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Research paper

Rheological properties of paste for self-compacting concrete with admixtures

He Liu[1], Guangchao Duan[2], Jingyi Zhang[3], Yanhai Yang[4]

Abstract: The paste content in the self-compacting concrete is about 40% in unit volume. The rheological properties of paste directly determine the properties of self-compacting concrete. In this paper, the effect of silica fume (2, 3, 4, and 5%), limestone powder (5, 10 and 15%), and the viscosity modified admixture (2, 3, 4, 5, 6, and 7%) on the rheological properties were investigated. The effect of admixtures on shear thickening response was discussed based on the modified Bingham model. The results indicate that yield stress and plastic viscosity increased with increased silica fume and viscosity modified admixture replacement. The paste's yield stress increases and then decreases with limestone powder replacement. The critical shear stress and minimum plastic viscosity are improved by silica fume and viscosity modifying admixture. The critical shear stress first increases and decreases as the limestone powder replacement increases. A reduction in the shear thickening response of paste was observed with silica fume and viscosity modified admixture replacement increase.

Keywords: self-compacting concrete, rheology properties, shear thickening, critical shear stress, minimum viscosity

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[1] PhD., Eng., Shenyang Jianzhu University, School of Transportation and Geometics Engineering, No. 25 Hunnan Zhong Road, Hunnan District, 110168 Shenyang, China, e-mail: heliu@sjzu.edu.cn, ORCID: 0000-0002-3867-0726

[2] M.Eng., Shenyang Jianzhu University, School of Transportation and Geometics Engineering, No. 25 Hunnan Zhong Road, Hunnan District, 110168 Shenyang, China, e-mail: d1045339052@163.com, ORCID: 0000-0002-6195-4065

[3] M. Eng., Shenyang Urban Construction University, School of Civil engineering, No. 380 Bai Ta Road, Hunnan District, 110167 Shenyang, China, e-mail: dq_zjy@syucu.edu.cn, ORCID: 0000-0003-4641-5191

[4] Prof. PhD., Eng., Shenyang Jianzhu University, School of Transportation and Geometics Engineering, No. 25 Hunnan Zhong Road, Hunnan District, 110168 Shenyang, China, e-mail: yangyanhai168@126.com, ORCID: 0000-0002-1599-7873

1. Introduction

Self-compacting concrete (SCC) has gotten wide attention for its high fluidity. It has been discovered that it can flow around steel bars and fill gaps of formwork under its self-weight [1–5]. SCC can save workforce and production costs, hence significantly improving construction efficiency. It has been applied to the CRTS III type slab ballastless track structure as the filling layer and the construction of a rock-filled concrete gravity dam [6, 7].

As a vital factor, the rheological properties decide the performance of SCC. Proper rheological properties can ensure flowability and improve the stability of the paste. In most conditions, shear thickening and shear thinning of fresh concrete will occur in concrete production, transportation, and construction. Shear thickening behavior is that the plastic viscosity has an increase trend with shear rate increase. Shear thickening results in a decrease in fluidity and difficulty in the pumping of concrete, even leading to blockage of the pipeline, which adversely affects concrete's pouring quality. On the other hand, shear-thinning is mainly presented as the plastic viscosity has a decreasing trend with an increased shear rate. The unsuitable shear-thinning will cause the segregation and bleeding of concrete, which finally induces quality problems [8, 9]. Considering the importance of construction quality, cement paste's shear thickening and thinning is a critical issue.

SCC usually contains a higher volume of fly ash (FA), silica fume (SF), and limestone powder (LP) as mineral admixtures, achieving self-compacting ability by the higher paste volume. These mineral admixtures affected the rheological properties of cement paste by altering the plastic viscosity and yield stress. FA is one of the primary waste materials in the thermal power generation process, the "ball effects" of FA are believed to affect the fluidity of cement paste positively. FA beads showed a round shape and smooth surface, which have an excellent effect of lubrication on cement paste, and therefore it will improve the fluidity of cement paste [10]. Jiao et al. [10] found that when FA was introduced into cement pastes, the shear thickening response of paste was reduced due to the decrease of flocculation structure. Güneyisi et al. [11] also found that FA could decrease the shear thickening of cement paste. SF and viscosity modified admixtures (VMA) are used to improve the stability and viscosity of cement paste [12]. Güneyisi et al. [11] found that the shear thickening response increased with nano-silica content. Zhang et al. [13] found that the addition of nano-silica decreased the apparent viscosity value of cement paste. VMA could absorb free water and enhance the stability of cement paste. Researchers also indicated that VAM could enhance mechanical properties and dense the interface transition zone. Additionally, SCC with VMA could enhance the viscosity and stability of paste [14]. With chemically inert, LP was used as the micro-aggregate to cement paste to reach adequate viscosity. Ma et al. [15] found that LP could improve the rheological properties of cement paste, for it could efficiently increase the yield stress and plastic viscosity in the fresh state. Vance et al. [16] found that the addition of 15 µm LP reduced the yield stress and plastic viscosity. Xiang et al. [17] believed that LP increased the yield stress of paste because it could provide a physical filling effect, resulting in the solid particles accumulating together compactly.

SF, LP, and VMA are used to improve the stability of SCC. However, there was insufficient research on SF, LP, and VMA on the minimum viscosity, critical shear rate, and shear thickening behavior of SCC. In this paper, the rheological properties of SCC with SF, LP, and VMA were investigated by measuring shear stress and apparent viscosity. The rheologic curves were applying the modified Bingham models. Based on the analysis of minimum viscosity, critical shear rate and critical shear stress expound the factors affecting the shear thickening of SCC.

2. Methods

2.1. Materials and specimen preparation

In this study, ordinary Portland cement (P.O 42.5) was used to produce the cement paste and accords with the Chinese Standards GB175-2007 [18], fly ash (FA), S95 ground granulated blast furnace slag (GGBS), silica fume (SF), and limestone powder (LP) were used to produce the paste mixture. The physical properties and chemical compositions of C, FA, GGBS, SF, and LP are shown in Table 1. The viscosity modified admixture (VMA) comprises cellulose and ultrafine inorganic powder. The only chemical admixture used was a polycarboxylic ether superplasticizer (SP) with a 30% water-reducing rate to achieve the desired workability in all concrete mixtures.

Table 1. Physical properties and chemical composition of C, FA, GGBS, SF, LP, (by wt%)

No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	eq-Na_2O	Los on ignition	Specific surface area (m^2/kg)	Apparent density (g/cm^3)
C	24.6	3.30	4.00	59.7	3.8	2.5	0.60	2.50	350	3.12
FA	52.3	26.3	9.70	3.70	1.20	1.20	1.80	4.70	450	2.45
GGBS	26.1	13.8	14.1	33.6	8.10	–	0.45	2.10	420	2.87
SF	90.6	0.60	1.50	0.30	0.60	1.30	–	1.80	17800	2.1
LP	0.07	0.04	0.02	58.3	–	0.03	–	43.96	573	2.63

All mix proportions are summarized in Table 2, and the total amount of binder is regarded as 100. The water/binder ratio was kept constant at 0.34. Based on previous test results, the flowability of paste will be of great influence when the replacement ratio of SF and VMA is over 5% and 7%, and when the replacement ratio of LP is over 15%, the strength of concrete mixes will be significantly influenced. Hence, the authors design fourteen different mixed proportions. They were considered for the relative contents of SF (2, 3, 4, and 5%), LP (5, 10, and 15%), and VMA (2, 3, 4, 5, 6, and 7%) by cementitious material weight and the paste without SF, LP, or VMA as a control group. The ratio of FA and GBBS were fixed as 15% and 20% of the total mass of cementitious material, respectively. All supplementary cementitious materials were used as a partial replacement for cement. SP was 1.2% of the total binder by weight.

Table 2. Mixing proportion of pure paste

No.	C	FA	GGBS	SF	LP	VMA	W	SP/%
P-0	65	15	20	0	0	0	34	1.2
P-1	63	15	20	2	0	0	34	1.2
P-2	62	15	20	3	0	0	34	1.2
P-3	61	15	20	4	0	0	34	1.2
P-4	60	15	20	5	0	0	34	1.2
P-5	60	15	20	0	5	0	34	1.2
P-6	55	15	20	0	10	0	34	1.2
P-7	50	15	20	0	15	0	34	1.2
P-8	63	15	20	0	0	2	34	1.2
P-9	62	15	20	0	0	3	34	1.2
P-10	61	15	20	0	0	4	34	1.2
P-11	60	15	20	0	0	5	34	1.2
P-12	59	15	20	0	0	6	34	1.2
P-13	58	15	20	0	0	7	34	1.2

2.2. Test set up and testing procedure

2.2.1. Rheological test

After fresh pastes were prepared according to Table 2, the viscosity of pastes was measured using a rheometer, and measurements were computer-controlled. This paper measured the rheology of several kinds of paste by Viskomat-NT rheometer, shown in Fig. 1. The rotator type was ST22-4V-40, the inner radius (R_1) was 41 mm, the rotator

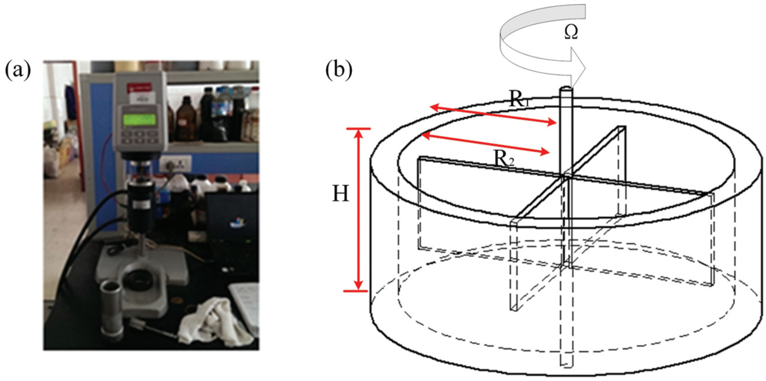

Fig. 1. The Viskomat-NT rheometer used in this study: a) rheometer; b) detailed schematic representation

radius (R_2) was 39 mm, and the height (H) was 34 mm. In order to ensure the correctness and the reliability of the test result, the rheology was tested at 5 min after mixing, with a water-bath temperature of $25 \pm 1^\circ$C. Took three batches of SCC paste repeated experiments and the average value of three batches was used as the final test result. The shearing rate gradually increased from 1 S^{-1} to 200 S^{-1}.

2.2.2. Test data processing

The method of H–B (Herschel–Bulkley) model, as shown in Eq. (2.1), is quite commonly used to describe the rheological properties of fresh SCC [10, 13, 19].

$$\tau = \tau_0 + K\dot{\gamma}^n, \qquad \tau_0 \le \tau \tag{2.1}$$

where τ is shear stress (Pa); τ_0 is yield stress (Pa); $\dot{\gamma}$ shear rate (1/s); n is flow index; K is consistency factor in (Pa·s).

The rheology shows that the paste behaved as Bingham fluids when $n = 1$, the shear thickening occurs when n is over 1, and the shear-thinning occurs when n is under 1. The value of n indicates the degree of shear thickening response [20, 21]. The modified Bingham model can be used to describe the rheological properties of fresh SCC with different admixtures. This model was the extension of the Bingham model. As shown in Eq. (2.2).

$$\tau = \tau_0 + \eta\gamma + c\gamma^2 \tag{2.2}$$

where τ is shear stress (Pa); τ_0 is yield stress (Pa); γ is the shear rate (1/s); η is plastic viscosity (Pa·s); c is the second-order parameter (Pa·s^2).

The shear thickening occurs when c/η is over 0, and the shear thinning occurs when c/η is under 0 [22]. The modified Bingham mode and the H–B model as the representation of the shear thickening have been applied widely. The modified Bingham mode and the H–B model have consistency in characterizing the rheologic behavior of cement paste. Compared with other models, the description of c/μ in the modified Bingham model is s more suitable for evaluating the impact of admixture on the shear thickening response of paste. This study obtained the yield stress, plastic viscosity, and shear thickening response of paste through the rheological fitting curve Eq. (2.2).

3. Results and discussion

3.1. Effect of mineral admixtures on rheological curves

The apparent viscosity-shear rate curves of fresh paste with different cementitious compositions are shown in Fig. 2. As illustrated in Fig. 2a, utilization of SF from 2% to 5% increased the apparent viscosity of paste under the same shear rate for each mixture. As shown in Fig. 2b, under the same shear rate, the apparent viscosity gradually decreases with LP replacement increase from 0% to 15%. As shown in Fig. 2c, with VMA content increase, the apparent viscosity of pastes was increased in the same share ratio and was consistent with the variation of SF contents. The result also indicated that the apparent viscosity of all mixtures decreased sharply at first and then increased smoothly with shear rate increase, which suggests that the shear-thinning occurred first. Then shear-thickening occurred, and the trend of rheological curves followed results reported by research [15]. The turning point lies in minimum viscosity (η_{min}) and its corresponding shear rate can be defined as the critical shear rate (γ_{crit}). Fig. 2 indicated that compared to the control group, the introduction of SF, LP, and VMA increases the γ_{crit}.

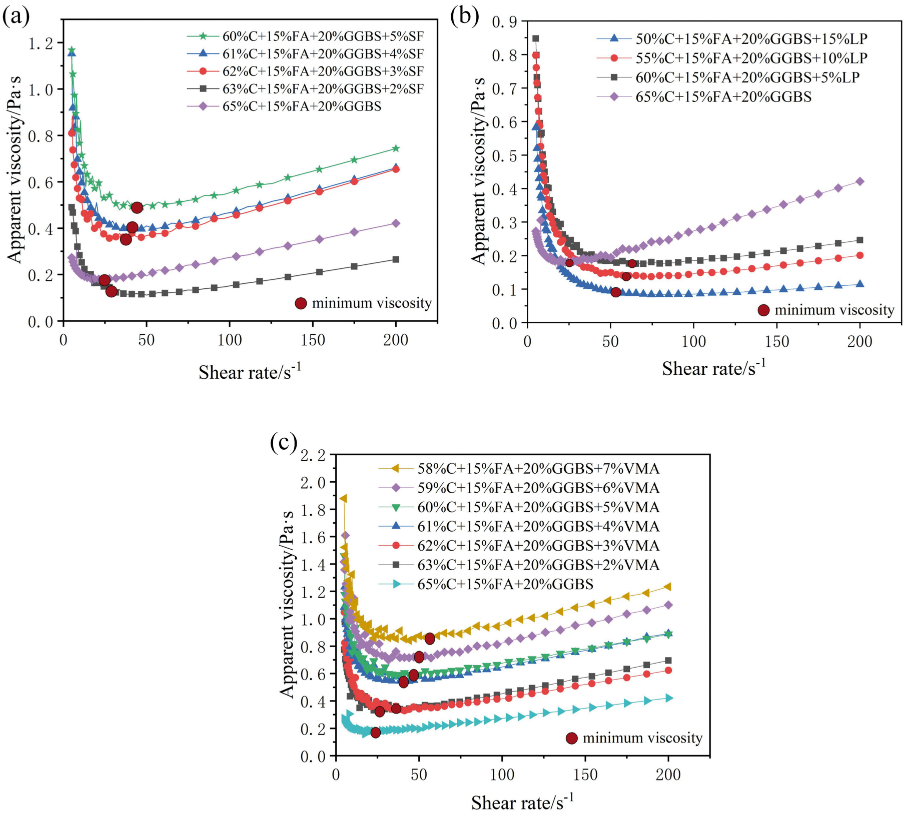

Fig. 2. Relationship between shear rate and apparent viscosity in different cementing systems: a) SF. b) LP. c) VMA

The shear stress-shear rate curves of fresh paste with different cementitious compositions and fitted by the modified Bingham model for all mixes are shown in Fig. 3. Previous studies have proved that the ratio of the second-order term to the linear term in the modified Bingham model can correctly describe non-linear behavior [10, 16, 21]. And the critical shear stress (τ_{crit}) in shear stress-shear rate curves has been pointed out in Fig. 3. The results showed that admixtures have a significant influence on τ_{crit}. η_{min}, γ_{crit} and these parameters can describe the rheological properties exactly which will be further discussed in the following paragraph.

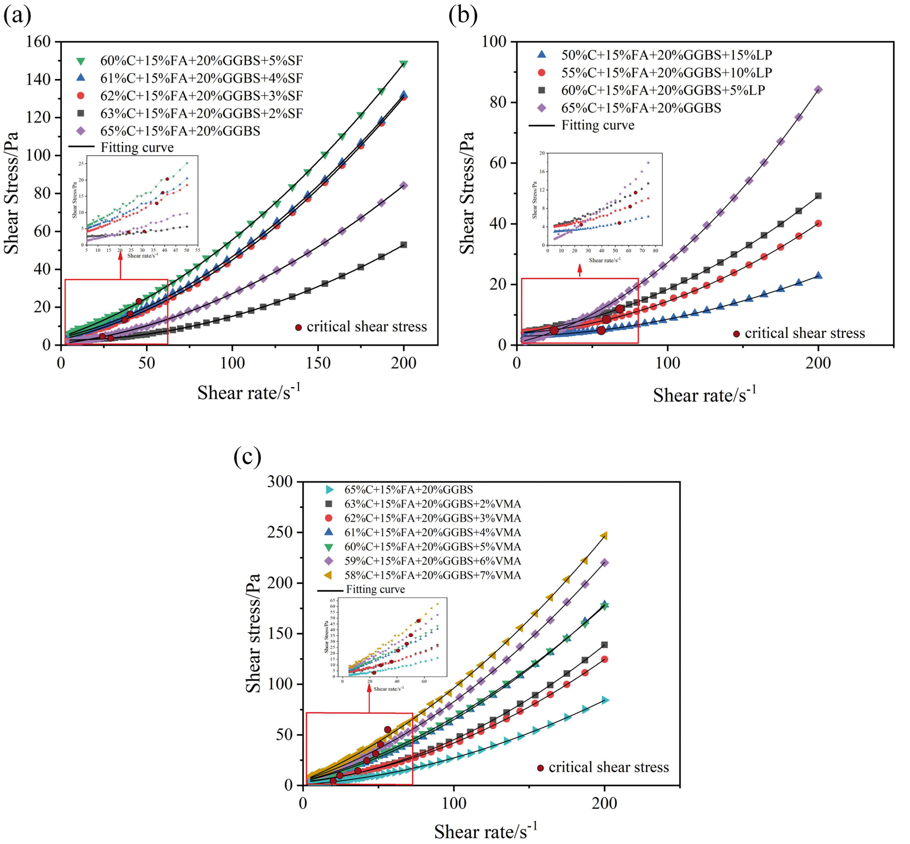

Fig. 3. Relationship between shear rate and shear stress in different cementing systems: a) SF. b) LP. c) VMA

3.2. Effects of mineral admixtures on yield stress and plastic viscosity

The rheological test results of fresh pastes with different cementitious compositions, including yield stress and plastic viscosity are shown in Fig. 4. As illustrated in Fig. 4a, compared to the control group, yield stress and plastic viscosity increase by 455% and 171.4% for 5% SF by weight replacement. This is due to the specific surface area of SF being almost 50 times larger than that of cement (see Table 1). Higher specific surface area can reduce free water content. The distance of particles will be close with SF content increase, leading to the friction forces of particles being increased [23]. From Fig. 4b, yield stress increases 273.2% and plastic viscosity descends 87.5% for 15% LP by weight replacement. The irregular surface of LP increases the friction between particles, it related to yield stress increase. Further increase of LP content results in the yield stress decreasing. As shown in Table 1, the specific surface area of LP was larger than that of GGBS and FA, accordingly, LP has a smaller particle size. When LP is used from 5% to 15%, the void of the cementitious system is filled by LP particles, free water of the cementitious system will be released [17]. Therefore, the yield stress and plastic viscosity are decreasing.

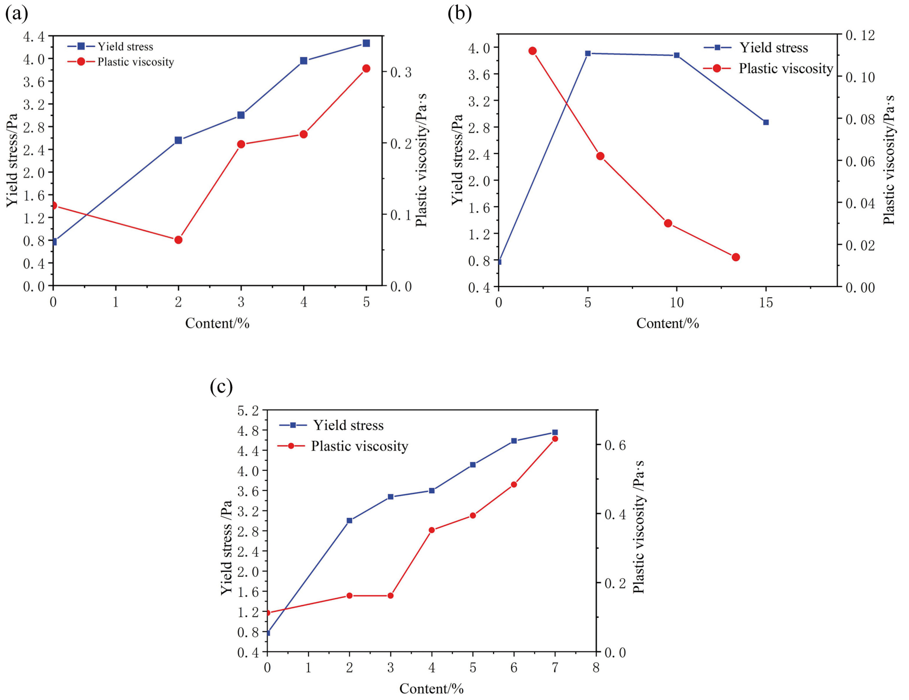

Fig. 4. Effect of different cementitious systems on rheological properties of paste: a) SF. b) LP. c) VMA

From Fig. 4c, yield stress increases 518.2% and plastic viscosity increases 450% for 7% VMA by weight replacement. The increase of the yield stress and plastic viscosity is similar to SF, VMA consists of cellulose and ultrafine inorganic powder, the inorganic powder with large specific surface area, and the cellulose can effectively improve the viscosity.

3.3. Effects of mineral admixtures on shear thickening response of paste

Fig. 5 shows the effect of shear thickening performance with different cementing systems. All the pastes (containing supplementary cementitious materials) are non-newtonian fluids with shear thickening behavior. The modified Bingham model obtained the relationship between supplemental cementitious materials content and "c/η". The "c/η" can be defined as the ratio of the second-order term to the first-order term given in Eq. (2.2).

Cement pastes with a larger “c/η” value make it easier to appear shear thickening. As shown in Fig. 5, there was a big difference in “c/η” between different admixtures. The “c/η” value descends 95% and 64.8% for 5% SF and 7% VMA by weight replacement, respectively, which means SF and VMA can weaken the shear thickening response. This may be due to SF and VMA resulting in more spheroidal particle insert cement particle, then the “c/η” value decrease. Meanwhile, the “c/η” value increases 122.1% for 15% LP by weight replacement. Fig. 5 also indicated that the cement pastes with LP reached a maximum “c/η” value. Improving the “c/η” value signifies the enhancement of shear thickening.

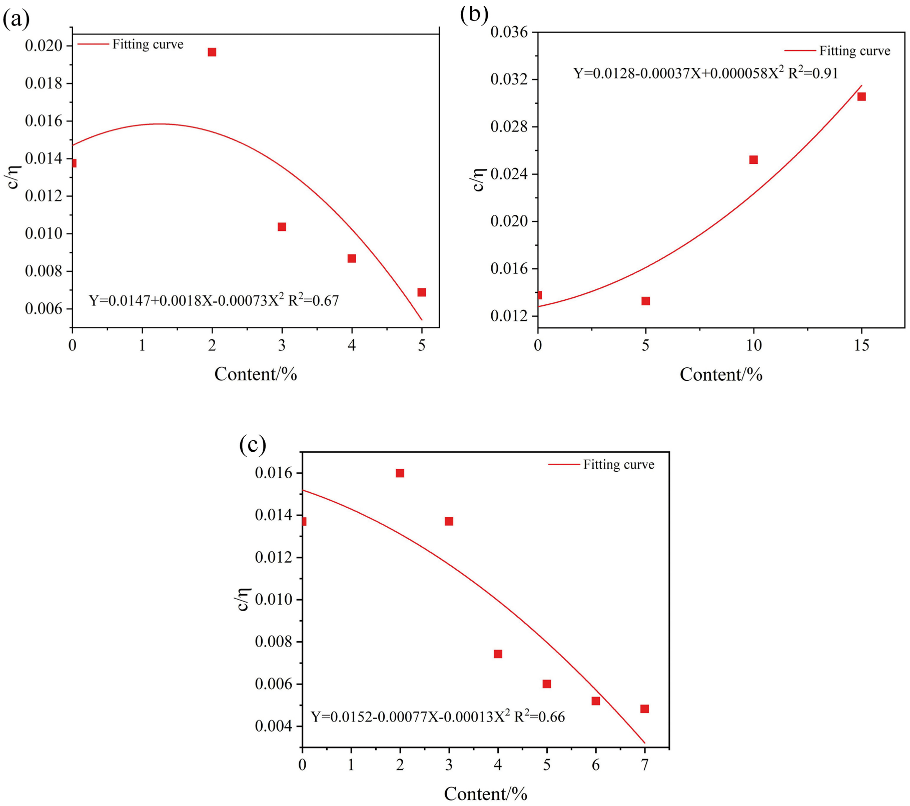

Fig. 5. Influence of different cementing systems on shear thickening performance:
a) SF; b) LP; c) VMA

3.4. Effects of mineral admixtures on η_{min}, γ_{crit} and τ_{crit}

As shown in Fig. 2, in the case of shear rate over the turning point γ_{crit}, apparent viscosity began to rise slowly, which means the shear thickening began to appear. A larger γ_{crit} implicates a more difficult shear thickening of cement paste. As can be seen in Fig. 6, γ_{crit}

increases 78.8% and 135.3% for 5% SF and 7% VMA by weight replacement, respectively. The increase of SF and VMA can reduce the occurrence of shear thickening under a high shear rate. Fig. 6b shows the γ_{crit} first increases and then decreases with the increase of LP content, which means that the shear thickening first decreases and then increases with the increase of LP content. This result may be due to the high specific surface area (573 m^2/kg) compared with cement (350 m^2/kg) and is basically consistent with previous studies [24]. High specific surface area of LP improves the particle arrangement in cement paste, which ensures the lubricant effect of free water.

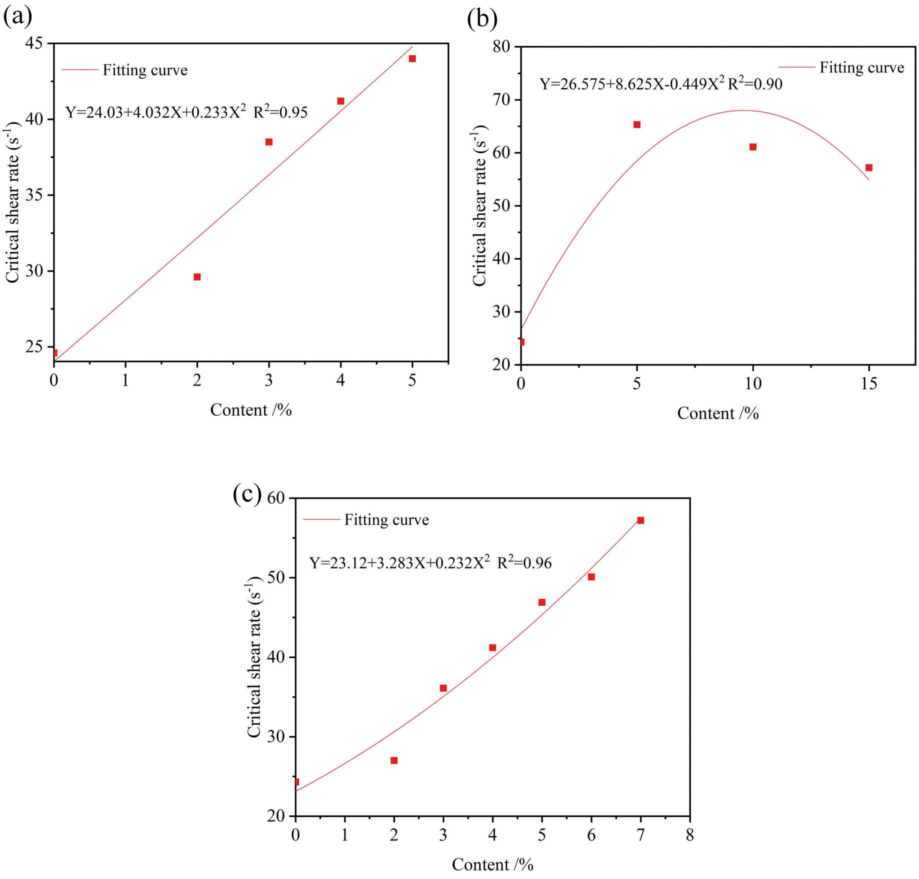

Fig. 6. Influence of different cementing systems on γ_{crit}: a) SF. b) LP. c) VMA

Critical shear stress is the variation trend mutational site of corresponding shear stress. This paper makes further discussion on the influence of critical shear stress of SCC paste under different dosages of SF, LP, and VMA under 0~200 S^{-1} share rate. The results are shown in Fig. 7. As shown in Fig. 7, the critical shear stress of paste increases 394.2% and 368.6% for 5% SF and 7% VMA by weight replacement, respectively. This means the shear thickening was reduced by SF, VMA. Hence, SF and VMA can ensure the cement paste has good fluidity under high shearing stress. When LP replaces the cement, the critical shear stress first increases to 10.76 Pa and then descends initially with LP content from 5% to 15%.

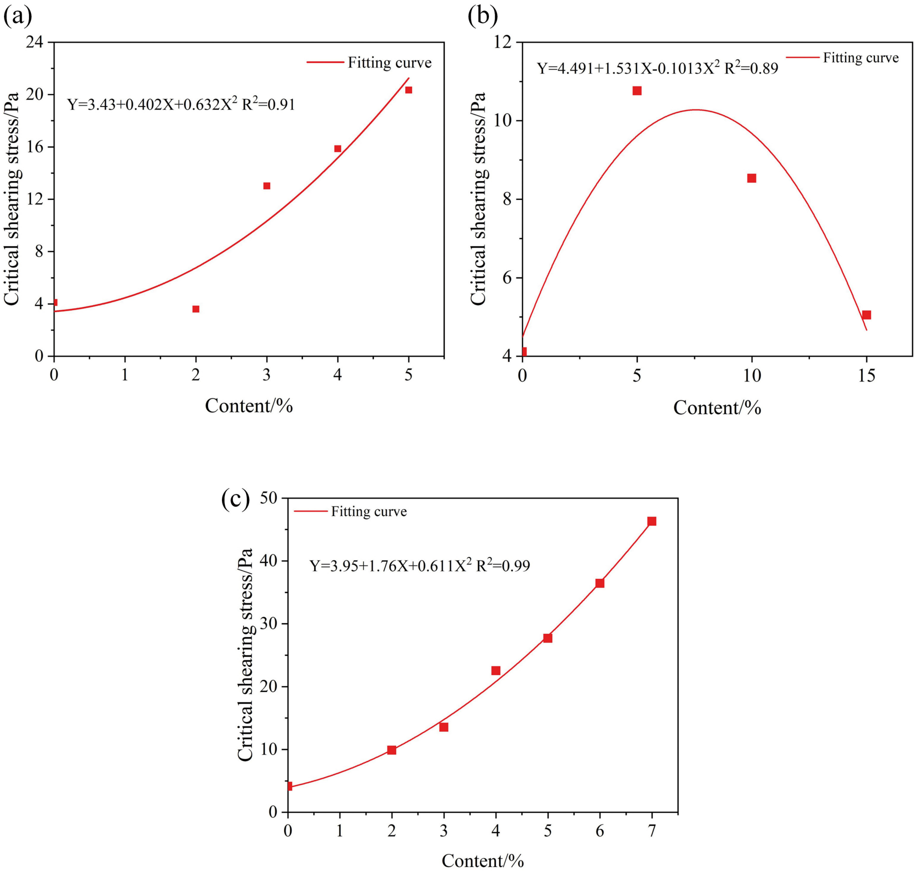

Fig. 7. Influence of different cementing systems on τ_{crit}: a) SF; b) LP; c) VMA

Minimum viscosity refers to the minimum data points in the full shear process. For shear-thickening paste, minimum viscosity refers to the turning point of apparent viscosity from low to high. The relationship between minimum viscosity and supplementary cementitious materials is shown in Fig. 8. As can be seen in Fig. 8, The minimum viscosity of paste increases 165.6% and 153.7% for 5% SF and 7% VMA by weight replacement, respectively. The minimum viscosity descends 54.6% for 15% LP by weight replacement. The lowest minimum viscosity can be obtained when the LP content is about 15%. These results indicated that the addition of SF and VMA can ensure the viscosity and stability of cement.

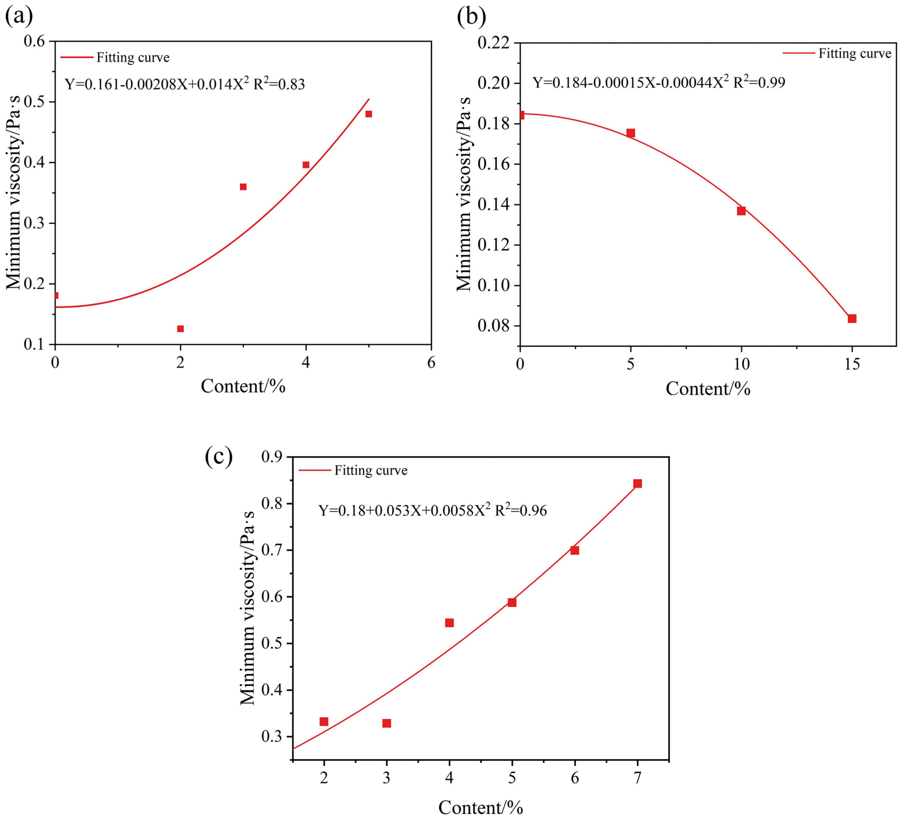

Fig. 8. Effect of different cementing systems on $\eta_{\min}$: a) SF; b) LP; c) VMA

3.5. Mechanism analyze

The shear-thinning or shear-thickening phenomenon can be explained by the hydro-clusters theory [10, 20, 25, 26]. As shown in Fig. 9, with shear rate increase, the particle transforms "disorder" into "order" and apparent viscosity decreases, rheology behavior is presented as shear-thinning. The intermolecular force is balanced by shear force when the shear rate increases, which results in the formation of hydroclusters, then apparent viscosity increases. Thus, the paste began to shear-thickening.

The shear-thickening performance of cement paste has several factors, mainly including particle shape, particle size, particle density, particle volume fraction, and the interaction of particles [27]. In this paper, LP with an irregular shape, which can promote hydroclusters formation. Therefore, it was easier to show shear-thickening on cement paste with LP [27]. The cement systems manufactured with SF content and VMA show a low shear-thickening performance attributed to the low interaction force of globular shape [25]. The specific surface area of SF is 17800 m^2/kg (see Table 1) and VMA is composed of cellulose and ultrafine inorganic powder with a higher specific surface area. The higher specific surface

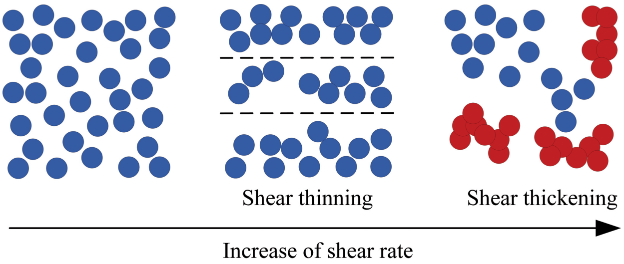

Fig. 9. The formation process of hydroclusters

area leads to a robust interaction force between particles, requiring a more significant shearing force to break the balanced state of the particle [16]. From a macroscopic view, increasing the SF and VMA content increases the critical shear rate and critical shear stress, hence attenuating the paste's shear thickening response.

The test result indicated that the addition of SF and VMA could effectively prevent the evolution of the flocculation structure of cement pastes. The above research shows that yield stress and plastic viscosity gradually increases with SF and VMA replacement. The shear-thickening response was weakened and the stability of paste was high with increasing SF and VMA replacement.

4. Conclusions

Rheological properties of SCC paste were studied incorporating SF, LP, and VMA. Cement was replaced on a mass basis at different levels, and rheological performances of pastes were studied for particular additives. Based on the obtained results, the following main conclusions can be drawn:

1. The incorporation of SF and VMA enhances the plastic viscosity and yield stress of SCC paste. The paste's yield stress increase with LP content from 0% to 5%.and then decreases with LP content from 5% to 15%.
2. All the pastes are non-Newtonian fluids with shear thickening behavior. The introduction of SF and VMA into SCC will significantly increase the paste's critical shear rate, critical shear stress, and minimum viscosity, reducing the shear-thickening performance. The shear-thickening performance of paste was first reduced and then enhanced with LP content from 0%~15%.
3. LP with an irregular shape, which is helpful to the development of shear thickening. The higher specific surface area of SF and VMA leads to a robust interaction force between particles, requiring higher fluid forces to make the particles disordered. On a macroscopic view, increasing the SF and VMA content increases critical shear stress and attenuates the paste's shear thickening response.
4. The polymers in VMA increase the viscosity of the paste and the inorganic ultrafine calcareous in VMA have very high fineness and surface area. Therefore, the introduction of VMA into a fresh paste can optimize the shear thickening performance of

SCC. VMA can improve the stability, viscosity and water retention of concrete, but it should not be used in overabundance, which can reduce the workability of concrete.

In summary, SF, LP and VMA play an important role in the rheological properties regulation of SCC. The rheological properties of SCC can be optimized by using different combinations between SF, LP and VMA. The results of this study on the rheological properties of SCC can serve as the basis for the design and engineering applications of SCC in infrastructure construction.

Acknowledgements

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