement particles, is better than that of FA. Another reason is due to the smaller particle size of continuously gradated microbead. Microbead can achieve better dense packing, making the space among particles lesser and replacing much more water from the space among relatively bigger particles. Hence, the water film on the surface of particles becomes thicker, resulting in the viscosity decrease.

3.3 The relationship between viscosity and workability of UHSC with low viscosity

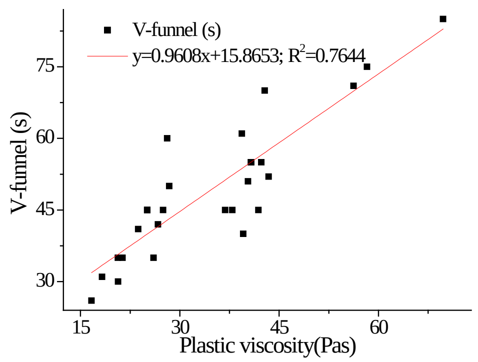
Base on the discussion of rheological properties of fresh concrete, it can be seen that if the viscosity value of fresh concrete is controlled in a proper range, the plastic viscosity (η) is related to the flowing speed of fresh concrete under the same external force. And the T50, V-funnel and inverted slump time, characterizing the workability of fresh concrete, are also characteristic parameters of its flowing speed. Therefore, it may be reasonable to assume that there must be a kind of inherent relationship between viscosity and the characteristic parameters. Based on the experimental results in tables 3 and 4, the relationships between the fresh concrete viscosity and the three parameters, T50, V-funnel and inverted slump time were shown in figure.7, respectively.

figure.7 showed good linear relationships between fresh concrete viscosity and the three parameters With the increase of fresh concrete viscosity, the fresh concrete's T50, V-funnel and inverted slump time all increased. The obtained relationship between T50 and plastic viscosity is shown as y=0.1957x+2.012（correlation coefficient R^2 value equals to 0.9334); the obtained relationship between V-funnel and plastic viscosity is shown as y=1.1222x+12.0631（R^2 value equals to 0.9298）; and the obtained relationship between inverted slump time and plastic viscosity is shown as y=0.2012x+2.4805（R^2 value equals to 0.9078）. These relationships show that viscosity of fresh concrete is well consistent with T50, V-funnel and inverted slump time respectively. Hence, the T50, V-funnel and inverted slump time can be used to intuitively reflect the fresh concrete viscosity.

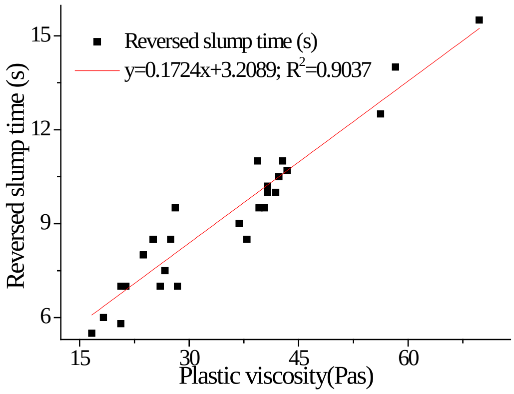
However, in practical engineering, when fresh concrete viscosity is too low and segregation occurs, T50 becomes very short, but the V-funnel and inverted slump time become longer, because the sinking coarse aggregate blocks up the outlet of V-funnel or inverted slump. And when fresh concrete viscosity is relatively high, T50 becomes longer, with increase of both V-funnel and inverted slump time. This shows that it is necessary to simultaneously use the three characteristic parameters, namely T50, V-funnel and inverted slump time, to characterize the workability of UHSC with low viscosity.



(a) The relationship between T50 and plastic viscosity



(b) The relationship between V-funnel and plastic viscosity



(c) The relationship between inverted slump time and plastic viscosity

figure.7. The relationship between: (a) T50 and plastic viscosity; (b) V-funnel and plastic viscosity; and (c) inverted slump time and plastic viscosity

4. Conclusions

Based on the results of this study, the following conclusions can be drawn:

(1) When binder content, microbead dosage, fly ash dosage or the water-binder ratio was increased or sand ratio was decreased, the fresh concrete viscosity would reduce correspondingly. However their effects were not the same.

(2) It was feasible to test the plastic viscosity of slurry with mineral fillers by BROOKFIELD R/S Plus Rotating Rheometer first, and then to calculate the plastic viscosity of mortar and concrete according to the micromechanics theory proposed by A.Ghanbari and B.L.Karihaloo. And the calculated results had high consistence with the objective reality.

（3）With viscosity increase of fresh UHSC, three workability characteristics of fresh UHSC, namely the T50, V-funnel and inverted slump time all increased. Good linear relationship between the viscosity and each characteristic was observed respectively. The relationships between T50 and fresh concrete viscosity, V-funnel and fresh concrete viscosity, and inverted slump time and fresh concrete viscosity can be represented as follows: $y=0.1957x+2.012(R^2=0.9334)$, $y=1.1222x+12.0631(R^2=0.9298)$ and $y=0.2012x+2.4805$ ($R^2= 0.9078$). These relationships show that fresh concrete viscosity is well consistent with T50, V-funnel and inverted slump time respectively. Therefore, by simultaneously using these three characteristic parameters, the fresh concrete viscosity can be intuitively reflected.

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