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Assessing particle packing based self-consolidating concrete mix design method

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HIGHLIGHTS

- A modified Brouwers particle packing based mix design algorithm is proposed.
- A wider range of particle distribution modulus (q) from 0.23 to 0.29 is proposed.
- Proposed design algorithm can reduce up to 20% binder content.
- Mixtures designed by proposed method have good performance based behaviors.
- Relationships are found in rheology, formwork pressure, and air structure.

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ABSTRACT

A particle-packing based mix design method, originally proposed by Brouwers, is modified and applied to the design of self-consolidating concrete (SCC) mix proportions. The essence of this method is to improve particle packing of the concrete system and reduce the paste quantity while maintaining concrete quality and performance. Using this method, a large matrix of SCC mixes, made of different aggregate types, sizes, and supplementary cementitious material (SCMs) types, was designed to have a particle distribution modulus (q) ranging from 0.23 to 0.29. Fresh properties (such as flowability, passing ability, segregation resistance, yield stress, viscosity, set time and formwork pressure) and hardened properties (such as compressive strength, surface resistance, shrinkage, and air structure) of these concrete mixes were experimentally evaluated. The concrete mixes designed using the modified Brouwers mix design algorithm and particle packing concept had a potential to reduce up to 20% binder content compared to existing SCC mix proportioning methods and still maintain good performance.

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1. Introduction

Self-consolidating concrete (SCC), as an innovation in concrete technology, has passed from the research stage to field application in the precast and cast-in-place (CIP) industries. To date, more than 17 proportion methods have been proposed worldwide. Even though there are an enormous number of publications on laboratory SCC mix design studies, there is no unique solution for any given application. Table 1 summarizes the possible ranges of the ingredient proportions recommended by a set of selected design methods.

Although the methods vary widely in overall approach and the level of complexity, most methods are proportioned to achieve desirable fresh concrete properties, such as passing ability, filling ability, and segregation resistance [3]. It is generally agreed that controlling the aggregate system, paste quality, and paste quantity is essential for SCC mix design. Minimizing void content among aggregate particle can permit more paste to cover aggregate surfaces in a given concrete system, thus improving workability. Reducing capillary pores, can further enhance concrete strength and durability [16].

This study aims at applying the improved particle packing based mix design method to SCC mix design and to minimize the paste quantity whilst maintaining concrete performance.

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Table 1
Existing methods for proportioning SCC.

Method	Cement (kg/m^3)	Filler (kg/m^3)	Water (kg/m^3)	Fine agg. (kg/m^3)	Coarse agg. (kg/m^3)	w/c	w/cm
Rational Mix Design by Okamura and Ozawa [1]	Rest of mixture volume		–	40 to 50% of mortar volume	50 to 60% of solid volume	–	0.9 to 1.0 by volume
Sedran et al. [2]	Combination of binders is fixed based on previous knowledge to satisfy compressive strength and material availability		–	Saturation level is determined and 50% of this amount is used	–	With previous knowledge of material properties to determine the water demand of the binder combination with HRWRA	
Excess paste theory [3]	Not specified, based on the applications			Not specified, based on the applications		Optimum between 0.8–0.9	
CBI and extension [4]	If the determined paste volume for both blocking and liquid criteria is higher than 420 l/m3, smaller size aggregate need to be considered			Make sure the average particle diameter is smaller than 6.5 mm		–	
LCPC [5]	430	50	170	847	825	–	
Particle–matrix model [6]	Flow resistance ratio between 0.6–0.8			–		–	
Su et al. [7]	>270	–	–	Sand to total aggregates ranges from 50% to 57%, total aggregate ranges from 59% to 68%		–	
Statistical design	250–600 kg/m^3		–	Varied to achieve volume	Hold constant	0.37–0.50	0.38–0.72
ACBM [8]	Similar to extension of CBI method			Similar to extension of CBI method		–	
EFNARC [9]	400 to 600 kg/m^3		Maximum 200 kg/m^3	Rest of mixture	28–35% by volume	Use slump cone and v-funnel test to determine	
Concrete manager software	Not specified, based on the applications						
DMDA [10]	Fly ash is considered as part of the aggregate		Minimum 160 kg/m^3	–		Minimum 0.42 to prevent autogenous shrinkage	
Brouwers and Radix [11]	Based on prior knowledge to provide the range		–	Combined aggregate gradation with the preferred range of distribution modulus q between 0.21 and 0.25		Depend on application and provide the ranges	
ACI 237R [12]	386–475 kg/m^3; Paste fraction: 34 to 40%			0.32–0.44	28–32%	–	0.32–0.45
ICAR [13]	Paste volume: 28–40%		–	16 mm for most applications; 9.5 mm for challenging passing ability, uniform grading with high packing density preferred, S/A = 0.40–0.50, equidimensional, rounded aggregates preferred		–	0.30–0.45, higher with VMA
UCL [14]	–		–	45% of mortar volume	30–40%	–	0.28–0.36
Strength based method [15]	Based on predetermined water content and w/cm		Based on air content and aggregate size	–	44–56%	Wide range	Wide range

2. Background

SCC, as a type of high performance concrete, comprises materials that have an enormous size range, i.e., from powder in the nano-meter (nm) range, up to very coarse particles, which can be as large as 25 mm [17]. The influence of the particle size distribution (PSD), governing both packing and internal specific surface area, has been reported [18–20]. Brouwers and Radix [11] proposed a particle packing based mix design method that considered the grading of all solids in a SCC mixture.

2.1. Particle packing theory development

There are a number of packing models available to describe both continuous and discrete packing. Five basic models were reviewed by Jones et al. [21], and they are: (1) Toufar, and modified Aim and Toufar model; (2) Dewar model; (3) Linear packing model (LPM); (4) Further development of the solid suspension model (SSM); (4) Compressible packing model (CPM). The LPM, the SSM and the CPM are so called third generation packing models.

Hunger [17] stated that the amount of solids in coarse and fine sections should be optimized separately because the fine fractions primarily contribute to the porosity of a mixture. An integral approach based on the particle size distribution of all solids is not found very often.

Aggregate selection for optimal packing density may follow one of several suggested ideal particle size distributions, empirical tests on various blends of aggregates, or a mathematical model [13]. In the majority of cases, continuously graded granular blends are described using the Fuller parabola, which represents the basic principle of most standard aggregate grading curves [17]. This power law size distribution is described in the following equation:

$$P_t = \left(\frac{d}{d_{\max}}\right)^{\frac{1}{2}} \tag{1}$$

where P_t is a fraction of the total solids (aggregate and SCMs) being smaller than size d, and $d_{\max}$ is the maximum particle size of the total grading. However, this equation has a deficiency in that it can never be fulfilled in practice because it assumes particles of infinite fineness, i.e., $d_{\min} = 0$, which is not the real case. Moreover, in order to avoid the lean mixtures, researchers further stipulated that at least seven percent of the total solids should be finer than the No. 200 sieve (0.074 mm opening). Powers [16] proposed another parabolic particle size distribution in which the power 0.5 is described as exponent q in the following equation:

$$P_t = \left(\frac{d}{d_{\max}}\right)^{q} \tag{2}$$

Andreasen and Andersen [22] reported that the voids content only depends on the value of q, which is called the distribution modulus. However, when the q value approaches zero, the void content follows as well. Due to the inability of fine particles to pack in a similar manner as bigger but geometrically similar particles, Andreasen and Andersen [22] limited the increase of packing to a