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Effect of water–powder ratio on shear thickening response of SCC

Huajian Li *, Fali Huang, Yongjiang Xie, Zhonglai Yi, Zhen Wang

Railway Engineering Research Institute, China Academy of Railway Sciences, No. 2 Daliushu Road, Beijing 100081, China
State Key Laboratory of High Speed Railway Track Technology, No. 2 Daliushu Road, Beijing 100081, China

HIGHLIGHTS

- Both H–B model and the modified Bingham model can describe the shear thickening response of SCC.
- The c/μ of modified Bingham is more suitable for evaluating the shear thickening response of SCC.
- The increase of water–powder ratio can weaken the shear thickening response of SCC.
- Different types of SCC have different sensitivity to water-powder ratio.

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ABSTRACT

The effect of the water–powder ratio on rheological properties of three types of self-compacting concretes (SCCs)—powder type SCC, viscosity modifying admixture (VMA) type SCC and powder–VMA combination type SCC were tested by RHM-3000 ICAR rheometer. The application of the Herschel–Bulkley (H–B) model and the modified Bingham model was discussed, and the effect of the water–powder ratio on shear thickening response of three types of SCCs were compared. The results showed that yield stresses of the three types of SCCs increased with the increase of water–powder ratio for the concrete with the similar slump flow and air content. However, the plastic viscosities differed in the opposite sense. The shear thickening response of SCC was found decreased with the increase of water–powder ratio, and there was a critical water–powder ratio from shear thickening to shear thinning. The shear thickening response could be well described by both H–B model and the modified Bingham model with good correlations, but the parameter of c/μ in the modified Bingham model was found to be more sensitive to the change of shear thickening. The shear thickening response of VMA type SCC was found to be the most sensitive to the change of water–powder ratio, and the least was combination type SCC.

1. Introduction

As a typical representative of concrete with special rheological properties—self-compacting concrete (SCC) has been applied to CRTSIII slab ballastless track in China on a large scale because of its high workability, cost effective and environmental friendliness [1,2]. The SCC mix is characteristized by the high powder content, high superplasticizer content, high sand rate, low water–powder ratio. And the characteristic of high workability determines that its rheological behaviors are different from traditional vibrated concretes, which are much more complicated and unpredictable, especially for the shear thickening and shear thinning during the production and construction process. Shear thickening means the apparent viscosity increases with the increase of the shear rate. Shear thinning means the apparent viscosity decreases with the increase of the shear rate [3,5]. Shear thickening may increase the pumping pressure of fresh concrete, or even lead to the failure of the pump construction. Shear thinning may cause segregation and bleeding after casting, leading to a thick layer floating on the top of the mold. Larrard et al. found that the fresh SCC showed shear thickening after testing the rheological properties of 78 groups of fresh concrete by the BTRHEOM rheometer [6]. However, Geiker et al. [7] believed that the shear thickening of fresh SCC was a misconception in the rheological property testing process because of the thixotropy, workability loss, segregation and other factors. The experiment done by Feys et al. [3] avoided the effect of the thixotropy, workability loss, particle migration and other factors through a series of methods. They studied the shear behaviors of fresh SCC with Tattersall Mk-II rheometer and Contec Viscometer 5 rheometer, and found the similar results, which confirmed the existence of shear thickening.

* Corresponding author at: Railway Engineering Research Institute, China Academy of Railway Sciences, No. 2 Daliushu Road, Beijing 100081, China.
E-mail address: chinasailor@163.com (H. Li).

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Table 1
Physical properties and chemical composition of cement, slag powder and fly ash.

Item	Loss of ignition/%	SO_3/%	Cl^-/%	$Na_2O + K_2O$/%	f-CaO/%	MgO/%	Specific surface/($m^2 \cdot kg^{-1}$)	Density/($g \cdot cm^{-3}$)
Cement	2.97	2.39	0.016	0.63	0.71	3.32	364	3.08
Slag powder	0.18	1.46	0.012	0.44	/	12.72	301	2.86
Fly ash	3.97	0.41	0.006	0.65	0.03	1.65	438	2.21

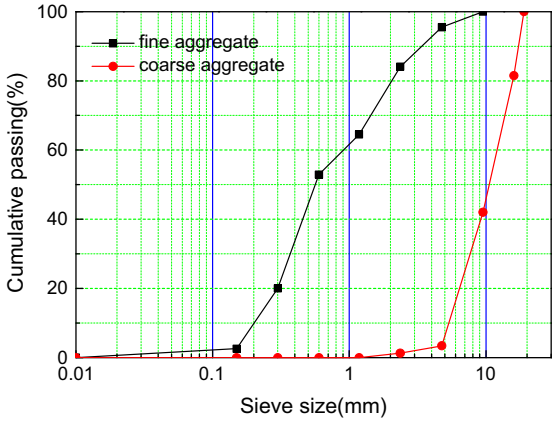

Fig. 1. Gradation curves of coarse and fine aggregate.

The shear thickening response of cement-based materials has become a research hotspot in recent years since it can significantly affect the quality and process of the construction. In the research of evaluation index of shear thickening response of cement-based materials, some researchers used the H–B model as shown in Eq. (1) to describe the rheological properties of fresh SCC.

$$\tau = \tau_0 + K\dot{\gamma}^n, \tau \geqslant \tau_0 \quad (1)$$

where τ is shear stress in Paτ_0 is yield stress in Pa$\dot{\gamma}$ is shear rate in 1/sn is flow indexK is consistency factor in Pa·s^n.

It is obvious from rheology that the shear thickening appears when $n > 1$, while the shear thinning appears when $n < 1$. The value of n indicates the degree of shear thickening response [8]. There are also some researchers using the modified Bingham model as shown in Eq. (2) to describe the rheological properties of fresh SCC.

$$\tau = \tau_0 + \mu\dot{\gamma} + c\dot{\gamma}^2 \quad (2)$$

where τ is shear stress in Paτ_0 is yield stress in Paμ is plastic viscosity in Pa·s$\dot{\gamma}$ is shear rate in 1/sc is second order parameter in Pa·s^2.

Obviously, under this condition the shear thickening appears when $c/\mu > 0$, while the shear thinning appears when $c/\mu < 0$ [9]. In the research of the shear thickening response of cement-based materials, researchers have studied the effect of mineral admixture type and content, admixture type and content, water–powder ratio, solid volume, shear rate and other factors. Feys et al. [4] believed that the shear thickening response of cement-based materials was related to the superplasticizer type and dosage, mineral admixture type, water–powder ratio, and so on. The research done by Yahia et al. [4] indicated that the cement paste with low water-powder ratio showed shear thickening. The degree of shear thickening was decreased with the increase of water–powder ratio and the shear thickening disappeared when the water–powder ratio increased to 0.4. Deng et al. [10] studied the effect of superplasticizer on the shear thickening response of fresh paste. They found that the degree of shear thickening was increased with the increase of superplasticizer content, and the effect of PCE was more obvious than that of the naphthalene sulfonate superplasticizer. Heirman et al. [8] made the similar conclusion for the SCC. Long et al. [11] studied the shear thickening response of cement-fly ash-limestone compound pastes, and they believed the paste exhibited shear thinning when the shear rate was small and shear thickening gradually when the shear rate was increased. Cyr et al. [12] thought the intensity of shear thickening depended on the mineral additives' natures. The shear thickening behavior could be ampli-

Table 2
Mixture proportions ($kg \cdot m^{-3}$) and the performance of SCC.

No.	Mixture proportions										Water-powder ratio	Slump-flow/mm	Air content/%
	Cement	Fly ash	Slag powder	Expansive agent	VMA	Coarse aggregate	Sand	Water	SP	AE			
P1	240	72.5	233.5	54	0	850	745	180	3.05	0.09	0.30	680	6.5
P2	240	72.5	233.5	54	0	850	745	186	2.85	0.09	0.31	685	5.9
P3	240	72.5	233.5	54	0	850	745	192	2.70	0.09	0.32	670	6.8
P4	240	72.5	233.5	54	0	850	745	198	2.55	0.09	0.33	680	7.0
P5	240	72.5	233.5	54	0	850	745	204	2.45	0.09	0.34	680	7.0
P6	240	72.5	233.5	54	0	850	745	210	2.15	0.09	0.35	680	6.0
P7	240	72.5	233.5	54	0	850	745	216	1.95	0.09	0.36	680	5.5
V1	248	45	105	36	15.8	838	872	162	7.30	0.06	0.36	690	7.0
V2	248	45	105	36	15.8	838	872	166.5	7.00	0.06	0.37	690	6.5
V3	248	45	105	36	15.8	838	872	171	6.50	0.06	0.38	670	7.2
V4	248	45	105	36	15.8	838	872	175.5	6.00	0.06	0.39	670	5.7
V5	248	45	105	36	15.8	838	872	180	5.60	0.06	0.40	670	6.1
V6	248	45	105	36	15.8	838	872	184.5	5.25	0.06	0.41	690	5.8
C1	250	63	142	47	/	747	913	171.6	6.60	0.075	0.33	670	6.4
C2	250	63	142	47	/	747	913	186.8	5.50	0.075	0.34	670	6.0
C3	250	63	142	47	/	747	913	182	4.50	0.075	0.35	690	6.2
C4	250	63	142	47	/	747	913	187.2	3.80	0.075	0.36	670	7.1
C5	250	63	142	47	/	747	913	192.4	3.45	0.075	0.37	670	6.0
C6	250	63	142	47	/	747	913	197.6	3.15	0.075	0.38	670	7.2
C7	250	63	142	47	/	747	913	202.8	2.80	0.075	0.39	680	7.0
C8	250	63	142	47	/	747	913	208	2.60	0.075	0.40	680	5.8