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Methodology for the mix design of self-compacting concrete using different mineral additions in binary blends of powders

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HIGHLIGHTS

- A methodology for SCC mix design was proposed to reconcile workability and strength.
- Interaction between the coarse aggregates and mortar phase particles was evaluated.
- Maximum volume of coarse aggregates strongly depends on the mortar phase properties.
- L-box test is more effective than Box test to evaluate the self-compactability level.

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ABSTRACT

Objective: Interaction between the coarse aggregates and the mortar phase of self-compacting concrete (SCC) was evaluated in a two phase program.
Materials and methods: In the first phase, 74 mortars suitable for SCC were produced, combining different volumetric ratios between powders and fine aggregates and different binary blends of powders. In the second phase, 60 concretes were produced with different volumetric ratios between the mortar phase and the coarse aggregates, and their fresh and hardened properties were evaluated.
Results: Based on this study, correlations between mix design parameters, fresh and hardened properties were obtained and a methodology was proposed for the mix design of SCC.

1. Introduction

Since the first developments of self-compacting concrete (SCC), several methods have been proposed for its mix design, especially in the 90s, coinciding to the period of a quick increasing use of SCC. In general, all methods reflect, with greater or lesser extent, some concern with the optimisation of the granular skeleton and the reduction of the paste volume. In large scale applications, the economy and robustness of the mixtures are always a present concern. It is a common ground that there is no single universal solution, but rather a very wide range of possible solutions that, taking into account locally available materials, are able to give a satisfactory outcome in each particular situation.

The first well known mix design method was proposed in 1993 by Okamura, Ozawa and Maekawa [1–3], which was later improved in 1998 by the contribution of Ouchi et al. [4]. This method, developed in the University of Tokyo, was then known as the general method. 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. In the mortar phase, the ratio between the volume of fine aggregate and the volume of the mortar excluding air (Vs/Vm) is 0.40, and the water/powder ratio by volume (Vw/Vp) and superplasticizer/powder ratio by mass (Sp/P) are adjusted to obtain the required flow properties. The volume of coarse aggregates (Vg), with a maximum size of 20 mm, is calculated on the basis of 50% of dry compacted bulk volume of coarse aggregate excluding air content (Vap). The slump-flow, v-funnel and U-box tests are used to evaluate the self-compactability of concrete. The general method considers some of the mix design parameters as almost constant, which

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allows little flexibility in optimising the granular skeleton, usually leading to higher portions of paste when compared to an optimised granular structure [5]. Afterwards, the general tendency was to focus on optimising mixture proportions, aiming to reduce paste volume, mainly by increasing the volume of aggregates. Some contributions to improve the general method were proposed by Pelova et al. [6], Domone et al. [7] and Edamatsu et al. [8]. The general idea was that it was possible to increase the volumetric ratio between the fine aggregate and mortar (Vs/Vm) and increase the volume of coarse aggregate (Vg) by reducing its maximum dimension, but the equilibrium between both variables is a focal point to achieve the self-compactability.

A different approach from that used in the general method was developed in CBI by Petersson, Billberg and Bui [9,10] in 1996. They based their work on previous studies conducted by Bui and Tangtermsirikul and Bui [11]. In the CBI method, the concrete was assumed to be consisted basically of two phases, namely, the liquid phase (paste) and the solid phase (coarse and fine aggregates). The reduction of the paste volume is achieved by optimising the solid phase, combining the maximum inter-particle distance criterion and the blocking criterion. The first allows estimating the optimal coarse/fine aggregate ratio, while the second allows estimating the maximum volume of aggregates. The model includes the external conditions, such as the diameter and the spacing between steel bars. Later developments by Bui and Montgomery [12] considered the introduction of an additional criterion, called the criterion of liquid phase. The liquid phase criterion, in conjunction with the blocking criterion, leads to the evaluation of the minimum volume of paste required to produce a satisfactory SCC and to ensure proper passing ability in L-box test.

The method developed by Sedran and Larrard [5] in the LCPC has also represented a contribution to optimisation of the solid skeleton of the SCC. Its main feature is based on the use of a mathematical model developed by LCPC and called Compressive Packing Model (CPM). This model considers any range of sizes of materials and differs from the previous in that the cement, additions and aggregates are all included in the CPM. The method is supported on mathematical models that estimate the fresh properties as a function of the characteristics of materials and external conditions, such as the border effect provoked by formwork or the effect of spacing and diameter of the steel bars.

Many other approaches were developed, as for example the one proposed by Su et al. [13] and Su and Miao [14] for medium strength SCC, that starts by determining the volume of aggregates using the packing factor (PF) and only later the properties of the paste. Sonebi [15] has also investigated the effects of the cement content, additions and SP on the fresh and hardened properties of SCC and proposed a statistical model to simplify the test protocol required to optimise a given mix. Improving performance and robustness of SCC in large scale production emerged naturally as a key factor concern. Kwan and Ng [16] argue that decreasing the W/C ratio and increasing the fine/total aggregate ratio are both effective means to improve the performance and robustness of SCC. Kwan and Ng [17] have also confirmed that the addition of pulverized fuel ash and/or condensed silica fume can significantly improve the performance and, more importantly, the robustness of SCC.

The EFNARC specification and guidelines for SCC [18], published in 2002, reflects the so far practical experience and the latest research findings, and provided to his members in Europe a framework for design and use of high quality SCC. Indicative typical ranges of proportions and quantities are given for initial composition, assuming that further modifications could be necessary to meet strength and other performance requirements. The initial parameters are: a water/powder ratio by volume (Vw/Vp) of 0.80–1.10; a total powder content (Vp) of 0.16–0.24 m^3/m^3 (400–600 kg/m^3); a coarse aggregate content (Vg) of 0.280.35 m^3/m^3; a W/C ratio selected based on EN 206-1:2000 [19] and a water content not exceeding 200 l/m^3. In 2005, the European Guidelines for SCC was published [20]. This document did not proposed any standard method for SCC mix design, because, as it is mentioned, many academic institutions, admixture, ready mixed, precast and contracting companies have developed their own mix proportioning methods. The option was to establish the mix design principles based on general recommendations. In America, ACI [21] recommends different contents of ultrafine material from 355 kg/m^3 to more than 458 kg/m^3 depending on the required slump-flow, a volume of paste (Vpw) from 0.34 to 0.40 m^3/m^3, a volume of mortar (Vm) from 0.68 to 0.72 m^3/m^3, a W/C ratio by mass from 0.32 to 0.45 and a content of cement from 386 to 475 kg/m^3.

Looking at the application of the SCC from 1993 to 2003, Domone [22] concluded that successfully performed SCC were obtained for a great variety of constituents and mix proportions, but considerable scope for optimisation of mixes for greater efficiency and economy was still possible. As the most critical parameters for successful SCC mix design, Domone [22] has identified: the coarse aggregate volume, the paste content of concrete and the fine aggregate percentage of the mortar. The powder content and water/powder ratio have shown greater flexibility. Median values of the key mix proportions were a coarse aggregate content (Vg) of 0.312 m^3/m^3, a paste content (Vpw) of 0.348 m^3/m^3, a powder content of 500 kg/m^3, a water/powder ratio by weight (W/P) of 0.34, and a fine aggregate/mortar ratio (Vs/Vm) of 0.475. The selection of the component materials seems to depend on local availability, but some predominant features can be identified: the crushed rock with a maximum size between 16 and 20 mm was predominant; nearly all cases used either a binary or ternary blend of Portland cement with additions of all the types used in conventional concrete, but the limestone was the most common addition; all mixes included a SP, but to make mixtures more robust, almost half cases use a VMA in addition to SP. The filling ability of the concrete was evaluated mainly by the slump-flow and flow rate values and in some cases the L-box and the U-box tests were used to evaluate the passing ability. Slump-flow varied mainly in the range of 600–750 mm, v-funnel times varied from 3 to 15 s, L-box passing ratio values were all in excess of 0.8 and U-box filling height values were in excess of 300 mm, with the reinforcement spacing varied in some cases to suit the application. The 28 day compressive strength varied from 20 to nearly 100 MPa.

Despite the time elapse of about two decades after the first proposal for the mix design of SCC, the attempted for the optimisation of SCC mortar phase still carried on. Li and Kwan [23] considered that the rheology of a fresh concrete was 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. Li and Kwan [23] have 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). As a result, Li and Kwan [23] extended this concept to cement–sand mortar and purposed a mix design method based on the WFT. They found that both the WFT and cement/aggregate ratio have major effects on the rheology of mortar, but the WFT is still the single most important factor. More recently, Kwan and Li [24], found that the WFT play an important role in the adhesiveness and strength of mortar, and is therefore a key parameter to be considered in the design of mortar and concrete mixes.

Nepomuceno et al. [25,26] have also proposed a methodology for the mix design of the mortar phase of SCC that allows to reconcile fresh properties and compressive strength when binary blends of powders are used. Later, a new methodology for the mix design