Construction and Building Materials 53 (2014) 102–109

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effects of particle packing density on the stability and rheology of self-consolidating concrete containing mineral admixtures

Parviz Ghoddousi [a], Ali Akbar Shirzadi Javid [a,*], Jafar Sobhani [b]

[a] School of Civil Engineering, Iran University of Science and Technology, P.O. Box 16765-163, Narmak, Tehran, Iran
[b] Department of Concrete Technology; Road, Housing & Urban Development Research Center (BHRC), Tehran 13145-1696, Iran

HIGHLIGHTS

- We present a novel wet method for determination of packing density of SCC mixtures.
- The particle size distribution of all of solids in a SCC mixture is considered.
- The stability of SCC mixtures is evaluated in the horizontal and vertical movement.
- We apply a new experimental study for the measurement of solid velocity in SCC mixtures.

ARTICLE INFO

Article history:
Received 6 July 2013
Accepted 21 November 2013
Available online 18 December 2013

Keywords:
Self-consolidating concrete
Packing density
Stability
Rheology
Mineral admixtures

ABSTRACT

This paper presents an experimental study on the influence of packing density of solid particles on the stability and rheology of self-consolidating concrete (SCC). Also it is tried to address a new method for determination the packing density of SCC mixtures. Seven powder-types of SCC mixtures with different packing density were made with inclusion of silica fume, metakaolin or low activity-granulated blast furnace slag as a substitution of Portland cement. Results demonstrated that there is an optimal packing density about 0.804 and a little lower than maximum packing density of 0.807 with minimum static segregation and final plastic settlement. Moreover in the optimum packing density of particles, the calculated velocity and rheological properties of SCC are improved. The results emphasized that the effects of mineral admixtures are completely different in the static and dynamic segregation. Mineral admixtures reduced static segregation (SCC at rest in vertical state) but increase dynamic segregation (SCC at flowing in horizontal state). This finding shows that the cementitious binder content must be sufficient in flowing state to restraint from dynamic segregation.

1. Introduction

One of the most important differences between SCC and conventional concrete is the incorporation of mineral admixtures and higher content of powder and fine aggregates. Since the Portland cement is the most expensive material of concrete, reducing the cement content and using of recycled materials such as limestone powder, fly ash and granulated blast furnace slag (GGBFS) in SCC is an economical solution. Also utilization of industrial recycled materials is one of the major arms towards sustainability development. Thus many studies regarding the effects of mineral admixtures on the properties of SCC have been established [1–9].

Many research studies has been published about the effects of mineral admixtures on the properties of fresh SCC in particular the rheology and workability [5,6,10–14]. However, one of the most important parameters has not yet been completely studied on SCC is the packing density of particles and the effects of mineral powders. Packing density of the solid particles is a fundamental parameter characterizing the properties of many granular systems; for example in the soil and concrete. Generally, SCC is characterized with a combination of water and solid phases, which the solid phases including coarse aggregates, fine aggregates, filler, cement and mineral admixtures. On the other hand, the packing density of solids influences SCC properties significantly. In the recent years, researchers have attained that the performance of concrete can be improved by maximizing the packing density of the solid particles contained therein [15–18]. For instance, the packing density of the materials is maximized to reduce the water to cementitious materials ratio in order to increase the strength and durability indexes in the 1994, by Delarrard and Sedran [19] and Lange 1997 et el. [20]. In 1996, Sedran et al. [21] tried to maximize the packing density of the entire granular skeleton, including the aggregate and cementitious materials, for the production of SCC. Later, in 2005,

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* Corresponding author. Tel.: +98 77182497.
E-mail addresses: shirzad@iust.ac.ir, a_shirzadi63@yahoo.com (A.A. Shirzadi Javid).

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http://dx.doi.org/10.1016/j.conbuildmat.2013.11.076

Brouwers and Radix [22] received that however the packing of the aggregate plays a major role; but the packing of all solid particles including coarse and fine aggregates, filler, cement and mineral admixtures, in the concrete mixture should be the basis for the mix design of SCC. Khayat et el. [23] realized that SCC with near optimum packing of aggregate exhibited lower viscosity and high-range water reducing admixture (HRWRA) demand, and better filling capacity than SCC with lower aggregate packing density. SCC with the optimum packing density exhibited a better stability due to the higher content of materials smaller than 80 µm and lower coarse aggregate volume. In the mixtures tested, adding more sand relative to coarse aggregates cause to reduce the binder and consequently reducing of packing density [24]. So it can be seen that there is a challenge on the packing density of SCC with regard to stability and rheological properties.

Some other researchers [25,26] tried to relate the packing density of solid materials and grading curve. In order to model the concrete mixture, all solids (aggregates, cementitious materials, filler and mineral admixtures) should be considered [26,27]. Consideration of packing of granular materials, the packing of particle size distribution (PSD) is presented by Andreasen and Andrersen [28] based on a semi-experimental study, and distanced the PSD with the higher packing density. Funk and Digner [29] revised this PSD to calculate for the smallest particle size (modified Andreasen and Andrersen model). Using the mentioned PSD, the rheological properties of mixtures can be improved. They concluded that with the higher packing, the more water is available to act as a lubricant for the solids, and accordingly the better fluidity could be gained. This emphasizes a positive relationship between rheological properties and the packing density of the concrete mixture [26,30]. In addition, there is a concern about the stability of SCC that is very important. In other words, it should be noted that there is a correlation between packing density, static segregation (means stability of SCC at rest) and dynamic segregation (means stability of SCC at the flowing state).

The problem here is that the conventional methods of packing density measurement, as presented in the existing standards [31–35], propose to measure the bulk density of the coarse and fine aggregates under dry condition and then determine the packing density. So they do not include finer solid materials like cement and mineral admixtures and the possible effects of water. These problems are more serious when finer particles cause agglomeration and have loosening effects on the coarser solids [36,37]. Hence the dry packing methods are not applicable to cementitious materials. Recently Wong and Kwan [38] have presented a new method to measure the packing density of cementitious materials. New method proposed the wet packing method, which mixes the cementitious materials with water and then; the solid concentration of cement paste formed at varying water to cementitious materials ratio is measured and subsequently characterized the packing density of the cementitious materials as the maximum solid concentration attained [39].

Thus in this experimental study, the wet packing method is intended to be applied for determination of the packing density of the self-consolidating concrete. Moreover, the effects of mineral admixtures on the packing density, plastic settlement strain, settling velocity of particles, static segregation, dynamic segregation and rheological properties of SCC are to be evaluated.

2. Experimental programs

2.1. Materials

In the present study, a locally available ordinary Portland cement type II conforming the requirements of ASTM C150 [40] was utilized. The mineral admixtures were limestone powder, silica fume, metakaolin and a type of low activity ground granulated blast-furnace slag (GGBFS). The chemical properties of cement and mineral admixtures are listed in Table 1.Two types of river sand (coarse and fine sand) with a specific gravity of 2550 kg/m^3 was also used as fine aggregate. Crushed limestone with maximum size of 19 mm and specific gravity of 2600 kg/m^3 was used as coarse aggregate. The particle size distribution of materials used as solids in this work is presented in Fig. 1. High-range water reducing admixture (HRWRA) with base of polycarboxylate was also utilized.

2.2. Mixtures proportions

The proportions of the SCC mixtures are summarized in Table 2. As can be seen, the volume of paste is similar for all of mixtures but with different compositions. Seven types of SCC mixtures are prepared as follows:

S-1 as a reference SCC mixture, S-2 containing of a coarser limestone powder comparing with S-1, S-3 containing of silica fume, S-4 containing of metakaolin, S-5 containing of a higher percent of coarser sand comparing with S-1, S-6 containing of a higher percent of fine sand comparing with S-1 and S-7 containing of GGBFS. Apart from the SCC mixture type S-2, fine limestone powder is used as filler in the other mixtures.

2.3. Test procedure

2.3.1. Workability and rheology of SCC mixture

The workability tests including slump flow, J-ring, T_{50}, V-funnel and visual stability index (VSI) were performed according to PCI methods [41]. For measuring the rheology parameters including yield stress and plastic viscosity, a coaxial rheometer was used. Fig. 2 shows the developed and utilized rheometer for this study.

2.3.2. Measurement of packing density

As it mentioned before, a new method of measuring packing density known as wet packing method developed by Wong and Kwan [38] was applied here for measuring the real packing density of SCC mixtures. Procedure of the measurements is described as follows:After making a SCC mixture in mixer, concrete is poured into a cylinder container of size 180 × 160 mm. The mass and volume of SCC in the mould were measured as M and V respectively. If the SCC mixtures consist of several different materials, the volume of the solid materials V_C in the mould may be worked out from Eq. (1):

$$V_C = \frac{M}{\rho_w u_w + \rho_g R_g + \rho_s R_s + \rho_c R_c + \rho_l R_l + \rho_m R_m} \tag{1}$$

where ρ_w is the density of water, u_w is the ratio of the volume of water to the solid volume of granular material and ρ_g, ρ_s, ρ_c, ρ_l and ρ_m are the densities of gravel, sand, cement, limestone powder as filler and mineral admixtures respectively. Also R_g, R_s, R_c, R_l and R_m are the volumetric ratios of gravel, sand, cement, limestone powder and mineral admixtures to the total solid materials respectively. Having obtained V_c and V packing density (ϕ) may be determined as Eq. (2):

$$\phi = \frac{V_C}{V} \tag{2}$$

Table 1
Chemical properties of cement and mineral admixtures.

Constituents	Cement	Coarse limestone powder	Fine limestone powder	Silica fume	GGBFS	Metakaolin
Sio_2	20.74	2.80	0.76	94.00	36.06	52.80
Fe_2O_3	3.50	0.50	0.7	0.10	0.70	4.21
Al_2O_3	4.90	0.35	0.63	1.00	9.16	36.30
CaO	62.95	51.22	42	1.00	36.91	0.10
MgO	1.20	1.80	12	0.60	10.21	0.81
SO_3	3.00	1.24	2.27	1.20	1.15	–
Loss of ignition	1.56	42.06	40.94	–	–	3.53
Insoluble residue	0.74	2.80	0.74	–	–	–