Construction and Building Materials 50 (2014) 598–608

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Combined effects of water film, paste film and mortar film thicknesses on fresh properties of concrete

Albert K.H. Kwan *, Leo G. Li

*Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong*

## HIGHLIGHTS

- Fresh properties of concrete are governed by the water, paste and mortar film thicknesses.
- Effects of these film thicknesses on flowability, cohesiveness and passing ability are studied.
- The mortar film thickness has negative effect on flow rate but critical effect on passing ability.
- A concrete mix design method based on these film thicknesses could be developed.

## ARTICLE INFO

*Article history:*
Received 27 February 2013
Received in revised form 1 October 2013
Accepted 4 October 2013
Available online 29 October 2013

*Keywords:*
Concrete mix design
High-performance concrete
Packing density
Mortar film thickness
Paste film thickness
Water film thickness

## ABSTRACT

It is well known that the water content, paste volume and aggregate grading have great effects on the flowability, cohesiveness and passing ability of concrete, but it is not easy to explain, quantify and predict their effects. Herein, it is proposed to evaluate their effects in terms of water film thickness (WFT), paste film thickness (PFT) and mortar film thickness (MFT). A series of concrete mixes with varying water/cement ratio, paste volume and fine/total aggregate ratio were produced for flow spread, flow rate, cohesiveness and passing ability tests. Correlation of the test results to the WFT, PFT and MFT revealed that besides the WFT and PFT, the MFT has certain effects on the fresh properties of concrete. Particularly, the MFT has little effect on flow spread, negative effect on flow rate, positive effect on cohesiveness and critical effect on passing ability. Based on these findings, suitable ranges of WFT, PFT and MFT are recommended.



## 1. Introduction

Although concrete has been the most widely used construction material [1] and the performance of concrete has increased tremendously in recent years [2], it is not clear yet how the various concrete mix parameters affect the performance of concrete and how these could be optimized for best performance. Most concrete engineers are still designing their concrete mixes by trial concrete mixing, which is tedious, time consuming and often too slow in responding to sudden changes in the properties of the ingredients. With the advent of high-performance concrete (HPC), which are required to have all round high performance in various attributes, such as strength, workability, durability, dimensional stability, cohesiveness and passing ability [2], the concrete mix design has become even more difficult. A more fundamental understanding of concrete and a more systematic approach to concrete mix design are desired.

For several decades, it has been postulated that the packing density of the solid particles has major effects on the performance of concrete [3,4]. Basically, a higher packing density of the aggregate particles would reduce the volume of voids to be filled with paste and thus allow the use of a smaller paste volume to improve the dimensional stability. Likewise, a higher packing density of the cementitious materials would reduce the volume of voids to be filled with water and thus allow the use of a lower water/cementitious materials (W/CM) ratio to increase the strength and durability. Alternatively, for a given paste volume, a higher packing density of the aggregate particles would result in more excess paste (paste in excess of that needed to fill voids between aggregate particles) for lubricating the aggregate particles whereas for a given W/CM ratio, a higher packing density of the cementitious materials would result in more excess water (water in excess of that needed to fill voids between cementitious materials) for lubricating the cementitious materials. Both the excess paste and excess water would increase the workability of concrete.

The surface area of the solid particles also has some effects because a larger surface area of the aggregate would lead to a smaller paste film thickness (PFT) and a larger surface area of the

* Corresponding author. Tel.: +852 28 59 26 47; fax: +852 25595337.
*E-mail addresses:* khkwan@hku.hk (A.K.H. Kwan), ligu123@msn.com (L.G. Li).

0950-0618/$ - see front matter 
http://dx.doi.org/10.1016/j.conbuildmat.2013.10.014

cementitious materials would lead to a smaller water film thickness (WFT). For this reason, the authors' research team has been advocating that the factors governing the rheological performance of concrete are the WFT and PFT, rather than the packing density (in fact, Neville [5] mentioned that an aggregate graded to give maximum packing density makes a harsh concrete mix). However, the packing densities of cementitious materials and fine aggregate are not easy to measure and without such data, the WFT and PFT cannot be determined. Due to the existence of inter-particles forces causing agglomeration, the traditional dry packing test tends to underestimate the packing density of fine particles. To resolve this problem, the authors' research team has developed a wet packing test that measures the packing densities of cementitious materials and fine aggregate under wet condition [6–8]. In reality, paste, mortar and concrete are wet when freshly mixed and thus the packing density of the solid particles contained therein should be measured under wet condition. This wet packing test has also been adopted by others [9].

For a paste (or the paste portion of mortar or concrete), which comprises of water and cementitious materials, there is no doubt that the water content, packing density and solid surface area of cementitious materials have major effects on the rheological properties. The water content and packing density of cementitious materials would together determine the amount of excess water available for lubrication and the solid surface area of cementitious materials would thin down the excess water to form water films coating the cementitious materials [10–14]. In recent years, the authors' research team has proposed to combine the water content, packing density and solid surface area of cementitious materials into the WFT, which may be calculated as the excess water to solid surface area ratio, and proved that the WFT is the single most important factor governing the fresh properties of paste [15,16].

For a mortar (or the mortar portion of concrete), which comprises of paste and fine aggregate, in addition to those factors affecting the WFT, the paste content also has major effects on the rheological properties. The paste content and packing density of fine aggregate would together determine the amount of excess paste and the solid surface area of fine aggregate would thin down the excess paste to form paste films coating the fine aggregate [17–21]. Recently, the authors' research team has proposed to combine the paste content, packing density and solid surface area of fine aggregate into the PFT, which may be calculated as the excess paste to solid surface area ratio, and showed that the WFT and PFT are the key factors governing the fresh properties of mortar [22,23].

For a concrete, which comprises of mortar and coarse aggregate, in addition to those factors affecting the WFT and PFT, the mortar content also has major effects on the rheological properties. Neville [5] observed that the workability is improved when there is an excess of mortar above that required to fill the voids in the coarse aggregate. Domone [24] suggested that there needs to be a layer of mortar, which has to be sufficiently thick and flowable, to coat every coarse aggregate particle. Lachemi et al. [25] and Ng et al. [26] both pointed out that the fresh properties of a concrete are closely related to the rheology of its mortar portion. Herein, the concepts of excess mortar and mortar film thickness (MFT) are introduced. The excess mortar is the mortar in excess of that needed to fill voids between coarse aggregate particles whereas the MFT may be determined as the excess mortar to solid surface area ratio. It is postulated that whilst the WFT and PFT govern the rheology of the mortar portion, the MFT has certain effects on the fresh properties of concrete.

The authors are of the view that the major factors affecting the performance of concrete are the WFT, PFT and MFT. If the combined effects of WFT, PFT and MFT are well understood, then it should be possible to develop a systematic concrete mix design method based on the WFT, PFT and MFT. The authors call this design method a three-tier concrete mix design method. The central idea is to design the concrete mix in three tiers, first the paste, then the mortar and finally the concrete, by choosing suitable values for the WFT, PFT and MFT. It is envisaged that this design method would allow the various concrete mix parameters to be optimized for best performance.

In the present study, the combined effects of WFT, PFT and MFT on the fresh properties of concrete are investigated by producing and testing concrete mixes with different combinations of paste volume, water/cement ratio and fine/total aggregate ratio. The test results revealed for the first time the combined effects of WFT, PFT and MFT on the flow spread, flow rate, sieve segregation index and U-box filling height of concrete and that the effects of MFT could be positive or negative.

## 2. Experimental details

### 2.1. Materials

An ordinary Portland cement (OPC) of strength class 52.5 N complying with BS 12: 1996 [27] was used. It had been measured to have a relative density of 3.11. Crushed granite rocks were used for the fine and coarse aggregates. The fine aggregate had a nominal maximum size of 5 mm whereas the coarse aggregate comprised of 10 mm nominal size aggregate and 20 mm nominal size aggregate. Both the fine aggregate and coarse aggregate, which were of the same origin, had the same relative density of 2.56. A polycarboxylate-based superplasticizer (SP) was added to each concrete mix. It was a milky white solution with a solid content of 20%. It can disperse the fine particles in concrete by both electrostatic repulsion and steric hindrance.

For the OPC and the portion of fine aggregate finer than 1.2 mm, a laser diffraction particle size analyzer was used to measure the particle size distributions. For the portion of fine aggregate coarser than 1.2 mm, the 10 mm coarse aggregate and the 20 mm coarse aggregate, the mechanical sieving method was used to determine the particle size distributions. From these particle size distributions, plotted in Fig. 1, the specific surface areas of the OPC, the fine aggregate, the portion of fine aggregate >75 μm in size (excluding the portion finer than 75 μm), the portion of fine aggregate >1.2 mm in size (excluding the portion finer than 1.2 mm), the 10 mm coarse aggregate and the 20 mm coarse aggregate were calculated as $1.55 \times 10^6$, $5.12 \times 10^4$, $1.03 \times 10^4$, $2.04 \times 10^3$, 642 and 398 $m^2/m^3$, respectively.

### 2.2. Mix proportions

A total of 32 trial concrete mixes with varying paste volume (PV), water/cement (W/C) ratio, and fine/total aggregate (F/T) ratio were produced for testing. The concrete mixes were divided into two groups, one with the PV set as 30% and the other with the PV set as 34% by volume of concrete. In each group, the W/C ratio by weight was varied from 0.25 to 0.55 in steps of 0.10 while the F/T ratio by weight was varied from 0.30 to 0.60 in steps of 0.10. In all concrete mixes, the 10 mm aggregate to 20 mm aggregate ratio was fixed at 1.0 and the SP dosage (measured in terms of liquid weight) was fixed at 2% by weight of the cement content. For easy identification, each concrete mix was assigned a mix number of PV-W/C ratio-F/T ratio, as listed in Table 1.

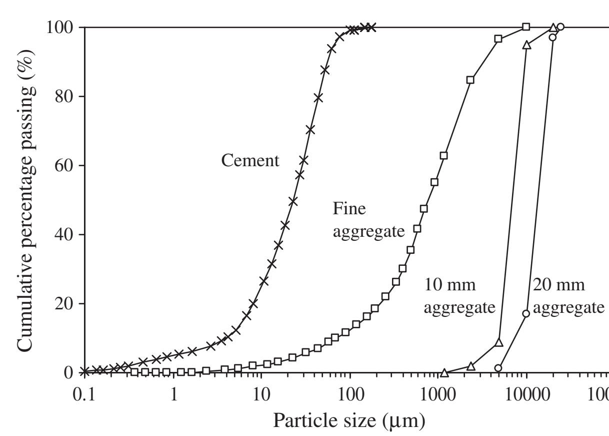


**Fig. 1.** Particle size distributions of cement, fine aggregate, 10 mm aggregate and 20 mm aggregate.