論　文

[1146] ポンプ圧送時におけるフレッシュコンクリートの変形性を表わす数学的モデル

MATHEMATICAL MODELING OF DEFORMATION FOR FRESH CONCRETE IN PUMPING

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1. INTRODUCTION

This paper reports a visual test carried out to obtain information on two phase material flow in tapered pipes and discusses the segregation process and blockage. Studying the sensitivity of viscosity to the kinematics of model concrete, the authors simulated the segregation process based on one dimensional computational model for pipe flow of fresh concrete.

2. VISUAL TEST

2.1 TEST METHOD

In order to observe the mechanism of blocking due to aggregate particles as the solid phase deformation in two phase material flow, the visual test developed by Hashimoto [4] was adopted.

A rectangular pipe section which consists of straight and tapered portions made of transparent acrylic panel was used (Fig.1). Transparent polymer was used as the paste media. Plastic balls (25 mm in diameter) and light weight aggregates (approx.15 mm in diameter) were used as coarse aggregates for model concrete. Cellulose was utilized for changing the viscosity of polymer paste.

After placing the polymer and particles as shown in Fig.2.a, the piston head was moved at a constant speed while recording the particle movement by video camera and the pumping force by a load cell. The experiment was carried out by changing the viscosity of paste for both light weight aggregates and plastic balls.

2.2 OBSERVATIONS AND DISCUSSION

Fig.2 shows the process of arch formation by plastic balls which initiate blocking in tapered pipes. In the case of light weight aggregates as aggregate phase, complete blockage occurred after the formation of

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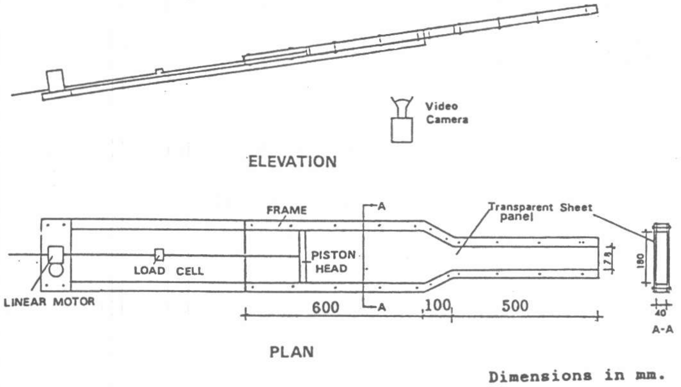
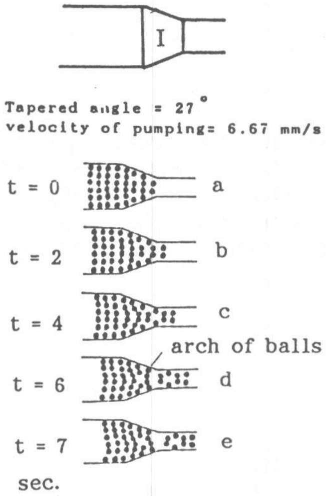
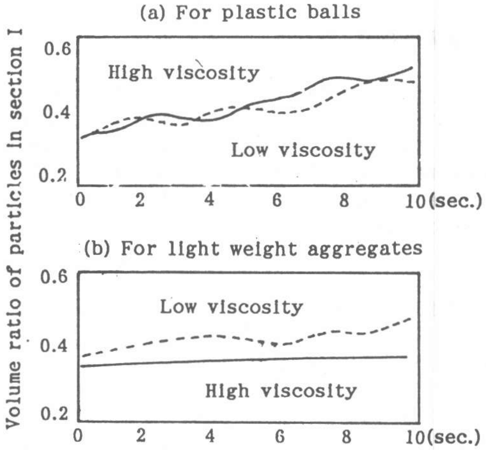


Fig(1) Apparatus for pumping



Fig(2) Flow pattern and formation of arch



Fig(3) Volume ratio of particles in the tapered section vs time

the arch, while the blocking did not take place in the case of plastic balls. This was due to the higher friction and interlocking between particles since light weight aggregates had irregular configuration on surfaces.

As shown in Fig.3, the rate of volume increase for plastic balls in the tapered section is found to be independent on the polymer viscositywhile the particle accumulation of light weight aggregates highly depends on viscosity of polymer. Due to the turbulence and rearrangement of balls in low viscosity paste, additional stress dependent on the surface condition should be produced on particles. Since plastic balls have smooth surfaces, even though the balls contact and slide each other, the contact stress developed in plastic balls may not increase appreciably. The wall friction and the normal reaction from the pipe wall acting on balls, which are functions of the contact stress, are expected to govern no appreciable change in accumulation of balls in the tapered section. High aggregate contact stress developed in lightweight particles is expected due to rough irregular surfaces. Accordingly, it should be simulated that the paste viscosity be effective on accumulation of particles with high inter-particle actions.

3. TWO PHASE MODEL FOR FLOW AND SEGREGATION OF FRESH CONCRETE

3.1 CONCEPT OF THE PROPOSED MODEL

The aggregate phase is assumed to be uniformly distributed throughout the cross sectional area of the pipe and to maintain continuity as shown in Fig.4. The mortar phase is assumed as the disperse medium filling the space between aggregates. $_a$ and ρ_m are Volume ratios of aggregate phase and mortar phases per unit concrete volume. Assuming incompressibility of concrete, we have

$$\rho_a + \rho_m = 1 \tag{1}$$

The mean sectional areas of the aggregate and mortar phases are modeled as $A\rho_a$ and $A\rho_m$, where A is the total cross-sectional area of the pipe line. The forces acting on aggregate and mortar phases are defined as $A\rho_a\sigma_a$ and $A\rho_m\sigma_m$. Then, the total pressure p is given by

$$p = \rho_a\sigma_a + \rho_m\sigma_m \tag{2}$$

3.2 AGGREGATE CONTACT STRESS

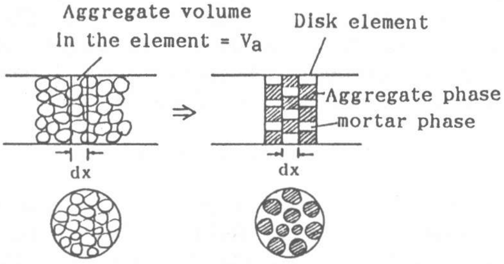
The aggregate contact force which may arise from interparticle collision or frictional sliding is resolved in the axial and the radial directions of the pipe. The axial contact stress σ_c is defined as the axial contact force F_c on the aggregate phase per unit cross sectional area of the pipe and the radial contact stress, σ_{rc}, is assumed as a function of axial contact stress as follows:

$$\sigma_c = F_c/A \tag{3}$$

$$\sigma_{rc} = k\sigma_c \tag{4}$$

where k depends mainly on the aggregate shape and the frictional property. The mean aggregate stress σ_a is evaluated as the mortar stress plus the interparticle stress as shown in Fig.5, then,

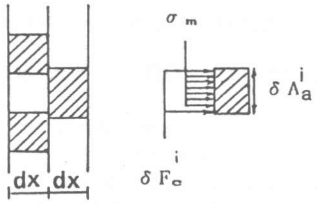
$$p = \sigma_m + \sigma_c \tag{5}$$



Fig(4) Idealization of aggregate phase and mortar phase

3.3 CONSTITUTIVE MODEL FOR AGGREGATE CONTACT STRESS

The inlet pumping pressure is reported to increase with the increase of aggregate content under the same flow rate of pumping [1]. Then, the aggregate contact stress is assumed as a exponential function of aggregate volume ratio and the function was selected in such way that it represents the test results[1] qualitatively. Further modifications were introduced regarding with velocity and



Fig(5) Forces acting on aggregate phase

tapered angle. With the increase in particle velocity, the contact stress due to particle collision may increase. Considering these factors, the contact stress is assumed as follows:

$$\sigma_c = \rho_a c(1+m\tan\theta)(1+fv_a)\exp(\alpha\rho_a)\tan(\beta\rho_a) \qquad (6)$$

Where f, c, α, β are constants to control the sensitivity of the volume ratio to the contact stress. θ and v_a denote the tapering angle and the velocity of the aggregate phase, respectively. The term $(1+m\tan\theta)$ is introduced to account for additional stress due to re-arrangement of particles and enhanced collision in tapered sections.

3.4 THE SEGREGATION RESISTANCE FORCE

When relative movement between aggregate and mortar phases is induced, segregation resistance forces Fs must be considered on both phases respectively. A model for this force is simply assumed based on the ball type viscometer[2] for cement paste as follows.

$$Fs = n\rho_a A\,(s(v_m - v_a)r + dr^2) \qquad (7)$$

where, v_a, v_m are average velocity of aggregate and mortar phases. The parameter r denotes average particle radius in length and s, d, n are the factors relating to viscosity of mortar, yield stress of mortar, number of particles per unit volume of aggregate phase respectively.

3.5 WALL FRICTION

The total wall friction to the flow of concrete can be assumed as the sum of the friction due to aggregate and mortar. The frictional force acting on aggregate phase per unit length of the non tapering pipe, T_a, is assumed as a function of radial contact force of aggregate phase.

$$T_a = 2\pi R\sigma_{rc}\mu \qquad (8)$$

where R is defined as pipe radius and μ as frictional coefficient between aggregate and pipe wall. Since the contact area between aggregate and pipe wall is negligible, the frictional force between mortar and pipe wall, T_m, is computed as the product of liquid adhesion stress with the pipe peripheral length [3] as

$$T_m = 2\pi R(a + bv_m) \qquad (9)$$

where "a" represents yield stress and "b" denotes the viscous coefficient.

3.6 EQUATIONS OF MOTION FOR AGGREGATE PHASE AND MORTAR PHASE

Considering forces developing in the aggregate phase as shown in Fig.6 and Fig.7, we have the following equations of motion by the Eulerian differentiation designated by "D/Dt" in the flow direction and the equilibrium in the normal direction of the pipe axis for the aggregate phase.

$$-\frac{d(A\rho_a\sigma_a)}{dx}\,dx - T_a\cos\theta - R_a\sin\theta + Fsdx = (D_a A\rho_a dx)\frac{Dv_a}{Dt} \qquad (10)$$

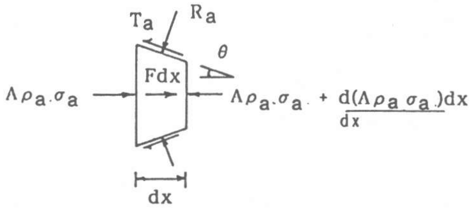
$$R_a\sin\theta = \sigma_c(\tan\theta\sin\theta + k\cos\theta)2\pi Rdx\sin\theta \qquad (11)$$

Frictional force of T_a must be the function of normal contact stress as μR_a similar to the friction in the straight part. Similarly, the kinematic equation for paste phase can be formulated as follows:

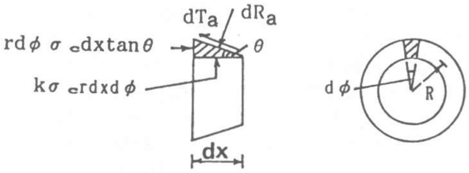
$$-\frac{d(A\rho_m\sigma_m)}{dx}\,dx - T_m\cos\theta - R_m\sin\theta - Fsdx = (D_m A\rho_m dx)\frac{Dv_m}{Dt} \qquad (12)$$

where T_m and R_m are the frictional force and the normal wall reaction acting on the mortar phase. Assuming isotropic paste stress, R_m can be derived as

$$R_m = \sigma_m 2\pi Rdx/\cos\theta \qquad (13)$$



Fig(6) Forces acting on aggregate phase in the tapered section



Fig(7) Forces acting on aggegate phase element

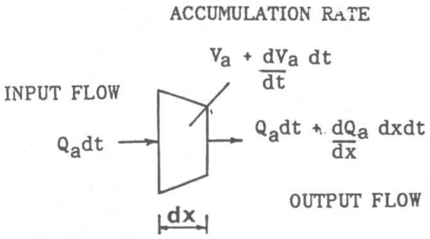
3.7 COMPATIBILITY EQUATION FOR AGGREGATE PHASE AND MORTAR PHASE

According to the compatibility of mass transfer, the total input mass in each phase should be equal to the sum of each volume increase with each output flow as shown in Fig.8. During time interval of dt, the following equations must be held.

$$\frac{dQ_a}{dx}dxdt + \frac{dV_a}{dt}dt = 0 \qquad (14)$$

$$\frac{dQ_m}{dx}dxdt + \frac{dV_m}{dt}dt = 0 \qquad (15)$$

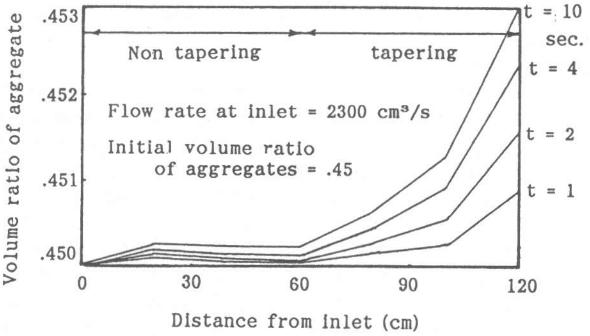
where $Q_a = v_a\rho_a A$ and $Q_m = v_m\rho_a A$ are input flow rates. $V_a = V\rho_a$ and $V_m = V\rho_m$ are volumes of aggregate and mortar in the element and V is the total volume of the element and equal to Adx.



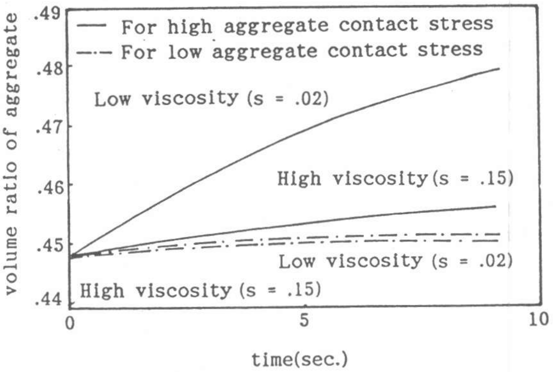
Fig(8) Input and output flow for aggregate phase

3.8 ANALYTICAL RESULTS AND DISCUSSION

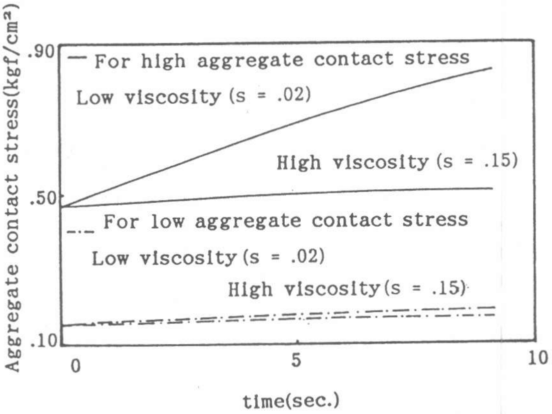
The nonlinear partial differential equations 10, 12, 14,15 are simultaneously solved by the finite difference method and Newtons iterative scheme. From the analytical results(Fig.9) it can be seen that the volume ratio of aggregate phase changes along the pipe indicating segregation. Segregation is defined as the change in volume ratio of aggregate



Fig(9) Volume ratio of aggregate vs distance from its initial one within the pipe. Sensitivity analysis indicates that the parameter related to the viscosity in the segregation force Fs is very sensitive on segregation. Analytical results also indicate that the effectiveness of viscosity of mortar depends on the the aggregate mutual interaction. We note from Fig.10 that, for higher aggregate contact stress, the viscosity of mortar phase is much sensitive to the segregation than that of lower aggregate contact action. This result coincides with the visual test results discussed in Section 2.3. In the analytical results shown in Fig.11, for the light weight aggregate case the aggregate contact stress is predicted to increase with time and to reach the final stage of blocking.



Fig(10) Volume ratio of aggregate at outlet



Fig(11) Aggregate contact stress at outlet vs. time

4 CONCLUSIONS

1. Segregation of aggregate which leads to accumulation of aggregates in the tapered section was observed by the visual test. It was found that the paste viscosity was more sensitive to the segregation of material having rough surface than that with smooth surface.

2. Computational flow simulation considering phase-segregation was carried out. By using the concept of aggregate contact stress and segregation resistance, the numerical simulation succeeded in explaining the effect of the paste viscosity on the accumulation of particles.

The authors express their gratitude to Ministry of Education of Japan for providing the financial support by the Grant-in- Aid No. 61850090.

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