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Mortar design based on water film thickness

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ABSTRACT

The rheology of a fresh concrete is largely determined by the rheology of its mortar portion and hence proper design of the mortar portion should be the first step in the mix design of concrete, especially high-performance concrete. In recent studies, it has been demonstrated that the factors affecting the rheology of cement paste include the water content, packing density and solid surface area and that the combined effects of these factors may be evaluated in terms of the water film thickness (WFT). The present study aims to extend this concept of WFT to cement–sand mortar for the purpose of developing a mix design method based on the WFT. In the study, mortar samples with various water, cement and aggregate contents were produced for packing density, flowability, rheology, cohesiveness and adhesiveness measurements. It was found that both the WFT and cement/aggregate ratio have major effects on the rheological performance of mortar, but the WFT is still the single most important factor. Lastly, based on the test results, a design chart for the mix design of mortar was developed.

1. Introduction

Although high-performance concrete (HPC) has been around for many years [1], the mix design of HPC having high performance in certain attributes, especially at the fresh state, is not an easy task. For a more systematic mix design, it has been suggested that the mortar portion of the concrete should first be considered. Domone [2] has pointed out that a layer of mortar, which must be sufficiently thick and flowable, should be provided to cover each and every coarse aggregate particle. Lachemi et al. [3] have demonstrated that the flow characteristics of a concrete are closely related to the rheology of its mortar portion. Likewise, Ng et al. [4] have found that the flowability of a concrete would increase with the flowability of its mortar portion. Hence, evaluation of the rheology of the mortar portion is an effective way of predicting the rheological performance of a concrete and proper proportioning of the mortar portion is a good basis for mix design of HPC, as advocated years ago by Billberg [5] and Okamura and Ouchi [6], who studied the properties of self-consolidating concrete (SCC) with particular interest in the rheology of SCC-equivalent mortar (the mortar portion of SCC).

For a HPC, especially SCC, the abilities to spread under own weight, flow up to a certain distance and fill into far-reaching corners without segregation are desired. To achieve such desirable properties, the mortar portion has to have high flowability, as advocated by Lachemi et al. [3] and Ng et al. [4], and high cohesiveness, as advocated by Safawi et al. [7]. Furthermore, the authors are of the view that the mortar portion also needs to have high adhesiveness (the ability to adhere to solid surfaces) so as to avoid separation of the mortar from the coarse aggregate particles. However, the desired high flowability, cohesiveness and adhesiveness are difficult to achieve simultaneously. Usually, an individual mix design measure that increases the flowability also decreases the cohesiveness, and vice verse. For example, the addition of a superplasticizer (SP) could effectively increase the flowability but would also substantially decrease the cohesiveness of the mortar [8]. Besides, although mortar with high adhesiveness has been used in concrete repair and brick works [9–11], a suitable test method for measuring the adhesiveness of mortar is still lacking and up to now little is known about the adhesiveness of mortar.

Throughout the years, a number of studies have been carried out to identify the main factors affecting the rheology of mortar. Banfill [12] found that both the yield stress and viscosity of mortar decrease exponentially with the water content. In other studies, it has been found that the characteristics of the fine aggregate also have significant effects. For example, De Schutter and Poppe [13] showed that the water demand of a mortar is closely related to the packing density of the fine aggregate. Reddy and Gupta [14] found that generally a mortar made of a finer sand would need a higher water content for a given workability and explained that this is because of the larger solid surface area of the finer sand used. From these studies, it may be inferred that the main factors affecting the rheology of mortar are the water content, packing density and solid surface area of the solid–water mixture.

On the other hand, at a smaller particle size scale, Kwan and Wong [15] demonstrated that blending of cement with pulverized fuel ash and condensed silica fume could increase the packing density of the cementitious materials and thereby decrease the amount of water needed to fill the voids between particles and

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increase the flowability of the cement paste formed. Hence, both the packing density of the cementitious materials and the packing density of the fine aggregate should have some effects on the rheology of mortar. Quite possibly, it is the packing density of all the particles (cementitious materials plus fine aggregate) that matters.

However, there have been many problems with the measurement of packing density. The conventional dry packing methods, such as those stipulated in British Standard BS 812: Part 2: 1995 and Eurocode EN1097-4: 1999, are not really suitable for cementitious materials and fine aggregate, which tend to form agglomerates under dry condition. Moreover, the packing density so measured is very sensitive to the amount of compaction applied [16]. To resolve these problems, the author's research group has recently developed a new method, called the wet packing method, for measuring the packing densities of cementitious materials [17], fine aggregate [18] and cementitious materials plus fine aggregate [19]. This wet packing method has the advantages that it is capable of simulating the actual wet condition in fresh cement paste/mortar and allowing for the presence of any SP, which may have significant effects on the packing density.

Using the above wet packing method to measure the packing densities of cementitious materials and fine aggregate, the authors' research group has conducted a series of studies to evaluate the combined effects of water content, packing density and solid surface area on the rheology of cement paste [20,21] and mortar [22,23]. The test results obtained so far indicated that the combined effects of water content, packing density and solid surface area may be evaluated in terms of the water film thickness (WFT) of the solid–water mixture and that the WFT is the single most important factor governing the rheology of cement paste and mortar.

This concept of WFT may be regarded as a microscopic version of the concept of paste film thickness, which can be dated back to several decades ago. In the 1960s', Powers [24] had proposed the excess paste theory that it is the excess paste (the paste in excess of the amount needed to fill up the voids between aggregate particles) that provides a thin film of paste lubricating each aggregate particle and gives the mortar or concrete workability. Later in the 1980s', Helmuth [25] suggested that it should be the thickness of the water films coating the cement grains that governs the consistence of cement paste and that such WFT may be evaluated simply as the excess water (the water in excess of the amount needed to fill up the voids between cement grains) to solid surface area ratio. Unfortunately, due to the lack of a suitable test method, the actual packing density of the cement was not measured and the above suggestion has for many years remained just a postulation.

The present study aimed at further expanding the concept of WFT to cement–sand mortar with its cement/aggregate ratio varying over the whole practical range (in previous studies, the cement/aggregate ratios were fixed at certain constant values) so as to cover all the mix parameters that might affect the rheology of mortar and to eventually develop a mortar mix design method based on the WFT. For such aim, mortar samples with different combinations of cement/aggregate (C/A) ratios and water/cement (W/C) ratios were made for testing. The rheological properties of each mortar sample were measured in terms of flow spread, flow rate, yield stress and apparent viscosity, whereas the packing density, cohesiveness and adhesiveness were measured using the wet packing method, sieve segregation test and a new stone rod adhesion test developed herein.

2. Experimental program

To investigate the role of WFT in the flowability, rheology, cohesiveness and adhesiveness of cement–sand mortar, an experimental program was launched, in which mortar mixes with different C/A ratios and W/C ratios were tested. All the

Table 1
Flowability, rheological properties, cohesiveness and adhesiveness results.

Sample No.	Flow spread (mm)	Flow rate (ml/s)	Yield stress (Pa)	Apparent viscosity (Pa s)	SSI (%)	Stone rod adhesion (g)
0.3–1.00	1	0	>30[a]	>30[a]	0.0	0.0
0.3–1.25	42	4	>30[a]	>30[a]	0.0	4.1
0.3–1.50	157	85	5.39	7.29	0.7	18.8
0.4–1.00	116	12	20.30	28.94	0.0	2.9
0.4–1.25	203	133	4.57	6.51	1.8	20.3
0.4–1.50	218	246	2.50	3.34	17.2	10.4
0.5–0.75	0	0	>30[a]	>30[a]	0.0	0.0
0.5–0.85	0	0	>30[a]	>30[a]	0.0	0.0
0.5–1.00	198	58	8.42	11.24	0.0	33.0
0.5–1.25	248	172	2.93	4.40	2.8	14.5
0.5–1.50	259	359	1.42	0.94	19.5	9.2
0.6–0.75	0	0	>30[a]	>30[a]	0.0	0.0
0.6–0.85	64	25	25.08	24.35	0.0	52.8
0.6–1.00	264	130	4.71	5.99	0.9	24.1
0.6–1.25	276	269	1.62	3.59	15.9	11.4
0.6–1.50	314	440	1.13	1.44	38.0	8.1
0.7–0.75	4	0	>30[a]	>30[a]	0.0	0.0
0.7–0.85	174	75	7.16	11.06	0.0	42.1
0.7–1.00	280	148	4.14	5.39	8.6	14.9
0.7–1.25	305	343	1.12	2.83	33.9	6.1
0.7–1.50	322	481	0.38	1.27	47.2	5.3
0.8–0.75	13	1	>30[a]	>30[a]	0.0	2.8
0.8–0.85	197	86	4.69	7.29	0.0	32.2
0.8–1.00	289	169	1.32	2.68	23.0	8.3
0.8–1.25	317	383	0.63	2.05	37.2	7.0
0.8–1.50	343	545	0.28	0.27	50.3	4.7
0.9–0.75	116	33	19.00	19.61	0.0	27.8
0.9–0.85	238	123	3.14	5.47	5.3	20.0
0.9–1.00	280	208	0.97	2.54	52.3	9.8
0.9–1.25	313	431	0.43	0.46	58.8	4.4
0.9–1.50	283	659	0.13	0.82	93.3	4.0

[a] These results were not obtained because the torque needed for measurement had exceeded the torque capacity of the rheometer.