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Ternary blending of cement with fly ash microsphere and condensed silica fume to improve the performance of mortar

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ABSTRACT

The addition of condensed silica fume (CSF) to fill into the voids between cement grains would release the water entrapped there to form water films for lubrication. However, the large surface area of CSF would thin down the water film thickness (WFT). By adding also a cementitious material that is finer than cement but not as fine as CSF, such as fly ash microsphere (FAM), the water entrapped in the voids could be released without excessively increasing the surface area. This may produce a larger WFT and better flowability than adding CSF alone. In this research, ternary blending of cement with FAM and CSF was studied by testing mortar mixes with different amounts of FAM and CSF added. It was found that the WFT is the key factor governing the properties of mortar and that ternary blending of cement with both FAM and CSF does offer some advantages.

1. Introduction

High-performance concrete (HPC), with high performance in both fresh and hardened states, is the future of our concrete industry [1]. To produce HPC, it is essential to lower the water/cementitious materials (W/CM) ratio; as suggested by Neville [2], "what makes the concrete a high performance one is a very low water/cement ratio". Such lowering of the W/CM ratio is made possible by the advent of superplasticizer (SP), which provides good workability even at very low W/CM ratio. However, since the water added must be more than sufficient to fill the voids in the bulk volume of the cementitious materials [3], there is a limit to which the W/CM ratio can be lowered, no matter how effective the SP is. This limit is not a constant, but is dependent on the packing density of the cementitious materials [4,5], which determines the volume of voids to be filled with water.

The addition of fine supplementary cementitious materials (SCM) to fill into the voids between cement grains is an effective way of increasing the packing density and reducing the volume of voids to be filled with water. With fine SCM particles filled into the voids, some of the water entrapped therein can be freed as excess water (the water in excess of that needed to fill the voids) to form water films coating the solid particles to provide lubrication [6]. This filling effect of fine SCM can produce a denser and more uniform mixture to improve the strength and durability of concrete [7]. Moreover, the pozzolanic reaction of fine SCM can produce further gel products to improve the microstructure [8]. In fact, concrete produced with fine SCMs added is often found to perform better in terms of workability, strength and durability [9–11]. Various kinds of SCM, such as fly ash, ground granulated blast furnace slag, silica fume, metakaolin and rice husk ash, have emerged. Most of the SCMs are industrial by-products and their use can help to reduce the cement consumption and carbon footprint of our concrete production [12–15].

The challenge in the application of SCM lies in the mix design. Due to the additional variable of SCM content, a much larger number of trial batches are needed to arrive at the optimum mixture proportions [16]. A scientific mix design method is desperately needed but is still lacking [17,18]. Moreover, the effects of SCM on the fresh properties of concrete are not easy to predict because of their dependence on the particle size distribution and shape of the SCM. For example, Kohno and Komatsu [19] reported that the addition of condensed silica fume (CSF) would impair the flowability of mortar, while Duval and Kadri [20] demonstrated that the addition of CSF up to 10% by mass has no adverse effect on the workability of concrete. More recently, Kwan and Fung [21] showed that the addition of CSF would increase the packing density and thus improve the flowability of mortar. These contradictory results have made the mix design of HPC containing SCMs a difficult task.

Although the addition of fine SCM to fill into the voids between cement grains would no doubt increase the packing density and thus the amount of excess water available for forming water films,

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it would at the same time increase the solid surface area to be coated with water films [22]. Ferraris et al. [23] suggested that the increases in packing density and solid surface area have opposite effects on the rheology of cement paste. Whilst the increase in packing density would make available more excess water for forming water films, the increase in solid surface area would thin down the thickness of water films formed. Therefore, the net effect of adding fine SCM is dependent on the relative magnitudes of the increase in packing density and the increase in solid surface area.

To combine these two effects, Kwan and his research team advocated to use the water film thickness (WFT), the average thickness of water films coating the solid particles, as the controlling parameter in the mix design of HPC [24,25]. They have also developed a wet packing method for direct measurement of the packing density of solid particles in cement paste and mortar [26,27]. From the packing density so measured, the excess water content may be calculated as the water content minus the voids volume and the WFT may be determined as the excess water to solid surface area ratio. The WFT has been found to be the single most important mix parameter governing the fresh properties of cement paste and mortar [24,28].

Being ultrafine, CSF is an effective filler for increasing the packing density in order to release more excess water to form water films. However, the large increase in solid surface area due to the high fineness of CSF would thin down the WFT. Hence, the addition of CSF may or may not increase the WFT. An intermediate sized SCM that is finer than cement so as to fill into the voids between cement grains to increase the packing density but coarser than CSF so as to avoid large increase in the solid surface area may be more effective in increasing the WFT. Herein, it is proposed that fly ash microsphere (FAM), which is a superfine fly ash captured from the exhaust smoke of coal-fired power stations, may be a suitable SCM for such usage. In fact, ternary blending of cement with both FAM and CSF may be even better because successive filling of the voids between cement grains by first the FAM particles and then the CSF particles should further increase the packing density.

Multiple blending of cement with more than one cementitious materials to harvest the synergic effect of the cementitious materials is not new [29,30]. In this regard, Aïtcin [31] has pointed out that there is a size gap between cement and CSF and that this size gap should be closed by adding an intermediate sized SCM. The authors concur with this statement and are proposing to ternary blend cement with both FAM and CSF so as to achieve a better particle size distribution. In this research, such ternary blending was studied by testing mortar mixes with different amounts of FAM, CSF and water added for their packing density, flowability, rheology, adhesiveness and strength. It will be seen that the WFT remains a governing factor in the properties of such kind of mortar and that ternary blending with the size gap closed is superior to binary blending.

2. Materials

Three cementitious materials, namely, OPC (ordinary Portland cement), FAM and CSF, were employed in this study. The OPC was of strength class 52.5N obtained locally in Hong Kong, whereas the FAM and CSF were imported from China and Europe, respectively. The OPC, FAM and CSF had been tested to comply with European Standard EN 197-1: 2000 [32], Chinese Standard GB 1596-91 [33] and American Standard ASTM C 1240-03 [34], respectively. The fine aggregate used was a crushed granite rock fine with a maximum size of 1.18 mm and a water absorption of 1.02% by mass. The relative densities of the OPC, FAM, CSF and fine aggregate had been measured in accordance with the European Standards EN 196-6: 2010 [35] or EN 1097-6: 2000 [36] as 3.11, 2.52, 2.20 and 2.54, respectively. Their particle size distributions were measured by a laser diffraction particle size analyzer and the results obtained are plotted in Fig. 1. Using the method proposed by Hunger and Brouwers [37], the specific surface areas of the OPC, FAM, CSF and fine aggregate were calculated from their particle size distributions as 1.12×10^6, 3.95×10^6, 13.3×10^6 and 0.148×10^6 m^2/m^3, respectively. Unlike the cement grains, the FAM and CSF particles are spherical in shape.

The SP added was a polycarboxylate type supplied in the form of an aqueous solution with a solid mass content of 20% and a relative density of 1.03. Since SP is a surface reactant and it is the SP dosage per solid surface area that governs its effectiveness, the SP dosage was expressed in terms of the liquid mass of SP per solid surface area of the solid particles in mortar [38]. Before setting the SP dosage to be used, trial cement paste mixing with various SP dosages was carried out and it was found that for OPC alone, the saturation dosage of the SP (the dosage beyond which further addition yields little further increase in flowability) was 2.6×10^{-5} kg/m^2. For simplicity, the SP dosage in terms of liquid mass of SP per solid surface area of the solid particles was set constant as 2.6×10^{-5} kg/m^2 for all mortar samples. It should, however, be noted that the saturation SP dosage could vary with the FAM and CSF contents, and this may have certain effects on the effectiveness of the SP added.

3. Experimental program

The experimental program consisted of three parts. The first part was to measure the packing densities of the mortar samples having different FAM and CSF contents in order to study the effects of FAM and CSF on the packing density. The second part was to measure the flow spread, flow rate, yield stress, apparent viscosity and adhesiveness of the mortar samples produced with different FAM, CSF and water contents. The last part was to measure the 28-day cube strength of the mortar samples. The WFT of each mortar sample was determined from the packing density results obtained in the first part and the W/CM ratio of the mortar. Then the testing results obtained in the second and third parts were correlated to the WFT to study the roles of WFT in mortar with ternary blended cementitious materials.

In this study, the FAM and CSF contents were each expressed as a volumetric percentage of the total cementitious materials because the packing density is governed by volume ratios rather than by mass ratios. Three FAM contents, namely, 0%, 20% and 40%, and two CSF contents, namely, 0% and 10%, were adopted for the design of the mortar samples. The W/CM ratio was varied from 0.4 to 1.4

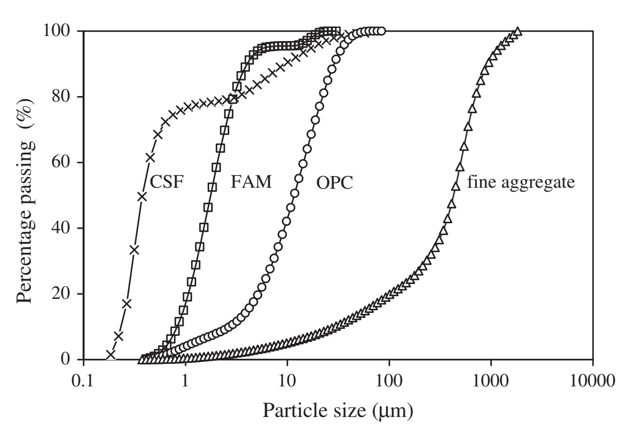

Fig. 1. Particle size distributions of CSF, FAM, OPC and fine aggregate.