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CFD simulations of self-compacting concrete with discrete phase modeling

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HIGHLIGHTS

- It is possible to numerically simulate the workability of fresh SCC.
- The behavior of aggregates can be modeled using DPM.
- Existing test procedures were used for validating the numerical model.
- Segregation and blockage is captured in the validated model.

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ABSTRACT

Self-compacting concrete (SCC), is a special type of concrete with high compaction ability in the formwork with its own weight and compacted without any vibration. The main important advantage of SCC is the stability of its cohesion and homogeneity with higher workability structural material behavior in densely reinforced and narrow cross-section structural members with least amount of segregation, bleeding, and pores. This study aims to simulate the workability behavior of SCC by numerical modeling. The numerical model is based on Computational Fluid Dynamics (CFD) and Discrete Phase Model (DPM). The data derived from V-funnel, L-box and rheometer tests were used for assessing the flow characteristics of SCC. One advantage of numerical modeling is the ability to characterize better the blockage risk and segregation of aggregates in the fresh concrete. As seen from test results the constructed CFD model showed a proper relation with the workability of SCC.

1. Introduction

1.1. Background

Self-compacting concrete (SCC) is known to have little resistance to flow. It can be placed and compacted under its own weight with little or no vibration effort, yet possesses enough viscosity to be handled without segregation or bleeding [1]. These mixes can be adequately poured into moulds and formwork in which the reinforcing rebars are distributed [2]. Mineral additives such as ground granulated blast furnace slag, fly ash and lime-stone filler can be used as powder material in SCC mixtures for obtaining the desired workability with increased durability and performance [3]. SCC has many advantages in practice due to high workability as a result of the developments in plasticizer technology. High compactness ratio, lower permeability and durability performance achieved by higher strength are the other advantages of SCC mixtures [4,5]. The rheological behavior of self-compacting is more complicated when a variety of chemical additives are added at the same time, especially the shear thickening and shear thinning behavior. This behavior is primarily influenced with the amount of powder content, plasticizer content and water/powder ratio of the SCC mixture [6]. Several different laboratory testing methods have been developed for the determination of the flow properties of SCC such as filling, flow, passing and viscosity properties [7,8]. On the other hand, investigation of such properties with numerical modeling is not very common. Indeed, just as numerical simulations of the loading of concrete structures allow a civil engineer to identify a minimum needed mechanical strength, numerical simulation of the casting process could allow the same engineer to specify a minimum workability of the fresh concrete that could ensure the proper filling of a given formwork [9].

To give background information, relevant studies in the literature to our best knowledge, and mostly representing multi-phase modeling are reviewed as follows.

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Firstly, the studies representing two-phase (liquid and gas) flow are summarized here. Vasilic and his group [10] investigated movements of fresh concrete around steel reinforced bars with Porous Medium (PM) method using Fluent as CFD solver. They focused on the permeability. They compared steel bar arrangement sand porous medium analogy with experimental results. Ferrara et al. [11] modeled mini-slump test with CFD method for various SCC samples. They mostly focused on the rheology of SCC for just the mini-slump test and they didn't consider aggregates in the model. Lashkarbolouk et al. [12] also created a numerical model for the filling ability and segregation of SCC on V-funnel test. They used Smoothed Particle Hydrodynamic (SPH) method. The SPH method is a meshless numerical approach which is based on an interpolation theory. It divides fluid into discrete particles. It might be considered insufficient to fully resolve complicated flows, especially for defining the behavior of aggregates in a flowing fresh concrete. Dhaheer et al. [13] were another group using SPH method for SCC on J-Ring Test. They found that the three-dimensional Lagrangian SPH numerical scheme is able to simulate the flow of SCC mixes of varying compressive strengths through a V-funnel and to provide discharge times that agree very well with experimental results. Gram et al. [14] focused on rheological parameters of SCC. They also compared rheological parameters with a CFD model of L-box test. The model is based on two-phase (free surface flow) for representing the behavior of concrete. But they didn't consider the third-phase for solid (aggregates) and they used just L-box test. Tichko et al. [15] created a CFD model determining maximum formwork pressure when the fresh SCC is pumped. They used Herschel-Buckley viscosity model which is the difference of this work from many others. They also neglected aggregates in concrete. They compared numerical predictions of the concrete sample for these two benchmark flows obtained by various teams using numerical techniques. But they just aimed to compare benchmark test to define a better method for them but they didn't intend to investigate the behavior concrete and aggregates together.

Another family of studies is the multi-phase cases where the aggregate is also modeled with the fresh concrete. Mori and Tanigawa [16] are pioneers to investigate and understand the fluidity of fresh concrete or SCC with solid particles to represent aggregate. Following such early studies, Noor and Uomoto [17] used a Particle Flow Code (PFC) to create a 3D numerical model of SCC, which includes a Discrete Element Method (DEM) in U-box and V-funnel test. In their model, the fresh concrete and aggregates were treated separately. They used spherical elements to represent the aggregates but this model wasn't validated with the experimental results. Švec and his group [18] modeled steel fiber reinforced SCC by means of CFD method. They modeled steel fiber with Immersed Boundary Method (IBM). The method is based on Fluid-Structure Interaction (FSI). They also used Lattice Boltzmann Method (LBM). The LBM is a valid method for single or multiphase fluid problems with complex geometries. It is based on the discretization of the Boltzmann equation instead of Navier-Stokes equations. They preferred Bingham model for viscosity and they validated the model with the slump test results. Gram and Silfwerbrand [19] compared three different CFD models for SCC modeling aggregates using different scales: particles, each representing an aggregate in the concrete; fluid, modeling fresh concrete as a homogeneous liquid. They benefited from DEM with OpenFOAM which is an open-source CFD solver. The DEM is a general method defining particle's behavior. Mechtcherine et al. [20] also used DEM method to model fresh concrete. They used "EDEM" which is a specific software for DEM method. They modeled aggregates of the concrete as a particle. Cao and his group [21] also used DEM method to investigate pressure and forces on the bend and the piston of the concrete pump for the cases of increasing coarse aggregate volume fraction. Roussel et al. [22] created two benchmark cases to predict the concrete flow. Wallevik et al. [23] created a numerical model with OpenFoam solver which uses Drift Flux Method (DFM) for prediction of segregation in a T-beam. They also considered multiphase flow and the coarse aggregate distribution was modeled as a function of time. They assimilated coarse aggregates to a fluidized bed for understanding the segregation of concrete. A clear gap exists regarding studies validating CFD models which incorporate both VOF and DPM together where also standard test procedures are used as validation cases.

1.2. Novelty and objectives

Although not many, the existing efforts show that numerical modeling of the flow of fresh concrete is possible. The accumulating knowledge on the model properties affecting the accuracy is promising yet not complete. The contribution of this work is two folds. Firstly, solid-fluid, two-way interaction is practiced to represent the behavior of SCC in a standard test environment in a multiphase model where all gas, liquid and solid phases are modeled. Here the fresh concrete properties obtained from preliminary experiments are used to characterize the fresh concrete. Secondly, the aforementioned multiphase model is validated through a quantitative comparison between the CFD and experimental results. Both contributions are rare and believed to become useful in investigations concerning realistic applications of fresh concrete flow.

This study aims to stimulate the fresh behavior of SCC by using numerical modeling. The numerical model is based on Volume of Fluid (VOF) and Discrete Phase Model (DPM) which are methods of Computational Fluid Dynamics (CFD). The main objective of the study is to show that our numerical model can define workability of SCC of the given mix design. Another goal of this study is to simulate the interaction and segregation between aggregates and concrete with 1:1 scale reinforced bars when pumping SCC into a formwork of column-beam joint. The behavior of fresh SCC was modeled by VOF model and the behavior of aggregates was modeled by DPM in the fresh concrete integrated with the former. Resulting CFD models were validated by 1:1 scale experiments for three mixes. Namely, the V-funnel, L-box and rheometer tests were performed which are widely used for determining the fresh properties of SCC. These tests former provide workability characteristics, the latter provide fundamental physical magnitudes of flow. Moreover, the time of V-funnel is related to filling ability in terms of flowability-viscosity and to narrow-opening passing ability [24].

2. Materials and methods

2.1. Materials

The ingredients of SCC mixture were obtained from different sources. CEM I 42.5R type ordinary Portland cement was supplied from Bilecik SANCIM cement factory (Turkey) in accordance with TS EN 197-1 cement code [25]. The fine powder content of the mixture is very important for the segregation and homogeneity of the SCC specimens. For this purpose F type [26] fly ash (FA) was obtained from Kutahya Tuncbilek thermal power plant as fine material. The density of FA is 2.36 g/cm^3 with spherical particles in average diameter between 0.5 and 15 μm [27]. The properties of cement and FA are given in Table 1. The crushed limestone aggregates are obtained from Eskisehir Seryapi ready-mixed concrete plant in two different particle sizes as 0–4 mm (fine) and 4–12 mm (coarse). Particle size distribution of the fine and coarse aggregates are presented in Fig. 1. As seen from the granulometry curve the maximum aggregate size of the aggregate is lower than 14 mm. The maximum aggregate size affects the flowability, passing ability and segregation resistance of the SCC mixture. Physical properties of the aggregates are also presented in Table 2. Plasticizing agent is a very important additive for the self-placing behavior of SCC. Therefore high performance and new generation polycarboxylic ether based plasticizer additive (supplied from BASF Turkey named as Glenium C 303) was used in SCC production. General properties of the plasticizer is given in Table 3.