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The rheological properties of self-compacting concrete containing superplasticizer and air-entraining agent

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HIGHLIGHTS

- The plastic viscosity of SCC decreases with the increase of SP dosage.
- The yield stress of SCC increases with the increase of AE dosage.
- Increasing air content appropriately reduces the shear thickening behavior of SCC.
- The air content for the transition of SCC shear thickening behavior was about 8.3%.

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ABSTRACT

This work investigates the effect of a polycarboxylate superplasticizer (SP) and a rosin resin type air-entraining agent (AE) on the rheological properties of powder-viscosity modifying admixture (VMA) combination type self-compacting concrete (SCC). The modified Bingham model was applied to describe the shear thickening behavior of this specific SCC. The results showed that both the yield stress and plastic viscosity of SCC deceased significantly while the shear thickening behavior of mixtures was intensified with an increase of SP dosage. The addition of AE led to an increase of yield stress and a decrease of plastic viscosity, whereas a high air content weakened the shear thickening behavior of SCC. The shear thickening behavior was found to be completely disappeared and shear thinning behavior occurred when the air content reached 8.7%, which indicated that increasing the air content was an easy and effective way to reduce the shear thickening behavior of SCC.

1. Introduction

It is a significant technological revolution to solve the durability problem of concrete structure resulting from construction factors by its own intelligent power to achieve the self-filling and self-compacting function [1,2]. As a special type of concrete with remarkable rheological properties, self-compacting concrete (SCC) has been applied to CRTSIII slab ballastless track in China High-speed Railway (CHSR) on a large scale because of its high workability, relatively low cost and environmental friendliness [3]. In order to achieve high flowability of fresh SCC mixtures and a desired durability performance of hardened SCC structures, certain kinds of chemical admixtures are often needed. One of the key chemical admixtures is the superplasticizer (SP), which can substantially change the rheological behavior of SCC through disassembling the flocculated cement particles via electrostatic and/or steric repulsion. An increase of water to powder ratio can improve the fluidity of concrete, but blindly increasing the water to powder ratio will decrease the mechanical properties of concrete. The use of SP can ensure the SCC completely fills the formwork and achieves full compaction under its own weight even at a very low water-powder ratio [4,5]. Another admixture that is often used in SCC is the air-entraining (AE) agents. Typically, the AE provides bubbles with the diameter ranging from 0.1 to 1.0 mm. The bubbles play a critical role in reducing surface tension at the water-air interface, and also protect the SCC against freezing and thawing damage by inducing approximately 6% air content in SCC [6–8]. The entrained air is also known to improve the slump of fresh concrete. It was reported that the slump increases by approximately 10 mm per 1% air [9]. In addition, the entrained air is also able to reduce the segregation tendency of fresh concrete mixtures [10]. However, increasing the air content generally reduces the strength of concrete [11].

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The rheological behavior of self-compacting concrete will be more complicated when a variety of chemical additives are added at the same time, especially the shear thickening and shear thinning behavior. Shear thickening means the apparent viscosity increases with the increase of the shear rate, while the shear thinning means the apparent viscosity decreases with the increase of the shear rate. Larrard et al. [12] found that the fresh SCC showed shear thickening when testing the rheological properties of 78 groups of fresh concrete by the BTRHEOM rheometer. However, Geiker et al. [13] claimed that the shear thickening of fresh SCC was a misconception considering the thixotropy, workability loss, segregation and other factors during the testing process of rheological property. In 2008, Feys et al. [14] confirmed that the shear thickening phenomenon really occurred in SCC. More recently, Yahia [15] found that the high-performance cement suspensions with a water to powder ratio lower than 0.40 exhibited shear thickening behavior while the shear-thinning behavior occurred at a water to powder ratio of 0.40. Li et al. [11] investigated the shear thickening behavior of powder-VMA combination type SCC and found that SCC showed shear thickening at a water to powder ratio below 0.40, while shear thinning occurred when the water to powder ratio was higher than 0.40. Mineral admixtures could also influence the rheology of cementitious materials. Cyr et al. [16] reported that metakaolin amplified the shear thickening phenomenon of the cement paste, while the opposite was true for the silica fume. The effect of micronized fly ash and crushed quartz on the shear thickening phenomenon of cement paste was not significant. The rheological curves measured by coaxial cylinder viscometer on the pastes made with three different types of SP at a water to powder ratio of 0.32 indicated that the polyacrylic-based SP showed evident shear thickening behavior above the critical deflocculant concentration [17]. Yahia [18] also found that the new generation of polycarboxylate SP exhibited high shear thickening behavior through its steric effect, while others could influence the shear thickening behavior via electrostatic effect. Moreover, it was also reported that the shear thickening behavior decreased with the increase of maximal aggregate size [19]. There are three popular theories to explain the shear thickening behavior, namely, the order-disorder transition theory, the clustering theory of fine particles and the grain inertia theory of large particles. The order-disorder transition theory was put forward by Hoffman [20], who found that it was easy to flow when the particles were ordered into layers, while the disordered structure dissipated more energy to flow due to jamming of particles, and hence increased the viscosity. The clustering theory was put forward by Bossis and Brady [21,22], who confirmed that the disordered state was not necessary to obtain a shear thickening behavior. They found that when the hydrodynamic forces caused by the flow became larger than the inter-particle repulsive forces at a certain critical shear stress, the "hydrodynamic clusters" formed. Consequently, the flow was blocked and the shear thickening behavior could occur. Feys et al. [19] claimed that the shear thickening could also be caused by the transfer of momentum between suspended particles and the dominance of grain inertia depending on the particle Reynolds number.

High shear rates occur frequently during the process of concrete mixing and casting. For example, during the mixing process, the average shear rates of concrete range from 10 to 60 s^{-1} [23], whereas the shear rate applied to cement paste is approximately 5 times higher than of concrete [24]. Pumping is a classical method to pour SCC into the formwork which induces high shear rates ranging between 20 and 40 s^{-1} [25]. In these cases, the shear thickening may increase the pumping pressure of fresh concrete, and even lead to the failure of pump construction. Shear thinning may cause segregation and bleeding during the pumping, resulting in the increase of friction resistance between the aggregate particles or the aggregate and pumping pipe which could potentially get the pumping pipe clogged, as shown in Fig. 1 [26]. In addition, the segregation and bleeding can cause a thick laitance layer floating on the top of mold, which would seriously affect the concrete strength and durability [27].

Generally, shear thickening was considered as a potential industrial problem in terms of producing and casting concrete. However, limited data are available in literature about the shear thickening behavior of concrete in particular SCC, and most of them are relevant to paste and mortar.

Due to the compositional characteristics of high powder content, high chemical admixtures content, high sand rate, low water to powder ratio and high flowability of SCC, it is difficult to obtain reliable shear thickening behavior of SCC particularly when it is admixed with a certain kind of chemical additive from cement paste, mortar or conventional concrete. The primary objective of this study is to evaluate the effects of SP and AE on the rheological properties of SCC, especially on its shear thickening behavior. It is expected that this work can provide useful information for determining the optimum dosages of SP and AE by using appropriate rheological techniques.

2. Experimental

2.1. Materials and mixture proportioning

Type P•O 42.5 cement complying with GB 175-2007 [28], type F fly ash complying with GB/T 1596-2005 [29] and type S95 slag powder complying with GB/T 18046-2008 [30] were used. The chemical and physical properties of cement, slag powder and fly ash are shown in Table 1. The calcium oxide-calcium sulphoaluminate composite expensive agent was used, which conforms with type II expansive agent in GB 23439–2009 [31]. The chemical composition of expansive agent is shown in Table 2. River sand with a fineness modulus of 2.6 was used as the fine aggregate. The coarse aggregate used was the crushed limestone with a continuous-grading of 5–20 mm. All admixtures used were commercially available products. The polycarboxylate SP with a density of 1050 kg/m^3 and 26% of solid content was used to achieve the expected slump-flow. The rosin resin type air-entraining agent was used to achieve the expected air content. The VMA was also used to avoid segregation and bleeding which composed of mineral admixtures and cellulose ether. The mix proportions and the corresponding slump flow, air content and visual stability index (VSI) are shown in Table 3. The air content of *C01* to *C04* was limited within the range from 5 to 7%, and the effect of SP dosage was evaluated. The slump flow of *C11* to *C15* was limited within the range from 670 to 690 mm, and the effect of AE dosage was also evaluated.

2.2. Test methods

2.2.1. Rheological test

Based on Table 3, each SCC was prepared in a batch of 40 L, of which about 30 L was used for measuring the rheological properties. To ensure statistical reliability of test results, all the tests were conducted in triplicated. Typically, all dry components (aggregates, cementitious materials, etc.) were firstly mixed for 15 s. Then water, SP and AE were added, and mixed for another 3 min. Rheological curve is tested immediately after the completion of the concrete mixing, and the test process controls within 5 min.

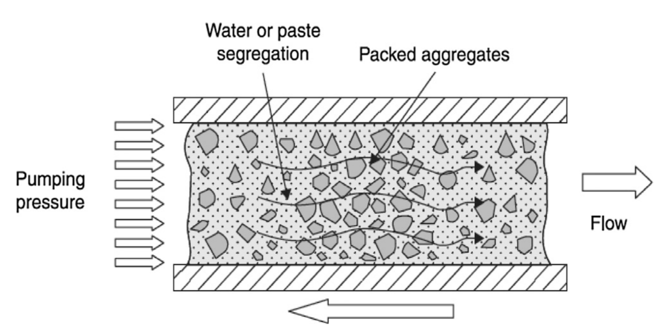

Fig. 1. Jamming the pipe caused by concrete segregation in the pumping process.