Construction and Building Materials 168 (2018) 412–421

Contents lists available at ScienceDirect

Construction and Building Materials

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

Blocking analysis of fresh self-compacting concrete based on the DEM

Wei Cui [a,b,*], Wei-shuo Yan [a,b], Hui-fang Song [a,b], Xin-li Wu [c]

[a] School of Civil Engineering, Tianjin University, Tianjin 300072, China
[b] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China
[c] College of Engineering, The Pennsylvania State University, University Park, PA 16802, USA

HIGHLIGHTS

- The irregularly shaped cluster particles are used to simulate the coarse aggregate.
- The effect of the coarse-aggregate distribution in causing the blocking are assessed.
- The effect of the rebar distribution in causing the blocking of SCC are compared.
- The randomness and variability of the blocking phenomenon are verified.

ARTICLE INFO

Article history:
Received 7 October 2017
Received in revised form 11 January 2018
Accepted 14 February 2018

Keywords:
Self-compacting concrete (SCC)
Passing ability
Random polyhedron aggregate
Coarse-aggregate distribution
Rebar distribution
Discrete element method (DEM)

ABSTRACT

Self-compacting concrete (SCC) is a type of highly flowable, non-segregated concrete that can spread into place, filling formwork and encapsulate the reinforcement without mechanical consolidation. Nevertheless, SCC contains coarse aggregates that could get clogged within the reinforced zones during the casting process. When concrete flows through certain types of obstacles, such as steel bars, several phenomena occur that should be distinguished. In this study, the simulation of fresh SCC were described using irregularly shaped polyhedron particles instead of the traditionally used spherical particles because the former can more realistically approximate the actual state of the coarse aggregate. On this basis, in this paper, an analytical correlation between the blocking phenomenon and the coarse-aggregate distribution of SCC for the L-box test using the discrete element method (DEM) is proposed. The obtained results show that the aggregate size tends to affect the passing ability of SCC more than the coarse-aggregate content. Additionally, the free space between steel bars affects the passing ability of SCC more than the stirrup addition. Furthermore, multiple sets of simulation results indicate that blocking is fundamentally probabilistic, the probability of blocking from the SCC crossing a flow constriction increases with the number of aggregates crossing the obstacles, and this blocking process is demonstrated using the DEM.

1. Introduction

With the increasing complexity of modern concrete structures, it is becoming more challenging to cast concrete with sufficient consolidation. In some cases, even if the access to a poker vibrator is not restricted, concrete compaction remains notably challenging. Thus, the fresh concrete must have high fluidity and self-compaction characteristics, which are the driving forces behind the use of self-compacting concrete (SCC). Accordingly, as a type of self-compacting high-performance concrete, SCC has been extensively applied in abounding projects around the world and has significantly affected concrete placement and construction economics. In concrete technology, SCC is considered one of the most crucial innovations because of its high flowability, passing ability and stability. These properties of SCC ensure the proper filling of a complex formwork without the need for vibrational consolidation, but an important problem is that SCC is likely to become blocked in a reinforced zone because of the presence of coarse aggregate and rebar. As Nguyen et al. [1] reported (Fig. 1), a mass of aggregates migrates to the vicinity of rebar and causes granular arches and blocking, which restricts and hinders flow. Although the probability of granular blocking is low, blocking can increase the risk of improper form filling, and subsequently cause the loss of mechanical resistance and durability of the concrete, even disrupt the structural integrity of the building. To benefit

* Corresponding author at: State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China.

E-mail address: cuiwei@tju.edu.cn (W. Cui).

https://doi.org/10.1016/j.conbuildmat.2018.02.078

Fig. 1. Granular blocking within the flow duration of SCC (from [1]).

from the full potential of SCC, the blocking phenomenon of SCC and its influencing factors must be systematically studied.

The discrete element method (DEM) has been widely used in many areas, especially in granular mechanics, which is a numerical method to solve the equation of motion for systems of many interacting particles, while concrete mixture is a type of heterogeneous multiphase composites that consists of aggregates as skeleton and cement paste as the matrix [2], thus, using the discrete element method to analyze the passing ability of concrete is feasible and efficient [3]. Currently, spherical elements are generally used to represent the aggregate, although the accuracy of characters computed for structures using spherical aggregates can be limited when the character contrast between aggregates and matrix is obvious because the aggregate actually has angular shapes. To solve this problem, Nolan et al. [4] and Thomas et al. [5] successfully simulated irregularly shaped particles using different method at the early stage, and based on their research results, Garcia et al. [6] proposed the cluster overlapping spheres (COS) algorithm to represent particles with complex shapes as clusters of overlapping spheres. In [7], to comprehensively evaluate the fresh concrete workability, a fast and efficient approach to establish irregularly shaped polyhedron particles is presented to simulate the real shape coarse aggregate.

The state of theoretical study continuously develops in terms of the blocking phenomena and passing ability of SCC. Nguyen et al. [1] proposed that if the shear stress generated by gravity became lower than the yield stress of the concrete, the flow would stop, and this effect has been quantified in the case of the L-box test with and without steel bars. In addition, Roussel et al. [8] proposed that granular blocking occurred for non-colloidal particles with a diameter smaller than the pore size, which implies that such a phenomenon is essentially a collective effect; the granular blocking phenomenon has a probabilistic nature.

In the case of the blocking and passing ability of SCC, there have been several attempts to relate the potential influence factors to the blocking phenomena. The cohesiveness and coarse-aggregate content appear to be the major factors because the passing ability and segregation stability are generally better for mixtures with higher cohesiveness and lower coarse-aggregate content [9]. Sonebi et al. [10] illustrated various trade-offs among the mixture parameters on the derived responses that affected the filling and the passing ability. The granular blocking probability of a suspension crossing a flow contraction increases with the number of particles that cross the obstacles, their volume fraction and the ratio between the particle diameter and the contraction gap [11]. El-Cheikh et al. [12] used a hard core soft shell DEM modeling, and on this basis, the relationship between ratio 'a' (bottom opening diameter/solid grain diameter) and blocking was systematically studied. Khaleel et al. [13] concluded that coarse aggregate properties such as the maximum size, texture and type of coarse aggregate directly affect SCC. Xiaobin Ding et al. [14] showed that it is important to properly consider the effect of the model scale and particle size distribution in Particle Flow Code 3D (PFC 3D) simulations. Nepomuceno et al. [15] proposed models to optimize the maximal aggregate volume fraction to achieve a proper passing ability of SCC for different flow restrictions and bar spacings. Moreover, Vasilic et al. [16] numerically evaluated the effect of the presence of reinforcing obstacles as a porous medium on the passing ability of SCC. In [17], numerical simulation of a self-consolidating concrete flow as a heterogeneous material in L-box configuration were presented, and the coupled effect of the reinforcing bars and aggregate content on the flow characteristics were analyzed.

Nevertheless, the existing studies on blocking simulation with DEM require further development because aggregates, particularly coarse aggregates, have angular shapes in the actual state. When spherical particles are used to describe the actual rolling resistance, the accuracy and authenticity are reduced. Furthermore, the influence of the coarse-aggregate size and distributions on the passing ability of SCC is accepted, but only limited studies have been conducted to estimate the relationship between the aggregate distribution and the passing ability of SCC. Similarly, there is a limited research to explicitly verify the effect of the rebar distribution on the passing ability of SCC. During the concrete casting process, several coarse aggregates may form an arch and become jammed in reinforced zones, but studies on concrete using the DEM have seldom implemented non-spherical particles to simulate the influence of various factors on the passing ability of SCC. Thus, the concrete workability, particularly the passing ability, cannot yet be comprehensively and accurately estimated.

Therefore, in this study, considering the aggregate shape, coarse-aggregate distribution and rebar distribution, four simulations were performed to evaluate the passing ability of SCC using the L-box test based on the DEM. In Section 2, a mathematical method to establish three-dimensional random-shape polyhedrons and the principle of the overlapping sphere algorithm are presented with a simplified introduction of the DEM and complicate contact relationship for SCC. In Section 3, to compare the effects of various factors, a modified L-box apparatus is proposed in this paper and describe a series of simulations, including those addressing the coarse-aggregate distribution and rebar distribution. In Section 4, the obtained results from numerical simulations are compared to evaluate the effect of the coarse-aggregate distribution and rebar distribution on the blocking of SCC. In addition, in this section, the randomness and variability of blocking are confirmed according to the obtained results. Finally, Section 5 provides the conclusions from the aforementioned simulations and make summary for this study.

2. Generation of the discrete element model for SCC

2.1. Mathematical representation of irregular polyhedrons

According to the reformed ellipsoid equation [18], i.e., Eq. (1), a series of points around a certain ellipsoid surface can be created at random to generate an irregularly shaped polyhedron containing these points as vertices. The shape and sharpness of the polyhedron are controlled by the properties of the ellipsoid. In Eq. (1), r is the half length of the longest diagonal of the polyhedron; θ and φ are the latitude and longitude of each vertex, respectively; δ_r is a random variable in the range of (0, 1); η is a coefficient in