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Optimum design of low-binder Self-Compacting Concrete based on particle packing theories

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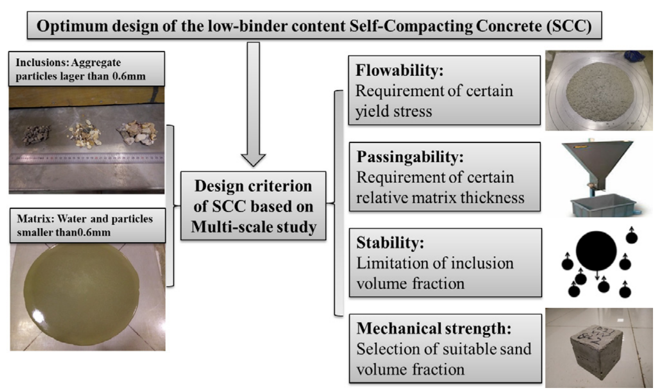
HIGHLIGHTS

- A multi-scales approach is successfully applied to design the low-binder SCC.
- The content of the inclusion dominates the flow status of low-binder SCC.
- The relative matrix thickness highly influences the passing ability of low-binder SCC.
- The increase of the matrix yield stress and inclusion content are beneficial to the stability of SCC.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper focuses on the optimum design of low-binder Self-Compacting Concrete (SCC) based on particle packing theories. It is first demonstrated that a multi-scales approach can be considered and the mortar with particle sizes smaller than 0.60 mm can be regarded as the matrix of the concrete mixtures. It is also shown that in order to design a low-binder SCC, it is necessary to consider the thresholds of the inclusion volume fraction, the relative matrix thickness and the yield stress of the matrix that respectively relating to flowability, passing ability and stability of the concrete mixtures. Finally, in order to simplify the mix design of the low-binder SCC, recommendations of the values of the distribution modulus ($\boldsymbol{q}$) in the optimum packing curves are proposed for both the aggregate mixtures and the total particle mixtures (including powders) in SCC, respectively.

1. Introduction

Since Self-Compacting Concrete (SCC) was invented several decades ago, it has undergone a great development and has solved many construction problems especially in the condition of the dense reinforcement structure (e.g. nuclear power plant), the special pouring space (e.g. high-speed rail board) and the pumping of super high-rise buildings [1–7]. However, according to Domone's study [8], in order to satisfy the properties of high workability of SCC, typical SCC usually has a binder content around 500 kg/m^3 which can result in many potential problems especially in the aspects of the structural safety and environmental degradation.

From the engineering point of view, the use of large amount of cementitious material can cause apparent shrinkage and cracking

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in the structure due to the fact that the total volume of solid phases reduce since the hydration of the cement clinker [9,10]. From the environmental point of view, the production of 1 t of the cement clinker will produce 0.7–0.9 t of CO_2 (e.g. 0.706 t in France, 0.9 t in China and 0.935 t in the United States of America) [11], which have a notably pernicious impact on the global greenhouse effect. Moreover, from the economic point of view, the use of a large amount of cement clinker will undoubtedly increase the cost of per unit volume of SCC as well.

In order to mitigate the negative effects of excessive use of the cement clinker, in recent years, many studies have focused on the design of the low binder or low paste content SCC. Su et al. [12,13] studied the design methods aiming at producing medium strength SCC or flowing concrete with low binder content by inducing the packing factor based on the packing of aggregates. By using this mix design method, it is possible to design the SCC with relatively low binder content comparing to the normal SCC. Kwan et al. [14–16] adopted the methods of aggregate proportioning and clinker substituted either by adding ground sand or limestone fines respectively, both of which proved to be effective to reduce the paste volume and the carbon footprint of SCC. Wallevik et al. [17,18] proposed the concept of Eco-SCC (the content of binder materials is lower than 315 kg/m^3), whose design principle is to modify the gradation of the total solid particles (coarse aggregate, fine aggregate, inert filler as well as cement clinker) in order to make it conform to the lattice effect [19] and the theoretical Particle Size Distribution (PSD) curves [20–22]. Long et al. [23] designed the low-binder SCC based on the packing densities of both aggregates and total solid mixtures, and the SCC mixtures show obvious ecological sustainability and cost savings.

$$\phi_{i\_3-PM} = \frac{1}{\sum_{k=1}^{n}\frac{y_k}{\phi_k} - \sum_{j=1}^{i-1}(1-b_{ij\_3-PM})(1-\phi_j)\frac{y_j}{\phi_j}\left[1-c_{ij}\left(2.6^{\sum_{j=1}^{i-1}y_j}-1\right)\right] - \sum_{j=i+1}^{n}(1-a_{ij\_3-PM})\frac{y_j}{\phi_j}\left[1-c_{ij}\left(3.8^{y_j}-1\right)\right]} \quad (4)$$

Practically, most of the studies which aim at lowering the required cement content or optimizing the properties of concrete during fabrication are all highly valued the nature of the particle packing mainly by the following three means [24,25]:

- Optimization packing curves: adjusting the proportion of concrete components to make the gradation close to the optimization curves such as Fuller curve [20], Andreasen and Andersen curve (Cf. Eq. (1)) [21], and its modified form (Funk and Dinger curve, Cf. Eq. (2)) [22], as well as other optimization curves considering the shapes of the particles [26,27], etc.;

$$P_d = \left(\frac{d}{d_{max}}\right)^q \quad (1)$$

where d is the particle size being considered; P_d is the fraction of the particle size smaller than d; d_{max} is the maximum particle size in the mixture; q is the parameter for adjusting the curve.

$$P_d = \frac{d^q - d_{min}^q}{d_{max}^q - d_{min}^q} \quad (2)$$

where d_{min} is the minimum particle size in the mixture.

- Particle packing analytical models: the theoretical packing density of a mixture is mathematically calculated by knowing the PSD and the packing density of different mean sizes of the particles in the mixture. In fact, there are numerous packing models such as Furnas model [28], Toufar model [29], Ouchiyama and Tanaka model [30,31], De Larrard model (also known as Compressible Packing Model, CPM, Cf. Eq. (3)) [32] as well as 3-Parameter model (3-PM, Cf. Eq. (4)) [33,34]. However, both the latter two models consider the influence of the presence of the larger particles to the smaller particles as well as the presence of the smaller particles to the larger particles which can be described as the "loosening effect" and the "wall effect", respectively. Further, the 3-Paremeter model proposed by Kwan et al. considers a third effect named "wedging effect" between the small and large particles making the modeling results to be more consistent with the experimental values.
- Numerical simulations: a virtual particle skeleton is built according to the particle size distribution input in the discrete element models to simulate the packing properties as well as the flowability of concrete mixtures [35–37].

$$\phi_{i\_CPM} = \frac{1}{\sum_{k=1}^{n}\frac{y_k}{\phi_k} - \sum_{j=1}^{i-1}(1-b_{ij\_CPM})(1-\phi_j)\frac{y_j}{\phi_j} - \sum_{j=i+1}^{n}(1-a_{ij\_CPM})\frac{y_j}{\phi_j}} \quad (3)$$

where y_i is the volumetric fraction of size class i with $\sum_{i=1}^{n}y_i = 1$; ϕ_i is the packing density of size class i; a_{ij_CPM} and b_{ij_CPM} are the loosing effect and wall effect of CPM, respectively (Cf. Eqs. (5) and (6)); a_{ij_3-PM}, b_{ij_3-PM} and c_{ij} are the "loosing effect", "wall effect" and "wedging effect" of 3-PM, respectively $s < 1$ (Cf. Eqs. (7)–(9)).

$$a_{ij\_CPM} = \left[1-(1-s)^{1.02}\right]^{0.5} \quad (5)$$

$$b_{ij\_CPM} = 1-(1-s)^{1.50} \quad (6)$$

$$a_{ij\_3-PM} = 1-(1-s)^{3.3} - 2.6\cdot s\cdot(1-s)^{3.6} \quad (7)$$

$$b_{ij\_3-PM} = 1-(1-s)^{1.9} - 2\cdot s\cdot(1-s)^{6} \quad (8)$$

$$c_{ij\_3-PM} = 0.322\cdot\tanh(11.9\cdot s) \quad (9)$$

where s is the size ratio of size class i and j (noting that $s < 1$, namely s is always the value of smaller size devided by larger size).

However, in order to further fabricate the sustainable SCC and reduce the use of cement clinker while maintain a acceptable flowability and stability, it is necessary to get a better understanding of the influence of particle packing on the rheological and hardened properties of SCC from a more theoretical point of view.

In this study, we first experimentally studied the packing properties of solid particles with and without powders to show the relationship between the particle packing status and the CPM and 3-PM mentioned above. We then show the rheological properties including the flowability, passingability, and stability of SCC (all of which are proved to be the basic performances that a SCC can be cast successfully [4,5,8]) as well as the mechanical properties of the designed medium strength (40 MPa) SCC. In the second part, key factors which control the fresh state of SCC were proposed based on several physical rheological models aiming at establishing several criterions to ensure that the designed low-binder mixtures can meet the basic requirements of SCC. Finally, the