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Improved mix design method of self-compacting concrete based on coarse aggregate average diameter and slump flow

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HIGHLIGHTS

- Relations among SF, $d_{av,i}$ and $V_{g,i}$ were discussed.
- An improved mix design method of SCC was proposed according to SF, $d_{av,i}$ and $V_{g,i}$.
- The proposed mix design method was verified availably by experiments.

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ABSTRACT

Based on the relations between slump flow (SF), coarse aggregate average diameter ($d_{av,i}$) and volume of coarse aggregate ($V_{g,i}$) used in self-compacting concrete (SCC), it was found that the preferable SF was that coarse aggregate could flow into a compact single layer status when *SF* testing was taken. Therefore, an improved mix design method of SCC was proposed according to relations among *SF*, $d_{av,i}$ and $V_{g,i}$. In the same $V_{g,i}$ condition, large $d_{av,i}$ is suitable for small *SF*, but small $d_{av,i}$ should match large *SF*. When nominal size of coarse aggregate was 5–20 mm, proper *SF* for SCC should be 570 mm–720 mm. Results from the validated experiment show that properties of SCC including workability and compressive strength can satisfy the requirements. This improved mix design method helps to further develop SCC and cuts cost in real engineering projects.

1. Introduction

Self-compacting concrete (SCC) is a kind of concrete that can flow and consolidate under its own weight, pass through the spaces between the reinforcement bars to fill the formwork completely, and maintain its stable composition simultaneously [1–4]. Because of the excellent workability of fresh SCC, good mechanics and durability of hardened concrete, SCC got more attention since it was born in Japan in 1980's [5]. And now SCC becomes an important developing direction in modern concrete technology.

Generally speaking, mix design is the first importance for concrete production. Mix design and the properties of fresh concrete are the most critical points in relation to the mechanical characteristics of hardened SCC [6]. A good mix design entitles concrete fulfilling workability and hardened properties. In 1993, Ozawa and Maekawa proposed the first well-known mix design method of SCC [7–9], which was later improved in 1998 by the contribution of Ouchi et al. [10]. The general method assumes as the starting point the design of the mortar phase, which must meet certain flow requirements, necessary to achieve a SCC. This method required quality control of paste and mortar prior to SCC mixing, while many ready-mixed concrete producers did not have the necessary facilities for conducting such tests and the mix design method and procedures were too complicated for practical implementation[11].

From then on, in order to put SCC into practice from theoretical studies easily, researchers kept an eye on mix design method of SCC and got fruitful results. Su et al. [11] proposed a simple mix design method for SCC. First, the amount of aggregate required was determined, and then the paste of binders was filled into the voids of aggregate to ensure that the concrete thus obtained had fluidity, self-compacting ability and other desired SCC properties. Long et al. [12,13] calculated the relative position of fine and coarse aggregate in SCC, analyzed the influence of relative position of aggregate on workability on SCC, and then proposed mix design method of SCC based on aggregate space model. Kheder et al.

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[14] presented a method which was capable of proportioning SCC mixtures with specified compressive strength, contrary to previous SCC proportioning methods that emphasized the fulfillment of fresh properties requirements more than strength requirements. Gong et al. and Li et al. [15,16] provided a convenient mix design method based on the distraction model of aggregate skeleton, the voids among aggregate and surplus thickness of sand and thickness of paste around aggregate. They both considered the voids among aggregate and calculated the volume of paste filled in the voids and surplus thickness paste around aggregate. Nepomuceno et al. [17] divided SCC into two phases with coarse aggregate and mortar, and evaluated the interaction between coarse aggregate and mortar phase particles. According on his study, correlations between mix design parameters, fresh and hardened properties were obtained and a methodology was put forward to the mix design of SCC. As strength was the first important parameter for concrete. For the sake of mineral admixtures playing an important role in SCC [18,19], absolute volume mix design method and related parameters of SCC with different mineral admixtures including ground granulated blast furnace slag, fly ash and limestone powder were provided [20,21]. The mix design method of SCC with addition of silica fume was also presented for obtaining high strength SCC [22–24]. As for plastic viscosity of cementitious materials took great influence on stability of SCC, Wu et al. [25] provided a mix design method based on plastic viscosity of mortar used in SCC. By the adjusting of mineral admixture, additives and water to binder ratio, plastic viscosity of mortar could be under control. Furthermore, in some standards [4,26], the range of different materials used in SCC was put forward, but how to choose the exact materials contents required rich experience.

From these analyses above, it was sure that mix design method of SCC does still not reach an agreement. Just as the first importance parameter of ordinary concrete (OC) is compressive strength. The primary difference between SCC and OC is that SCC owns excellent workability. Therefore, workability should be the first important mix design parameter for SCC. Practically, as volume contents of coarse aggregate in SCC is no less than 280 L/m^3, coarse aggregate plays an important role in SCC workability. Some studies showed that coarse aggregate properties such as maximum size, texture and type have direct effects on achieving SCC [27,28]. Mechanical properties should decrease when volume of coarse aggregate from 60% to 30% in SCC [29]. Higher SCC coarse aggregate's volume for lower flow restrictions keeping passing ability, and optimization of coarse aggregate volume for different flow restrictions reduces SCC cost [30]. However, more attentions were paid to the influence of cement, mineral admixtures and additives on SCC workability.

This paper explored the relations between SF, $d_{av,i}$ and $V_{g,i}$ in SCC, and developed an improved mix design method of SCC. Objectives of the proposed method were to present SCC containing more coarse aggregate with great convenience in field application and low cost.

2. Principle

For fresh SCC can flow and consolidate spontaneously under its own weight, workability is the most critical characteristic of SCC. The testing method of slump flow (SF) is the most convenient and rapid way to judge fresh SCC workability for concrete workers in site. Specifically, in the SF testing process, after slump cone is lifted, SCC can flow smoothly out from slump cone, and form a concrete layer on the ground. Fig. 1 shows two typical SCC workability states when SF testing is carried out. The main difference between the state I and state II is that the space between coarse aggregate particles in SCC. Under state I condition, there are large spaces among coarse aggregate particles, and the mortar fills in these spaces, called loose single coarse aggregate layer. However, under the state II, the spaces between coarse aggregate particles are close, and a thin mortar layer fill among coarse aggregate particles, called compact single coarse aggregate layer. In this state the spaces between coarse aggregate in SCC are as close as possible. Obviously, when SF is same, SCC with state II contains more coarse aggregate. SCC with more coarse aggregate can obtain good mechanical properties, excellent durability and also low price.

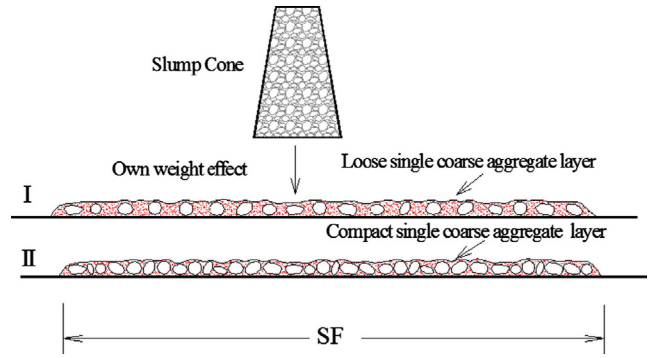

Fig. 1. SF testing schematic diagram of SCC.

Fig. 2(a) & (b) provide typical pictures of SF testing. As can be seen from Fig. 2(a), the distribution of coarse aggregate in SCC is uniform. The mortar layers among coarse aggregate particles are thick. Mortar content is obviously large. SCC presents some tendency of segregating and bleeding, likely resulting in quality fluctuation in hardened concrete. Fig. 2(b) shows that small coarse aggregate filling in the void of large coarse aggregate. Spaces between coarse aggregate are close, and mortar layers packing coarse aggregate are thin. In this condition, volume content of coarse aggregate is large, and the SCC is low cost. The main effect of mortar among coarse aggregate is to lubricate.

According to the analysis between SF and coarse aggregate above, the maximum coarse aggregate volume content would occur when coarse aggregate approximately reaches compact arrangement single layer in SF testing. As a result, the maximum coarse aggregate volume content can be took as an important mix design parameter for SCC. Therefore, the assumptions for SCC mix design in this paper are as follows.

(1) SCC is mainly consisted of mortar and coarse aggregate, and both mortar and coarse aggregate satisfy the requirements of standards involved.
(2) Coarse aggregate used in SCC can be approximately described as sphere shape, and coarse aggregate can flow into compact single layer in SF testing.
(3) Strength of SCC is decided by water to binder ratio.
(4) Fluidity of SCC can be adjusted through mortar properties.

3. Mix design method

Fig.3 shows the schematic diagram of compact single coarse aggregate layer in SF testing. As can be seen from Fig. 3, if coarse aggregate flows into a single compact layer under the effect of own weight, the area taking SF as diameter will be consisted by horizontal projected area of coarse aggregate, mortar layer thickness embracing coarse aggregate and void between coarse aggregate.

Fig. 3 shows there should be two kinds of void among coarse aggregate. One void is S_0 surrounded by three coarse aggregates, and the S_0 area can be calculated through Eq. (1). That another void is S_1 surrounded by four coarse aggregates can be calculated by Eq. (2).