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Prediction of time-dependent flow behaviors of fresh concrete

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HIGHLIGHTS

- A new Discrete Element Method (DEM) was developed.
- The new DEM is used to predict the time-dependent behaviors of fresh concrete.
- Clump elements are used to represent the particles bonded by the cement hydrates.
- The contact force of the parallel bond model in the new DEM is not a constant.
- The contact force changes with the physical dispersion-flocculation of particles.

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ABSTRACT

The time-dependent performances of fresh concrete greatly affect the production and construction from mixing to casting. In this paper, the mechanism of the time-dependence was discussed, followed by proposing a new numerical approach to predict the time-dependent flow behaviors on the basis of the Discrete Element Method (DEM). In the proposed DEM model, both the effects of hydration and physical flocculation were taken into account. To validate the numerical method, the experimental results were compared to the numerical calculation of the gravity-induced funnel flow of fresh mortar at different times after mixing.

1. Introduction

Fresh concrete is essentially a particle assembly containing water. The quality of hardened concrete depends on its rheological behaviors from mixing to placement [1]. In these processes, the rheological property evolves with the elapsed time, usually called time-dependent behavior. A better understanding of such time-dependent behavior makes it possible to explain the phenomena at construction site, such as segregation behavior, flow ability decline during waiting to pump, and the change of formwork pressure [2].

The term "thixotropy" was introduced by Freundlich [3]. It includes two main aspects: (1) structural build-up at rest, which is due to the physical flocculation of particles [4,5], and (2) structural break-down when shaken, agitated, or stressed. A usual thixotropic phenomenon in laboratory is that the up-curve and down-curve of torque-angular rotation velocity relationship are not coincident [6]. The area of the hysteresis loop formed by the up and down curves is usually employed to quantify thixotropic degree [6,7]. However, the area depends on the test conditions such as the shear history, the maximum rotation velocity, and the increasing and decreasing rates of rotation velocity [8]. Another approach is to monitor the decay of measured torque from the beginning to the equilibrium state under a constant rotation velocity [7]. However, it is almost impossible to use these test results to predict the change of fresh concrete' s consistency with time.

Thixotropy of non-reactive granular material, resulting from only particle flocculation-dispersion, is a reversible process. However, for fresh cementitious materials, the structural buildup attributes to both physical flocculation and hydration of cement particles. Thus, the structural breakdown due to an agitation includes the dispersion of physically flocculated cement particles, and the destruction of the hydrate linkages between cement

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Notation

A	area of parallel bond cross-section
a	constant about the hydration rate of cement
b	constant about hydration degree
B	specific surface area of binder
C_n, C_s	normal, and shear damping coefficients
CM	mass of binder in a cubic meter of concrete
D_i	viscous damping force of particle i
E	activation energy of binder
F	contact force
F_{ave}	average contact force of parallel bond force
f_e	correction factor
f_p, f_w	frictional coefficient of particles, and walls
g	acceleration of the gravity
I	moment of inertia
J	polar moment of inertia
k	Boltzmann constant
k_n^p, k_s^p,	normal, and shear stiffness of inter-particle bond
k_n, k_s	normal, and shear stiffness of parallel bond
k_n^w, k_s^w	normal, and shear stiffness of wall-particle bond
m	mass of particle
M	moment of particle
N	total number of particles
N_d	number of dispersed particles
N_{d0}	number of dispersed particles in the initial state
N_f	number of flocculent particles
N_h	number of hydrated particles
P_{FA}, P_{Slag}	replacing ratio of fly ash, and blast furnace slag by mass
$P_{C3A}^{0.30}$, $P_{C4AF}^{0.25}$	content of C_3A, and C_4AF in cement by mass
P_{FACao}	CaO content in fly ash by mass
r	bond radius
R	constant of gas
t_e	equivalent age
t_i	time at the critical point
T	environmental temperature
V_i	relative movement velocity at contact point
x''	translational acceleration

Greek letters

$\alpha(t_e)$	degree of hydration
α_∞	maximum degree of hydration on the standard temperature
ΔF_i^n, ΔF_i^s	increment of normal force, and shear force
Δk_n^{pb}, Δk_s^{pb}	increment of normal, and shear stiffness
ΔM_i^n, ΔM_i^s	normal, and shear moment
ΔU_i^n, ΔU_i^s	normal, and shear displacement
$\Delta \theta_i^n$, $\Delta \theta_i^s$	normal, and shear rotation
η	viscosity of mixing water
λ	bond radius multiplier
σ_c, τ_c	normal and shear strength
ω	constant about the hydration rate of cement
ω'	angular acceleration

particles. Since the destructed hydrate linkages can't recover completely, the structural buildup-breakdown process is irreversible. Hence, slump loss occurs with time in fresh concrete, re-mixing can't restore the consistency. The time dependence of fresh concrete's performance is resulted from physical flocculation, which leads to a thixotropic behavior, and chemical reaction of cement particles.

On a short timescale, the flocculation of cement particles in fresh concrete may dominate, while on a long timescale, the hydration leads to an irreversible evolution in the structure of cement paste matrix [9]. With the advance of particle flocculation and cement hydration, reversible and irreversible bonds between the particles form simultaneously. The time dependence of fresh concrete's performance is essentially caused by the formation and evolution of particles' bonds. Therefore, in principle, it is possible to predict the variation of fresh concrete's performance with time, based on the analysis of inter-particle bond evolution.

The Discrete Element Method (DEM), called particle approach, is a traditional numerical approach to the mechanical behaviors of granular materials, such as sand and soil. The DEM has also been recently applied to the flow simulation of fresh concrete during mixing, transport, placement, and compaction [10–13]. DEM has the advantage of displaying discreetly the movement of concrete mixture as a whole, and of its individual components.

In the DEM, the movements (translation and rotation) of distinct particles occur only when their subjected forces are greater than the strengths of particle-particle bonds or particle-model wall bonds. The bond strengths are constants in the traditional DEM that incorporates the parallel bond model. The authors, however, treated the bond strengths with a linear function of elapsed time, considering the physical flocculation of cement particles but ignoring the hydration in the induction or dormant period, and then analytically investigated the thixotropic behavior of fresh concrete [14,15]. In this study, besides using the parallel bond model to express the contact between the particles, we also introduce particle clumps to reflect the effect of hydration. The particles in the particle clumps are linked by the hydrates to form irreversible bonds, and the numbers of the clumps increase with the elapsed time. In order to verify that this newly proposed DEM model is applied to the prediction of the variation of flow performance of fresh concrete with time, gravity-induced funnel flow rates of fresh mortar at different moments after mixing were measured and compared to the results of the DEM simulation.

2. Discrete element method

2.1. General formulation

The DEM is a particle approach, of which a fundamental assumption is that the analyzed material consists of separate discrete particles: circular particles (2D) or spherical particles (3D). The particles themselves are defined to be rigid, and each particle has mass, density, and dimension. Their interaction is treated as a dynamic process with a developing state of equilibrium whenever the internal forces are in balance. A contact between two neighbour particles is only at one point. The particles move according to the Newton's Second Law, and the contacts between the elements (particles or walls) follow the force-displacement law. That is to say, the Newton's Second Law determines the motion of each particle subjected the inter-particle contact forces, while the force-displacement law is used to calculate the contact forces arising from the relative motion at each contact. The displacements and rotations of the particles follow the governing Eqs. (1) and (2).

$$F_i = m \cdot (x_i'' - g) \tag{1}$$

$$M_i = \cdot \omega_i' \tag{2}$$

where, F_i is the contact force vector acting on particle i, m is the mass of the particle i, x_i'' is the translational acceleration, g is the acceleration of gravity, M_i is the resultant moment acting on