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MULTI-PHASE MODEL FOR FLOW OF LIQUID-SOLID ASSEMBLY THROUGH PIPELINES

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This paper is to propose the liquid-solid two phase modeling for simulating the flow and segregation of fresh concrete with the authors' intention of getting the mathematical background for mixture design concept serving super fluidized fresh concrete. The multi-component structure of solid phase was newly introduced into the frame of conventional liquid-solid two phase model in fluid dynamics. The partial stresses carried by gravel, sand and cement powder were implemented and the compatibility equations derived from experimental works were incorporated in the scheme of formulation for multi-component solid suspended by liquid. For verifying the capability of the physical model concerned, the trial model for particle-to-particle interaction was combined with the entire frame of formulation. It was examined that the model can follow the behaviors qualitatively in terms of the fluidity and segregation of particulate flow.

Key Words : *multi-phase flow, fresh concrete, pumpability, segregation, deformability*

1. INTRODUCTION

In the fields of mechanical and mining engineering, liquid-solid two phase flow has been of interest to engineers with regard to the sedimentation of solid particles in pipe lines, blockage and erosion. Similar problems arise in the pumping transportation of fresh concrete concerning the pumpability and risk of blockage[1]. Here, the segregation resistance as well as the deformability will be associated with the pumpability of fresh concrete.

This paper aims at the computational modeling to simulate the particulate flow with different sizes of particles, deformation and segregation of fresh concrete on the line of multi-phase and multi-component assembly of solids. Through this mathematical discussion, the authors expect that some physical and mechanical background will be obtained for establishing the mixture design of self-placable concrete with super fluidity[2], because the requirement of both segregation resistance and fluidity is the key of this self-placable concrete.

In the past, some theoretical discussions have been developed on concrete flow[3)~6)]. Since those approaches treated fresh concrete as a single phase fluid of nonlinear continuum, the material properties as an uniform continuum are represented by the fluid constants, i.e., the viscosity coefficient and the yield stress in the frame of rheology.

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However, the single phase fluid approach is not applicable to the segregation and the blockage in principle. Furthermore, the mixture of fresh concrete cannot be directly linked with the computation. This is one of the weak points of single continuum approach. **Fig.1** shows the volume passing through small spacings just under gravity action[7]. It is noticeable that the greater slump concrete turns out to be less fluid after all due to the segregation which gave rise to the blockage by water-discharged concrete cohesive around some openings. It is self-evident that the single phase approach based on the rheology cannot deal with segregation and its associated fluidity of flowing concrete.

As for segregation, the authors adopted multi-phase approach in which the degree of freedom on segregation is naturally incorporated as the relative rate of flow between particulate solids and liquid[8),9)]. In this study, further improvement was attempted in terms of partial stresses based on the multi-component assembly for solid phase. Conducted will be the numerical case study and sensitivity analysis of each physical model, which is supposed advisable for constructing the practical fresh concrete models.

2. GENERAL FORMULATION

In the series of study[10)~12)], the authors adopted the spatially averaged technique to generate the smeared-out continuous field of particle velocity and the volume fraction of solids[12)]. Hereafter, we follow the same line for continuum formulation based on the control volume. In the multi-phase idealization, categories of gravel (g), sand (s), powder (p) and free water (w) may be acceptable for concrete. Let C_i denote the index of volume

Regardless of material properties, i.e., compressibility and incompressibility, we have to satisfy the compatibility requirement of volume. When we neglect the presence of air for instance, we have,

$$\bar{C}_g+\bar{C}_s+\bar{C}_p+\bar{C}_w=1 \quad\cdots\cdots(6)$$

Other requirement to be satisfied is Newton's second law of motion for each phase. Based on the control volume as shown in **Fig.2**, the net change of momentum within the volume is to be equilibrated with the total force acting on the surface of the control volume. Then, we have,

$$\iint_{c.s.}\vec{F}_i dA+\iiint_{c.v.}\vec{f}_i dV$$
$$=\iint_{c.s.}\rho_i C_i\vec{V}_i(\vec{V}_i\cdot\vec{n})dA$$
$$+\frac{\partial}{\partial t}\left\{\iiint_{c.v.}\rho_i C_i\vec{V}_i dV\right\} \quad\cdots\cdots(7)$$

where, $\vec{F}_i$ and $\vec{f}_i$ are defined as the force acting on the surface of the control volume and the body force on phase (i).

The left side of Eq.(7) represents the resultant force and the right, the substantial change of momentum on Eulerian expression. The axial component of the above vector equations yields the following form.

$$\left[-\iint_{A(s+\frac{ds}{2})}F_i' dA+\iint_{A(s-\frac{ds}{2})}F_i' dA\right]\cos\left(\frac{\phi ds}{2}\right)$$
$$-\oint_L H_i dr\cdot ds+\iint_{A(s)}f_i dA\cdot ds$$
$$=\iint_{A(s+\frac{ds}{2})}\rho_i C_i\left\{u_i\cos\left(\frac{\phi ds}{2}\right)+\nu_i\sin\left(\frac{\phi ds}{2}\right)\right\}\cdot u_i dA$$
$$-\iint_{A(s-\frac{ds}{2})}\rho_i C_i\left\{u_i\cos\left(\frac{\phi ds}{2}\right)-\nu_i\sin\left(\frac{\phi ds}{2}\right)\right\}\cdot u_i dA$$
$$+\frac{\partial}{\partial t}\left(\iint_{A(s)}\rho_i C_i u_i dA ds\right) \quad\cdots\cdots(8)$$

where, F_i', H_i and f_i are defined as the specific normal compression force on cross sections of the flow pipe, the axial component of specific force acting on the pipe wall and the specific body force parallel to the flow axis, respectively. The values of (u_i, ν_i) are components of $\vec{V}_i$ parallel and normal to the flow axis expressed by "s". The former component represents the rate of main flow and the latter, the secondary flow within the section. The value of ϕ, as shown in **Fig.2**, indicates the local curvature of the pipe lines.

By neglecting the higher order term with respect to ϕ and the derivative "ds", we have,

$$-\frac{\partial}{\partial s}\left(\iint_A F_i' dA\right)-\oint_L H_i dr+\iint_A f_i dA$$
$$=\frac{\partial}{\partial s}\left(\iint_A\rho_i C_i u_i^2 dA\right)+\frac{\partial}{\partial t}\left(\iint_A\rho_i C_i u_i dA\right)$$
$$+\left(\iint_A\rho_i C_i\nu_i u_i dA\right)\phi \quad\cdots\cdots(9)$$

With the definition of the sectional, peripheral and volumetric averaged forces denoted by,

$$\left.\begin{array}{l}\bar{\sigma}_i\equiv\dfrac{\iint_A F_i' dA}{A},\quad \bar{\tau}_i\equiv\dfrac{\oint_L H_i dr}{2\pi R}\\ \bar{f}_i\equiv\dfrac{\iint_A f_i dA}{A}\end{array}\right\}\quad\cdots\cdots(10)$$

we consequently have the averaged momentum conservation equations with respect to each phase (gravel, sand, powder and water) as follows.

$$-\frac{\partial\{A(\bar{\sigma}_i\bar{\sigma}_i')\}}{\partial s}-2\pi R\bar{\tau}_i+A\cdot\bar{f}_i$$
$$=\frac{\partial(A\rho_i\bar{C}_i\cdot\bar{u}_i^2)}{\partial s}+A\frac{\partial(\rho_i\bar{C}_i\cdot\bar{u}_i)}{\partial t}+A\cdot\bar{Q}_i$$
$$=\rho_i\bar{C}_i A\left(\frac{\partial\bar{u}_i}{\partial t}+\bar{u}_i\frac{\partial\bar{u}_i}{\partial s}\right)+A\cdot\bar{Q}_i \quad\cdots\cdots(11)$$

where

$$\bar{Q}_i\equiv\rho_i\overline{C_i u_i\nu_i\phi}$$
$$\bar{\sigma}_i'\equiv\rho_i(\bar{C}_i\cdot\overline{u_i'^2}+\bar{u}_i\cdot\overline{C_i'u_i'}+\overline{C_i'u_i'^2})$$

The secondary stress denoted by $\bar{\sigma}_i'$ is fictitious and similar to Reinolds stress of turbulent flow with regard to the mixing of particles along the direction of main flow. The value of Q_i physically corresponds to the fictitious body force due to the mixing of particles excited by the secondary flow over the section.

According to the requirement of thermodynamics, we need to simultaneously satisfy the governing equations with respect to the balance of kinematic, potential and specific energy for each phase. This requirement is crucial especially for high rate compressive flow under varying temperature field or flows accompanying phase transformation[13]. Since we may assume the constant temperature during the multi-phase flow concerned and the incompressibility of constituent materials of each phase, the conservation of energy can be implicitly satisfactory provided the mass balance being maintained at any time and space domains.

For finalizing the self-consistent system of governing equations, we relate each phase stress to the condition of flow, i.e., constitutive equations with the authors' intention to incorporate the concept of partial (phase developing) stresses, respectively.

First, let us consider the stress acting on the water phase in concrete mixture. At a section of the control volume, the specific area where free water segregation takes place when the relative rate of flow would happen. Accordingly, we have,

$$\left.\begin{aligned}\bar{f}_i&=\rho_i\bar{C}_i\cdot g_s+\sum_{k\neq i}^{No.phase}\\ S_{ik}&=-S_{ki}\end{aligned}\right\}\cdots\cdots(16)$$

where, g_s is the component of the gravity acceleration in the direction of main flow and S_{ki} is the specific drag force acting on the i-phase from the k-phase as segregation resistant factor.

The past approach where fresh concrete was treated as single fluid with complex material properties in appearance made it impossible to deal with segregation. However, since we have different degrees of freedom on the flow of constituent components and phases, the segregation resistant factor is introduced as a natural result. This is the other major advantage and the kernel which the authors sought in this study, because the segregation was proved to be associated with the macroscopic fluidity and easiness of fresh concrete being placed without external actions (See **Fig.1**).

3. DEGENERATED MODEL FOR CONCRETE

As far as the mathematical potential is concerned, the proposed model is effective to any sort of segregation. But, as the segregation process of gravel from fresh concrete under flow is of interest to the authors, we degenerate the degree of freedom on the motion of components as follows.

$$\left.\begin{aligned}&\bar{u}_w=\bar{u}_p=\bar{u}_s(\equiv\bar{u}_m)\\ &\bar{u}_g\neq\bar{u}_m\end{aligned}\right\}\cdots\cdots(17)$$

For quasi-static behaviors of fresh concrete, the authors degenerated the freedom of motion with respect to the motion of water and other components[15),16)]. In this study, the motion of water, powder and sand is assumed to be common and regarded as the kinematics of mortar designated by the subscript "m", because the segregation of gravel and mortar is our concern for total evaluation of fluidity. Accordingly, the degeneration of motion leads to the simple simultaneous equations of motion in terms of gravel (g) and mortar (m) as,

$$\left.\begin{aligned}&-\frac{\partial(A\bar{\sigma}_g)}{\partial s}-2\pi R\bar{\tau}_g+S_{mg}+\rho_g\bar{C}_g g_s A\\ &=\rho_g\bar{C}_g A\left(\frac{\partial\bar{u}_g}{\partial t}+\bar{u}_g\cdot\frac{\partial\bar{u}_g}{\partial s}\right)\end{aligned}\right\}\cdots(18)$$

$$\left.\begin{aligned}&-\frac{\partial\{A(\bar{\sigma}_s+\bar{\sigma}_p+\bar{\sigma}_w)\}}{\partial s}-2\pi R(\bar{\tau}_s+\bar{\tau}_p+\bar{\tau}_w)\\ &-S_{mg}+(\rho_s\bar{C}_s+\rho_p\bar{C}+\rho_w\bar{C}_w)g_s A\\ &=(\rho_s\bar{C}_s+\rho_p\bar{C}_p+\rho_w\bar{C}_w)A\left(\frac{\partial\bar{u}_m}{\partial t}+\bar{u}_m\cdot\frac{\partial\bar{u}_m}{\partial s}\right)\end{aligned}\right\}\cdots\cdots(19)$$

where, the fictitious body force and the stress in Eq.(11) are explicitly neglected. It can be thought that these values are implicitly involved in the constitutive laws to define the axial mean stress and segregation resistance.

The material properties are reflected by the constitutive laws for contact stress of each component. Since the source of contact stress is particle rearrangement in shear, some indicator for intensity of shear mode deformation of particle assembly is deemed an essential one. The authors have reported the empirical compatibility equations to relate the intensity of rearrangement of particles densely suspended in liquid matrix to the mean flow rate of particles as follows.

$$\left.\begin{aligned}&\bar{J}_g=0 &&\text{for straight pipe}\\ &\bar{J}_g=\frac{\sqrt{3}}{r}\cdot\tan\theta\cdot\bar{u}_g &&\text{for taper pipe}\\ &\bar{J}_g=\frac{\phi}{2}\cdot\bar{u}_g &&\text{for bend pipe}\end{aligned}\right\}\cdots(20)$$

where, r and θ are defined as the radius of the section and the tapering angle in radian. $\bar{J}_g$ is the second invariant (shear mode) of Euler strain rate tensors of gravel assembly arising at the bend and taper pipes, and expressed[12)] by,

$$\left.\begin{aligned}&\bar{J}_g\equiv\frac{1}{A}\int\int_A\sqrt{\frac{1}{2}e_{ij}e_{ij}}\,dA\\ &e_{ij}\equiv\frac{1}{2}\left(\frac{\partial\overline{u_{g.i}}}{\partial x_j}+\frac{\partial\overline{u_{g.j}}}{\partial x_i}\right)-\frac{1}{3}\delta_{ij}\sum_{k=1}^{3}\frac{\partial\overline{u_{g.k}}}{\partial x_k}\end{aligned}\right\}\cdots(21)$$

where, $u_{g.i}$ is the spatially averaged rate of flow of gravel phase in the i-direction on the Cartesian coordinate.

The sands existing in the voids of gravels expressed by $(1-\bar{C}_g)$ and the powder which can exhibit its presence in $(1-\bar{C}_g-\bar{C}_s)$ will undergo higher local shear intensity. Concerning the shear intensity of sand and powder in the mixture, we tentatively assume the inverse proportion in terms of volume as,

$$\left.\begin{aligned}&\bar{J}_s=\left(\frac{1}{1-\bar{C}_g}\right)\cdot\bar{J}_g\\ &\bar{J}_P=\left(\frac{1}{1-\bar{C}_g-\bar{C}_s}\right)\cdot\bar{J}_g\end{aligned}\right\}\cdots\cdots(22)$$

Since the above intensity indicates the shear rate of each phase, we can relate this to the partial contact stress of particular components as,

$$\sigma_{ci}=K_i\cdot\bar{J}_i\cdots\cdots(23)$$

where, K_i is defined as the secant stiffness of phase i.

It can be easily assumed that the stiffness is associated with how the particles be compacted, i.e., the volume fraction of the particles. It was

The seven equations can be discretized by the backward finite difference scheme. As for the finite difference equation (5) of mass balance on gravel phase, we have the following algebraic equation.

$$F_1(\bar{C}_g(s,t),\bar{u}_g(s,t))=0$$

$$\left.\begin{aligned}F_1\equiv&\left(\frac{\bar{C}_g(s,t)-\bar{C}_g(s,t-\Delta t)}{\Delta t}\right)A(s)+\\&\frac{\bar{C}_g(s,t)\bar{u}_g(s,t)A(s)}{\Delta s}-\\&\frac{\bar{C}_g(s-\Delta s,t)\cdot\bar{u}_g(s-\Delta s,t)A(s-\Delta s)}{\Delta s}\end{aligned}\right\}\cdots\cdots(28)$$

where, $\bar{C}_g(s,t)$ and $\bar{u}_g(s,t)$ are valuables at location s and time t. $\bar{C}_g(s,t-\Delta t)$ and $\bar{u}_g(s-\Delta s,t)$ are backward values of one step in space and time.

With the same manner as above in Eq.(28), we have discretized four mass balance equations (F_1, F_2, F_3, F_4) regarding four individual phases. The momentum conservation by Eq.(18) is also discretized in time and space domains as,

$$\left.\begin{aligned}&F_5[\bar{C}_{i=g,s,p,w}(s,t),\bar{u}_g(s,t),\bar{u}_m(s,t),P(s,t)]=0\\&F_5=-\frac{A(s)\bar{\sigma}_g(s,t)-A(s-\Delta s)\bar{\sigma}_g(s-\Delta s,t)}{\Delta s}\\&-2\pi R\bar{\tau}_g(s,t)+S_{mg}(s,t)+\rho_g\bar{C}_g(s,t)A(s)\\&-\rho_g\bar{C}_g(s,t)A(s)\frac{\bar{u}_g(s,t)-\bar{u}_g(s,t-\Delta t)}{\Delta t}\\&-\rho_g\bar{C}_g(s,t)A(s)\bar{u}_g(s,t)\cdot\\&\frac{\bar{u}_g(s,t)-\bar{u}_g(s-\Delta s,t)}{\Delta s}\end{aligned}\right\}\cdots\cdots(29)$$

where, the stresses expressed by $\bar{\sigma}_g(s,t)$ and $\bar{\tau}_g(s,t)$, and the segregation resistance force as $S_{mg}(s,t)$ are also functions of the seven valuables at (t,s).

Eq.(29) includes the seven valuables at particular time and location with the backward known values. Similarly, we have the discretized algebra (F_6, F_7) of Eq.(19) and Eq.(6), respectively. Accordingly, we can get unique solution of the seven valuables at (t,s) with the values at previous time step t-Δt and the backward adjacent location s-Δs by solving the above seven nonlinear algebraic equations. In this study, Newton Raphson method of iteration was adopted for simultaneously solving $\{F_i=0\}$.

The authors applied the model to the pipe flow of fresh concrete. Along the axis of pipes, the analysis domain was discretized into finite difference nodes and the constant time partition was adopted in dividing the time domain (See Chapter 5). The rates of flow and the volume fractions of components were defined as the boundary condition at the inlet. The pore pressure denoted by P must be zero (This means that pore pressure is defined based on the atmospheric one) at the outlet. It is another boundary condition to be satisfied at any time. Initial conditions have to be also specified in terms of $\bar{u}_g$, $\bar{u}_m$, $\bar{C}_{i=g,s,p,w}$ and P.

In step-by-step computation, first, the pore pressure at the inlet was assumed. If we have the solution at the previous time step, the solution at the next position from the inlet can be obtained by solving the above seven algebraic equations. Under the assumed inlet pore pressure, we can get finally the solution at the outlet where the pore pressure must satisfy the boundary condition. If the boundary condition at the outlet would not be satisfactory, the inlet pore pressure of water phase was redefined again until the convergence criterion would be met. The Modified Newton method of iteration was adopted regarding the inlet pore pressure.

5. NUMERICAL SIMULATION

(1) Material constants

The lateral stress ratio is obtained by solving generic constitutive law if any. The microscopic contact model for particulate compactness brings one to one relation between the value of κ and the local contact friction between particles. Concerning aggregates under higher confinement, the lateral stress ratio was reported approximately 0.5[19]. In this simulation, the authors adopted 0.5 as common value of solid components, and 1.0 for water with perfect isotropy.

The common value of frictional constant $\mu_{i=g,s,p}$ between solids and pipe wall was used as 0.4. Since water is confinement independent material, μ_w must be zero.

The viscosity constants ($\tau_{vo,i}$,η_i) of aggregates should be zero. As for water and powder whose rates of flow are assumed same, the sum of viscosity constants of water and powder phases becomes substantial in the formulation, because Eq.(19) requires the sum of the shear partial stresses of powder and water phases. According to Tanigawa's one-plane shear test of paste and mortar[20], the authors set the standard values for computational simulation as,

$$\tau_{vo,w}+\tau_{vo,p}=2\times10^{-3}\text{kgf/cm}^2$$

$$\eta_w+\eta_p=1.2\times10^{-4}\text{kgf}\cdot\text{s/cm}^3$$

The drag force test conducted by Kishitani[18] can be used to set the standard constants in Eq.(27) for simulation although these viscous parameters are affected by water to cement ratio. With reference

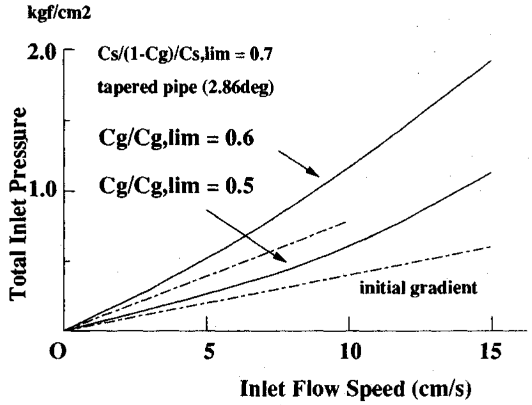

Fig.7 Variation of total inlet pressure versus inlet flow rate.

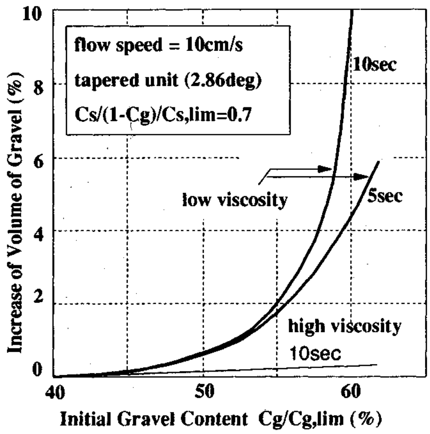

Fig.9 Variation of increase in volume content of gravel at outlet with respect to initial volume concentration.

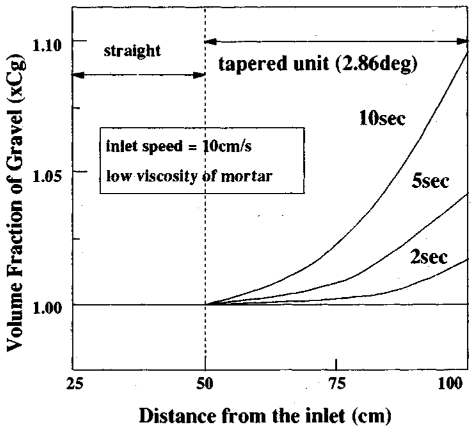

Fig.8 Transient distribution of volume content of gravel : $C_g/C_{g,\mathrm{lim}}=0.6$ and sand : $C_s/(1-C_g)/C_{s,\mathrm{lim}}=0.7$

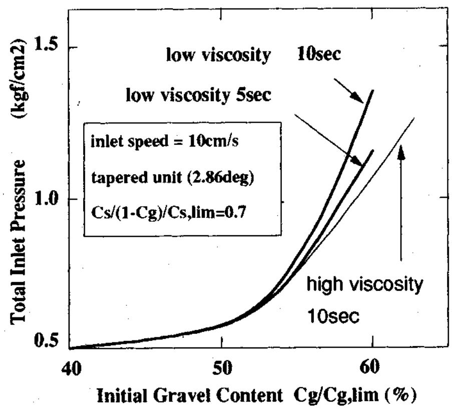

Fig.10 Total pressure of tapered pipe with respect to the mixture content of gravel.

outlet of the pipe has the maximum volume concentration of the gravel. This means that some of the mortar matrix was discharged during the flow through the pipe. The stuck zone is found to expand from the outlet into the upper stream.

However, as shown in **Fig.9**, the segregation is hardly computed in the case of lower content of gravel. The pore pressure is excited by the higher partial stress of gravel so as to mobilize the particles forward against the interaction of particles and the wall friction as described in Eq.(15) and Eq.(19). The higher gradient of pore pressure needed to drive the solids is consequently associated with the drag force acting on the gravel in the dynamic equilibrium described by Eq.(19). Accordingly, the high concentration of gravel in mixture brings segregation. Then, the higher viscosity on segregation tranquilizes the segregation effectively as shown in **Fig.9**.

The increase in the total inlet pressure depends on the segregation in progress if the lower segregation resistance would be assumed as shown in **Fig.10**. In computation, the instability on accumulated gravel around the outlet never terminate similar to the buckling of structural members if the segregation would start and the elevated contact stress further accelerate the segregation again.

The transient aspect of gravel accumulation is profound when the specific volume fraction is greater than 50%. But, no computational instability nor segregation takes place for the case of bent pipe unit (See **Fig.11**). The bent pipe unit was reported hardly to bring segregation in comparison with the tapered unit[21]. As a matter of fact, it was reported that the blockage involves segregation in tapered pipes, but no change of volume fraction of components in bent pipe. In other words, the blockage may happen around the bent pipe if any without accompanying segregation. The deforma-

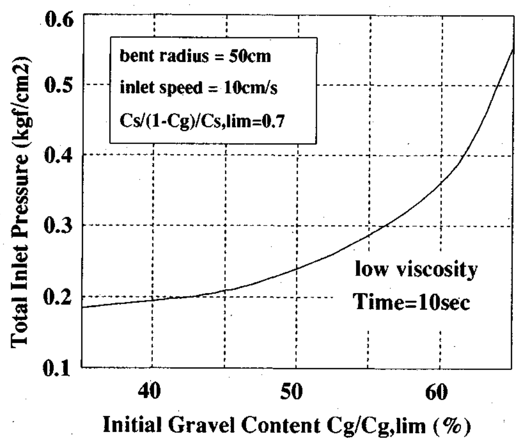

Fig.11 Total pressure of bent pipe with respect to the mixture content of gravel.

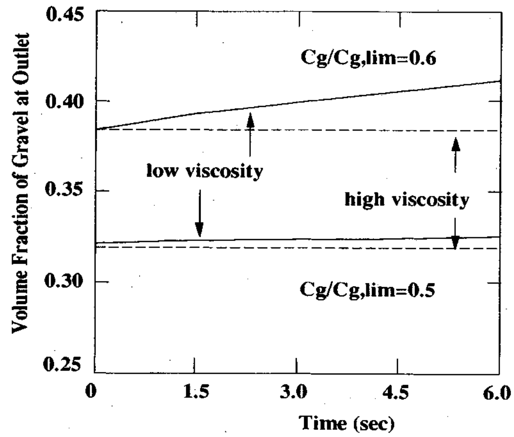

Fig.13 Volume content of gravel at the outlet with time for different viscosity and the mixtures of concrete : C_g=0.63.

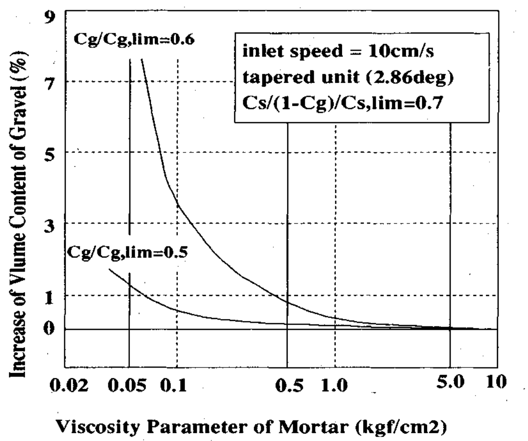

Fig.12 Sensitivity of viscosity parameter H in segregation resistance to the stability of gravel fraction at the outlet.

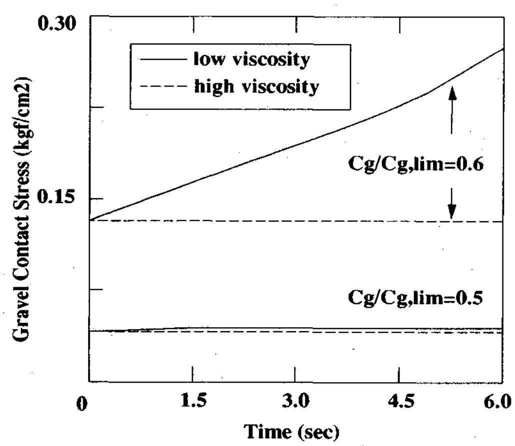

Fig.14 Gravel contact stress at the outlet of tapered pipe for different viscosity and the mixtures of concrete.

bility of the fresh concrete will be directly associated with the pumpability. On the other hands, the segregation resistance is problematic as well as the deformability of concrete. This has been also verified by the pumping test of fresh concrete in site[21].

(4) Effect of segregation resistance on pumpability

Shown in **Fig.12** is the sensitivity of the viscosity parameter H to the segregation. The accumulation of gravel at the outlet is sharply affected by the viscosity parameter in case of the lower viscosity of drag force in Eq.(27). This means that the paste mixture with lower water to cement ratio is much effective to avoid segregation. It has to be noticed again that the gravel content plays an important role as theoretically discussed above. This computational result draws the point that the water to cement ratio depends on the amount of aggregates for the purpose of avoiding the segregation.

In time scale, the accumulation of gravel and corresponding contact stress are shown in **Fig.13** and **Fig.14**. The contact stress is firmly elevated without convergence and finally, the iterating solution diverges. In analysis, the recovery of the instability is not obtained at all. Although the volume fraction of gravel at the outlet of the tapered pipe looks converging to some stable level as shown in **Fig.13**, the instability which is not recoverable takes place in the transferred contact stress of gravel as shown in **Fig.14**. This is owing to the nonlinear stiffness model of the gravel phase with respect to the volume fraction of gravel. When the segregation happens to concrete, the computational model implies that no matter what we would do, the progressive segregation is not avoidable.

6. CONCLUSIONS

The liquid-solid two phase modeling with multi-components of particulate assembly with various sizes was proposed as a versatile approach to the particulate flow suspended by liquid and segregation of fresh concrete around the obstruction. The spatially averaged procedure was performed to produce the smeared continuum flow field of solid particles. The advantage of this approach was verified as that the effect of segregation on the macroscopic fluidity of fresh mixture can be dealt with, and that the sensitivity of the mixture proportion of concrete to fluidity and workability can be computed as a whole.

The computational simulation showed that the instability of flow due to segregation was found to be influenced by the volume content of gravel as well as the viscosity of cement paste. Furthermore, it was successfully simulated that the lower viscosity of paste produced by the greater water to cement ratio brings blockage around the tapering flow despite greater value of slump. It was also simulated that blockage and the instability of flow around bent pipe hardly occur in comparison with the case of tapering flow. These analytical results were empirically reported and experienced at cite. Here, it should be emphasized that the partial stress concept proposed in this scheme of analysis enables us to examine the sensitivity of concrete mixture to the fluidity and segregation.

The reasonable solution mentioned above will encourage us to carry on in line with the multi-phase theory for fresh concrete. The versatility required as engineering tool in practice relies on the material modeling, e.g., constitutive law for describing the particle interaction occurring under the particulate flow. Much effort is to be concentrated on the development of stiffness model for each component as the next stage.

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固体粒子と液相から成る管内混相流に関する多相モデル

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本研究は，フレッシュコンクリートの変形性と流動途上の材料分離に対して，固液２相—固体３要素による流動モデルを提案するものである．粗骨材，細骨材，粉体，液相のそれぞれを構成している粒子群同士の衝突・せん断と，相間相互作用との２者を構成則で代表させることにより，任意の配合に対応可能な理論構成を得ている．これにより，フレッシュコンクリートの変形抵抗性のみならず，流動途上に発生する材料分離が全体の流動性を大きく損なうことが，管内流動において解析的に再現された．