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FLOW AND SEGREGATION OF FRESH CONCRETE IN TAPERED PIPES — TWO-PHASE COMPUTATIONAL MODEL

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ABSTRACT

The objective of this paper is to clarify the deformation and aggregate segregation of fresh concrete in tapered pipes, for the development of high performance concrete with high pumpability. Visual tests on flow of model concrete were conducted to investigate the segregation and blocking process which is triggered by coarse aggregate particles in liquid-solid flow.

The effect of liquid phase viscosity on the segregation of aggregate particles is found to be highly dependent on the collisional and frictional interaction of solid. To simulate this behavior, the authors employ a simple mathematical model for concrete flow in tapered pipes, and discuss it's relation with high performance concrete.

NOMENCLATURE

A	cross sectional area of pipe
D_a, D_m	density of aggregate and mortar
F_s	resisting force against segregation between liquid and solid phases per unit volume of concrete
k	ratio of internal radial stress to axial stress of aggregate
p	total pressure of concrete at a pipe section
R	pipe radius
r	average radius of aggregate particles
R_s	resisting force on a sphere from liquid phase
R_a, R_m	normal reactions acting on aggregate and mortar phases per unit length of pipe, respectively
T_a, T_m	frictional shear forces acting on aggregate and mortar phases per unit length of pipe, respectively
v_a, v_m	mean velocity of aggregate and mortar phases, respectively
μ	frictional coefficient between aggregate and pipe wall
θ	taper angle of pipe
τ	yield stress of liquid phase (mortar)
η	plastic viscosity of liquid phase (mortar)
η	semi-viscous parameter of liquid phase
ρ_a, ρ_m	volume fraction of aggregate and mortar phases, respectively
σ_c, σ_m	aggregate contact and mortar stresses with respect to cross sectional area of pipe
σ_{co}	aggregate contact stress in straight pipes
σ_{cr}	aggregate stress in the radial direction

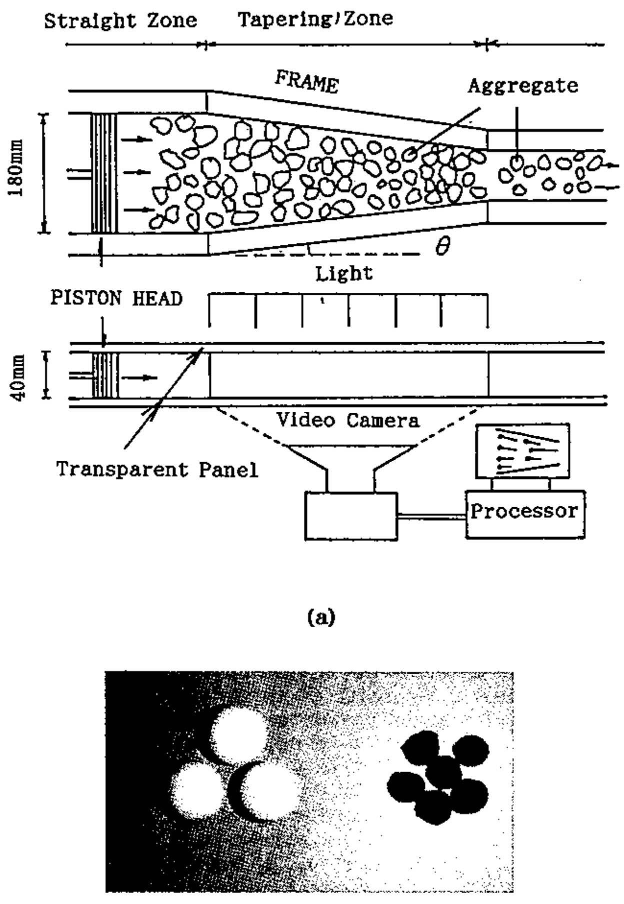
1 INTRODUCTION

Even though concrete pumping has gained much popularity in the construction of concrete structures, there exists no rational mix design method for pumpable concrete, free from blocking and segregation between aggregate (solid phase) and cement mortar (liquid phase). In order to establish the mix design concept for pumpability, the deformational behavior of fresh concrete, especially in tapered pipes, should be made clear, since flow of concrete in tapered pipes often exhibits the segregation of aggregate and subsequent blocking of fresh concrete flow during pumping.

This paper reports on the flow of concrete treated as a two phase material in tapered pipes and discusses the segregation process of aggregate from the liquid phase. After studying the sensitivity of liquid viscosity to the flow of model concrete, the authors have simulated the segregation process by means of a one dimensional computational model for flow of fresh concrete in both straight and tapered pipes.

2 VISUAL TEST ON MODEL CONCRETE

Concrete is a multi-phase material consisting of air, water, cement powder, fine and coarse aggregates (sands and gravels). Taking the size of particles into consideration, we treat concrete in pipe lines as a two-phase mixture, with coarse aggregate as solid phase and mortar slurry (mixture of air, water,



(a)

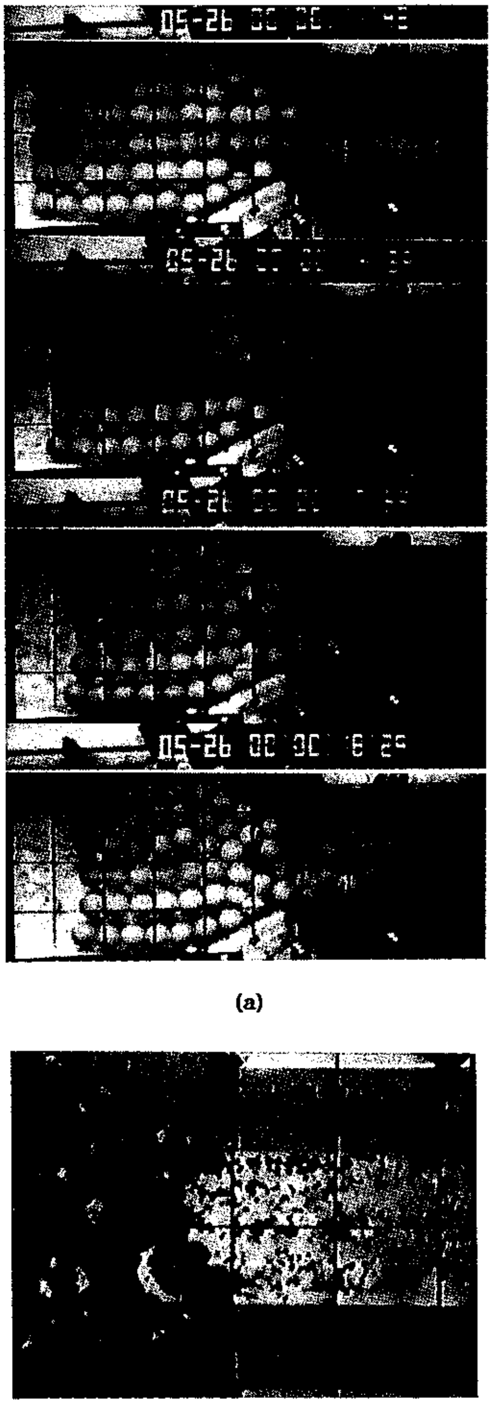
(b)

Fig.1 (a) Pumping apparatus for visual test
(b) Coarse aggregate used in the test

cement and sand) as continuous liquid phase, because coarse aggregate particles having the specified size of 5-25mm, which is 1/25 - 1/5 of the pipe diameter in general, are expected to display the mutual interaction as a solid phase. On the other hand, since the maximum size of constituent particles of mortar is at most 5mm (1/25 of the pipe diameter), we hypothesize the mortar behavior to be liquid continuum.

2.1 Test Method

The visualization method discussed in the reference[1] was adopted in this research. This method utilizes a model concrete consisting of coarse aggregate and transparent liquid polymer having the same viscosity as mortar[2]. The liquid viscosity was changed by adding a cellulose thickening agent to the liquid polymer in order to study the effect of liquid phase viscosity on the solid particle movement. To observe the movement of solid particles, a rectangular pipe line with straight and tapered portions made of transparent acrylic panel was used (Fig.1(a)). Plastic spheres (25 mm in diameter) as well as light-weight aggregate (approx.15 mm in diameter) were used as the coarse aggregate for the model concrete. The two types of particles have similar shape and specific gravity of 1.5, but their surface conditions are different as shown in Fig.1(b).

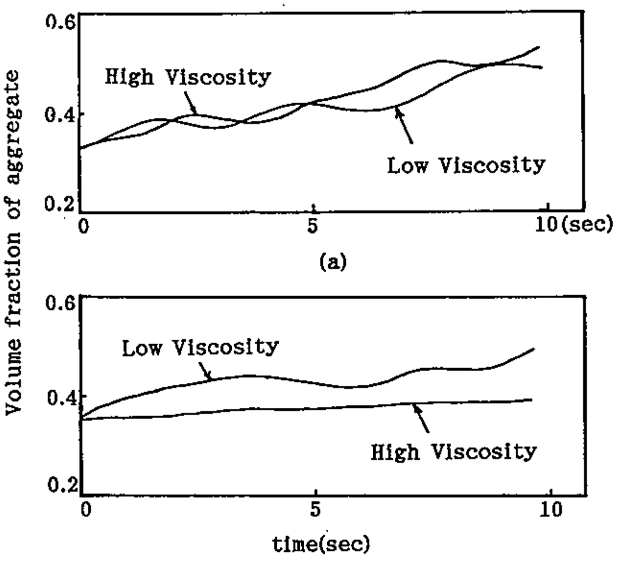


(a)

(b)

Fig.2 (a) Flow pattern of aggregate (plastic spheres)
(b) Blocking due to arch of aggregate
(light weight aggregate)

After placing the particles, the piston was moved at a constant speed while recording the movement of aggregate by a video camera and image processor[1].



(a)

(b)

Fig.3 Accumulation of particles in tapered pipe
(a) Plastic spheres
(b) Light weight aggregate

2.2 Segregation Process and Effect of Viscosity

The flow pattern of plastic spheres with smooth surface in a tapered pipe, where a steep angle of 27deg was adopted to accelerate particle re-arrangement, is shown in Fig.2(a). Particles were disturbed with mutual interaction (collision and friction) and arches supported by the side walls were formed near the outlet as shown in Fig.2(a). Arch formation by the solid phase implies the development of high internal stress which act directly to block the flow of solids. As a result, segregation of solid from liquid phase, the so-called "dewatering", took place. Using light-weight aggregate, we observed significant segregation because of the greater interaction between particles due to rough surface condition, and the subsequent flow of model concrete was completely blocked as shown in Fig.2(b). This indicates that the segregation process is closely related to the internal stress transferred through solid phase.

The segregation induced by the internal stress in the solids resulted in an increase in volume of light-weight aggregate as shown in Fig.3(b), where the adopted taper angle of 27deg. A higher liquid viscosity, with the 'P' funnel draining time of 12min. (3 times greater than the low viscosity indicated in Fig.3), reduced segregation and produced stable flow of the model concrete. The high liquid viscosity is effective for resisting the development of relative motion between solid and liquid phases.

In discussing the blocking of concrete, we must therefore regard the solid-solid interaction as a negative influence and the liquid viscosity as a positive one on the resistance to segregation. The solid-liquid flow in tapered sections is governed by the balance of these two effects. We can see an interesting result in Fig.3(a) that the accumulation of plastic spheres in the tapered portion is not significantly affected, on the contrary, by the viscosity of liquid. The solid phase of plastic spheres appears to involve less frictional interaction, which means that the negative effect is relatively small compared with the positive influence.

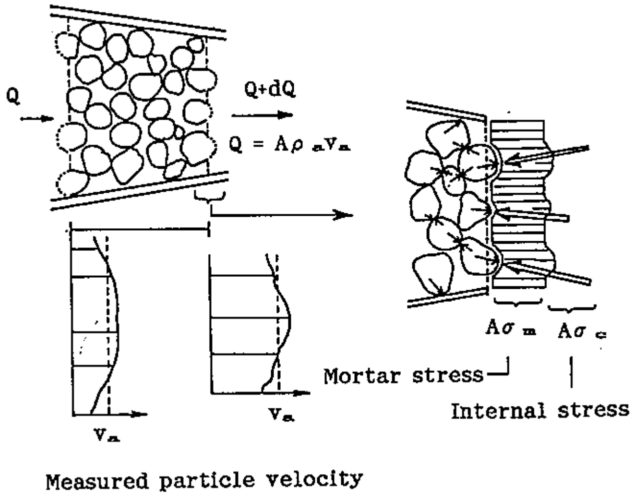


Fig.4 Continuity of mass flux

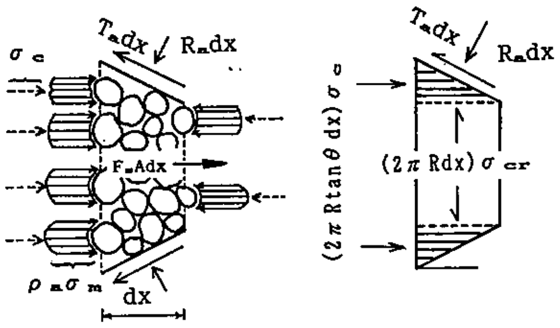


Fig.5 Forces acting on aggregate phase

There are limits on our ability to explain the sensitivity of liquid viscosity and solid interaction by means of a purely experimental approach. Accordingly, we have carried out a numerical simulation, taking both positive and negative effects on the segregation into account, and have also conducted a sensitivity analyses.

3 TWO PHASE MODEL FOR FLOW AND SEGREGATION OF FRESH CONCRETE

The aggregate phase is assumed to be uniformly distributed and continuous throughout the cross sections of the pipe[3] as shown in Fig.4. The liquid phase, corresponding to mortar, is assumed as the continuous medium filling the space between aggregates. Let subscripts "a" and "m" denote the aggregate and mortar phases, and v_a,v_m represent mean velocity of particles and liquid phase over the section shown in Fig.4. Similarly, the stress σ in this paper is defined as the mean value over a cross section.

3.1 Continuity and Incompressibility

The values of ρ_a and ρ_m are defined as volume fractions of each constituent material. Assuming incompressibility, we have

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

The mass flux of each phase passing through a cross section per unit time is evaluated as $v_a \rho_a A$ and $v_m \rho_m A$, respectively. According to the continuity equation, the divergence of mass flux in each phase must be balanced with the time rate of increase of each volume fraction. Considering that the cross sectional area A is not constant in a tapered portion, we have

$$\frac{\partial (v_a \rho_a A)}{\partial x} + A \frac{\partial \rho_a}{\partial t} = 0 \tag{2}$$

$$\frac{\partial (v_m \rho_m A)}{\partial x} + A \frac{\partial \rho_m}{\partial t} = 0 \tag{3}$$

3.2 Stress of Mortar and Aggregate Phases

Let us consider the equilibrium governing total pressure p at a cross section as shown in Fig.4. Since the total force pA must be equal to the addition of the mortar pressure component($\sigma_m A$) and the contact force contribution($\sigma_c A$), the total pressure becomes

$$p = \sigma_m + \sigma_c \tag{4}$$

Furthermore, we define σ_{cr} as the radial component of solid contact stress transferred through aggregates, while, on the other hand, the radial stress in liquid is assumed to be σ_m corresponding to an isotropic hydrostatic stress. According to observations in Section 2.2, σ_c and σ_{cr} represent inter-particle collision and frictional sliding.

3.3 Equation of Motion for Aggregate and Mortar Phases

The forces acting on the infinitely small volume of solid phase of volume $\rho_a Adx$ are shown in Fig.5, where there exist three types of forces. The first one acts from the wall to the solid phase as R_a and T_a. The second is the segregation resistance force F_s acts on both phases equally and opposite directions and the third is the resultant of forces developing at x and x+dx. Based on the assumption in Section 3, the average cross sectional area of solid phase is equal to $A\rho_a$. Accordingly, the resultant force at section x is $(A\sigma_c + A\rho_a \sigma_m)$ and we have the following equation of motion in the flow direction and equilibrium of forces in the radial direction.

$$-\frac{\partial (A\sigma_c + A\rho_a \sigma_m)}{\partial x} - T_a \cos\theta - R_a \sin\theta + F_s A = (D_a A \rho_a) \frac{Dv_a}{Dt} \tag{5}$$

and

$$R_a = (\sigma_c \tan\theta \sin\theta + \sigma_{cr} \cos\theta) 2\pi R \tag{6}$$

where, $Dv_a/Dt = (\partial v_a / \partial t) + v_a (\partial v_a / \partial x)$ represents the mean acceleration of solid particles. Similarly, the equation of motion and equilibrium equation for mortar phase can be formulated as,

$$-\frac{\partial (A\rho_m \sigma_m)}{\partial x} - T_m \cos\theta - R_m \sin\theta - F_s A = (D_m A \rho_m) \frac{Dv_m}{Dt} \tag{7}$$

$$R_m = \sigma_m (2\pi R / \cos\theta) \tag{8}$$

where, the segregation resistance in Eq.(7) has the opposite sign of that in Eq.(5).

4 MATERIAL MODELS

The governing equations Eqs.(1)-(8) for two-phase flow are independent of material properties. To complete the description and necessary simultaneous differential equations, material constitutive laws must be defined.

4.1 Wall Friction

Regarding the stress transfer between solids and pipe wall, we adopt Coulomb's frictional law,

$$T_a = \mu R_a \tag{9}$$

where, 0.35 was assumed as the friction coefficient of μ in our computations.

On the contrary, the force between the mortar phase and pipe wall is not depending on the normal force R_m but rather on the slippage velocity at the pipe walls [4]. Mortar can not be assumed as a Newtonian material because of its non-linear shear stress-shear rate relationship and from the experiments carried out by Tanigawa et al[5], slipping resistance of mortar was found to be linearly proportional to slipping velocity. Based on those experimental results[5], the shear force is roughly idealized as the following equation.

$$T_m = 2\pi R(\tau + \eta' v_m) \tag{10}$$

where, τ and η' are material parameters representing yield stress and semi-viscous parameter of mortar and representative values used in the analysis, based on the experimental result[5], are 2×10^{-3} kgf/cm^2 and 1.25×10^{-4} kgf.s/cm^3, respectively.

4.2 The Segregation Resistance Force

When relative movement between aggregate and mortar phases occurs, the interface resistance F_s must be considered on both phases. Based on viscous drag on a sphere [6], the resisting force R_s exerted on a sphere of radius "r" by the mortar phase is given by

$$R_s = \eta (12\pi r)(v_m - v_a) + 7\pi^2 r^2 \tau \tag{11}$$

The number of particles per unit volume of concrete is proportional to the volume fraction of ρ_a. Assuming that the force on the solid phase subjected to segregation or slip velocity $(v_m - v_a)$ results from the sum of forces on individual particles, we have,

$$F_s = (3\rho_a / 4\pi r^3) R_s \tag{12}$$

where, the first term in Eq.(12) represents the number of particles in unit volume of concrete.

4.3 Aggregate Internal Stress

Since internal stress in aggregate phase represents the mutual interaction between particles, σ_c should depend on ρ_a, v_a and θ. The volume fraction of ρ_a represents a mean separation between particles. Both v_a and θ reflect the intensity of turbulence of the solid phase (collision and friction).

It has been reported[7] that the pump pressure for straight pipe lines, where θ is zero, varies

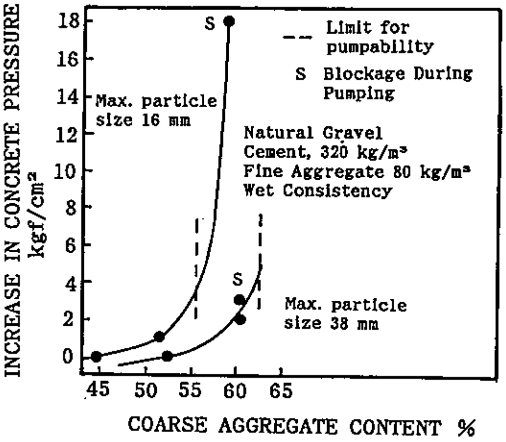


Fig.6 Effect of coarse aggregate content on pump pressure[7]

exponentially on the volume content of aggregates, as shown in Fig.6.

The pressure increase is highly dependent on the increase in the aggregate internal stress. And also from the test results of the static compaction test on aggregate[8], it was found that the shape of the stress-volume fraction of aggregate curve is similar to the curve given by Eq. (13-1) with $v_a = 0$ and the shape of this curve is independent of the type of particle. Even though the data is not available for the effect of velocity on aggregate contact stress, a linear variation was assumed due to simplicity in the analysis. Referring to these experimental results, we adopt the following constitutive equation for aggregate contact stress with respect to the straight pipe where $\theta = 0$.

$$\sigma_{co} = c(1+f\ v_a)\rho_a \exp(\alpha\ \rho_a)\tan(\beta\ \rho_a) \text{ for } \theta = 0 \qquad (13\text{-}1)$$

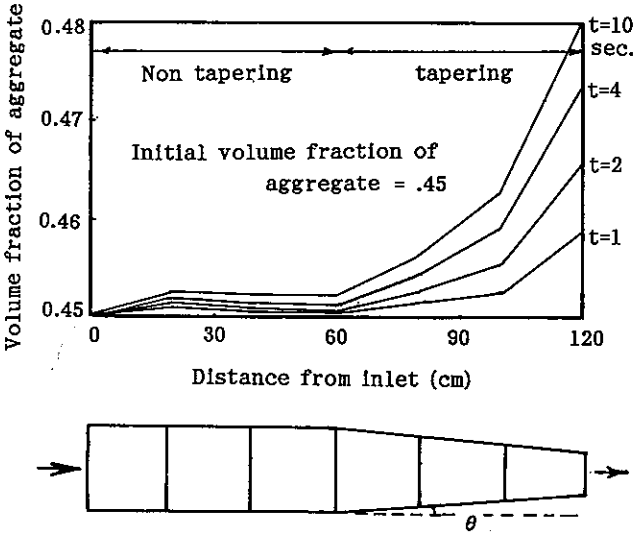
$$\sigma_{cr} = k\ \sigma_{co} \qquad (13\text{-}2)$$

The parameters α, β and f, with $\alpha = 15$, $\beta = \pi/4$ and f=1.5 are representative values used in the analysis, govern the sensitivity of the volume content and flowing speed to the inter-particle actions. The parameter k in Eq.(13-2) corresponds to the Poison's effect in the continuum mechanics, and 0.35 was adopted in the analysis.

The enforced particle re-arrangement in tapered pipes, as discussed in section 2 above, corresponds to increase in the contact stress and depends on the surface condition of the particles. However, as we have no appropriate method to evaluate the effect of θ experimentally, the following expression which satisfies the extreme case where the stress becomes infinite at $\theta = \pi/2$, was used for our sensitivity analyses:

$$\sigma_c = (1 + m \tan\theta)\sigma_{co} \qquad (13\text{-}3)$$

The parameter m may represents the surface condition of the particles. The value of m representing light weight aggregate is lager than that of plastic spheres since light weight aggregate introduce higher aggregate contact stress due to its rough surface condition than the plastic spheres.



Inlet velocity of concrete = 13 cm/sec

Fig.7 Analytical results of transient volume fraction distribution of aggregate

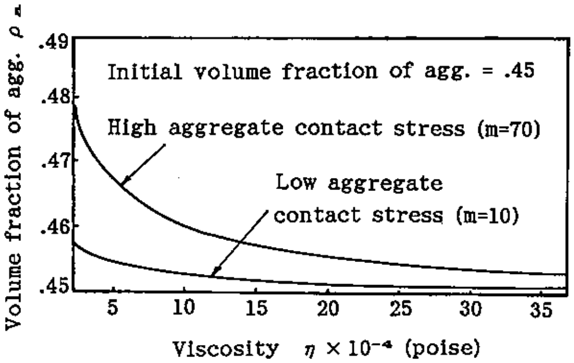


Fig.8 Sensitivity of viscosity parameter on segregation

5 ANALYTICAL RESULTS AND DISCUSSION

The non-linear differential equations in Eq.(1)-Eq.(13), are simultaneously solved by the finite difference method and Newtons iterative scheme.

The numerical simulation shows that the volume content of aggregate phase changes with time and distance as shown in Fig.7. A sensitivity analysis indicates that the parameter η, related to the viscosity of mortar, is very sensitive to the segregation when the aggregate contact stress is high, as shown in Fig.8 which shows the volume fraction of aggregate in the tapered pipe is increasing with respect to it's initial value, with the decrease in parameter η.

Further, results of sensitivity analysis on σ_c indicate that the effect of mortar viscosity depends on the the aggregate mutual interaction. For higher aggregate contact stress (corresponds to m=70 in Eq.(13-3)) which represents light-weight aggregates, the mortar phase viscosity is found to be

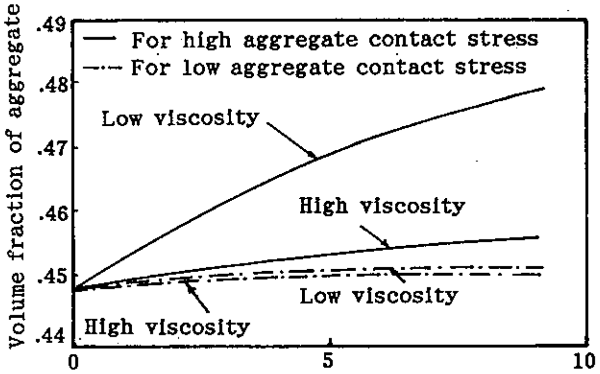


Fig.9 Analytical results of volume fraction of aggregate with time and viscosity

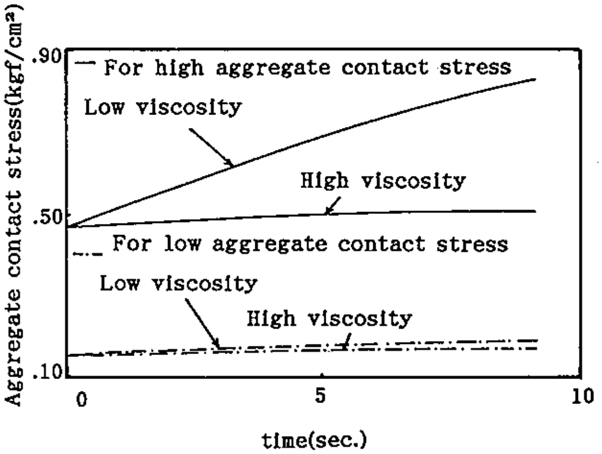


Fig.10 Analytical results of contact stress of aggregate phase at outlet

much more sensitive to the segregation(i.e. change in volume fraction of aggregate from its initial value) than that of lower aggregate contact stress (corresponds to m=10 in Eq.(13-2)) which represents plastic spheres, as shown in Fig.9. This sensitivity coincides with the observations discussed in Section 2.2.

In the plot of Fig.10, the aggregate contact stress is also predicted to increase with time for the high aggregate contact stress case corresponding to light-weight aggregate and to reach the final stage of complete blocking. If high viscosity is utilized, the contact stress or the mutual interaction of solid particles is reduced greatly, even though the total pressure "p" at the pipe inlet becomes great. On the other hand, the contact stress for plastic spheres is limited even though a lower viscosity for liquid phase is assumed. This results coincide with the observations of Section 2.1.

The high particle interaction initiates the segregation and subsequent blocking of concrete flow. But the sensitivity of mortar viscosity depends on the solid interaction. Thus, the design of mortar viscosity necessary to avoid segregation should be based on the roughness or "stiffness" of aggregate phase. Even though the high viscosity of mortar reduces the segregation, the total pump pressure increases due to high frictional resistance and reduces the pumpability of the fresh concrete. To obtain high performance concrete, with minimum amount of material segregation and high pumpability, the effect of mortar viscosity and effect of aggregate interaction should be balance each other. The determination of how easily aggregate particles can deform, subject to some specified re-arrangement, is one of the most important problems to be solved in practice.

6 CONCLUSIONS

1. Segregation of aggregate which leads to accumulation in tapered pipes was observed. It was found that the viscosity of liquid phase is more influential on the segregation of solid particles having rough surface than that on smooth ones.

2. Computational flow simulations involving phase-segregation were carried out. By using the concept of aggregate contact stress and segregation resistance, the numerical simulation succeeded in explaining the effect of the mortar viscosity on the accumulation of particles in tapered pipes.

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