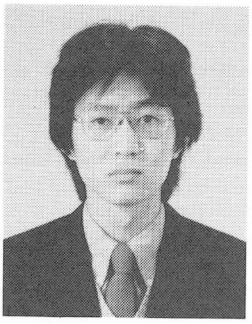
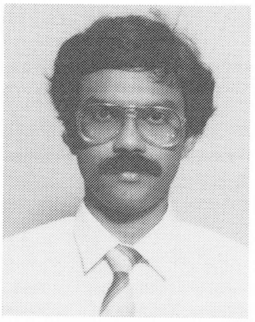
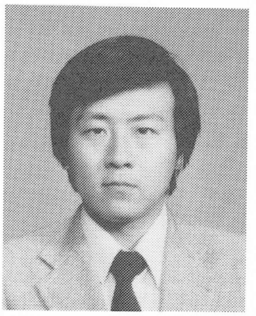
CONCRETE LIBRARY OF JSCE NO. 15, JUNE 1990

FLOW AND SEGREGATION BEHAVIOR OF A TWO-PHASE MODEL CONCRETE AROUND BIFURCATING PIPELINE

(Reprint from Proceedings of JSCE, No.408/V-11, August 1989)

Kazumasa OZAWA Anura NANAYAKKARA Kohichi MAEKAWA

SYNOPSIS

The objective of this research is to investigate the deformation and segregation process of fresh concrete as two-phase material around bifurcations in a pipeline network. Visualized test with model concrete, simulating fresh concrete, under idealized two-dimensional condition were carried out. By Lagrangian and Eulerian evaluations of aggregate phase with the use of image analysis, the deformation and segregation of model concrete around bifurcations were clarified, which were highly affected by boundary conditions and liquid viscosity. High viscous liquidphase was found to relax the mutual interaction between aggregate particles and to unify the localization of shear deformation of aggregate phase around bifurcation point.

K. Ozawa is an assistant lecturer of Department of Civil Engineering at University of Tokyo. He received his Master of Engineering Degree in 1986 from the University of Tokyo. His research interest includes behavior of fresh concrete and development of High Performance Concrete. He is a member of JSCE, JCI, ACI and IABSE.

A. Nanayakkara is a graduate student in the Department of Civil Engineering at University of Tokyo. He graduated from the University of Moratuwa, Sri Lanka, with a Bachelor of Science of Engineering in 1982 and received his Master of Engineering degree from the University of Tokyo in 1987. His research interests includes analyses of solid-liquid flow and computational modeling of fresh concrete pumping.

K. Maekawa is an associate professor of Department of Civil Engineering at University of Tokyo. He received his Doctor of Engineering Degree in 1985 from the University of Tokyo. His research interest includes constitutive models for concrete, cracks and reinforced concrete in-plane elements, structural analysis of reinforced concrete and development of High Performance Concrete.

[PROC. OF JSCE No. 408/V-11 (Concrete Eng. and Pavements) August 1989]

FLOW AND SEGREGATION BEHAVIOR OF A TWO-PHASE MODEL CONCRETE AROUND BIFURCATING PIPE LINES

By Kazumasa OZAWA, Anura NANAYAKKARA** and Kohichi MAEKAWA****

The objective of this research is to investigate the deformation and segregation process of fresh concrete as two-phase material around bifurcations in a pipe line network. Visualized tests with model concrete simulating fresh concrete under idealized two-dimensional condition were carried out. By Lagrangian and Eulerian evaluations of aggregate phase with the use of an image analysis, the deformation and segregation of model concrete around bifurcations was clarified, which was highly affected by boundary conditions and liquid viscosity. High viscous liquid phase was found to relax the mutual interaction between aggregate particles and to unify the localization of shear deformation of aggregate phase around the bifurcation point.

Keywords : two-phase model concrete, bifurcation, segregation, inter-particle stress, liquid viscosity

1. INTRODUCTION

The concrete placing by pumping technology is now one of the most popular processes for 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 for concrete, such as gravels, sands and cement paste. Blockage of flowing concrete is one of the most serious troubles which causes the terrible loss of time, labor and cost. Even though the blocking does not occur, segregation will cause troublesome problems. A great deal of shrinkage in concrete containing greater amount of liquid phase introduces many cracks into concrete structures. Honeycombing due to the water discharged concrete deteriorates the durability of structures.

Basically, there exist no problems concerning blocking or segregating 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 for flowing concrete. We selected this research target on which we focus our efforts for understanding the segregation process and creating the concept of high performance concrete with high deformability and segregation resistance.

2. IN-SITU PUMPING TEST

The new "Wishbone Tree Pipe (Bifurcating Pipe) Layout Method" for pumping concrete has been

* Member of JSCE, M. Eng., Assistant Lecturer, Department of Civil Engineering, University of Tokyo (Hongo 7-3-1, Bunkyo-ku, Tokyo 113)
** Member of JSCE, M. Eng., Graduate Student, Department of Civil Engineering, Univ. of Tokyo
*** Member of JSCE, Dr. Eng., Associate Professor, Department of Civil Engineering, Univ. of Tokyo

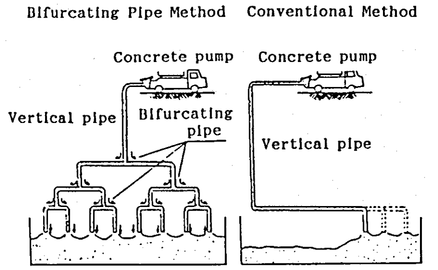


Fig. 1 Wishbone Tree Pipe (Bifurcating Pipe) Layout Method[1].

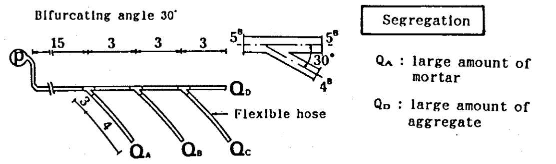


Fig. 2 Segregation of concrete through bifurcation[2].

developed by Takase and Tanabe et al[1]. The pipe system, as illustrated in Fig. 1, bifurcates symmetrically at several stages and enables monolithic concrete to be cast concurrently and continuously. In process of developing this new method, many interesting pumping test results were obtained. In the case of non-symmetric arrangement of pipes, the concrete coming from bifurcations was segregated or blocked, as shown in Fig. 2[2]. The concrete coming out from the branched outlet pipe was found to have a large amount of cement paste or water, while that coming out from the main pipe was found to have a large amount of coarse aggregates.

This phenomenon cannot be explained by the concept that concrete is a uniform non-linear material such as a Bingham body fluid. Although actual concrete is a five-phase material, that is, coarse aggregates, sands, cement particles, water and air, in this study we treat fresh concrete 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 of this boundary condition. In comparison with the existence of coarse aggregates, that of cement particles, which have much smaller size than that of pipe, is supposed to be negligible as solid because their behavior have 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, such as mortar phase and aggregate phase, was adopted.

3. VISUALIZED TEST AND IMAGE ANALYSIS

Visualized test with model concrete and authors' image analysis[5] was carried out by applying the Hashimoto's model concrete[3),4)] so as to get information on aggregate movement around a bifurcation point.

The apparatus used, as shown in Fig. 3, consists of a rectangular pipe, pistons with rods and a video camera which records motion of plastic balls. Width of both outlet pipes was the same size as that of the inlet, 180 mm, and the angle of the bifurcating pipe was decided to be 48.6 degrees. The piston head in the inlet pipe was controlled by an electric motor at a constant speed.

Model concrete used consisted of water absorbent polymer as mortar (liquid) phase and plastic balls as aggregate (solid) phase. Plastic balls had consistent size of 25 mm in diameter and specific gravity of about 1.4. Specific gravity ratio of plastic balls to polymer media was about 1.4, which corresponded to that of normal aggregates to mortar in actual concrete. The size of plastic balls versus the pipe size is equivalent to the maximum

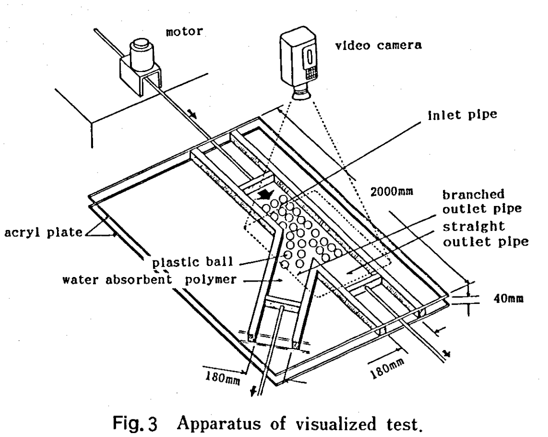


Fig. 3 Apparatus of visualized test.

size of coarse aggregates in actual concrete versus the pipe size.

The piston head in the inlet pipe was moved at a constant speed, about 4 cm/s. By use of the video data recorded, image analysis was conducted[5]. From position data of each aggregate connected through a series of screen, the behavior of aggregate phase was evaluated with Lagrangian and Eulerian treatments, explained in the reference[5].

4. SEGREGATION PROCESS AND MECHANISM ON VISUALIZED TEST

(1) Factors affecting segregation mechanism around bifurcations

As an extreme case, let us consider a one-phase solid flow in a pipe with bifurcations. Without any external obstructions at the two outlets as shown in Fig. 3, almost all particles flow into the 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 the straight outlet pipe and push away into the branched outlet pipe provided that 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 and associated dilatancy.

If there would be no interaction between solid and liquid phases in two-phase flow, the same results as those 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, the specific gravity 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 investigate the effect of the balance of two outlet flow speeds as a boundary condition, and series B on the effect of viscosity of the liquid phase. In series A, the volume density of solid particles used was designed to be smaller than that in series B (See Table 1).

(2) Lagrangian evaluation of aggregate phase

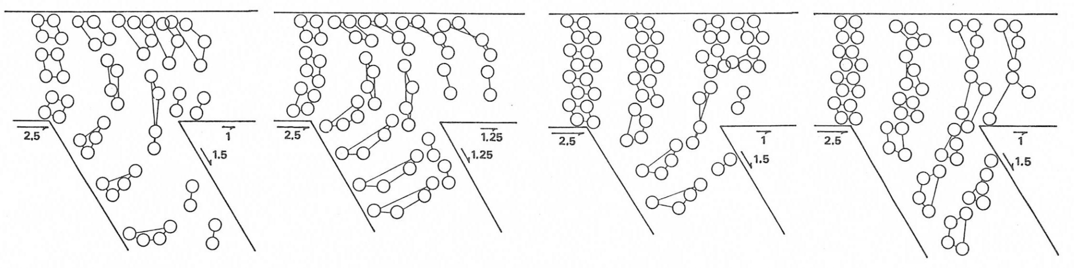
Trace of particles in adjoining two lines at constant time intervals is shown in Fig. 4 (a) to Fig. 4 (d). In these figures the following observations can be derived.

Test A1 gives unbalanced speeds of flowing concrete in two outlet pipes, where the speed in the straight

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



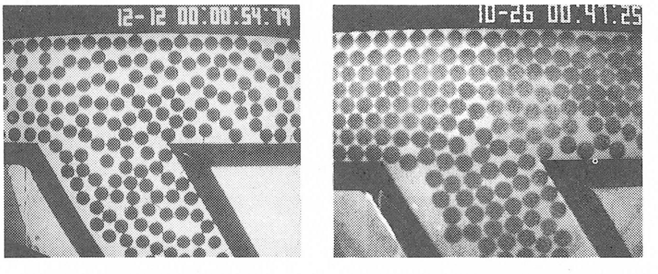
(a) Test A1 (b) Test A2 (c) Test B1 (d) Test B2

Fig. 4 Lagrangian trace of particles.

outlet pipe was 1.6 cm/s and the speed of 2.4 cm/s at the branched outlet was introduced. In Test A2, both piston heads in the outlet pipes were controlled so as to move at the same speed, 2.0 cm/s. The inlet speed of piston head, viscosity of liquid phase and initial volume density of particles were common to both tests. In Test A2 particles are found to be divided equally into two outlet pipes. In case of Test A1, however, particles are distributed equally in spite of unbalanced speed condition of flowing concrete, which implies the accumulation of particles in the straight outlet pipe and small amount of liquid phase due to mass balance. It may be considered that particles in the middle of pipe cannot turn into the branched outlet pipe associated with liquid phase, which means segregation between solid and liquid phases. Particles near the upper wall of the straight pipe are enforced to move slowly by wall effect in both tests. Concerning the transformation of particle interrelation, shear deformation can be observed just in the bifurcating area of both tests because of their loose contact arrangement of particles as shown in Fig. 5(a).

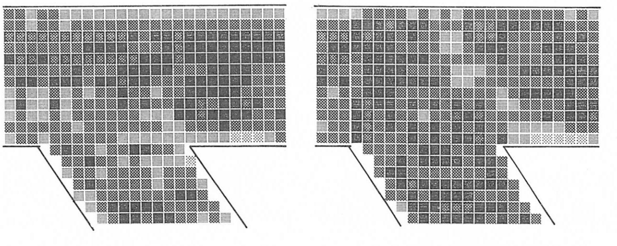
On the other hand, locational interrelation of particles is less transformed in Series B, especially in Test B1 than in Series A. Series B has a closer arrangement of particles with the mean spacing of one fifth of their diameter as shown in Fig. 5(b). Particle interaction is considered to restrain the rearrangement of particles. On the trace lines of particles, particles are found to accumulate in the straight outlet pipe in Test B1, where segregation may be more promoted in comparison with that in Test A1, While in Test B2 particles are distributed in proportion to the velocity ratio of flow of two outlet pipes. Test B2 gives the same condition as Test B1, except that the viscosity of liquid phase is higher than that used in Test B1. Flowing time of the P funnel test, according to the JSCE specification, is about three times longer in Test B2 than that in Test B1. Accordingly it is considered that high viscous liquid phase has high performance of segregation resistance because of its high flowing capacity associated with solid particles.

As mentioned above, each particle flow or movement can be clearly seen with Lagrangian description. It is,



(a) Series A (b) Series B

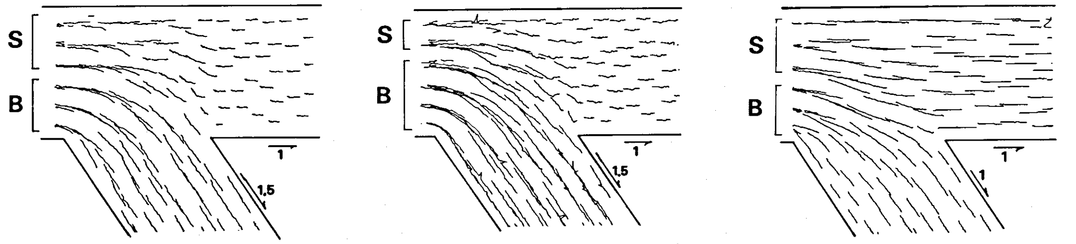
Fig. 5 Particle arrangement.



(a) Test A1 (b) Test A2

0 ←——→ 100(%)

Fig. 6 Volume density distribution.



(a) Test A1(before accumulation) (b) Test A1(after accumulation) (c) Test A2

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

Fig. 7 Stream lines of particles.

however, difficult to understand the mechanical inter-particle action with only the trace of each particle. Then we investigated the global kinematics and deformational behavior of aggregate phase with spatial averaging technique[5].

(3) Eulerian evaluation of aggregate phase

a) Effect of boundary condition on the volume change of aggregate phase

The volume density distribution of particles in a steady state is shown in Fig. 6, where the size of a cell is determined to be about one-half the particle diameter for detecting the global distribution satisfactorily. The volume density in Test A2 is uniformly distributed in both outlet pipes as shown in Fig. 6(b). The stream lines are also found to be equally separated 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 the straight outlet pipe rather than in the branched outlet and inlet ones. This is the segregation between solid particles and liquid phase defined in Section 1.

The stream lines of particles in Test A1 indicate 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 indirectly means segregation and coincides with the accumulation pattern in Fig. 6(a). According to the compatibility of mass transfer, the inconsistent flow of particles 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 between particles in the straight inlet and outlet pipes, which results in the accumulation of particles.

After accumulation of particles, as shown in Fig. 7(b), the number of stream lines into the branched pipe increases in comparison with Fig. 7(a) because particles from the inlet pipe cannot proceed against the interparticle action by the forward accumulated particles.

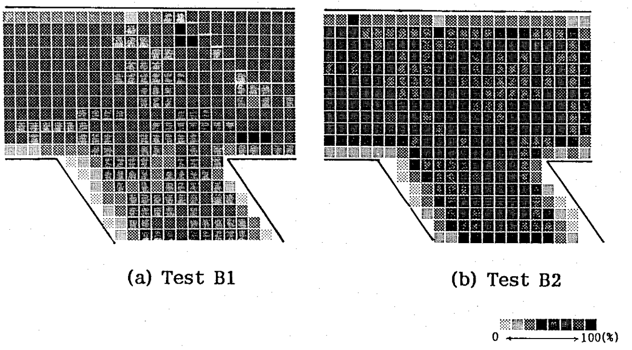
In case of the large unbalanced condition between two outlet speeds, particles must turn abruptly to a branched pipe with resistance of the segregation. If particles cannot turn into a branched outlet pipe associated with liquid phase, particles will be accumulated in a straight outlet pipe, which means segregation. Segregation would be controlled by the balance between momentum of particles, carrying capacity of the liquid phase and curvature of particle turning affected by boundary condition. In-situ pumping test also proved these concepts because the concrete coming out from a short branched pipe is composed of a large amount of mortar with small amount of aggregates as shown in Fig. 2.

In Series A, particles were initially arranged in a loose condition, where the mean clear spacing between particles is as large as their diameter. It is easy to consider that closer spacing between particles should have an influence on the aggregate movement around the bifurcation point.

b) Effect of particle contact

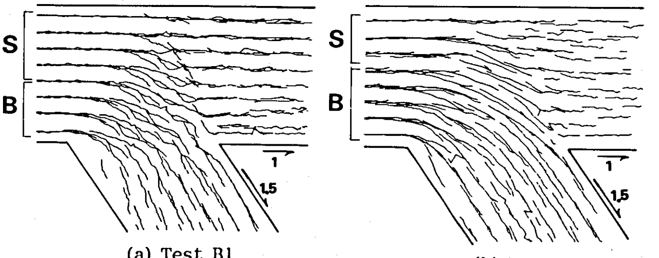
Test B1 gives the same condition as Test A1, except that the particle arrangement is designed for the closer contact condition. The volume density distribution represents segregation as shown in Fig. 8(a). Lower density distribution can be seen in the branched pipe than that in the inlet pipe, while volume density in the straight outlet pipe seems to be the same as that in the inlet pipe. This is a little bit different phenomena from that in Test A1 where accumulation of particles can be seen at the entrance of the straight outlet pipe. This is because particles are restrained by surrounding particles to relative movement and are difficult to accumulate as shown in Test A1.

Stream lines of Test B1, as shown in Fig. 9(a), indicate that more than one-half of the particles flow into the straight pipe, which means larger segregation



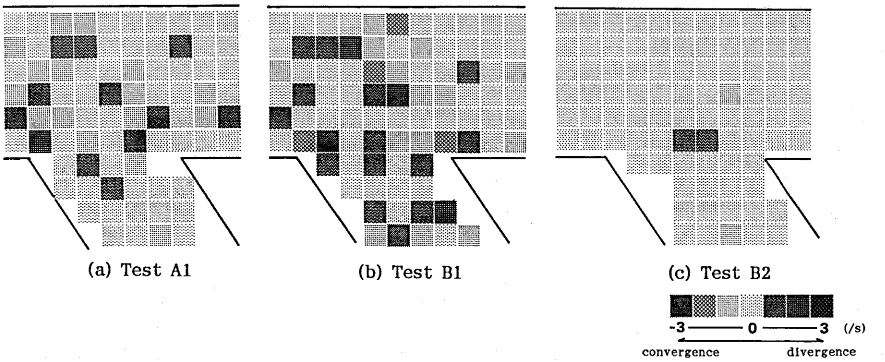
(a) Test B1 (b) Test B2

Fig. 8 Volume density distribution.



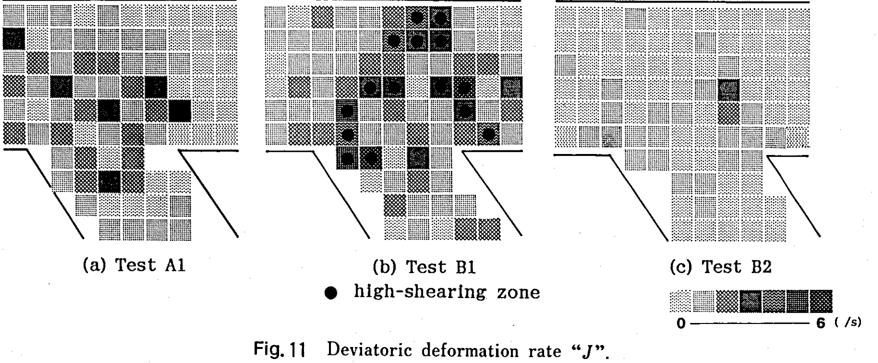
(a) Test B1 (b) Test B2

Fig. 9 Stream lines of particles.



(a) Test A1 (b) Test B1 (c) Test B2

Fig. 10 Mean deformation rate "I".



(a) Test A1 (b) Test B1 (c) Test B2

Fig. 11 Deviatoric deformation rate "J".

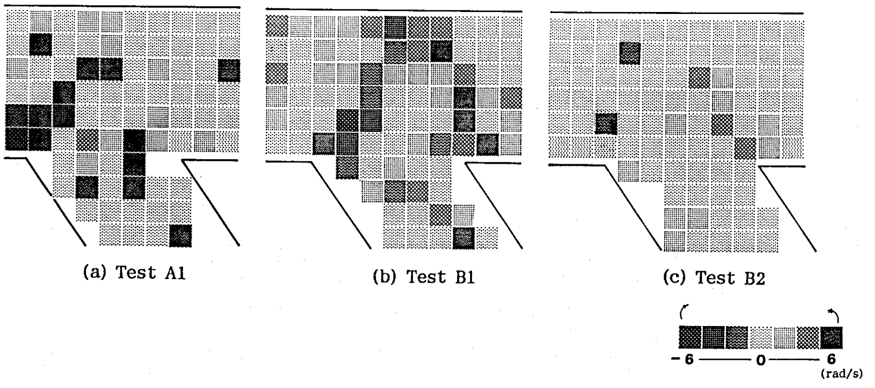


Fig. 12 Spin tensor ω_{xy}.

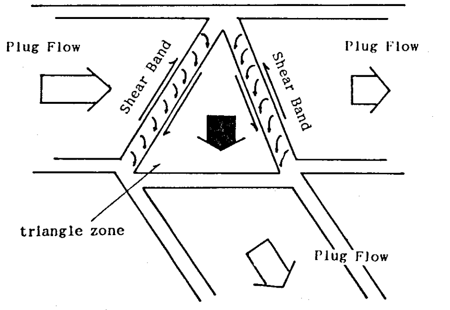


Fig. 13 Deformation of solid phase around bifurcation in Test B1.

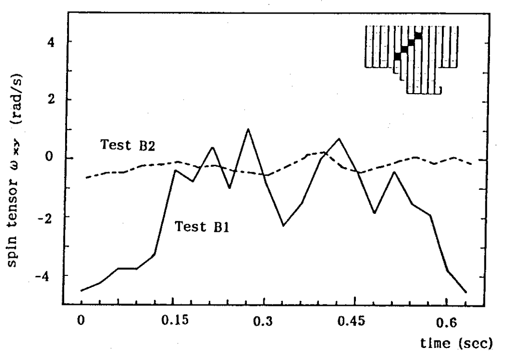


Fig. 14 Spin tensor in the high-shearing zone in time domain.

between particles and liquid phase than that of Test A1. This is because it is more difficult to change the direction of movement of solid particles to a branched pipe in such an arrangement. When an assemblage of particles is enforced 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 localized around the bifurcation, as discussed later.

From a view point of the deformation rate of particles as solid phase, let us consider the behavior of particle relative motion having close relation to the inter-particle stress. Assuming the aggregate phase as a continuous phase, mean deformation rate "I" defined as the first invariant of deformation rate tensors[5] in Test A1 and B1 is shown in Fig. 10(a) and (b) respectively. It can be seen that the convergence of particles where "I" is negative and the divergence where "I" is positive are distributed around the bifurcation zone in both Test A1 and Test B1. Mean deformation rate "I" represents the variance of mean relative distance between particles, which means the segregation between solid particles and liquid phase.

Furthermore, deviatoric deformation rate "J" defined as the second invariant[5] represents the intensity of shear deformation rate, which shows two distinct high-shearing (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 zone indicates almost negative rotation in Test A1 as shown in Fig. 12(a), which represents spin tensor ω_{xy}[5]. 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).

These behaviors lead to the deformation mode around the bifurcation as shown in Fig. 13, that particles in the triangle zone of the bifurcation is induced to move down to a branched outlet pipe by the following particles from the inlet pipe. This particle behavior occurs at regular intervals in time domain as shown in

Fig. 14.

From these results it is concluded that particle contact restrains the deformation of particles, which produces localization of shear deformation such as two sliding zones where stress by particle contact will increase considerably. This tends to promote the segregation between solid particles and liquid phase, and the following blocking due to high inter-particle stress transfered in solid phase. These informations cannot be derived without Eulerian evaluation of aggregate phase.

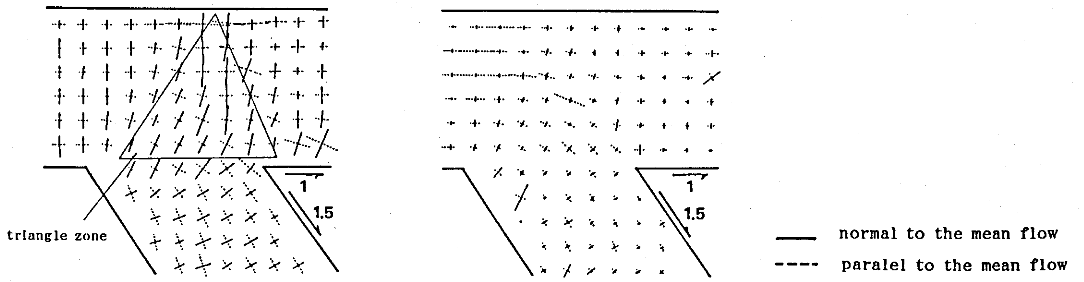
c) Effect of viscosity of liquid phase

The volume density distribution of particles in Test B2 where high viscosity of liquid phase was specified shows very little segregation in Fig. 8 (b), where the volume density condition is stable in the inlet pipe, the straight pipe and the branched pipe, compared with that in Test B1. Stream lines in Test B2 show that particles from the inlet pipe are divided into two pipes almost in proportion to the speed ratio of the piston head in two outlet pipes. The smoother 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, a high viscous liquid phase resists separation between solid particles and liquid phase. This is because the highly viscous liquid phase can carry particles to a branched pipe against their inertia forces and mutual interaction between particles.

In comparison with data of Test B1, mean deformation rate indicates the smaller intensity and uniform distribution in Fig. 10 (c), which means that the high viscous liquid phase controls the particle movements in divergence or convergence. The shear deformation rate and rotation rate of particles show no distinct shear sliding band but uniform distribution in Fig. 11 (c) and Fig. 12 (c), which implies the smoother flow of particles with very little mutual collision between particles. Spin tensor at the corner of the bifurcation in time domain is almost stable condition as shown in Fig. 14, which means steady flow of particles.

Furthermore, standard deviation distribution in velocity field is shown in Fig. 15, which is computed from the variance about time averaging velocity vector at each element[5]. It can be seen that in Test B2 particle flow does little vary at almost all locations in Fig. 15 (b), which means microscopically steady flow of particles. On the other hand, in Test B1, the higher magnitude of deviation can be seen in Fig. 15 (a), which implies the turbulent flow of particles. Rather great magnitude of deviation normal to the mean velocity direction can be observed especially in the triangular zone bifurcating the inlet flow. This implies the particle flowing behavior caused by the high particle interaction such as collision and sliding between particles. Due to mixing to the normal direction, the additional momentum must be transferred similar to the turbulent flow[6].

From these results it is concluded that a high viscous liquid phase relaxes the mutual interaction between particles and results in flowing smoothly associated with particles into a branched pipe, which leads to unify 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



(a) Test B1 (b) Test B2

Fig. 15 Distribution of standard deviation to the mean flow of particles.

contact stress. High viscous liquid is supposed to lessen the shear resistance of aggregate phase as a whole, though it makes the greater shear resistance of liquid phase. This is why a high viscous liquid phase prevents segregation and blocking of particles even though it increases the total pressure.

5. 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. Segregation between solid particles and a liquid phase is proved to be highly affected by boundary condition and liquid viscosity, which is controlled by the particle contact condition.

Boundary condition governs the needed turning curvature of particles flowing into a branched outlet pipe. When increasing the turning curvature or velocity of particles, liquid phase cannot carry particles against their momentum into a branched outlet pipe, which results in accumulation of particles in a straight pipe and segregation.

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

Viscosity of liquid phase affects its capacity to carry particles against the relative movement between solid particles and liquid phase. Low viscosity of liquid phase introduces the localization of the intensity of shear deformation in particles, while high viscous liquid phase relaxes the mutual interaction between particles and unifies the localization of shear deformation, which results in lessening the intensity of shear deformation represented by "J".

Finally, it must be noted that the experimental results discussed in this paper are qualitative. It is impossible to adjust the properties of the model concrete perfectly similar to those of actual concrete, because of the difference of the specific gravity, shape and size of particles, mechanical behaviors of liquid phase and so on. As the quantitative correlation for segregation process is concerned, the similarity rule for multi-phase flow should be formulated based on the governing equations for the material.

ACKNOWLEDGMENT

The authors appreciate his invaluable advice and suggestion by Prof. H. Okamura, University of Tokyo, and express their gratitude to the Ministry of Education of Japan for providing the financial support by the Grant-in-Aid for scientific research No. 61850090.

REFERENCES

1) Tanabe, K. and Takase, S. : 'Wishbone Tree' Pipe Layout for Concrete Pumping, IABSE Symposium Paris-Versailles, pp. 691-692, 1987.
2) Tanabe, K. and Takase, S. : Bifurcating Pipe Layout Method for Concrete Pumping, Concrete Journal, Vol. 25, No. 6, pp. 40-50, June 1987 (in Japanese).
3) Hashimoto, C., Maruyama, K. and Shimizu, K. : Study on Visualization of Blocking of Fresh Concrete Flowing in Pipe, Concrete Journal, Vol. 26, No. 2, pp. 119-127, Feb. 1988 (in Japanese).
4) Hashimoto, C. et al. : Study on Visualization of Deformability of Fresh Concrete Pumping, Proceeding of the Japan Concrete Institute, Vol. 10, No. 2, pp. 79-84, 1988.
5) Ozawa, K., Nanayakkara, A. and Maekawa, K. : Evaluation of Aggregate Particle Motion in Liquid -Solid Flows of Model Concrete, Proc. of JSCE, No. 408/V-11, August 1989.
6) Rotta, J. C. : Turbulent Flow (translated by Oji), Iwanami Book Co. Ltd., 1975.

(Received August 24 1988)