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Fillers to lessen shear thickening of cement powder paste

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HIGHLIGHTS

- Shear thickening of concrete is created by superplasticiser.
- Shear thickening can be lessened by replacing cement partially with fillers.
- Optimal filler's replacement ratios are proposed for minimum shear thickening.
- Wet packing density and shear thickening can be well correlated.

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ABSTRACT

Superplasticiser (SP) is an indispensable ingredient in the production of contemporary concrete, which is designed to satisfy multi-concurrent performance criteria such as strength, flowability, passing ability, segregation and dimensional stability. Use of SP can decrease flocculation of fine powder and enhance the workability of concrete. However, at the same time it increases the shear thickening of concrete resulting in reduced pumping distance, less uniform mixing and more difficult on-site manual handling, e.g. shovelling or surface trowelling. Therefore, the SP dosage for concrete mix design should be limited, or more practically, fillers should be added to reduce the shear thickening. This paper proposes to decrease the shear thickening of cement powder paste by replacing part of the cement with an equal volume of filler. From the test results, it was evident that when fly ash, silica fume or limestone is added to replace cement, the shear thickening decreases significantly. Also, it was found that the shear thickening of cement powder paste can be correlated negatively to the wet packing density. As the wet packing density increases, the tendency of having clustering of particles or free polymer chains from the SP decreases and thus shear thickening.

1. Introduction

High performance concretes (HPC) such as high-strength concrete, high-flowable concrete, self-consolidating concrete, low-heat and low-shrinkage concrete have been increasingly used as structural concrete in the construction industry. In the production of these concretes, superplasticiser (SP) is added to decrease flocculation of fine powder and the total amount of free water for a specified flowability. Since the dosage of SP is usually limited to 3% of cementitious powder by weight, the water content in SP is so low that it will not affect the water/cement ratio and in turn the concrete strength. Hence, the concrete strength at certain flowability can be improved. Given this advantage, SP has become an indispensable ingredient in HPC. However, although SP can improve the flowability of concrete at a given strength, too much of it causes segregation and shear thickening, which impairs the consistency and workability of concrete.

Many studies regarding the effects of SP on the consistency or segregation stability of concrete, mortar and cement pastes have already been conducted [1–3]. Segregation in HPC normally refers to the separation of mortar or paste from the aggregates, which will impair the consistency and strength of concrete. It is widely known that excessively segregated concrete cannot be used in construction as most of the aggregates will settle to the bottom of the formwork, and thereby leaving just the paste/mortar on the top surface of the casting member. This will create a weak layer of material on the top part of the member in the direction of casting. Therefore, there is a maximum acceptable segregation ratio for designing high-performance concrete mixes, e.g. 15–20% [4]. In contrast to the segregation stability, the effect of SP on shear thickening of HPC has not been paid enough attention. Similar design guidelines for controlling the extent of shear thickening of HPC are not well developed as yet. However, it should be noted that

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excessive shear thickening of concrete can impair its workability and mixing uniformity, causing it more difficult to mix, transport and place.

In the rheology design of HPC, usually a set of performance criterion should be satisfied. Common tests include the slump-flow test for deformability and yield stress, V-funnel for flow rate and viscosity, L-Box and J-Ring for passing ability and U-box for filling ability. Nonetheless, all of these tests are gravity driven and reflect the working performance of concrete at low shear rates. These tests can be considered adequate to indicate the ability of concrete to fill in formwork by its self-weight. However, those will not tell the performance of concrete at high shear rates.

The testing of concrete performance at high shear rate is important to reflect the workability and placing ability of concrete, which has normally been neglected. High shear rate usually happens in the process where large amount of work is done on the concrete to make it workable, such as in mixing or placing of concrete. In a mixing process, shear rates as high as 10–60 s^{-1} can be experienced by fresh concrete [5,6], whereas the shear rate can increase to >200 s^{-1} for interstitial cement paste [7]. Pumping is a popular way of transporting concrete from concrete trucks to within formwork, especially for concreting carried out in tall buildings and long span bridges such as those concrete-filled-steel-tube columns [40,41]. Herein, concrete is likely to experience high shear rate in the range of 20–40 s^{-1} [6]. High shear rate will also occur in manual handling of fresh concrete on site by workers using hand tool, e.g. shovel.

A commonly adopted performance criterion of HPC, e.g. in self-consolidating concrete [4], is that concrete should not be too viscous. Otherwise it affects the flowability of fresh concrete. It is not unreasonable to extend this acceptance criterion to concrete working in high shear rate. Concrete working in the range of high shear rate should be maintained a low viscosity. Some disadvantages of having viscous concrete mix in high shear rate are: (1) a more powerful mixer is needed for achieving mixing uniformity, or otherwise the mixing time should increase, which increase the cost of concrete production. (2) The vertical and horizontal pumping distances will decrease because of the larger head loss during pumping. The head loss is caused by the larger friction between the concrete and the pipes experienced by a more viscous concrete. (3) Manual handling of concrete becomes more difficult or impossible. If the fresh concrete followed the behaviour of linear Bingham model, the viscosity obtained from the V-funnel test could be used under both low and high shear rates (e.g. casting and mixing/pumping respectively). However, it is not the case for HPC, as the SP commonly adopted nowadays in HPC mix design will increase significantly the shear thickening because of the nonlinear shear stress-shear rate behaviour. Accordingly, behaviour of HPC under mixing and pumping could not be obtained by the V-funnel flow.

Previous rheological research in concrete [8–11] has shown that shear thickening does happen in HPC. It was found that SP is the main reason for introducing shear thickening. The phenomenon of shear thickening that occurs in highly cement-based suspensions with SP can be explained by the order-disorder transition theory or cluster theory [12–14]. When a shear rate applied to a suspension is low, the repulsive particle-particle interaction force is equal to the attractive force so that the particles are in their equilibrium position. As the shear rate applied exceeds a critical value, the equilibrium condition will be destroyed. The polymer chains of the SP that are wrapped on the fine particles to provide steric hindrance will then be dislocated under high shear rate. Subsequently, fine particles will agglomerate to form packed clusters. When shear rate keeps increasing, hydrodynamic clusters will form that increase the viscosity. Microscopically, the shear thickening is created by the formation of clusters that prevent the particle flowing around each other easily. Macroscopically, the hydrodynamic clusters formed at high shear rate increase the disorderly of the system and hence higher rate of energy dissipation is needed. The consequences are that the microstructure of the cement suspension will change, the flow rate during pumping will decrease and the filling capacity will drop. In order to improve the performance of HPC during high shear rate, the shear thickening should be minimised.

However, reducing SP is not a solution to decrease the plastic viscosity of high-performance concrete/cement paste at high shear rate. To reduce shear thickening, the tendency of forming cluster within the interstitial void of concrete/cement paste mix has to be reduced. Various cementitious or non-cementitious inert fillers that are finer than cement particle could be good choices for decreasing the interstitial voids [15]. In this paper, cementitious fillers such as fly ash (FA) and silica fume (SF), as well as inert filler limestone (LS) have been selected for investigation given that they are commonly used in the industry. The shear thickening of four groups of cement powder paste studied were, which are classified as per their powder content: (Group 1) Cement only; (Group 2) Cement + FA; (Group 3) Cement + SF; (Group 4) Cement + LS. In Groups 2 to 4, the content of fillers (i.e. FA, SF or LS) were varied from 5% to 40% (20% for SF), which were to replace an equal volume of cement in Group 1. A constant dosage of SP was applied to all mixes. The objectives of the study are to: (1) investigate and understand the effects of adding fillers on the shear thickening of cement powder paste; (2) relate the shear thickening to the wet packing density in cement powder paste.

2. Materials and testing procedure

2.1. Materials

Cement used in this study is the General Purpose Portland Cement, which complies with AS 3972 [16]. This type of cement is primarily used in the construction industry in Australia. Two types of fillers were used. The first type was cementitious fillers which consisted of FA and SF. They comply with AS 3582.1 [17] and AS/NZ 3582.3 [18] respectively. The second type was an inert (non-cementitious) filler consisted of limestone. A third generation polycarboxylate-based SP was used in all concrete mixes. It should note that this type of SP effectively disperses the cementitious materials by both electrostatic repulsion and steric hindrance [19]. Specific gravity SG (dimensionless) and specific surface area SSA (m^2/kg) of the above stated materials are given in Table 1 and particle size distribution is shown in Fig. 1. It can be seen from Table 1 and Fig. 1 that particle size of limestone is comparable to cement. Particle size of SF is finer than cement, which can broaden the Particle Size Distribution (PSD) of powder. Their determined typical PSD are also shown in Fig. 1.

2.2. Test methods

Half of the prepared dry powder was mixed for 1 min in a table-mounted mortar mixer with planetary mixing action that consisted

Table 1
Specific gravity (*SG*) and specific surface area (*SSA*) of materials used in concrete mixes.

Material	*SG* (–)	*SSA* (m^2/kg)	*SSA* method
Cement	3.1	365	Laser diffraction
Fly ash	2.2	416	Laser diffraction
Silica fume	2.4	6000	Supplier data
Limestone	2.7	473	Laser diffraction
Superplasticizer	1.065	NA	NA
Water	1.0	NA	NA