Powder Technology 253 (2014) 514–521

Contents lists available at ScienceDirect

Powder Technology

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

Packing density of concrete mix under dry and wet conditions

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ARTICLE INFO

Article history:
Received 27 May 2013
Received in revised form 1 December 2013
Accepted 7 December 2013
Available online 15 December 2013

Keywords:
Concrete mix design
High-performance concrete
Packing density

ABSTRACT

It is well known that the packing of particles in concrete has great effects on the performance of concrete, but existing codified methods for packing density measurement are all carried out under dry condition and do not account for the effect of water in the concrete mix. In recent studies by the authors, a wet packing method has been developed and the packing densities of cementitious materials, fine aggregate and blended fine plus coarse aggregate were found to be higher under wet condition than dry condition. In this study, both the dry and wet packing methods were applied to concrete mixes containing cementitious materials, fine aggregate and coarse aggregate. It was found that for the entire particle system in a concrete mix, the packing density is higher, the voids ratio is smaller and the filling effects of ultrafine supplementary cementitious materials are better revealed under wet condition than dry condition. Therefore, when measuring the packing density of a concrete mix, the wet packing method should always be used.

1. Introduction

High-performance concrete (HPC), which has not only high strength but also all round high performance, has become more and more popular in recent years [1]. Neville [2] has pointed out that "what makes the concrete a high performance one is a very low water/cement ratio". However, there is a limit to the lowering of the water/cement ratio, especially if only ordinary Portland cement (OPC) is used. This is because the water added must be sufficient to fill up the voids in the bulk volume of the cementitious materials in order to avoid entrapping air in the voids. With only OPC used, the voids content (the voids volume to bulk volume ratio) tends to be quite large. To overcome this problem, supplementary cementitious materials finer than OPC, such as ultrapulverized fly ash [3] and condensed silica fume [4], can be added to fill into the voids so as to improve the packing density (the solid volume to bulk volume ratio) of cementitious materials.

The above should also apply to the entire particle system in concrete, which comprises of cementitious materials, fine aggregate and coarse aggregate. With the particle size distributions of the entire particle system optimized so that the amount of medium size particles is just enough to fill up the voids between larger size particles and the amount of smaller size particles is just enough to fill up the voids between medium size particles and so on, the packing density of the particle system can be maximized to minimize the amount of water needed to fill up the voids. This would allow the water/cementitious materials (W/CM) ratio to be reduced to increase the strength and durability, and/or the cementitious paste volume to be reduced to increase the dimensional stability of the concrete. All in all, the packing density of the entire particle system should be a fundamental parameter governing the performance of concrete.

The packing density of the particles in concrete may have the following effects. Considering the water in paste/mortar/concrete, it is the excess water (the water in excess of that needed to fill up the voids in the particle system) that lubricates the particles. Therefore, a higher packing density of the particle system would at the same water content lead to a higher flowability [5] or at the same flowability requirement allow the use of a lower W/CM ratio to increase the strength and durability [6,7]. Considering the paste in mortar/concrete, it is the excess paste (the paste in excess of that needed to fill up the voids between the aggregate particles) that lubricates the aggregate particles [8]. Therefore, a higher packing density of the aggregate would at the same paste volume lead to a higher workability or at the same workability requirement allow the use of a smaller paste volume to increase the dimensional stability, cement consumption and carbon footprint.

Meanwhile, several theoretical packing models have been developed for modeling the packing of multi-blended solid particles (two or more size classes of particles blended together) for the purpose of predicting and optimizing the packing densities of cement paste, mortar and concrete [9–14]. More recently, Wong and Kwan [15] and Kwan and Fung [16] compared their experimentally measured packing density results with the theoretically predicted results by existing packing models to counter check the accuracies of the experimental results and the applicability of the existing packing models. Apart from packing models, computer simulations have also been developed to study the packing of particles [17–19].

However, the packing densities of cement paste, mortar and concrete have rarely been directly measured. For fine and coarse aggregates, there are codified test methods for measuring the packing density under dry condition [20–23], but for cementitious materials,

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http://dx.doi.org/10.1016/j.powtec.2013.12.020

there is up to now no generally accepted test method for measuring the packing density under dry or wet condition. Besides, it should be noted that the dry packing methods have the following problems: (1) the measured packing density is quite sensitive to the compaction applied [24]; (2) they do not include the possible effects of water and admixtures; and (3) the agglomeration and loose packing of the finer particles may seriously affect the measured packing density under dry condition [25–27]. Hence, the dry packing methods are not applicable to cementitious materials or any particle systems containing cementitious materials. To resolve these problems, the authors' research team has developed a wet packing method for measuring the packing density of cementitious materials under wet condition [28]. This method has been employed to study the effect of packing density on the rheology of cement paste [29,30]. Later, it was extended for application to fine aggregate [31] and blended fine and coarse aggregate [32], and then employed to study the effect of packing density on rheology of mortar [33,34].

In this research, the wet packing method was extended to measure the packing density of concrete mix under wet condition. Using this wet packing method, the wet packing densities of typical concrete mixes were measured with or without compaction applied and with or without superplasticizer added. The wet packing density results were compared with the respective dry packing density results obtained by the conventional dry packing method to study the effect of water. Furthermore, the effects of cement content, compaction, superplasticizer, double or triple blending of cementitious materials were also investigated. This is a very important step for further development of the wet packing method, which is an indispensable tool for studying the effects of packing density and for incorporating the concept of packing into mix design methods for high-performance concrete.

2. Testing program and methods

The testing program comprised of two phases, namely, Phase A and Phase B. The objectives of Phase A and Phase B were to measure the packing density of various concrete mixes under different conditions and to study the effects of blending on the packing density of concrete, respectively. In Phase A, ordinary Portland cement (OPC) was the only cementitious material used and concrete mixes with cement contents ranging from 5% to 30% in steps of 5% by volume were produced to measure their packing densities under different conditions. In Phase B, pulverized fuel ash (PFA) and condensed silica fume (CSF) were added to replace part of the OPC. The PFA and CSF contents each varied from 5% to 20% in steps of 5% by a volume of the total cementitious materials whereas the total cementitious materials content varied among 15% and 20% by volume. In both phases, crushed granite rock aggregates were used as the fine and coarse aggregates. The fine to total aggregate ratio was fixed at 0.4 whereas the 10 mm to 20 mm aggregate ratio was fixed at 1.0. In order to investigate the effects of water, compaction and superplasticizer (SP), a total of six testing conditions were applied, as summarized in Table 1 and explained later. When required, the SP was added at a constant dosage of 3%, measured in terms of liquid mass of SP by mass of the total cementitious materials.

For easy identification, each concrete mix sample was assigned a sample number. In Phase A, the sample number is in the form of X–Y, in which X = A denotes a concrete sample in Phase A and Y denotes the cement content as a percentage by volume of the concrete mix. In Phase B, the sample number is in the form of X–Y–Z, in which X = B denotes a concrete sample in Phase B, Y denotes the total cementitious materials content as a percentage by volume of the concrete mix and Z denotes the serial number of the test.

Table 1
Testing conditions.

Testing condition	Dry/wet	Compaction	Superplasticizer
D1	Dry	Uncompacted	Nil
D2		Compacted using a tamping rod	Nil
W1	Wet	Uncompacted	Nil
W2		Compacted using a tamping rod	Nil
W3		Compacted using a vibrator	Nil
W4		Uncompacted	Added

2.1. Dry packing tests

The test methods stipulated in British Standard BS 812-2: 1995 [21] for measuring the uncompacted and compacted packing densities of aggregate under dry condition were adopted. Basically, the concrete mix sample was filled into a steel container and the weight of the sample was measured to determine the packing density as the solid volume to bulk volume ratio. For easy reference, the testing conditions under which the uncompacted and compacted packing densities were determined are designated as D1 and D2, respectively (see Table 1). For testing under condition D1, the concrete mix sample was filled into the container for packing density measurement without any compaction applied. For testing under condition D2, the concrete mix sample was filled into the container in three equal portions and each time after filling a one-third portion, the concrete mix in the container was compacted by applying 20 compactive blows with a metal tamping rod.

For the concrete mix samples in Phase A, each sample was first used for measuring the uncompacted packing density under condition D1, and then remixed and reused for measuring the compacted packing density under condition D2. This was to study the effect of compaction on the dry packing density. For the concrete mix samples in Phase B, only the uncompacted packing density under condition D1 was measured because the tests in Phase B were mainly to study the effects of blending cementitious materials, not compaction.

2.2. Wet packing tests

The test method employed was essentially the same as the wet packing method developed previously for blended fine and coarse aggregate by the authors' research team [32]. It involved the following steps. First, the concrete mix sample was thoroughly mixed with predetermined amounts of water and SP (if any). Then, the sample was filled into a steel container. During filling, compaction was applied to the sample (if required). Finally, the bulk density of the sample was measured to evaluate the solid concentration of the particles. The container used was the same as that stipulated in BS 812-2: 1995 [21] for dry packing tests.

Four different testing conditions, namely, W1, W2, W3 and W4, had been applied during the wet packing tests (see Table 1). For testing under condition W1, no SP was added and no compaction was applied. For testing under condition W2, no SP was added but the concrete mix sample was filled into the container in three equal portions and each time after filling a one-third portion, the sample in the container was compacted by applying 20 compactive blows with a metal tamping rod (same compaction applied as for testing under condition D2). For testing under condition W3, no SP was added but the concrete mix sample was filled into the container in three equal portions and each time after filling a one-third portion, the sample in the container was compacted by using a poker vibrator. For testing under condition W4, SP was added but no compaction was applied.

For the concrete mix samples in Phase A, each sample was tested successively under all the four conditions W1, W2, W3 and W4. This was to study the effects of compaction and SP on the wet packing density. For the concrete mix samples in Phase B, each sample was tested under the condition W4 only because CSF is usually added together with SP and the tests in Phase B were mainly to study the effects of blending cementitious materials, not compaction.

Under wet condition, the spatial distribution and solid concentration of solid particles are dependent on the water to solid ratio by volume,