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Effects of limestone fines on water film thickness, paste film thickness and performance of mortar

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ABSTRACT

The addition of limestone fines (LF) to mortar or concrete can improve the performance of the mortar or concrete. However, the effects of adding LF appear to be dependent on the water content and paste volume, and thus it is not easy to comprehend how LF actually works. Herein, it is postulated that the effects of LF are caused by the corresponding changes in water film thickness (WFT) and paste film thickness (PFT). To study the effects of LF, a series of mortar mixes with different paste volumes and LF contents have been tested for their packing density, flowability, cohesiveness and strength. From the packing density results, the WFT and PFT of the mortar mixes were calculated and the measured properties of the mortar mixes were correlated to the WFT and PFT. It was found that the WFT and PFT are the major factors governing the performance of mortar and the effects of LF are caused by the decrease in WFT and the increase in PFT due to the addition of LF.

1. Introduction

Self-consolidating concrete (SCC) has gained popularity for its high performance in terms of flowability, filling ability, passing ability and segregation stability [1,2]. To produce SCC, it is essential to have a larger paste volume than conventional concrete for achieving the required performance [3]. However, increasing the paste volume is not without concern. In general, concrete with a larger paste volume would have higher cement and water contents. High cement content would increase the heat generation, cost and carbon footprint of the concrete while high water content would reduce the segregation stability and dimensional stability of the concrete. Besides, it is difficult to achieve the conflicting performance requirements of SCC, such as high flowability and high segregation stability, at the same time [4].

In recent years, various kinds of fillers, such as limestone fines (LF), have been used in the production of concrete [5–7], especially SCC [8]. Basically, the addition of a filler to replace part of cement or to fill into the voids between aggregate particles to reduce the paste volume needed can lower the cement and/or water contents of the concrete. Depending on the fineness of the filler and the amount added, the addition of a filler has significant effects on the fresh and hardened properties of mortar/concrete, and may improve the overall performance of the mortar and concrete. However, despite years of research, widely different and even contradictory results regarding the effects of LF on the performance of mortar or concrete have been obtained.

On fresh properties, Tezuka et al. [9] found that for mortar, replacing 5% of cement by LF would improve workability and thus allow the water/cement ratio to be reduced without changing workability. Schmidt et al. [10] found that for concrete, replacing 17% of cement by LF would enhance workability and thus allow the water/cement ratio to be lowered. Likewise, Moir and Kelham [11] observed that concrete with cement blended with 20% LF would have a higher workability than concrete with cement blended with other materials. Kanazawa et al. [12] demonstrated that the incorporation of LF in certain ways can enhance both the workability and segregation stability of concrete. However, Matthews [13] reported that concrete with part of cement replaced by LF would need a higher water/cement ratio to maintain workability.

On hardened properties, Sprung and Siebel [14] found that the use of LF up to 15% in cement would increase the early strength (at an age of 2–3 days) by improving the particle packing through filling of LF particles into the voids of cement grains, while maintaining the same later strength (at an age of 28 days). They also reported that when cement is replaced by LF up to 25%, the strength would be adversely affected. Likewise, Schmidt [15] found that cement replacement by LF up to 10% would not reduce the strength and Livesey [16] found that cement replacement by LF up to 5% would increase the early strength.

Besides replacing cement, fillers have also been added to replace aggregate. Malhotra and Carette [17] observed that the addition of LF to replace part of sand can increase or decrease the strength of concrete, depending on the water/cement ratio and LF content. Furthermore, they

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noted that the incorporation of LF would increase the cohesiveness of the fresh concrete and the drying shrinkage of the hardened concrete but has little effect on the durability of concrete structures. Celik and Marar [18] found that the use of crushed stone dust to replace up to 10% of sand would increase the compressive and flexural strengths of the hardened concrete, and to replace up to 30% of sand would decrease the slump and air content of the fresh concrete.

Due to the complexities of mix design of SCC, some researchers suggested that the mortar portion should be designed first [3,19,20]. As SCC should possess high flowability, filling ability, passing ability and segregation stability, the mortar portion should be designed to have both high flowability and high cohesiveness. However, adding more water and/or more superplasticizer to increase the flowability would tend to reduce the cohesiveness and vice versa. Hence, the desired high flowability and high cohesiveness of mortar are contradictory to each other, and are thus not easy to achieve at the same time. One way of overcoming this problem is to add LF, which fills into the paste to increase the paste volume.

Opoczky [21] postulated that the main effects of LF are due to its physical nature and that LF would render a better packing of the cement granular skeleton. Soroka and Setter [22] attributed the increase in strength after addition of LF to the increase in packing density of the solid particles. Meanwhile, several studies [23–25] have revealed that the packing density of the cementitious materials is an important factor governing the flowability of cement paste, especially at low water/cementitious materials ratio. De Schutter and Poppe [26] demonstrated that the packing density of fine aggregate has certain effects on the water demand of mortar. On the other hand, Reddy and Gupta [27] noted that the increase in specific surface area arising from the addition of fine sand (as a filler) in mortar would increase the water demand.

However, due to the presence of inter-particle forces causing agglomeration, the packing density of cementitious materials or a mixture of cementitious materials and aggregate particles is not easy to measure. The conventional methods, as stipulated in British Standard BS 812-2: 1995 [28] and European Standard BS EN 1097-3: 1998 [29] and BS EN 1097-4: 2008 [30], measure the packing density of the solid particles under dry condition. These methods, which may be classified as dry packing methods, are not really applicable to particle system containing fine particles, such as cementitious materials, LF and fine aggregate. This is because under dry condition, the fine particles tend to form agglomerates and the packing density so measured is very sensitive to the compaction applied [31]. More importantly, the effects of water and superplasticizer (SP) present in the paste/mortar/concrete cannot be included.

To resolve these problems, the authors' research group has developed a new method, called the wet packing method, for measuring the packing densities of cementitious materials [32], fine aggregate [33] and cementitious materials plus fine aggregate [34] under wet condition with the effects of water and SP included. Basically, the test results revealed that the presence of water and SP would increase the packing density and decrease the voids ratio of a granular material containing fine particles, and therefore the wet packing method is a more appropriate test method for the packing density measurement of paste, mortar and concrete, which are actually wet when freshly mixed. Diederich et al. [35] have used this wet packing method to study the effects of LF on the excess water ratio, yield stress and apparent viscosity of cement based matrix.

Based on packing density measurement by the wet packing method, the excess water (water in excess of that needed to fill the voids) and water film thickness (average thickness of water film coating the solid particles taken as the excess water to solid surface area ratio) in cement paste/mortar, and the excess paste (paste in excess of that needed to fill the voids) and paste film thickness (average thickness of paste film coating the aggregate particles taken as the excess paste to aggregate surface area ratio) in mortar have been determined. It was found that the water film thickness (WFT) and paste film thickness (PFT) are the key factors governing the rheology, flowability and cohesiveness of cement paste and mortar [36–41].

In the case of mortar or concrete containing LF, the authors envisage that the addition of LF would affect the packing density, increase the specific surface area and increase the paste volume. All these effects would change the WFT and PFT. It is the authors' belief that the LF exerts its effects mainly through the corresponding changes in WFT and PFT. To study the effects of LF on the WFT, PFT and performance of mortar, an experimental program was launched, as reported herein. It will be seen that the concepts of WFT and PFT are also applicable to mortar containing LF.

2. Materials

An ordinary Portland cement (OPC) of strength class 52.5 N complying with BS EN 197-1: 2000 [42] and a finely ground limestone fines (LF) were used. The OPC has a Blaine fineness of 376 m^2/kg and a 28-day mortar cube strength of 59.0 MPa, as measured in accordance with BS EN 196-1: 2005 [43]. The fine aggregate (FA) used was a local crushed granite rock fine with a maximum size of 1.18 mm and a water absorption of 1.0% by mass. The relative densities of the OPC, LF and FA had been measured in accordance with BS EN 196-6: 2010 [44] as 3.11, 2.64 and 2.61, respectively. A laser diffraction particle size analyzer was used to measure the particle size distributions of the materials and the results are plotted in Fig. 1. Based on these particle size distributions, the specific surface areas of the OPC, LF and FA were calculated as 1.12×10^6 m^2/m^3, 1.03×10^6 m^2/m^3 and 1.15×10^5 m^2/m^3, respectively, and the volumetric mean particle sizes of the OPC, LF and FA were calculated as 11.8 μm, 13.6 μm and 0.506 mm, respectively. Since all the OPC, LF and FA particles were produced by crushing and grinding, they were all angular in shape, as observed by eye or through a microscope. The superplasticizer (SP) added was of 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.

3. Experimental program

Twenty mortar mixes were produced for testing. Their cement paste volume (volume of water plus solid volume of cement, expressed as a percentage of the mortar volume) varied from 46% to 62% in increments of 4% while their LF volume (solid volume of LF, expressed as a percentage of the mortar volume) varied from 0% to 12% in increments of 4%. The remaining volume of the mortar was the FA volume (solid volume of FA, expressed as a percentage of the mortar volume). Since the LF has similar particle size as the cement, the LF added would fill into the paste and thus, after adding LF, the paste would contain not only water and cement but also LF. To be more precise, the paste formed of water, cement and other solid particles smaller than 75 μm is called

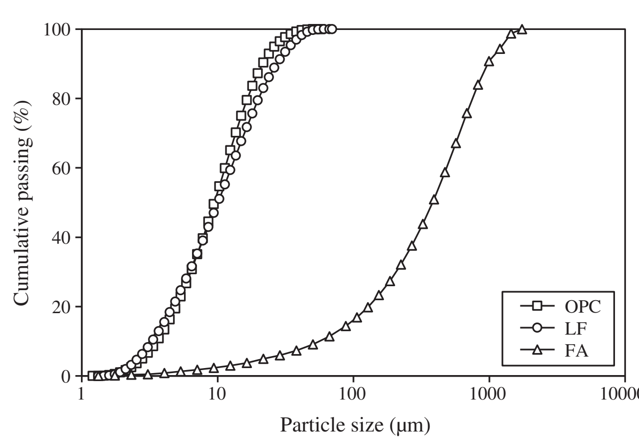

Fig. 1. Particle size distributions of OPC, LF and FA.