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Numerical and experimental studies of aggregate blocking in mortar extrusion

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HIGHLIGHTS

- Blocking in mortar extrusion is studied by experimental and numerical approaches.
- For a paste volume proportion >0.54 blocking is avoided for ratio ‘a’ >4.
- For ‘a’ ≈4.25 and paste volume proportion 0.54 blocking occurs only in experiments.
- Paste volume proportion might be a more relevant factor than MPT regarding blocking.

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ABSTRACT

Numerical and experimental study of aggregate blocking in extrusion of mortar is presented. The studied system consists of a pipe with a nozzle at the tip. Fresh mortar is modeled by composite particles consisting of hard-core representing a sand particle surrounded by soft-shell layer representing interstitial cement paste. For the experimental study, two kinds of mortars are studied. The first kind is a mortar composed of monosized glass beads. This mortar is used for comparison with numerical results. The second kind of mortar is more realistic, polydispersed particles are used by replacing glass beads by standard sand. The effects of the dimension of the bottom nozzle opening, the rheological properties of the cement paste and the paste volume proportion on the blocking of mortar are studied both experimentally and numerically. For mortars composed of monosized beads, experiments and simulations both show that the main parameter governing aggregate blocking is the ratio ‘a’ between the bottom opening diameter of the nozzle and the beads diameter. Rheological properties of the paste and paste volume proportion are less influential. Experimental results obtained on both kinds of mortar confirm the limit ratio ‘a’ identified numerically in all the cases, except for the lower cement paste volume proportion (0.54 in our study) for which ‘a’ has to be slightly increased to avoid blocking.

1. Introduction

Extrusion is a manufacturing process used to produce long objects of a fixed cross-sectional profile. This process has found important practical applications such as for processing of agro-food and producing of pharmaceutical and cement-based products [1–3]. More recently, extrusion is used for 3D printing of mortar or concrete. 3D Printers are machines that produce physical 3D models by printing a material layer by layer [4,5]. This revolutionary process for creating 3D models is used in progress in a variety of industries where printable materials include a wide range of plastics and metals. For these materials, literature includes many advanced scientific publications [6–10].

Recently, 3D printing has been used for construction materials (mortar or concrete) to rapidly design and build structures. 3D printing of mortar consists in mixing, pumping, and then depositing the material layer by layer. During pumping the material passes through a pipe then flows from a nozzle. Unlike concrete pumping [11], in 3D printing the width and the thickness of the printed layer must be uniform and controlled. Findings about 3D printing of mortar or concrete are limited to some applications described on the web [12–14] and few scientific papers [15–18]. Very specific rheological and chemical requirements have to be met so that the material can be considered as “printable”. Indeed, mortar for 3D printing application has to be both “extrudable” and “buildable” [19,20]. The material is considered as extrudable when

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it is fluid enough in such a manner to find a way out of the nozzle without causing filtration, bleeding, segregation or blocking. Blocking problem can be very costly. If the nozzle remains blocked, it is absolutely necessary to disassemble and clean the whole system. This procedure causes financial and time losses. Therefore, it is important to make sure that no blocking can occur during extrusion. Once the material has been extruded, it has also to be buildable, meaning that it can withstand the weight of other layers without causing relevant deformation. To superimpose thin layers without encountering blocking, smaller nozzle opening and particles size must be used. In this paper, we focus on the extrudability of mortar 3D printing.

In the literature, the flow of granular matter through a silo orifice has been widely studied by laboratory experiments or numerical simulations [21–24]. In such studies, the granular material is composed of assembly of dry grains. It has been found that for spherical beads, blocking in silo can be prevented when the ratio between the diameter of the outlet orifice and the diameter of the beads is higher than 4.94 ± 0.03 [21]. However, the flowability of the granular material is related to the complex force network resulting from the contacts between grains. In the case of a mortar, solid grains are embedded in an interstitial fluid, the fresh cement paste, the presence of which will influence the contact network between particles. Studies conducted on these complex materials are mostly interested in suggesting new modeling approaches and conducting experiments for a better understanding of the material behavior during flow [3,25–30] or extrusion [3,31,32]. But to our knowledge, there have been few studies conducted on blocking of cement-based material during extrusion [1–3].

In this paper, the aggregate blocking of mortar during extrusion is studied both experimentally and numerically. The studied system consists of a pipe with a nozzle at the tip. The material finds a way out of the nozzle by normal confining. The system is modeled using an in-house code based on the discrete element method. Three parameters related to mortar formulation have been varied: the ratio between the bottom opening diameter and the maximum coarse grain diameter, the rheological properties of the cement paste and the paste volume proportion. Then, the effect of these three parameters on the aggregate blocking is studied.

This paper is organized as follows. Section 2 describes the numerical model, different steps for simulation and post processing methods needed to analyze the numerical data. Formulation of the mortar used in experiments and experiment process are given in Section 3. Section 4 combines the results from the numerical simulations and experiments. Finally, section 5 presents main conclusions.

2. Discrete element modeling of mortar extrusion

Modeling of the concrete or mortar flow by particle methods [3] or computational fluid dynamics (CFD) [33] have attracted attention of researchers for better understanding of the material behavior and of its rheological properties. Vasilic et al. [25] proposed a new modeling approach that treats fresh concrete as a Bingham fluid and reinforcement network as a porous media. This new approach based on CFD allows a significant reduction in total simulation time in comparison to those conducted on discrete rebars. Comparison with experiments conducted on SCC flow casting in reinforced formworks showed good agreement. In addition, many Discrete Element Method-based approaches have been widely used to model fresh concrete flow. The quality of the model depends both on the appropriate discretization of the aggregates (and fibres, if needed) by discrete particles and on the correct description of the force–displacement relations between these particles [29]. Ball-wall tests have been conducted on UHPC and SCC mortars by Shyshko et al. [29]. Experimental force–displacement relations data obtained have been used as a basis for generalizing material model for the interaction in the normal direction between discrete elements. The contact force acting between the entities was resolved into elastic and viscous components. As well, Mechtcherine et al. [30] used a numerical approach based on the Discrete Element Method to model fresh concrete during its different working processes. Fresh concrete was modeled by spherical particles representing not only coarse aggregates, but a layer of cement paste or fine mortar covering them as well. The numerical simulations provided quantitatively correct results compared to analytical solutions obtained from Slump flow and LCPC-box tests. Therefore, the proposed algorithm has been proven to be a sound procedure to link the yield stress of the simulated concrete and the bond strength which is the main parameter of the suggested model. Moreover, the Discrete Element Modeling has been used by the group at the TU Dresden to visualize the flow of the fibres and track their positions and orientation during the entire extrusion process of fibre-reinforced mortar. For further details, an overview of the development and the contemporary state of research in the field of simulating fresh concrete using the Discrete Element Method is given by Mechtcherine et al. [3].

2.1. Numerical model

The simulations are performed with a three-dimensional in-house numerical code [34–37] based on the Discrete Element Method [38]. The material is modeled by an assembly of composite particles. A composite particle is a solid grain of diameter d (sand grain for mortar and coarse aggregate for concrete) surrounded by a spherical layer of thickness Wm (cement paste for mortar and mortar for concrete) (Fig. 1). Newton's second law of motion is used to update the position and velocity of each particle.

The contact forces between composite particles are calculated from the hard-core soft-shell model [35]. This model has been used previously to model the flow of a fluid concrete [35]. Hard core describes the solid-solid interaction between two solid grains, while soft shell describes fluid-fluid interaction between two spherical layers. Depending on the type of interaction (hard-core or soft-shell), the contact force can be calculated. Each type of contact force has normal and tangential components. The contact force $F_{hc,ij}$ of the hard-core interaction between two solid grains i and j is calculated according to the slight overlap between contacting grains and their micromechanical characteristics. The appropriate equations of the normal and tangential components of the hard-core contact force are described in details in [35,36].

The interaction force $F_{ss,ij}$ due to overlap between two soft-shells depends on the rheological characteristic of the interstitial fluid. The tangential component $F^{t}_{ss,ij}$ between two soft shells is computed considering that the volume of fluid located between

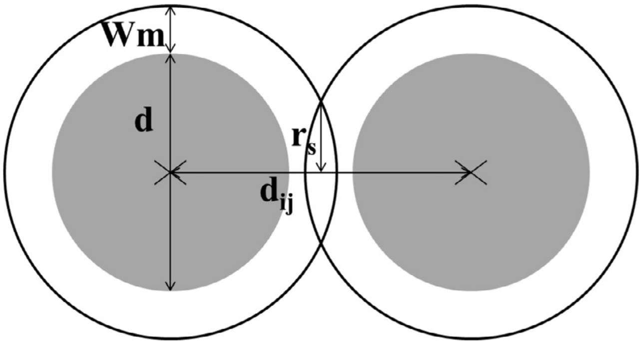

Fig. 1. Schematic representation of two soft-shells being in interaction.