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# Grating-box test: A testing method for filling performance evaluation of self-compacting mortar in granular packs

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## HIGHLIGHTS

- “$h_2^N$” reflecting SCM filling performance in quasi-3D granular packs is obtained.
- Results of grating-box test are found in good agreement with theoretical analysis.
- “$\eta$” is found to reflect granular packs’ resisting ability to SCM filling movement.
- Grating-box test is promising to assess filling performance in real granular packs.

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## ABSTRACT

Grating-box test is proposed and applied to evaluate the resisting ability of granular packs to the filling movement of self-compacting cementing materials. Firstly, parameter “$h_2$” (“$h_2^N$”), reflecting the filling performance of SCM, is obtained from theoretical analysis of self-compacting-mortar’s filling performance in quasi-three-dimensional (quasi-3D) granular packs. Second, experimental results of grating-box test with quasi-3D molds using cylindrical obstacles are found in good agreement with the theoretical analysis above. Third, damping coefficient “$\eta$”, an indicator being positive correlated with the resisting ability of granular packs to filling movement of SCM, is found to represent the inherent properties of granular packs.

## 1. Introduction

The usage of self-compacting cementing materials, particularly self-compacting concrete (SCC), facilitates the construction procedures by eliminating the vibration process, which aims to compacting the cementing materials. Based on the advantage of SCC, rock-filled concrete (RFC), formed by pouring fresh SCC into pre-placed large-scale rocks to fill the voids between rock grains, was developed by Tsinghua University in 2003, presenting less cement usage, faster construction speed, and less $CO_2$ emission in concrete construction. RFC is a promising material for large-scale construction projects in hydraulic engineering and has achieved $2 \times 10^6$ m$^3$ use in about 80 dam projects since 2003 [1,2]. It is obvious that the filling of SCC in the voids of the packed rock grains dominates the mechanical properties of the RFC, thus the SCC-filling-movement-resisting ability of rock grain packs becomes a crucial issue. A simple and effective test is desired to assess the resisting ability of granular packs to filling movement of SCM.

Recently, numerous testing methods such as slump flow test, V-funnel test, U-box test, and L-box test have been introduced to investigate the filling ability of self-compacting cementing materials [3–7]. Makul et al., Shahidan et al. and Shin et al. use slump flow test to measure the rheological features of self-compacting materials [8–10]. Kannan used slump flow test, V-funnel test and L-box test to represent the fresh state properties of SCC [11]. The J-ring test, developed by Bartos et al., attempts to evaluate the filling ability, passing ability (primary aim), and flow-rate (secondary aim) [12–15]. Whereas Bartos et al. failed to simulate the piling pattern of rock grains in real construction situation. Kumar et al and Lenka et al. used J-ring test and U-box test as methods to evaluate the rheological properties of self-compacting cementing materials [16,17]. Kamal et al. compared the suitability of a number of test methods, including J-Ring, L-box, U-box, and V-funnel tests, in assessing the stability of SCC [18]. They found that the L-box test

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can enable the evaluation of passing ability characteristics and is recommended along with the slump flow test for field-oriented quality control of SCC [18]. However, there is still a lacking of a testing method for evaluating the resisting ability of rock grain packs to the filling movement of fresh self-compacting cementing materials. Xie et al. have used in-lab experiments to preliminarily investigate the filling capacity of SCC in rock skeleton considering the effect of aggregate size and SCC yield stress [2]. Whereas their test profile and process are complicated and not suitable for onsite application-oriented evaluation of filling capacity of SCC in rock grains.

The filling performance of self-compacting cementing materials in rock grain packs can be evaluated from two aspects: (1) the rheological properties of fresh SCC that are the inherent properties of self-compacting cementing materials and (2) the resisting ability of rock grain packs (which can be regarded as one kind of "granular packs" in this paper) to the filling movement of fresh SCC [2]. Jin and his colleagues proposed a numerical approach based on Lattice Boltzmann method to simulate the flow characteristic of SCC in porous media [19–21]. Numerous researchers have verified that the rheological properties of fresh SCC could influence the passing and filling ability of SCC. Sonebi's experimental results verified that the passing ability of SCC increases as the slump flow increases [22]. Shape of granules in granular packs (Rock grain packs can be viewed as one kind of "granular packs".) significantly influences the piling pattern of granules and thus influences the filling performance of self-compacting cementing materials flowing in the granules [23]. Besides, the other properties of granular packs, including granular size distribution, volume fraction of voids, piling pattern of granules and even the texture of the granules, could obviously affect the filling performance of self-compacting cement materials [24–26]. As a result, the complexity of characterizing the properties of granular packs makes it difficult to evaluate the filling performance of self-compacting cementing materials in granular packs. In order to solve this problem, a simplified methodology, using the theory of obtaining the permeability coefficient based on Darcy's Law, is proposed in this study. In the research of water permeability of sand or soil, Darcy's Law is commonly used and the permeability coefficient "$K$", which is independent of the nature of fluid but depends on the properties of the porous media, is extracted from the analytical equations as a comprehensive indicator of the properties of porous media without considering the detailed properties of porous media such as texture, skeleton pattern of porous media etc. [27–29]. Inspired by the permeability coefficient in the Darcy's Law, a similar coefficient is extracted from the analytical equations in this study to characterize the SCM-filling-movement resisting ability of granular packs neglecting the influence of granular packs' detailed properties such as granular shapes, granular size distributions, textures, or piling patterns.

The aim of this study is to design an alternative testing method for evaluation of resisting ability of granular packs to the filling movement of self-compacting cementing materials in laboratory. Self-compacting mortar (SCM) is used to represent the self-compacting cementing materials. In order to simplify the testing, measuring and theoretical analysis, quasi three-dimensional (quasi-3D) granular packs are considered. The layout of this paper is as follows. In Section 2, theoretical analysis of filling performance of SCM in quasi-3D granular packs is conducted. Section 3 presents the design of grating-box test and the indicator of resisting ability of granular packs to the filling movement of SCM. Section 4 provides the details of experimental strategy and the experimental results, which together with the results from the theoretical analysis confirm the proposed grating-box test. Lastly, conclusions are drawn in Section 5.

## 2. Theoretical analysis of filling performance of self-compacting mortar in quasi three-dimensional granular packs

In recent studies, fresh self-compacting cementing materials are regarded as one kind of Bingham fluids and the key characteristics of fresh self-compacting cementing materials consist of filling ability, passing ability, and segregation resistance [30]. Numerous studies have confirmed that the fresh concrete can be modeled with good accuracy regarded as Bingham fluid [31–34]. Hence, the fresh self-compacting cementing materials are considered to be one kind of Bingham fluids in the theoretical analysis in this study.

In order to simplify the testing, measuring, and theoretical analyzing processes, quasi-3D situation and cylindrical obstacles are used in this study. Based on the following four hypotheses, the equation describing the SCM surface when its flow stops (the static SCM surface) in quasi-3D granular packs can be obtained. The theoretical equation for filling performance evaluation of SCM in quasi-3D granular packs can be deduced from the equation describing the static SCM surface.

### 2.1. Hypotheses in theoretical analysis

Four hypotheses (i.e. H.1, H.2, H.3, & H.4) are built in terms of dimensionality, self-compacting mortar, granules, and drag force, as shown in Fig. 1.

*H.1 Two-dimensional (2D) situation:*

Numerous properties of granular packs such as volume fraction of void and piling patterns of granules can obviously affect the filling performance of SCM in granular packs, which makes it difficult to evaluate the filling performance in granular packs. Therefore, the quasi-3D granular packs (so called simplified model) are used in this study, in order to simplify the testing, measuring, and theoretical analyzing processes. The SCM flow in the simplified model can be regarded as a 2D flow because the model has a relatively smaller thickness compared with its length and height. The SCM flows into the simplified model from the midpoint of the top edge and spreads out to the sides, as shown in Fig. 2.

*H.2 Bingham fluid:*

Due to the good accuracy of regarding fresh self-compacting cementing materials as Bingham fluid [31–34], self-compacting mortar is regarded as one kind of Bingham fluid in this study, and its rheological mechanism fits the following equations [35,36]:

$$\begin{cases} \tau < \tau_0 & \gamma = 0 \\ \tau = \tau_0 + \mu_P \cdot \gamma & \gamma > 0 \end{cases} \tag{1}$$

where $\tau$ is the shear stress, $\tau_0$ the yield stress, $\gamma$ the shear rate and $\mu_P$ the plastic viscosity of a Bingham fluid, and it is the yield stress $\tau_0$ that makes a flow of Bingham fluids stop. Based on the results of slump flow tests, the yield stress can also be obtained, and the specific calculation formula is given as follows [35]:

$$\tau_0 = \frac{225\rho g (V')^2}{128\pi^2 R^5} \tag{2}$$

where $V$ is the inner volume of the slump cone, $\rho$ is the density of the self-compacting cementing materials, $R$ the half of the spreading diameter, which can be measured through the slump flow test.

*H.3 Cylindrical obstacles:*

In order to meet H.1, the thickness "$b$" of the simplified model is set to be significantly less than its length and height. Meanwhile, in the 2D situation, granules are replaced by a lot of commensurate cylindrical obstacles within the same sectional diameter along the thickness direction and the same length, and they are well-distributed in the simplified model, as shown in Fig. 3.