研 究 速 報

Properties of Shotcrete (12)

Summarized Research Report on the Numerical Modeling of Shotcrete

吹付けコンクリートの特性に関する基礎的研究（12）

－DEMによる吹付けコンクリートの数値計算方法の概要－

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1. INTRODUCTION

The analytical flow simulation of fresh concrete is a recent challenge to researchers. Due to its heterogeneity, the concrete mix shows neither a perfectly viscous nor perfectly particulate behavior. However, the particulate behavior of fresh concrete flow like arching and blocking in pipes and in complex boundary conditions, is very common. This is further magnified due to high pressure in the case of shotcreting. For the first time in shotcrete research, the application of the Distinct Element Method (DEM)[1,2] is proposed for the numerical prediction of its behavior. The basic idea of DEM modeling of fresh concrete is to assume it as a two-phase material as shown in Fig. 1.

At first, this research took a shape by simulating a few qualitative shotcrete behaviors by imaginary parameters and considerably big element sizes ($\geq$ 1 m)[3]. The modeling starts from the available DEM source code for granular flow simulation. At the first stage of this research, the DEM tool is modified and some new factors are added, making it capable of modeling fluid-solid[4] mixtures. Authors prolonged this research first by incorporating the real particle size based on its Fineness Modulus[5]. Then, rheological law is introduced[2]. Considering the properties of fresh concrete, some factors among the new added factors are dropped to enhance the computational efficiency of the tool[2]. Furthermore, the two-phase modeling (gravel and mortar) is stressed indicating many drawbacks of the single-phase modeling (only mortar)[4]. The two-phase model is then applied for simulating shotcrete and obtains many qualitative results of its process[4,5,6].

Broadly speaking, the shotcrete mechanism can be separated into three modeling phases as shown in Fig. 2. First phase includes the fresh concrete supply through hose to the nozzle. Second phase includes applying high pressure and consideration for the accelerating agent when the concrete just ejected out the nozzle. The third phase includes the target wall modeling. In this research, a summary of all phases of modelings will be explained briefly, however it is recommended to go through a cited publication for details.

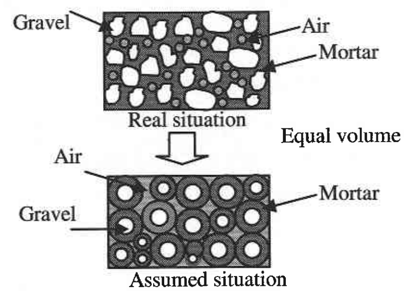

Fig. 1 Principle of the DEM modeling

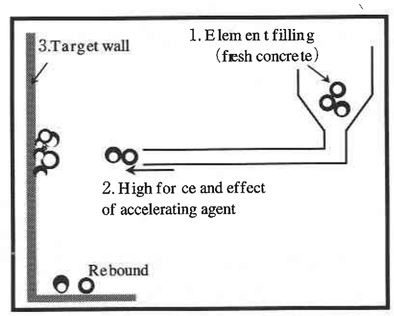

Fig. 2 Schematic diagram of a shotcrete site

2. MODELING OF CONCRETE SUPPLY THROUGH HOSE

In this stage, concrete is in a fresh stage. So, the properties of fresh concrete must be modeled. An important point in DEM simulation is how to take DEM parameters (stiffness, dashpot,

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cohesion, etc.) separately for both mortar and gravel part. For gravel part, it is from the wave propagation theory. A major concern is how to define mortar DEM parameters. To define it, the simulation is connected with the rheology of fresh concrete[7,8,9,10] that defined the parameters satisfactorily. After defining the DEM parameters, fresh concrete is simulated quantitatively. Slumping behavior is first simulated. It is found that, the slump is controlled by the yield value while rate of slumping is controlled by the viscosity[10]

3. MODELING OF AN ACCELERATING AGENT

For the numerical modeling of the accelerating agent, various models are investigated[4]. The essential features of all models are increasing the work done to its value before the addition of the accelerating agent and changing the force displacement law. A model is found appropriate that enables the work done $\alpha(t)$ times and displacement $1/\alpha(t)$ times to their values before adding the accelerating agent [4] shown in Fig. 3 ($\alpha(t) = 1$ for no accelerating agent).

$$\frac{1}{2}\alpha(t)F_1S_1 = \frac{1}{2}F_2S_2 \qquad (1)$$

Putting $\alpha(t)S_2 = S_1$. Following equations are obtained.

$$\alpha(t)^2F_1 = F_2 \qquad (2)$$

$$\alpha(t)^3K_1 = K_2 \qquad (3)$$

So, conditions in Eqs. (2) and (3) are necessary to impose in the calculation. According to this, DEM parameters for fresh concrete are modified as such after the addition of the accelerating agent.

$$Q_{stk}(t) = \alpha(t)^2 Q_{stk} \qquad (4)$$

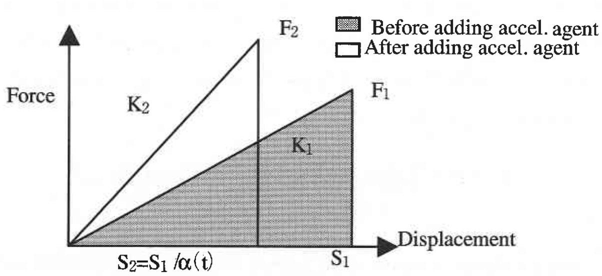

Fig. 3 Consideration of the accelerating agent in DEM

$$k_{pn}(t) = a(t)^3 k_{pnINI} \qquad (5)$$

$$\eta_{pn}(t) = a(t)^3 \eta_{pnINI} \qquad (6)$$

$$k_{ps}(t) = \alpha(t)^3 k_{psINI} \qquad (7)$$

$$\eta_{ps}(t) = \alpha(t)^3 \eta_{psINI} \qquad (8)$$

where Q_{STK} , k_{pnINI}, η_{pnINI}, k_{psINI}, and η_{psINI} are the initial DEM parameters set for the flow simulation of fresh concrete. The expression for $\alpha(t)$ is taken by simulating the exponential increment of the *stiffening effect of the accelerating agent*, which is assumed similar to the setting of fresh concrete during hydration[3,11] as shown in Fig. 4. The following exponential increment as shown in the Eq. (9) is assumed.

$$a(t) = Q_a - (Q_a - 1)\exp\left[-Q_b(t - t_0)^2\right] \qquad (9)$$

where, Q_a, Q_b are properties of the exponential curve (usually, $Q = 1.0$), t_o it total time required for elements to reach the nozzle (from the start of simulation), t total time from the start of simulation to the instant of time when shooting is finished or stopped.

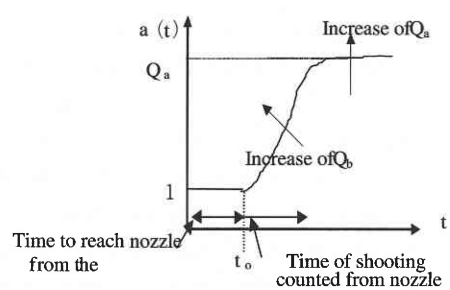

Fig. 4 Stiffening upon the addition of the accelerating agent

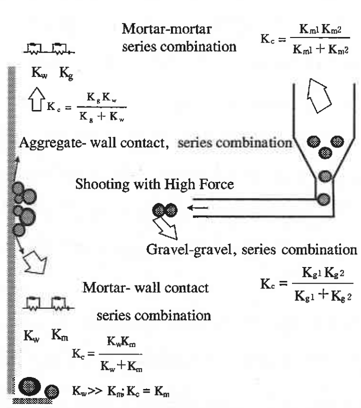

Fig. 5 Taking combined stiffness at different level of collisions

4. TAREGT WALL MODELLING

Different conditions of a target wall from soft to hard surfaces pose difference in DEM modeling, on the rebound loss and void characteristics of shotcrete[12]. The way of taking the combined stiffness at different levels of collisions is shown in Fig. 5.

Upon hitting a distinct element to the target wall, if the contact is within the mortar layer, the softer mortar parameters are taken (since the major deformation is given by mortar). If the contact is more than the thickness of the mortar layer, it means that inside gravel element and target wall surface are in contact. The series combination is considered for this situation as well.

The creation of the geometry of the target wall will be essentially of two types (same for any boundary). A type is conjunct type of generating wall boundary and B is the overlap type for the same as shown in Fig. 6. Wall profile proximity is designated by SAR[4,12]. This SAR approximates close to a real boundary. The lower the SAR the closer it becomes to the real target wall boundary.

$$SAR(\%) = \frac{S}{D \times R} \quad \cdots\cdots (10)$$

So, these creations of the geometry and taking the combined stiffness reflect the different characteristics of the target wall.

EXAMPLE OF QUANTITATIVE SHOTCRETE SIMULATION

Collecting these ideas, the quantitative simulation is put forwarded. A flow chart for checking consistency and shotcrete performance is shown in Fig. 7.

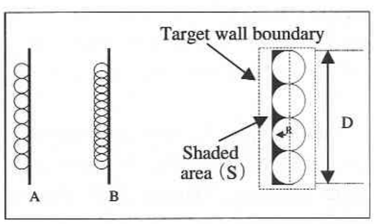

Fig. 6　Creation of the target wall boundary

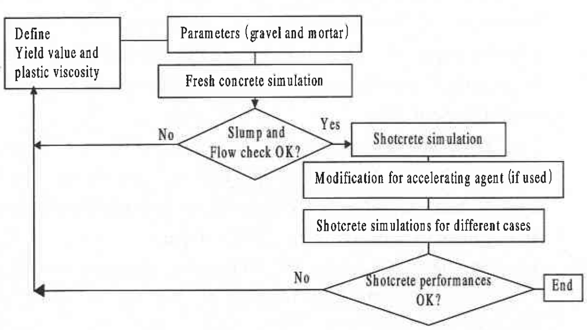

Fig. 7　Steps of the quantitative DEM simulation

At first, the rheological constants (yield value and plastic viscosity) are defined for fresh concrete. These things basically come from mix proportion characteristics. The DEM parameters are obtained from the rheological constants[10]. Using these parameters, the workability of fresh concrete is simulated. If the workability is satisfactory, then shotcrete simulation can proceed. Investigation of the effect of rheology on shotcrete process is performed. It is obtained that the yield value of fresh concrete plays an important role in shotcrete[13]. An example of slump and flow simulation and then shotcrete simulation using the parameters shown in Table 1 is illustrated in Figs.8–9.

It should be noted that in this calculation, the rheological constants are the input parameters which need to be obtained from the rheological tests. However, it is known that the yield value has a direct relation with slump. An empirical formula relating slump value (for 12.5 to 26cm) with the yield value is given by Jiro[14]. A similar formula holds true with resonable accuracy in present sim-

Table 1　DEM parameters for fresh concrete mix (uplifting)

Mortar (Normal)	Spring constant QKNP, N/m	600.0	Mortar (Shear)	Spring constant QKSP, N/m	150.0
	Dashpot coeff. QYNP, N.s/m	8.46		Dashpot coeff. QYSP, N.s/m	9.2
Gravel (Normal)	Spring constant* QKN, N/m	1.29 x10^5	Gravel (Shear)	Spring constant* QKS N/m	5.4x 10^4
	Dashpot coeff.* QYN, N.s/m	9.74		Dashpot coeff.* QYS, N.s/m	12.62
Friction (mortar-mortar)		0.14	Friction (gravel-gravel)		0.4
Time step, Dt		10^{-5}	Simulation time, T		5.0 s
Element no., NEL		230	Allowance of tension, R_d		2.3%

* Gravel parameters based on element size 15 mm (dia.). Spring constants for gravel are scaled to 1/1000 times to that calculated by the wave propagation theory to ensure stability in the calculation (due to real size of gravel used).

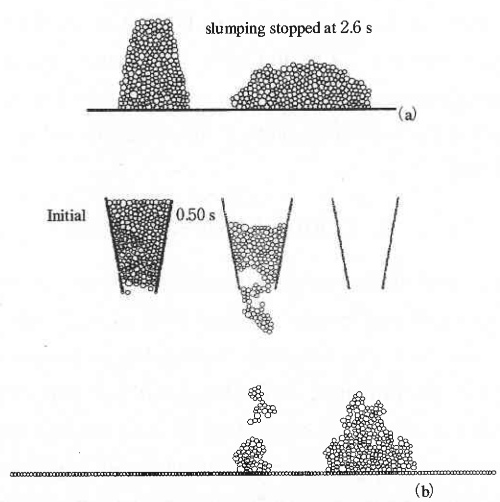

Fig. 8　(a) Slump test (slump 20 cm in exp., 19.2 cm in simulation)
(b) opposite slump test (flow time 1.15 s)

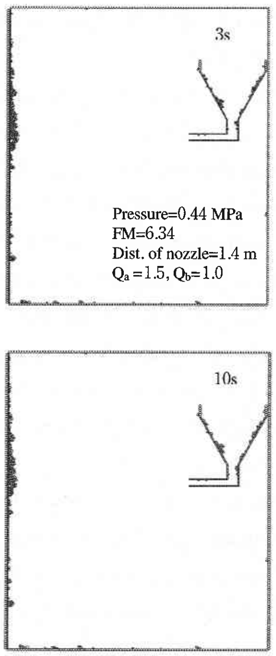

Fig. 9 Shotcrete simulation for 10 s (shown at only 3 s and 10 s)

ulation as well.

But, the values of experimental constants (A and B) will be different. As for the viscosity, it will be defined by the slumping curves as given in Eq.(7).

$$\tau_0 = A \log Sl. + B \quad \cdots\cdots (6)$$

$$sl. = Sl. - \frac{1}{\frac{\alpha \rho g}{600\,\eta} t + \frac{1}{Sl.}} \quad \cdots\cdots (7)$$

where, τ_o is the yield value in Pa (× 100), A and B are experimental constants (− 4.83 and 7.29), *Sl.* is slump value (cm), *sl.* is slumping value (cm), t is time of slumping (s), α equal to 1/2, ρ is density of fresh concrete, and g is the acceleration due to gravity (9.81 m/s^2).

5. CONCLUDING REMARKS

This simulation procedure establishes a general numerical way for checking the consistency of fresh concrete and shotcrete performances. It is now possible to predict the consistency and the shotcrete performances beforehand without performing any experiment. The input parameters are only the mix proportion characteristics, which is known at the early stage of concrete works. This simulation procedure is expected to be very useful for practical engineers working in fresh concrete and shotcrete.

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