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FLOW AND SEGREGATION OF FRESH CONCRETE AROUND BIFURCATION IN PIPE LINES

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ABSTRACT

This research was aimed to study the deformation and segregation of fresh concrete as two-phase material around bifurcations in pipe line network. The movement of coarse aggregates having close correlation with blocking of flow was observed in the visualized test with model material simulating fresh concrete. The image analysis based on video recorder, A/D converter and micro processors was conducted and images of all solid particle movements were processed. Applying Eulerian expression to the aggregate phase, the deformation and segregation process of two-phase material around bifurcations were clarified, which were highly affected by boundary conditions and liquid viscosity. Its macroscopic information on deformational behavior of aggregate phase is useful for finite element modeling of fresh concrete as two-phase material.

NOMENCLATURE

I :mean deformation ratio(/s)
J :deviatoric deformation ratio(/s)
u :velocity of aggregate phase in x direction(cm/s)
v :velocity of aggregate phase in y direction(cm/s)
ε_x :normal strain in x direction(/s)
ε_y :normal strain in y direction(/s)
ε_{xy} :shear strain in x-y co-ordinates(/s)
ω_{xy} :spin tensor in x-y co-ordinates(/s)

INTRODUCTION

Placing concrete by pumping is now widely applied in architectural and civil engineering construction. It is important to convey fresh concrete through pipe lines or sometimes pipe line networks without any blocking and segregation defined as the transient variation of the volume content of constituent materials in concrete which are gravels, sands and cement paste. Blockage of flowing concrete causes terrible loss of time, labor and cost. Even though the blocking does not occur, segregation causes problems. Shrinkage in concrete containing large amount of liquid phase introduces many cracks into concrete structures. Honeycombing due to water discharged concrete deteriorates durability of structures.

Basically, there exists no problems concerning blocking or segregation of concrete in straight portions, but we may encounter serious troubles around tapered, bending and bifurcation points, where concrete as solid-liquid tends to segregate and finally concrete flow is blocked by the stiffened concrete in consequence of water discharge. This bifurcation point may be the most severe condition to segregation of flowing concrete. Considering this fact, the effort was pushed forward to clarify the segregation process and create the concept of high performance concrete with high deformability and segregation resistance.

IN-SITU PUMPING TEST

The new "Wishbone Tree Pipe (Bifurcating Pipe) Layout Method" for pumping concrete has been developed by Taisei Corporation[1]. The pipe system, as shown in Fig.1, bifurcates symmetrically at several stages and enables monolithic concrete to be cast concurrently and continuously. In process of developing this method, many interesting pumping test results were obtained. For non-symmetric pipe arrangement, the concrete coming from bifurcations was segregated or blocked. The concrete coming out from the branched outlet pipe was found to be rich concrete or water while that coming out from the main pipe contained large amount of coarse aggregates, as shown in Fig.2[2].

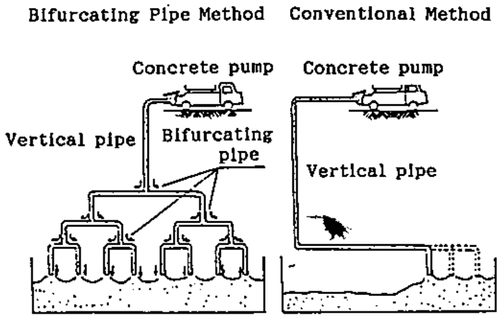


Fig.1 Wishbone Tree Pipe (Bifurcating Pipe) Layout Method[1]

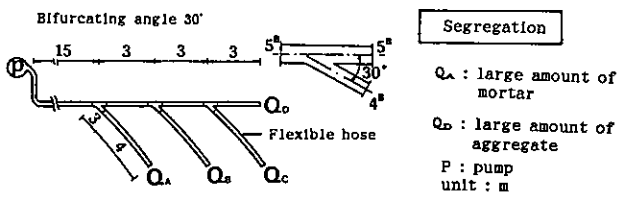


Fig.2 Pipe system of bifurcations[2]

This phenomenon cannot be explained using the concept of uniform non-linear material such as a Bingham body. Though actual concrete is a five-phase material, that is, coarse aggregates, sands, cement particles, water and air, it is treated in this study as a two-phase material consisting of mortar (liquid) phase and aggregate (solid) phase which is considered to play an important role in segregation and blockage of flowing concrete in this boundary condition. Comparing with coarse aggregate, cement particles, which have much smaller size than that of pipe, is supposed to be negligible as solid because their behavior has less effect peculiar to solid particles such as collision between particles and shear dilatancy on the global behavior of flowing concrete. This is the reason why the following visualized test based on two-phase flow, that is, mortar phase and aggregate phase, was adopted.

VISUALIZED TEST

Visualized test with model concrete was carried out by applying HASHIMOTO's method[3] to get information on aggregate movement around a bifurcation point.

Apparatus and Material

The apparatus, as shown in Fig.3, consists of a rectangular pipe, pistons with rods and a video camera which records movements of plastic balls. A rectangular pipe, instead of a circular pipe, was selected so as to watch movement of balls away from pipe walls and was made of two transparent acrylic panels fixed by aluminum frames. Thickness of the pipe section was designed so that only one layer of balls could be accommodated inside the pipe. This enables us to observe the two-dimensional behavior of balls clearly. Width of both outlet pipes was the same as that of the inlet, 180mm, and the angle of the bifurcating pipe was 48.6 degrees. The piston head in the inlet pipe was controlled by an electric motor at a constant speed.

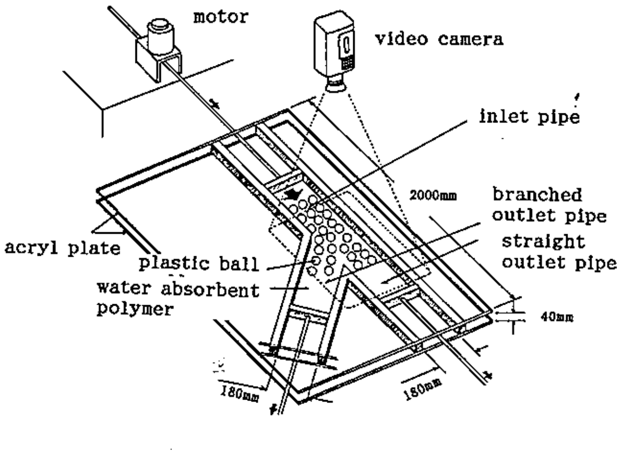


Fig.3 Apparatus of visualized test

Model concrete contained water-absorbent polymer as mortar (liquid) phase and plastic balls as aggregate (solid) phase. The water-absorbent polymer dissolved in water was confirmed to be equivalent to real mortar in the flowing test [3]. Its viscosity was controlled by adding cellulose-type polymer agent. Plastic balls had consistent diameter of 25mm and specific gravity of about 1.4. Specific gravity ratio of plastic balls to polymer media was about 1.4, which corresponds to that of aggregate to mortar in real concrete.

In this visualized test we idealized and simplified the material and the dimension of flowing condition in order to get information on the movement of aggregate phase and to build up the concept of segregation process and mechanism of flowing concrete around bifurcations. The size of plastic balls versus the pipe size is also one of the important factors with respect to the behavior of flowing concrete, which is equivalent to the maximum size of coarse aggregates in actual concrete versus the pipe size.

Testing Procedure and Image Analysis

Plastic balls were arranged uniformly in the pipe filled with polymer media in such a way that balls touch with each other. After charging the polymer and balls in the pipe set up horizontally, the piston head in the inlet pipe was moved at a constant speed, about 4cm/s, and the movement of balls around the bifurcation was recorded with a digital video camera.

Using the video data recorded, as shown in Fig.4, image analysis was conducted through A/D converter and micro processor. Through the image analyzer, gravity center positions of all balls at regular intervals were obtained. Each gravity center in a screen could be connected to that in the next screen with the micro processor, which draws stream lines and velocity vectors at each time. In this study the time interval measured was decided so that each particle did not move over its radius during that intervals.

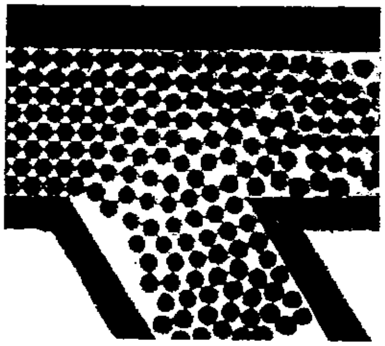


Fig.4 Recorded video data(Test B1)

Eulerian Expression of Aggregate Phase

Using position data of each aggregate connected through a series of screen, the behavior of aggregate phase can be evaluated with two method, that is, Lagrangian treatment and Eulerian treatment.

From Lagrangian expression such as a particle trace line of aggregates, fluctuational and turbulent movement of each aggregate can be observed, which may signify the segregation indirectly. Under the unsteady flow condition, it is difficult to describe the global flowing condition with the use of only one trace of particles.

On the other hand, assuming the aggregate phase in model concrete as a continuous phase, the global deformation field of aggregate can be represented using Eulerian expression. Eulerian expression should be adopted to observe and understand the global movement and interaction of flowing aggregate phase. Its macroscopic information of aggregate phase is also advantageous for finite element modeling of fresh concrete as two-phase material.

Virtually, using discrete velocity data derived from each aggregate, the velocity field of aggregate phase is obtained assuming that velocity varies linearly between each aggregate data. Then the velocity vector at any point can be obtained. Each grid element is decided to be as large as the aggregate size. In the two-dimensional strain problem, Cartesian co-ordinates system is defined for this purpose. Normal strains ε_x in the x direction and ε_y in the y direction are defined in the velocity field of smoothed or "smeared" aggregate phase as follows.

$$\varepsilon_x = du/dx \tag{1}$$

$$\varepsilon_y = dv/dy \tag{2}$$

Shear strain ε_{xy} is expressed as follows.

$$\varepsilon_{xy} = (du/dy + dv/dx)/2 \tag{3}$$

Normal strains ε_x and ε_y give the velocity gradient of the aggregate phase in the x and the y directions respectively. They represent the variance of relative distance between aggregates in their directions. Positive values of ε_x mean that the relative distance of aggregates in the x direction is increasing. On the contrary, negative values mean that the relative distance is decreasing. Then, ε_{xy} expresses the shear deformation component with constant relative distance of aggregates. Using the above strain components, the deformation rate of the aggregate phase can be expressed with invariants "I" and "J", independent on the co-ordinate transformation in two-dimensional tensorial expression.

$$I = (\varepsilon_x + \varepsilon_y)/2 \tag{4}$$

$$J = \sqrt{((\varepsilon_x - \varepsilon_y)/2)^2 + \varepsilon_{xy}^2} \tag{5}$$

The first invariant "I" denotes the mean deformation rate and represents the variance of mean relative distance between aggregates. Positive value means divergence of aggregate phase and negative value gives convergence of aggregates. Assuming incompressibility in a continuum body, we have "I" as zero.

The second invariant "J" denotes the deviatoric deformation rate which represents the intensity of shear deformation rate. The spin tensor ω_{xy} peculiar to hydrodynamics can be defined as follows.

$$\omega_{xy} = (du/dy - dv/dx)/2 \tag{6}$$

The deformation of aggregate phase can be represented by these invariants "I", "J" and a tensor ω_{xy}, assuming that the aggregate phase is a continuous.

The method to derive "I","J" and ω_{xy} is as shown in Fig.5. First, the target area on a screen is divided into finite square elements having four sides equivalent to the ball diameter. Mean velocity vector of an element is derived by computing mean value of aggregate velocity data in the element, though vacant elements should be filled up with mean velocity of surrounding elements by means of linear interpolation. At last "I","J" and ω_{xy} can be calculated at a point using the strain components derived from the mean velocity vector of surrounding four elements.

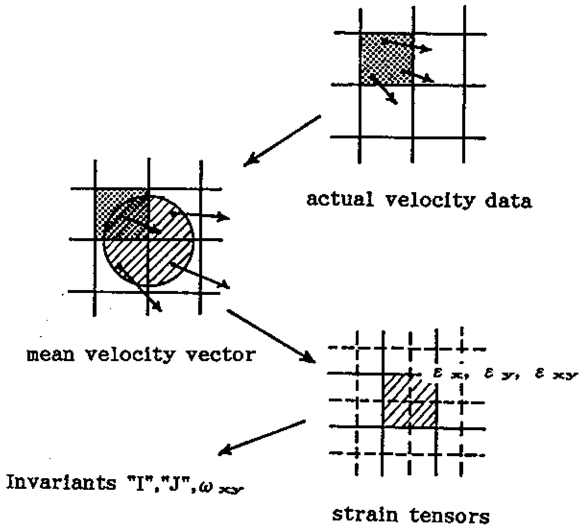


Fig.5 Procedure to derive invariants and spin tensor

SEGREGATION PROCESS AND MECHANISM AROUND BIFURCATION POINT

Factor Affecting Segregation Mechanism around Bifurcations

Consider an one-phase solid flow in a pipe with bifurcations as an extreme case. Without any external obstructions at two outlets as shown in Fig.3, almost all particles flow into a straight outlet pipe because traction forces acting on particles in the direction of the branched outlet pipe are not expected. In the controlled condition where the piston head in the straight outlet pipe moves slower than that of the inlet pipe, however, solid particles are accumulated in a straight outlet pipe and push away into a branched outlet pipe if applied inlet pressure is greater than the particle interlock and friction.

On the other hand, liquid phase, including no solid particles, flows easily into both outlet pipes because of its higher deformability than the solid phase having the great resistance against the shear mode. If there was no interaction between solid and liquid phases in two-phase flow (perfect segregation), the same results as that in one-phase condition could be expected. In actual cases, some segregation resistance forces acting on both phases is induced when the relative velocity occurs between solid and liquid. Provided that the liquid phase has capacity enough to carry solid particles, their kinematics will be highly associated with the liquid phase. It is, therefore, considered that the factors affecting segregation are liquid viscosity, solid momentum controlled by its velocity, and particle interactions.

In this study, the authors intentionally changed boundary conditions at outlet pipes, aggregate contact conditions and liquid viscosity to observe the segregation process virtually. Test series conducted are shown in Table 1. Series A was planned to study the effect of the balance of two outlet flow speeds as a boundary condition, and series B, the effect of viscosity of the liquid phase. In series A, the volume density of solid particles was designed to be smaller than that in series B (See Table 1).

Table 1. Test series

Test No.	Particle[*1] arrangement	Viscosity[*2] of liquid phase	Boundary[*3] condition
A1	loose	low	unbalanced
A2	loose	low	balanced
B1	compact	low	unbalanced
B2	compact	high	unbalanced

*1) loose ; mean spacing between particles is about 20mm
compact ; mean spacing between particles is about 0.5mm
*2) low ; flowing time in P funnel test is 4mts 15sec
high ; flowing time in P funnel test is 12mts
*3) unbalanced ; speed of piston head in a straight pipe is 1.6cm/s and that in a branched pipe is 2.4cm/s
balanced ; speed of piston heads in both pipes are same 2.0cm/s

Eulerian Evaluation of Aggregate Phase

Effect of boundary condition on the volume change of aggregate phase. Test A1 gives unbalanced flowing speed of concrete in two outlet pipes, where the speed in the straight outlet pipe was 1.6cm/s and 2.4cm/s for that in the branched outlet pipe. In Test A2, both piston heads in the outlet pipes were operated at the same speed, 2.0cm/s. The inlet speed of piston head, viscosity of liquid phase and initial volume density of particles were common to both tests.

The volume density distribution of particles in a steady state is shown in Fig.6, where the size of an element is determined to be about half the particle diameter for detecting the global distribution satisfactorily. The volume density in Test A2 is uniformly distributed in both outlet pipes shown in Fig.6(b). The stream line is also found to be equally divided into two outlet pipes as shown in Fig.7(c), where we can see smooth stream lines due to less particle interaction.

On the other hand, in Test A1, higher volume content, in other words, accumulation of particles is shown in a straight outlet pipe rather than in a branched outlet and inlet ones. This is the segregation defined between solid particles and liquid phase. The stream line of particles in Test A1 indicates that particles do not flow into two outlet pipes in proportion to the ratio of outlet speeds but their flow is almost equally divided as shown in Fig.7(a). This inconsistency means segregation and coincides with the accumulation pattern in Fig.6(a). According to the compatibility of mass transfer, the inconsistent flow of aggregates also means the inconsistency of liquid flow itself.

It is considered that liquid phase with low viscosity can not carry particles into the branched pipe against the particle momentum. Furthermore, velocity gradient enforced by the boundary condition causes collision among particles in the straight inlet and outlet pipes, which results in particle accumulation. After accumulation of particles, as shown in Fig.7(b), the number of stream lines into a branched pipe increases in comparison with Fig.7(a) because particles from a inlet pipe cannot proceed against the obstruction by the forward accumulated particles.

In case of large unbalance between two outlet speeds, particles must turn abruptly to a branched pipe with aid of segregation resistance. If particles cannot turn into a branched outlet pipe associated with liquid phase, particles accumulate in a straight outlet pipe, which means segregation. Segregation would be controlled by the balance between momentum of particles, carrying capacity of the liquid phase and turning curvature of particle affected by boundary condition. In-situ pumping test also proved these concepts, where the concrete coming out from a short branched pipe was mortar-rich with small amount of aggregates.

In series A, particles were initially arranged in loose condition, where the mean clear spacing between particles is as large as their diameters. It is considered that closer spacing should have an influence on the aggregate movement around bifurcation point.

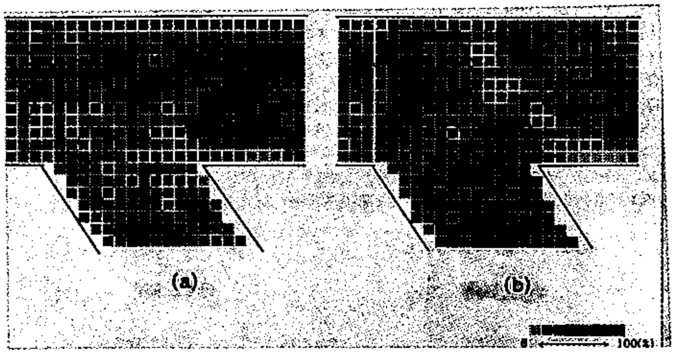


Fig.6 Volume density distribution
(a) Test A1
(b) Test A2

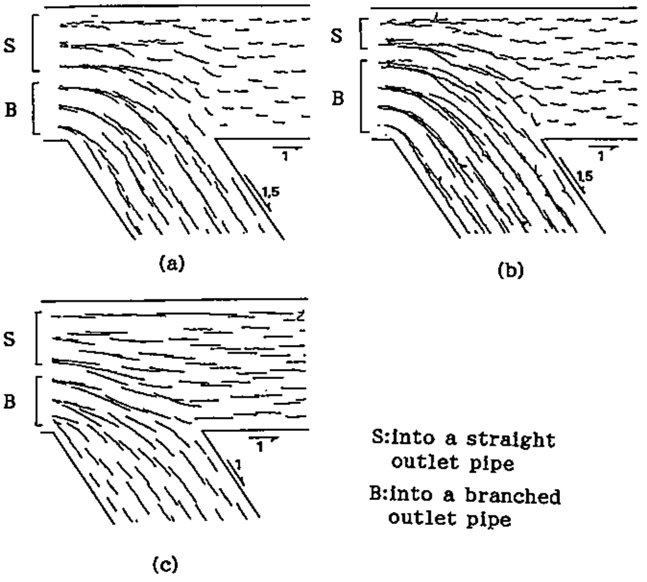


Fig.7 Stream line of particles
(a) Test A1(before accumulation)
(b) Test A1(after accumulation)
(c) Test A2

Effect of particle contact. Test B1 has the same condition as Test A1, except that the particle arrangement is designed to be closer contact condition, as shown in Fig.4. The volume density distribution represents segregation as shown in Fig.8(a). Lower density distribution can be seen in a branched pipe than in the inlet pipe, while volume density in a straight outlet pipe seems to be same as that in an inlet pipe.

Stream lines of Test B1, as shown in Fig.9(a), indicates that more than one-half of the particles flow into a straight pipe, which means larger segregation between particles and liquid phase than that of test A1. This is because it is difficult to change the movement direction of solid particles to a branched pipe in such an arrangement. When an assemblage of particles is forced to undergo shear deformation, not only shear resistance but also normal reaction and deformation, so called shear dilatancy, will act on it for the mutual interaction between particles. This interaction grows with the close contact of particles and two distinct shear band are found to be localized around the bifurcation.

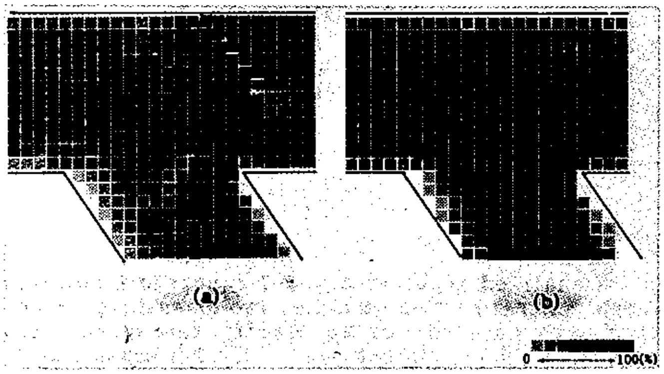
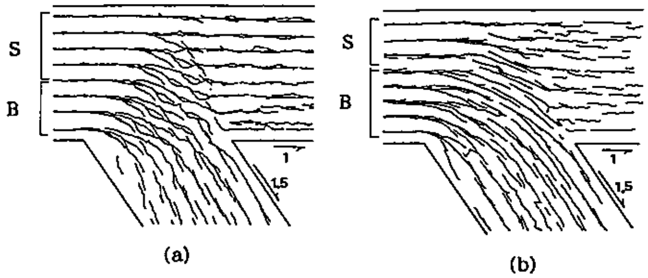


Fig.8 Volume density distribution
(a) Test B1
(b) Test B2



S:Into a straight outlet pipe
B:Into a branched outlet pipe

Fig.9 Stream line of particles
(a) Test B1
(b) Test B2

From a view point of the deformation rate of particles as solid phase, let us consider the behavior of particle movements. Mean deformation rates "I" in Test A1 and B1 are shown in Fig.10(a) and (b) respectively. It can be seen that the convergence of particles is distributed around the bifurcation zone in Test A1. Conversely, in Test B1, both divergence and convergence are shown in the bifurcating zone. Furthermore, deviatoric deformation rate shows two distinct sliding zones in Test B1 as shown in Fig.11(b), compared with that in Test A1 as shown in Fig.11(a). The deformation direction around bifurcation point indicates almost negative rotation in Test A1 as shown in Fig.12(a), which represents spin tensor ω_{xy}. On the other hand, in Test B1 the deformation direction in the left side of the two sliding zones gives negative rotation and that in the right side positive rotation as shown in Fig.12(b).

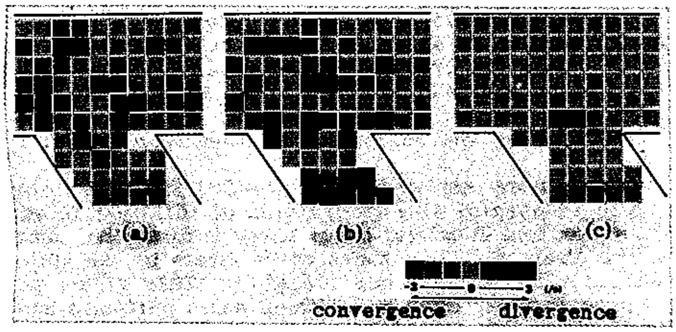


Fig.10 Mean deformation rate "I"
(a) Test A1
(b) Test B1
(c) Test B2

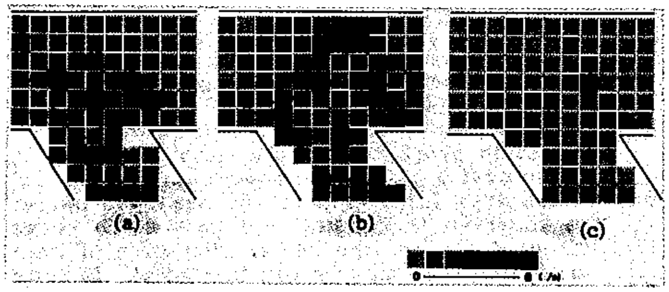


Fig.11 Deviatoric deformation rate "J"
(a) Test A1
(b) Test B1
(c) Test B2

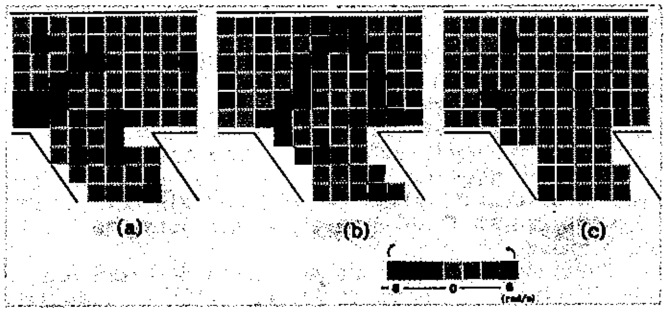


Fig.12 Spin tensor ω_{xy}
(a) Test A1
(b) Test B1
(c) Test B2

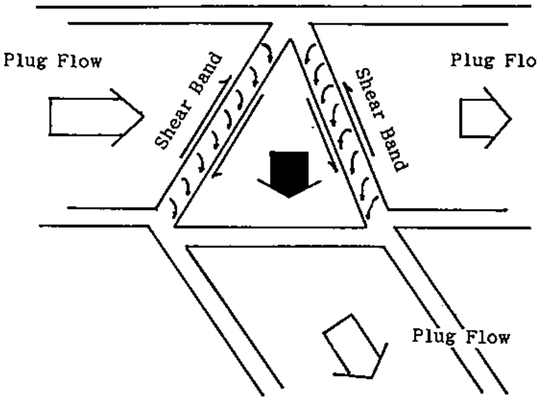


Fig.13 Deformation around bifurcation in Test B1

These behaviors lead to the deformation around the bifurcation as shown in Fig.13, that particles cannot flow into the branched outlet pipe associated with liquid phase and that particles in the triangle zone of the bifurcation are pushed downward to a branched outlet pipe by the following particles from the inlet pipe.

From these results it is concluded that particle contact restrains the deformation of solid particles, which produces localization of shear deformation, that is, two distinct sliding zones where stress by particle contact will increase considerably. This tends to promote the segregation between solid particles and liquid phase.

<u>Effect of viscosity of liquid phase</u>. Test B2 gives same condition as Test B1, except that the viscosity of liquid phase was higher, as is shown in Table.1. The volume density distribution of particles in Test B2 shows very little segregation in Fig.8(b), where the volume density condition is stable in an inlet pipe, a straight outlet pipe and a branched outlet pipe, comparing with that in Test B1. Stream lines in Test B2 show that particles from an inlet pipe flow into two pipes almost in proportion to the ratio of the piston speed in two outlet pipes. The smooth stream line and smooth turn from inlet side to the branched outlet pipe are observed in Fig.9(b), though Test B1 shows fluctuation of stream line and sudden turn of particles in the bifurcation, as shown in Fig.9(a). In spite of the unbalanced speed condition of both outlet pipes and close contact arrangement of particles, high viscous liquid phase resists segregation between solid particles and liquid phase. This is because the highly viscous liquid can carry particles to a branched pipe against inertia forces and mutual interaction of particles.

Comparing with data of Test B1, mean deformation rate indicates small intensity and uniform distribution in Fig.10(c), which means that high viscous liquid phase controls the particle movements in divergence or convergence. The shear deformation rate and spin tensor of particles show no distinct shear sliding band but uniform distribution in Fig.11(c) and Fig.12(c). It implies the smooth flow of particles without mutual collision among particles.

Furthermore, standard deviation distribution in velocity field is shown in Fig.14, which is computed from the variance about time averaging velocity vector at each element. It can be seen that in Test B2 particle flow does little vary at almost all locations in Fig.14(b), which means steady flow of particles. On the other hand, in Test B1, the higher magnitude of deviation can be seen in Fig.14(a), which implies the turbulent flow of particles. And rather great magnitude of deviation perpendicular to the mean velocity direction can be observed especially in the triangular zone bifurcating the inlet flow. This is also considered to be the particle flowing behavior caused by the high particle interaction, such as collision and sliding between particles.

From these results it is concluded that high viscous liquid phase has high capacity to carry solid particles, and also relaxes the mutual interaction among particles, which causes smooth flow associated with particles into a branched pipe, unifying the localization of shear deformation of particles. Accordingly, it is considered that deformation of particles induced by the mutual collision is restrained considerably, which reduces the interparticle contact stress. This is why high viscous liquid phase prevents segregation and blocking of particles though it increases the total pressure.

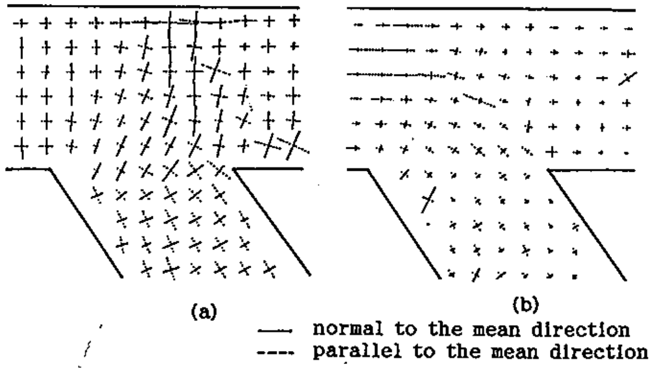


Fig.14 Standard deviation distribution in velocity field
(a) Test B1
(b) Test B2

CONCLUDING REMARKS

Visualized tests with model concrete simulating fresh concrete under idealized two-dimensional condition were carried out to clarify the segregation process around bifurcations. Eulerian expression is applied to understand the flow and global deformation of aggregate phase. Segregation between solid and liquid phases is proved to be highly affected by boundary condition and liquid viscosity, which is controlled by the particle contact condition.

Boundary condition governs the required turning curvature of particles flowing into a branched outlet. Increasing particle turning curvature velocity, liquid phase cannot carry particles against their momentum into a branched outlet pipe, which causes particle accumulation in a straight pipe and segregation.

Particle contact condition controls the deformability of particles. In close contact arrangement, relative movement of particles is restricted by the mutual interaction between particles, which increases the particle contact stress and promotes segregation.

Viscosity of liquid phase affects its capacity to carry particles against the relative movement between solid and liquid phases. Furthermore, high viscous liquid phase relaxes the mutual interaction between particles and unifies the localization of shear deformation in particles.

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