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Numerical method for thixotropic behavior of fresh concrete

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HIGHLIGHTS

- A rest & shearing time-dependent Discrete Element Method (DEM) was developed for the prediction of time-dependent fluidity of fresh concrete
- The effects of cement hydration, physical flocculation of cement particles and agitation was considered on the numerical analysis of time-dependent fluidity of fresh concrete.
- The changes of chemically bonded, flocculated, and dispersed particles in quantity with agitating time in agitated state, later after rest for a certain time, were clarified theoretically.
- The rest & shearing time-dependent DEM was confirmed to be applicable to the prediction of the change of fluidity in agitated state and the hysteresis loop for fresh concrete with or without addition of mineral admixture.

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ABSTRACT

The thixotropic characteristic or rest & shearing time–dependence of fluidity of fresh concrete has an influence on its production and construction processes. In this paper, the mechanisms of the thixotropy and rest & shearing time-dependence were discussed, followed by proposing an analytical approach to numerical prediction of the rest & agitating time-dependent flow behaviors on the basis of Discrete Element Method (DEM). In this new DEM, the effects of cement hydration, physical flocculation of cementitious particles, and agitation were taken into account. To validate the numerical method, the rheological tests of fresh mortars with or without mineral admixtures were performed after the mortar samples stood still for different times, using the B-type viscometer, of which the rotor's rotation would break down its surrounding particles' flocculation structure. The numerical results of toque-rotational speed relationship were close to the experimental results.

1. Introduction

Fresh concrete is essentially a particle assembly containing water. From mixing to placement, the rheological properties change with the elapsed time. With the increase of rest time, the fluidity declines. However, re-mixing or agitation may recover partly the fluidity. This characteristic is usually called thixotropy or time-dependence. Hence, ready-mixed concrete usually needs to be mixed again in mixer or agitator truck before pumping or casting. The thixotropic behavior greatly influences the workability and the construction quality of concrete, such as flow ability decline during waiting to pump, slump loss even re-mixing in agitator truck before pumping, fluidity gain under a vibration in mould, change of formwork pressure [1], collapse in 3D concrete printing [2], and weak concrete joint [3].

The fluidity decline of cementitious materials at rest is resulted from physical flocculation and hydration of cement particles [4]. The flocculated particles enclose the mixing water and the hydration consumes the mixing water so that free water is reduced. And the structural buildup would increase mean particle contact angle (θ_m) and mean inter-particle angle (ϕ_m) to raise the deformation resistance of fresh cementitious material [5]. The fluidity gain after re-mixed again is attributed to the breakdown of the flocculent structure, which releases the enclosed water, and the decrease of θ_m and ϕ_m.

The thixotropy is generally evaluated by the area of hysteresis loop formed by the up and down curves of torque and rotational speed relationship [6,7]. However, the hysteresis loop depends on loading history (e. g. re-mixing, agitating, and tamping before or while sample is filled into rheometer), growth rate of rotational

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speed, and maximum rotational speed, etc. [8]. It is believed that these factors affect the breakdown degree of the flocculent structure of particles. The thixotropy is also always described by the decrease of toque under a constant rotational speed or the increase of rotational speed under a constant toque with the elapsed time. However, if the rotational speed or the toque is kept to be a too small constant value, the corresponding toque increases, or the corresponding rotational speed decrease [8,9].

The physical flocculation and the hydration of cement particles generate the network of interactions between particles. The physically flocculated particles can be easily dispersed again by an agitation. However, the network structured by the hydrates is usually strong. The shear rejuvenation is mainly attributed to the destruction of flocculent structure of particles. Coussot et al. proposed a phenomenological model to predict shear stress-shear rate curve later after a rest time [9]. But it is only valid for short rest time [10]. Ignoring the effect of cement hydration is one of the reasons.

Roussel proposed another phenomenological model to describe the thixotropic behavior after a relatively long rest time [11]. Roussel found that the shear stress, corresponding to a certain shear rate, is a linear function of rest time. However, Lecompte and Perrot concluded that the relationship between yield stress and rest time becomes non-linear over longer time scale [4]. The yield stress is resulted from the microstructure of particles in fresh concrete [12]. The yield stress and apparent viscosity decrease when the microstructure is destroyed by shearing, but conversely increase when the microstructure reforms at rest. That is to say, the rheological properties of fresh concrete are rest & shearing time dependent. For properly evaluating fresh concrete's rheological properties and predicting its flow behavior, the rest & shearing time dependence or the thixotropy must be considered.

Discrete Element Method (DEM), as a particle approach, is well applied to the flow simulation of fresh concrete [13–16]. In general DEM, a parallel bond model is usually used to describe the interaction and re-dispersion condition of flocculated particles. The dispersion of the flocculated particles occurs only when their subjected forces are greater than the bond strength limits of particle-particle contact. The bond strength limits and the normal and shear stiffnesses of the parallel bond model are generally constants. However, for fresh cementitious materials, the particle contacts increase with time due to physical flocculation and cement hydration. Thus, for a given external force, its ability of destroying the inter-particle contacts or bonds decreases with time. In order to numerically analyze the rest time-dependence of fresh concrete's fluidity, the authors proposed a rest time-dependent DEM [13]. In this DEM, we introduced clumped particles with rigid contacts to reflect the effect of the hydrates, and let the normal and shear stiffnesses of the parallel bond model change with the number of flocculated particles, i.e. with rest time in consideration of the effects of physical flocculation and cement hydration. We further confirmed that the rest time-dependent DEM is also applied to the concrete that uses mineral admixtures in place of part of Portland cement, such as fly ash and ground granulated blast furnace slag [14].

In order to predict the thixotropic behavior, i.e. rest & shearing time–dependence of fresh concrete's fluidity, in this study we first investigated theoretically the particle dispersion under a shear force, and then expanded the rest time-dependent DEM to rest & shearing time-dependent DEM (td-DEM). By this td-DEM, not only the fluidity decline in standing state but also the rejuvenation under shear can be predicted numerically.

For verifying the td-DEM, we further did rheological tests of three kinds of fresh mortars, using a B-type viscometer to measure the torque-rotating speed relational curves after different rest times. It is considered that the rotation of viscometer's rotor would partly break down its surrounding inter-particle's structure. Among the three mortar mixtures, two series of mortars used fly ash or ground granulated blast furnace slag in place of 20% or 50% of ordinary Portland cement. We also performed numerical analyses of the torque-rotational speed relationship by using the td-DEM, and compared them to the experimental results.

2. Proposal of DEM for thixotropy analysis of fresh concrete

2.1. Type of discrete particles and interaction

Two basic elements are used in present DEM: spherical (3D) particle and wall. The former is used to discretely express fresh concrete, and the latter is used to represent the boundary, such as sample container, mould, reinforced bar, and rheometer's blade. The particles move according to the Newton's Second Law, and the inter-particle force follows the force-displacement law. That is to say, the Newton's Second Law determines the motion of each particle subjected to inter-particle force, while the force-displacement law is used to calculate the inter-particle force arising from the relative motion at each contact point. The positions of wall elements are updated according to the wall motion velocity, unrelated to the Newton's Second Law.

Cement hydrates continually after it met water. The hydration products connect cementitious particles and aggregate particles. In standing state, because some of cementitious particles flocculate, the fluidity of fresh concrete goes down with rest time. However, if an agitation is applied to fresh concrete, the fluidity partially recovers because some of the flocculated particles are dispersed again. This is called thixotropy.

Therefore, three types of discrete particles should be considered for numerically analyzing the time-dependence of fluidity of fresh concrete by DEM: dispersed particles, chemically clumped particles, and physically flocculated particles.

In our past work [14], the interaction models were given for different types of discrete particle, as shown in Fig. 1. The interactions between two dispersed particles or dispersed particle and wall element are described by a viscous damping model, as shown in Fig. 1(a). The interactions consist of elastic force and viscous force that are expressed by springs with stiffnesses k_n^p and k_s^p, and dashpots with viscosity coefficients C_n and C_s, in normal and tangential directions, respectively. Slip is an intrinsic property and is described by a slip component.

The parallel bond model is used to express the interactions between two physically flocculated particles and their contact failure conditions, as shown in Fig. 1(b). The contact of flocculated particles is modeled as a set of springs with normal and shear stiffnesses k_n and k_s, uniformly distributed over a circular area on contact plane and centered at contact point. In general DEM, the stiffnesses k_n, k_s are dealt with two constants. But in present DEM, for describing the time-dependence of fresh concrete, the stiffnesses k_n, k_s should change with the number of flocculated particles. Besides k_n, k_s, the parallel bond model has other three parameters: normal and shear bond strength limit σ_c and τ_c, and bond-radius coefficient l. The σ_c and τ_c are used to describe the re-dispersion condition of flocculated particles. When the maximum tensile stress σ or shear stress τ acting on the contact point of two flocculated particles is greater than the σ_c or τ_c, the contact breaks and the two flocculated particles are accordingly dispersed again. Once flocculated particles are dispersed again by an agitation, their interactions follow the viscous damping model. The bond radius is a product of the bond-radius coefficient l and the minimum value of radius r_i, r_j of flocculated particle i and j [13].

On the other hand, the clumped particles in present DEM represent chemically bonded particles. They can't be dispersed again by an agitation or re-mixing. We described the contact of two