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Effect of solid concentration and shear rate on shear-thickening response of high-performance cement suspensions

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HIGHLIGHTS

- Factors affecting rheology of paste are outlined and discussed.
- Factors affecting shear-thickening response of cement-based suspensions are identified and discussed.
- Shear-thickening behavior of concentrated cement suspension is observed.
- The behavior of new generation of superplasticizer acting by steric hindrance in concentrated cement suspensions is highlighted.

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ABSTRACT

Flow performance, placement, and consolidation of concrete are mainly related to its rheology. Rheology of paste plays a key role on rheology of concrete. Cement pastes exhibit complex rheological behavior affected by several physical and chemical factors, including the solid concentration, type and dosage of high-range water-reducer (HRWR), cement characteristics, and shear history. An experimental investigation was carried out to investigate the effect of solid concentration, HRWR–cement combinations, and shear rate regime on pseudoplastic behavior of high-performance cement grouts. Grout mixtures proportioned with w/c of 0.30, various cement–HRWR combinations, 8% silica fume, and different limestone powder additions were investigated.

Solid concentration and shear rate regime are shown to be key factors affecting shear-thickening response of concentrated cement-based suspension (i.e. low w/c). Concentrated high-performance grout mixtures are shown to exhibit shear-thickening behavior. The use of polycarboxylate HRWR acting by hindrance effect exhibited greater shear-thickening behavior compared to polynaphtalene type acting by electrostatic effect. The use of finer particles enhances the powder skeleton and ensures polydisperse systems, hence resulting in lower shear-thickening response. For concentrated cement-based suspensions, shear-thickening is due to disorder state, and at higher shear rate, hydrocluster formation is prevailing.

1. Introduction

Fresh concrete is a solid suspension of aggregate in cement paste. Investigations of cement paste rheology are essential for understanding flow properties of concrete and securing good flow performance, placement, and consolidation. In addition, rheology can be used as a design parameter of self-consolidating concrete (SCC) to tailor proper profile of apparent viscosities that can take into account the various requirements, including pumping pressure and distance, free fall of concrete into formwork, required stability level after placement and consolidation during the dormant period, and formwork pressure [1–4]. Cement paste constitute flocculent systems, resulting in a complex rheological behaviour affected by several physical and chemical factors [4–8]. Rheology of cement paste is dominated by solid concentration, size distribution and chemical composition of cement, mixing energy, shear history, and the presence of HRWR. Such behavior is further complicated by the use of low water-to-cement ratios (w/c) to improve mechanical properties and durability characteristics of concrete. In low w/c mixtures, the dispersing ability of HRWR and cement–HRWR compatibility plays also a critical influence on their rheological behavior [9].

The shear-thickening phenomenon is encountered during the processing of concentrated dispersion in various industries [10]. Shear-thickening refers to the increase in apparent viscosity with shear rate. For example, high-performance grout proportioned with a w/c below 0.40 exhibited shear-thickening and shear-thinning

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behavior for a w/c of 0.40 [2]. Jones and Taylor investigated the flow curves of cement paste using a cone and plate viscometer at shear rate up to 150 s^{-1} and reported that cement paste was shear-thickening at w/c below 0.40, shear-thinning above 0.40, and a Bingham material at 0.40 [11]. Experimental data generated on 78 mixtures (concrete and mortar) made with and without admixtures exhibited shear thickening behavior [12]. Rheological measurements were carried out using plane-to-plane rheometer. On the other hand, rheological measurements carried out using a coaxial-cylinders rheometer on 0.32 w/c paste made with three different types of HRWR, including a melamine resin, lignosulfonate, and a polyacrylic-based HRWR showed that when used above a certain dosage, the polyacrylic-based HRWR results in shear thickening response [13]. Furthermore, cement pastes proportioned with water-to-powder ratio (W/P) between 0.22 and 0.26 exhibited shear-thickening behavior [14]. The use of new generation of polycarboxylate ether (PC) HRWR acting by steric effect exhibited high shear-thickening response compared to those acting by electrostatic effect [2,13,14]. It is also reported that mineral admixtures, such as metakaolin increase the shear-thickening response, while the silica fume reduce it [14].

The onset of shear-thickening marks the point when hydrodynamic interactions begin to predominate in the system [15]. The pioneering studies carried out by Hoffman showed that the incipience of shear-thickening at a critical shear rate corresponds to a transition from an easy flowing state where the particles are ordered into layers to a disordered state [16]. This mechanism is generally referred to an order–disorder transition. On the other hand, it is reported that shear-thickening is not related to the destruction of ordered layers but to the generation of particles cluster [10]. Indeed, further evidence for cluster formation hypothesis has been provided through optical dichroism measurements [10]. Boss and Brady carried out dynamic simulations and showed that shear-thickening may be due to consequence of the formation of a transient cluster that jams the flow [17].

The shear-thickening behavior observed with cement-based suspensions is usually explained by either an order–disorder transition theory or cluster theory [2,14,15]. For both theories, suspensions exhibit shear-thickening when the solid fraction is very high. Furthermore, for such concentrated suspensions, the shear rate can also play a critical effect. Indeed, Hoffman conducted rheological and light diffraction measurements and reported the existence of critical shear rate where the suspension changes from ordered state to a disordered one [16]. It is also reported that hydrolyzed polyacrylamide solutions containing 20 g/L of NaCl exhibit shear-thinning behavior at shear rates lower than 27.4 s^{-1} and shear thickening at higher values [18]. High shearing induces sufficient shear forces to drive particles into contact and form clusters composed of compact groups of particles. If this is a viable hypothesis, cement-based suspensions containing higher volume of fine particles should present more or less shear-thickening response depending on the solid concentration. The objective of this study is to evaluate the effect of solid concentration and shear rate on rheological flow curves of high-performance grout mixtures. This study aims to elucidate the influence of testing procedures on the pseudoplastic responses of cement-based suspensions.

2. Research significance

Shear-thickening behavior is usually associated with low w/c cement suspensions containing new generation of HRWR acting by steric effect. The coupled effect of solid concentration and shear rate on pseudoplastic response is not well understood. Test results presented in this paper provide a good understanding of the coupled effect of shear-histroy and solid concentration on the shear-thickening behavior of cement-based suspensions.

3. Experimental program

Experiments were carried out on high-performance cement suspensions proportioned with a w/c of 0.30 and two different cement types. All the investigated mixtures contained an optimum HRWR dosage of 0.14%, by weight of cement, to ensure proper dispersion of the powder material. The effect of adding silica fume at a dosage of 8%, by weight of cement, was evaluated. Furthermore, the addition of limestone particles at concentrations up to 20%, by weight of cement, is also investigated. Rheology of various grout mixtures was then determined using a coaxial cylinders viscometer.

3.1. Materials and mixture proportioning

Ordinary (OC) and low heat cement (LH) types complying with ASTM C150 Type I and IV cements, respectively, a densified silica fume (SF), and limestone powder (LP) were used. The chemical and physical properties of these materials are given in Table 1. The SF has a mean diameter (D_{50}) of approximately 0.065 μm (Table 1), which is approximately 250 times lower than that of portland cement. Two different HRWR types were used: a polynaphthalene-based HRWR (PNS) with solid content of 42% and specific gravity of 1.21 and a polycarboxylate-type HRWR (PC) with solid content of 35% and specific gravity of 1.09. Water in the HRWR was accounted for to maintain constant w/c.

3.2. Test methods

All investigated mixtures were mixed in batches of 6 L using a high-shear mixer rotating at 1500 rpm to ensure a complete dispersion of solid particles and homogeneous suspension. The temperature of mixing water was controlled to keep the temperature of grouts at 23 ± 1 °C. Following the end of mixing, all grouts had constant temperatures of 22 ± 1 °C. The mixing sequence consisted of mixing water and HRWR for 20 s. The cement was then introduced gradually during 60 s while the mixer was turned on, and the mixture was mixed for a total time of 120 s. After a rest period of 60 s, the mixing was resumed for an additional 60 s.

The flow curves of investigated grout mixtures were determined using a coaxial cylinders viscometer with a shear gap size of 1.17 mm. A 350-mL sample of grout was used for such measurements. The test protocol consists in shearing the paste at low or high shear rates (100 or 250 s^{-1}) during 60 s. The descending flow curve was then determined by decreasing the shear rate from 100 or 250 s^{-1} to 1.7 s^{-1} during 90 s. The rheological measurements were completed within 10 min following the initial contact of cement with water.

4. Test results and discussion

4.1. Effect of cement–HRWR combinations

The shear stress–shear rate data are fitted using the Herschel–Bulkley model. This model is given by: $\tau = \tau_0 + K^n\dot{\gamma}$, where τ_0 is the yield stress, K is the consistency, and n is the pseudoplastic index. The mixture is shear-thinning when $n < 1$ and shear-thickening when $n > 1$. The mixture behaves as Bingham material when $n = 1$. The flow curves for various mixtures made with different cement–HRWR combinations determined at a maximum shear rate of 250 s^{-1} are summarized in Fig. 1.

As can be observed, the use of OC resulted in higher shear-thickening response compared to LH, regardless of the HRWR type. For example, the pseudoplastic index of mixtures made with OC was either 1.30 or 1.77 depending on the HRWR type. In the case of LH, this index was either 0.97 or 1.23. On the other hand, higher shear-thickening response is observed with PC HRWR acting by steric effect than PNS type, regardless of the type of cement. For example, in the case of OC, the pseudoplastic index of mixture made with PC HRWR was 1.77. In the case of PNS, this index was 1.30. These results are consistent with those presented in previous study where PC HRWR acting by hindrance effect resulted in higher shear-thickening behavior than those made with PNS, especially for lower w/c mixtures [2,13,14]. The high shear-thickening response observed with mixtures made with OC may be due to the relatively higher reactivity of OC compared to LH. This may also be due to relatively higher degree of adsorption of HRWR that