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EVALUATION OF DEFORMABILITY OF FRESH CONCRETE FLOWING IN BENT PIPES AND TAPERED PIPES

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SYNOPSIS

The objective of this research is to investigate the required characteristics for fresh concrete to flow smoothly in a bent pipe. In greater detail, it should be studied how fresh concrete can deform itself while flowing in tapered or bent pipes and how the blocking process takes place in such pipes. The experimental study was conducted using the visualization technique which was previously developed by the authors. The deformation of model concrete in a certain region was evaluated by measuring the relative distance of 8 tracer particles. The applicability of the findings in the test to actual concrete was proved by a field test where a given amount of concrete was circulated through pipes connected in a closed loop.

Keywords: deformability, fresh concrete, bend pipe, tapered pipe, visualization technique, strain rate, field test

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1. INTRODUCTION

It is required in the concrete engineering field to establish an appropriate evaluation method for pumpability of fresh concrete because of the quantification of the pumping schedule as well as improvement of the durability of hardened concrete[1].

The evaluation methods adopted so far are mainly the field test in the actual situation[2] or the bleeding test of concrete with pressure[3]. They are not necessarily adequately efficient. Since the field test requires large-scaled equipment, it is not profitable for parametric study. In contrast, the bleeding test has limitations for application. Taking these aspects into account, some efforts have been made to develop a new testing method for evaluation of pumpability of concrete on a laboratory scale[4].

The field test in the actual situation may not be superior because the obtained data are limited to the mix proportion of concrete, the condition of pipelines and the results of whether blockade occurs or not. It is impossible to examine the mechanism of blocking by one trial. In order to study the mechanism by the field test, a large number of test results should be gathered. Currently, the research results in this field are not definitive as to how blocking occurs in a certain pipeline, nor do they specify the most influential parameters to blockade[5].

The authors have developed and proposed a visualization technique which makes it possible to see how aggregates in concrete move when concrete flows in pipes[6]. The technique involves a visual model of concrete, and is intended for obtaining fundamental understanding on how fresh concrete deforms during flow in pipes, and how the blocking occurs.

The technique also involves the development of a measurement system for quantitative evaluation of behavior of both the aggregate phase and mortar phase. The system makes it possible to discover the existence of fluctuation of concrete flow in a tapered pipe, and to examine the causality between the fluctuation and the occurrence of a blockade[7].

The visualization technique has helped to develop the mathematical model of concrete flow in tapered pipe[8] as well as in bifurcated pipelines[9,10].

During arrangement of a pumping plan, it is necessary to examine the blocking in bent pipes as well as in tapered pipes. However, the concrete flow in bent pipes is more complicated than the flow in tapered pipes, which is symmetrical to the pipe's axis. Even in hydromechanics, the water flow in bent pipes is very complicated by the occurrence of secondary flow[11]. Thus, it is indispensable to study the deformability and the blocking mechanism of fresh concrete in bent pipes for establishing an evaluation method of pumpability.

The objective of this research is to identify the required characteristics of fresh concrete flowing in a bent pipe by investigating how concrete can deform itself while flowing in straight pipes, tapered pipes and bent pipes, and how blocking occurs in such pipes. In addition, the applicability of the findings in this test was examined by conducting a field test in which a given amount of concrete was circulated through pipes connected in a closed loop.

2. EVALUATION METHOD FOR DEFORMABILITY OF MODEL CONCRETE

2.1 Characteristics of Solid Phase of Model Concrete for Deformability

The behavior of model concrete flowing in pipes was studied by measuring the movements of tracer particles in the [Xi(t),Yi(t)] coordinate system. It was, however, necessary to define a characteristic index to evaluate the flowability of the model concrete quantitatively.

In the previous study with tapered pipes, "velocity vector" and "acceleration vector" were used to describe the movements of aggregates and mortar as the characteristic indexes. The velocity vector was defined by the relative location of the tracer particle within a unit time. The fluctuation of concrete at the outlet of a tapered pipe was, then, determined quantitatively by measuring the variation of relative velocity between the aggregate and the surrounding mortar. The acceleration vector, defined by the variation of the velocity vector within a unit time, was used to evaluate the inner stress between aggregates generated just before the occurrence of a blockade. The two vectors could be used as indexes to express the relationship between the magnitude of fluctuation and the occurrence of a blockade[7].

From the observation of the behavior of visualized model concrete, it was found that the concrete flow involved two different phases, liquidlike flow and solidlike flow. When the concrete flowed smoothly in pipes, the movements of aggregates and mortar were continuous and the flow of concrete resembled that of a liquid. In contrast, the movements of aggregates and mortar became irregular both at the beginning of blocking and at arching of aggregates. The irregularity must come from the solid-phase flow of aggregates.

Observation of actual concrete also showed us that high slump concrete was fluidity-oriented while low slump concrete behaved as an assemblage of solid. This could be attributed to the fact that fresh concrete consists of multi-phase particles with a wide distribution in size and with different specific gravities, and that the mechanical and chemical properties of fresh concrete are time-dependent.

Both the velocity vector and the acceleration vector may be appropriate for expressing liquid phase features but they are not applicable to the solid phase. Hence, "strain rate" was introduced in this study to evaluate the properties of solid phase of concrete flow[12].

Figure 1 shows a time sequence of two tracer particles when the visualized model concrete was flowing in the pipes. In the case of a straight pipe, the relative distances of two tracer particles remained constant because the concrete flowed as a plug. On the other hand, the relative distances between two

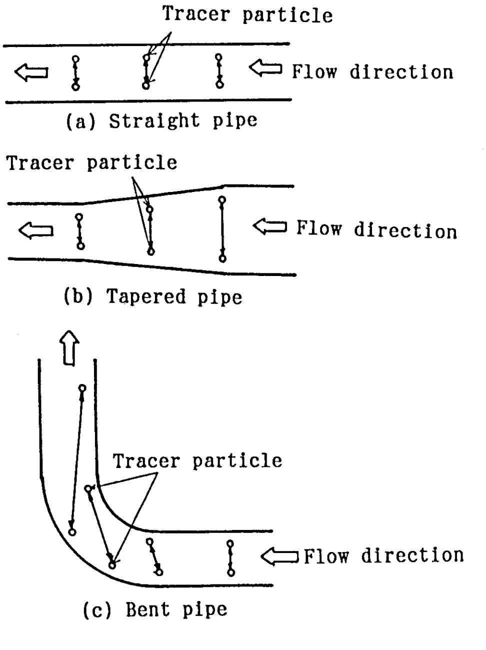

Fig.1 Relative displacement of tracer particles

tracer particles in the tapered portion and in the curved portion of such pipes varied significantly. For this reason, the change in the relative distances between two tracer particles with the elapsed time, was quantified as a physical index, called "strain rate" in this study.

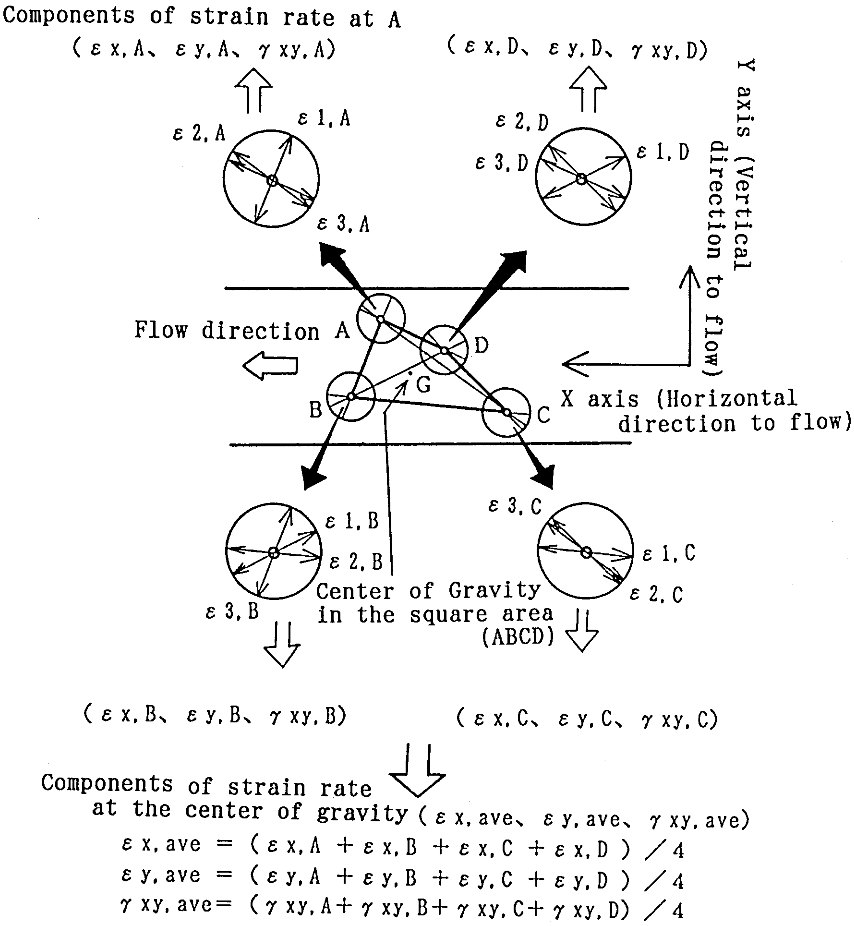

Fig.2 Definition of strain rate by strain rosette method

2.2 Definition of "Strain Rate"

Although the flow of actual fresh concrete is three-dimensional, the flow of model concrete is dealt with as a two-dimensional problem in this research. Figure 2 indicates four tracer particles (A,B,C,D) in the model concrete flowing in a pipe. While the concrete is flowing, the square area surrounded by the four particles may change its shape with the lapse of time. "Strain rate" represents this change. Therefore, the "strain" is different from the usual strain defined in the theory of elasticity.

The principle of a measurement system for the "strain rate" comes from the strain rosette method which is widely used in the experimental study of material science[13].

3. FLOW OF MODEL CONCRETE IN DEFORMED PIPES

3.1 Objectives

In order to evaluate the deformability of the model concrete in the straight, tapered and bent pipes, an experimental test was conducted using concrete pumping equipment in the laboratory. Based on the experimental results, the deformability of fresh concrete in a bent and tapered pipe was examined. Then, the examination was extended to the required characteristics for fresh concrete and its blocking mechanism in a bent pipe.

3.2 Testing Method and Mix Proportions of Model Concrete

Figure 3 shows three different kinds of pipes used in this research. All pipes, straight, tapered and bent, were made of transparent acrylic plate. Although the cross-sectional shape of the actual pipe was circular, that in this study was rectangular because it was necessary to remove the influence of the force orthogonal to the wall in the two-dimensional problem. In the rectangular cross section, it is possible to measure the displacement of tracer particles accurately in the two-dimensional coordinates, [Xi(t),Yi(t)].

Figure 4 shows a deformed pipe with the pumping equipment. Figure 5 shows the tracer particle injection equipment. Eight tracer particles were directly injected into the model concrete from the wall of the pipe. In order to observe the solid phase deformation, three square areas (upper, middle and lower) were delineated by the eight tracer particles. The initial square areas of both the straight and bent pipes were 5.0*2.0, 5.0*2.5, and 5.0*2.0cm (the distance parallel to the pipe's axis * the

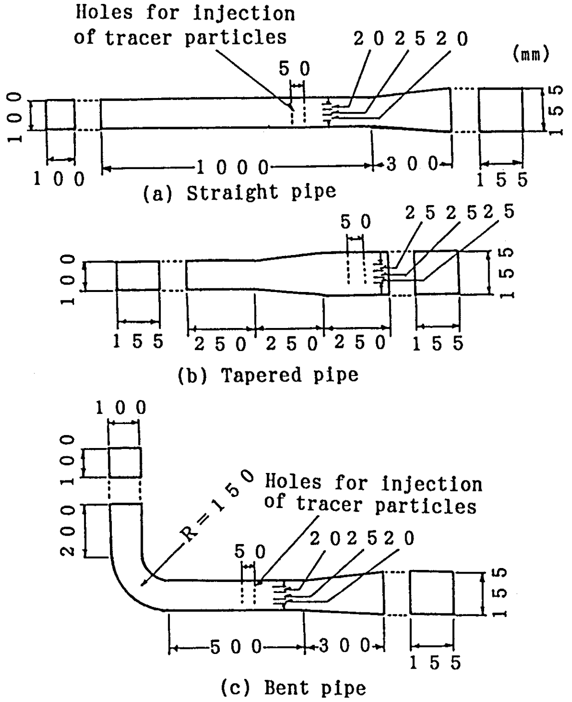

Fig.3 Dimensions of pipes

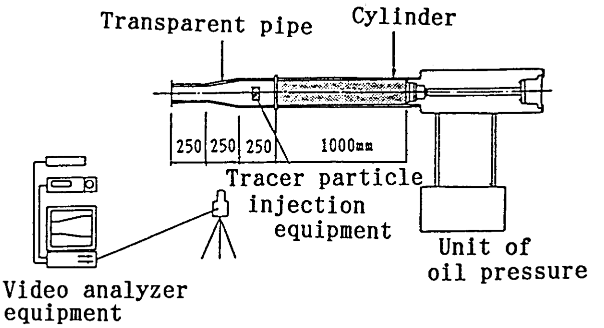

Fig.4 Pumping apparatus for laboratory test

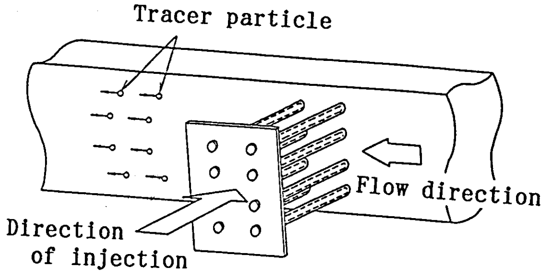

Fig.5 Tracer particle injection equipment

distance vertical to the pipe's axis) for the upper, middle and lower squares, respectively. The initial square area of the tapered pipe was 5.0*2.5cm for all three areas. One unit area was determined to involve eight coarse aggregate particles at maximum. The average grading size was 12.5mm. The number of particles in a square area varied depending on the volumetric ratio of the coarse aggregate to mortar. The deformation of the square area with elapsed time was taken as the strain rate of the model. The strain rate obtained by measuring the movements of tracer particles was considered to represent the deformation of the square area. Further study is required to consider the effects of the size of the coarse aggregate particles, the pumping rate and the size of the pipe on the size of the initial square area.

The mix proportions of the model concrete are shown in Table 1. The model mortar was made of colorless, transparent viscous material, which was a mixture of water and superabsorbent polymer. Coarse aggregates, whose maximum size was 25mm, were represented by the mixture of artificial lightweight aggregates (specific gravity of 1.527, grading size of 5-15mm) and gravel coated with asphalt (specific gravity of 1.239, grading size of 15-25mm). By mixing the artificial lightweight aggregates with the gravel at equal volumes, the grading of the entire aggregate was determined within the allowable range of grading specifications by the JSCE standard.

Table 1 Mix proportions of model concrete

No.	Supposed slump (cm)	Content of Super-absorbent polymer (gf/liter)	Vg/Vm (%)	Vgl/Vgc (%)	Unit weight(kgf/m^3)			
					W	P	Gl	Gc
Mix.1	------	1.8	0	-----	1000	1.80	----	----
Mix.2	> 21	1.8	60	100	625	1.00	257	211
Mix.3	21	1.8	80	100	556	1.00	304	250
Mix.4	19	1.8	90	100	526	0.95	324	266
Mix.5	------	3.0	0	-----	1000	3.00	----	----
Mix.6	> 12	3.0	60	100	625	1.88	257	211
Mix.7	12	3.0	80	100	556	1.67	304	250
Mix.8	10	3.0	90	100	526	1.58	324	266

P :Superabsorbent polymer
Gl:Artificial lightweight aggregate(specific gravity of 1.527)
Gc:Gravel coated with asphalt(specific gravity of 1.239)

Main test parameters were the volumetric ratio of aggregate to mortar (Vg/Vm) and the additive amount of superabsorbent polymer. The model concrete with the volumetric ratio (Vg/Vm) of 0% was a simulation of mortar flow without aggregate. The volumetric ratios (Vg/Vm) of 60% and 80% simulated concrete flow in a stable pumping state. The volumetric ratio of 90% exhibited an unstable pumping state in a tapered pipe just before the occurrence of blocking due to the arching of aggregates.

The model mortar with 1.8g/l(low viscosity) and 3.0g/l(high viscosity) of the additive amount of superabsorbent polymer represented the mortar part in the actual fresh concrete having a slump of 21cm and 12cm, respectively.

The pumping rate was set constant at 3.0cm/sec at the location where the tracer particles were injected. The pumping test was conducted at least five times under the same conditions and was repeated when a large discrepancy was observed.

The movement of the tracer particles in the pipe was recorded and stored using a video tape recorder. The displacement in the two-dimensional coordinates was read and the distribution of strain rate was calculated by the data reducing system consisting of an image analyzer, microcomputer, digitizer and video tape recorder. All of the strain rate vectors were calculated every 0.5 seconds.

3.3 Test Results and Discussion

Figure 6 shows an example of the distribution of the maximum and the minimum principal strain rates of the model concrete flowing in straight, tapered and bent pipes. It was not appropriate to take the average of the distribution of the maximum and the minimum principal strain rates as an index of deformability, because the locus of the gravity center of squares surrounded by the four tracer particles was not the same in any one of five tests. As a consequence, taking the maximum shear strain rate out of the three strain rate vectors into account, the average of five tests was calculated in the two-dimensional coordinates.

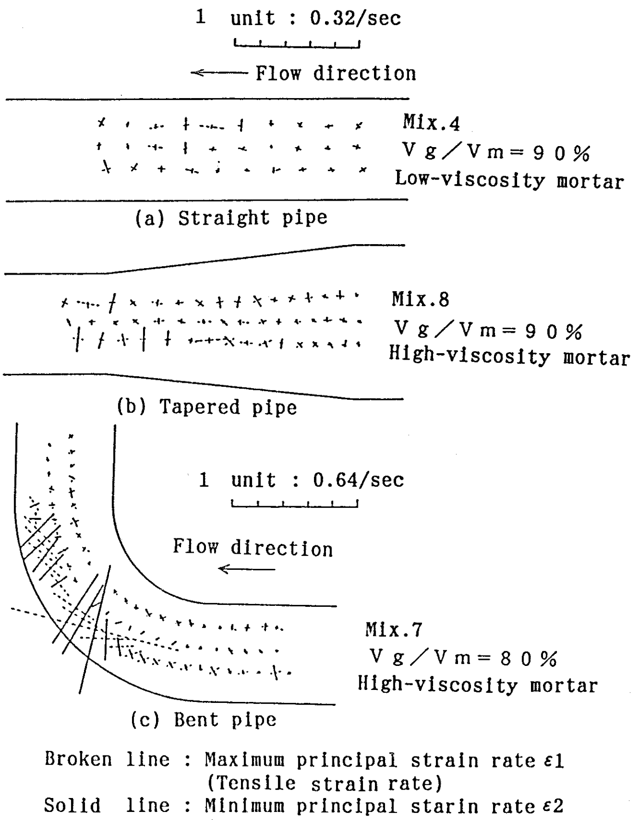

Fig.6 Distribution of maximum and minimum principal strain rate

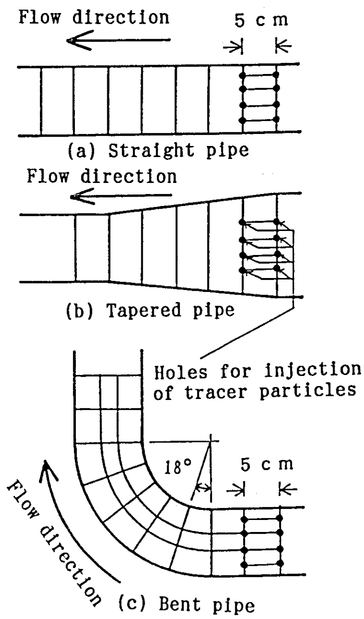

Fig.7 Division of pipe into elements

Figure 7 shows the element divisions of each pipe. First of all, the maximum shear strain rate vectors were calculated and the average was chosen as a representative index of the strain rate in each element. The angles of the maximum shear strain rate vectors were not considered, but the absolute values of the vectors were taken. Each pipe was divided into elements of 5cm in width. However, in the bent portion of a bent pipe, the elements were formed so as to have 18 degrees of arc angle and 4.71cm of arc length at the central axis of the pipe. Moreover, the section was divided into three parallel layers because the strain rate vectors varied significantly in the outside, center and inside of the bent portion.

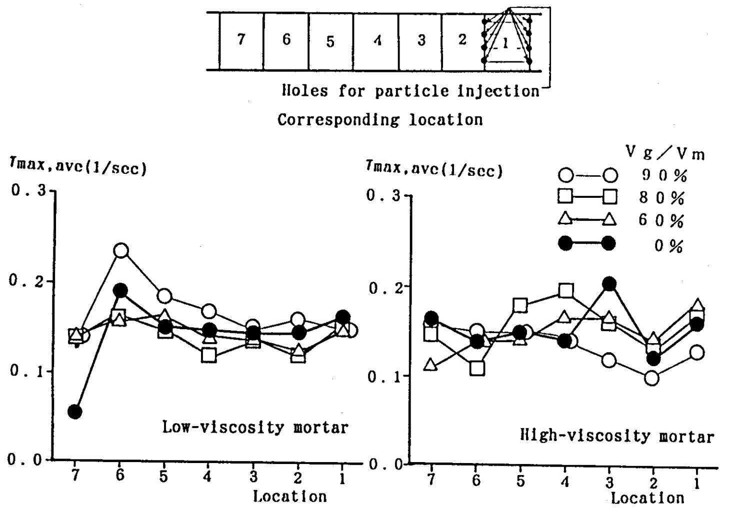

Fig.8 Distribution of $\gamma_{max,ave}$ in straight portion

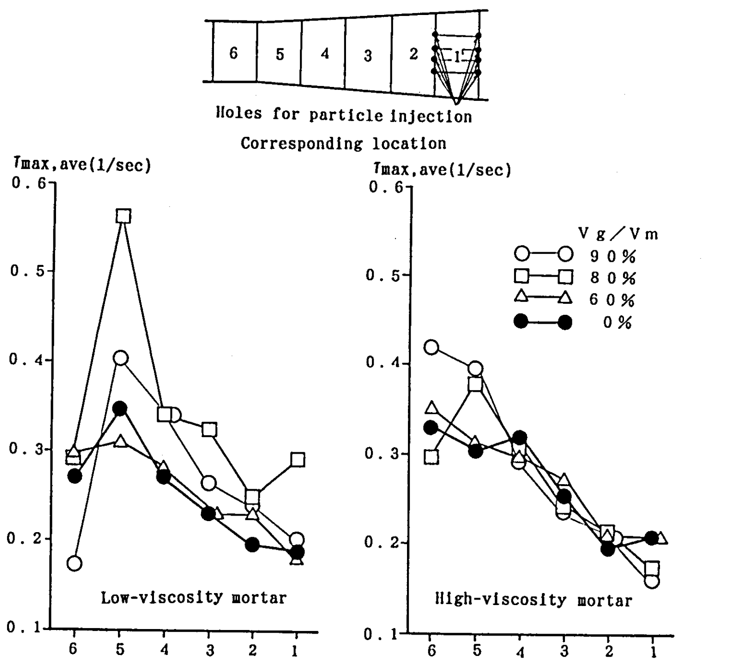

Fig.9 Distribution of $\gamma_{max,ave}$ in tapered portion

The deformability of the model concrete flowing in the pipes can now be examined by the strain rate, which is the average of maximum shear strain rate vectors in each element, called "$\gamma_{max,ave}$".

Figure 8 and Figure 9 show the distribution of $\gamma_{max,ave}$ of the straight and the tapered pipes, respectively. Figure 10 shows an example of the distribution of $\gamma_{max,ave}$ in the flow routes (outside, center and inside).

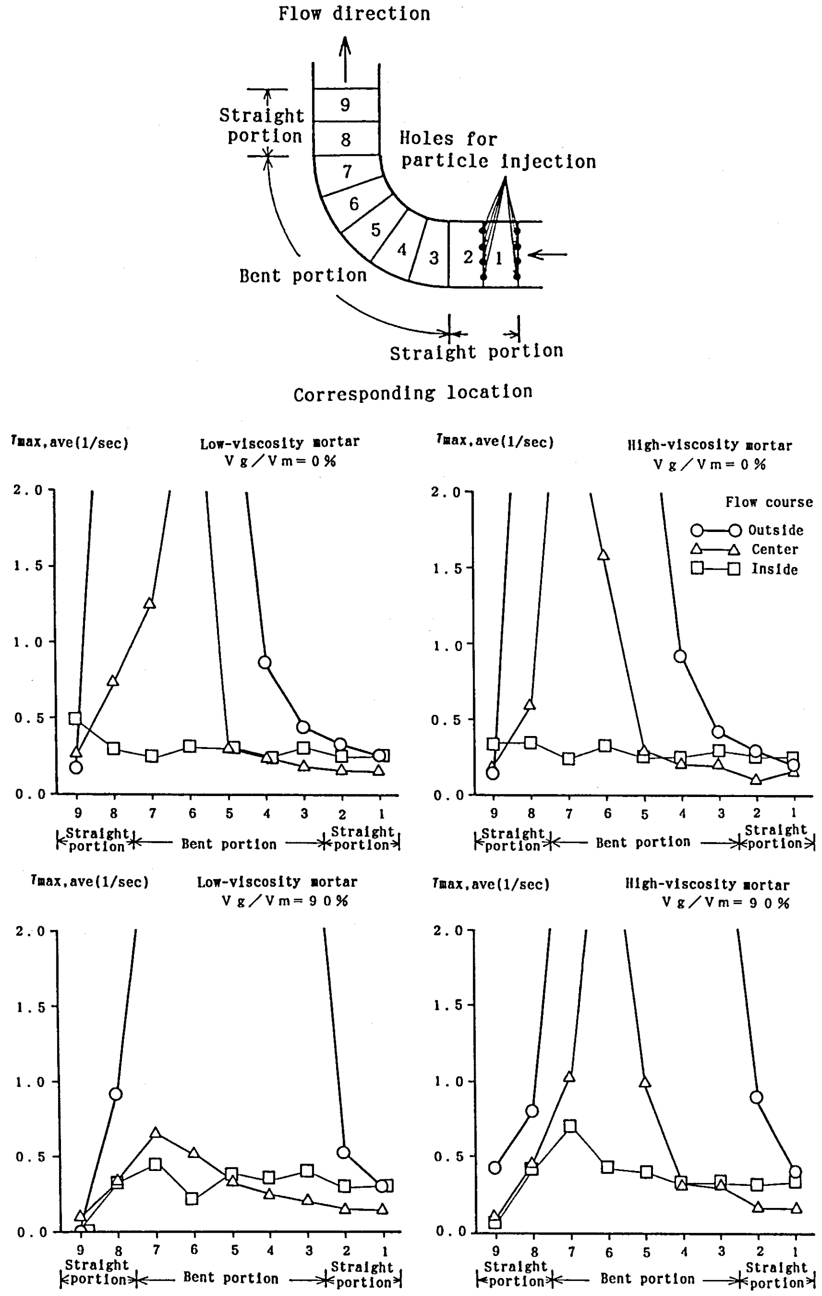

Fig.10 Distribution of $\gamma_{max,ave}$ in bent portion

3.3.1 Distribution of $\gamma_{max,ave}$ of Model Concrete Flowing in Straight Pipe

In the case of straight pipe, $\gamma_{max,ave}$ was consistent in the entire region regardless of the viscosity or Vg/Vm ratio, and was smaller than in the tapered or the bent pipe.

This was because the relative deformation of the model concrete in the straight pipe was so small that all of the concrete flowed as a unit mass. This fortifies the plug flow of fresh concrete in pipes.

3.3.2 Distribution of $\gamma_{max,ave}$ of Model Concrete Flowing in Tapered Pipe

As for the flow in the tapered pipe, compressive strain rate occurred near the outlet of the pipe in the direction perpendicular to the pipe axis. This suggested that the compressive deformation of the model concrete took place in the direction from the wall to the center of the axis. As the volumetric ratio(Vg/Vm) increased, $\gamma_{max,ave}$ became larger near the outlet of the pipe. In the case of low-viscosity mortar, under the stable state of pumping, $\gamma_{max,ave}$ became the largest near the outlet of the pipe when the volumetric ratio(Vg/Vm) was 80%. In contrast, when the volumetric ratio(Vg/Vm) was 90%, the concrete flow became unstable just before the occurrence of blocking, but, $\gamma_{max,ave}$ in the pipe decreased. This can be explained as follows. When the volumetric ratio(Vg/Vm) is small, the distance between coarse aggregate particles is large enough for the particles to deform and the particles flow smoothly with less collision among themselves. On the other hand, as the volumetric ratio becomes large, the relative displacement among coarse aggregate particles becomes large due to collision, spinning and sliding, and $\gamma_{max,ave}$ also becomes large. However, when the volumetric ratio exceeds a certain value, the coarse aggregate particles become densely packed near the outlet of the pipe. Consequently, the relative displacement of the particles decreases and $\gamma_{max,ave}$ becomes small. Moreover, as the volumetric ratio increases further, the arching of coarse aggregate particles takes place and blocking occurs.

In the case of high viscosity of mortar, there was no significant difference in the distributions of $\gamma_{max,ave}$ between the volumetric ratios of 80% and 90%. It can be said that when the viscosity of mortar was high, the mortar in between the coarse aggregate particles restrained the movement of the particles.

When the viscosity of mortar was low, $\gamma_{max,ave}$ in the entire tapered pipe was observed to be large. The low viscosity of mortar consequently provided low adhesion. The mortar segregated easily from the particles and $\gamma_{max,ave}$ became very large. Conversely, as for the arching just before the blockade, no influence of the viscosity of mortar was observed. At any viscosity, the blockade occurred when the volumetric ratio(Vg/Vm) exceeded 90%. Hence, the deformability of fresh concrete flowing in the tapered pipe should be dealt with in two cases: the deformability before the occurrence of blocking and that at the arching. The viscosity of mortar was the important factor in the former case.

3.3.3 Distribution of $\gamma_{max,ave}$ of Model Concrete Flowing in Bent Pipe

In the bent portion, $\gamma_{max,ave}$ was large outside of the pipe section regardless the of viscosity of mortar and the value of Vg/Vm. Concrete flowing in the bent pipe deformed as a one-phase composite. The behavior was very different from that in the tapered pipe.

In addition, $\tau_{max,ave}$ outside of the bent portion was more than twice as large as $\tau_{max,ave}$ near the outlet of the tapered pipe. The difference became large as the volumetric ratio(Vg/Vm) decreased. Since the modulus of rigidity of fresh concrete was constant, more pressure was created in the flow of fresh concrete in the bent pipe than in the tapered pipe.

As for the tapered pipe, compressive strain occurred symmetrically to the pipe's axis. When the strain exceeded the deformability of fresh concrete, coarse aggregate particles gathered to form the blockade. On the other hand, the blockade in the bent pipe was not followed by the occurrence of arching by coarse aggregates particles. It was caused by the increase in the modulus of rigidity of fresh concrete which led to a pumping pressure greater than the capacity of the pump.

Consequently, in the experimental test of the blocking in the bent pipe, the model concrete should be designed to have a high modulus of rigidity using the high-viscosity mortar. In this case, the model concrete could not represent the consistency of fresh concrete with slump of less than 12cm. Thus, the blocking in the bent pipe could not be simulated by the model concrete here. Another model must be developed corresponding to the low-slump concrete.

3.3.4 Influential Factors for Deformability of Fresh Concrete

It is predicted through the discussion so far that the deformability required for the fresh concrete to flow smoothly in a tapered pipe was different from that in a bent pipe.

The deformability required for a tapered pipe was expected to lead to a reduction in the number of internal reactions due to collision, spinning and sliding of coarse aggregate particles by the reduction of section, and was expected to prevent the particles from arching. The influential factors in the mix proportion were the viscosity of mortar and the volumetric ratio(Vg/Vm).

On the other hand, the deformability required for a bent pipe was expected to accomodate the shear deformation with minimal resistance but without the segregation of aggregate and mortar. Since the pipe diameter of a bent pipe was constant, the frequency of collision, spinning and sliding of particles was lower in a bent pipe than in a tapered pipe. The influence of the volumetric ratio on the deformability was slight. The modulus of rigidity of fresh concrete was rather influential with respect to the occurrence of blockade. Another factor influencing deformability may be the change in properties of mortar. However, it was not studied in this experiment.

4. APPLICABILITY TO ACTUAL PIPELINES IN THE FIELD TEST

4.1 Objectives

The factors influencing the deformability of fresh concrete were determined through the experiments using the visualization model for fresh concrete. In the next stage, it is necessary to examine the applicability of those factors to actual fresh concrete in pipelines in the field. The field test was conducted by circulating a constant volume of fresh concrete through straight, tapered and bent pipes in a closed loop. In this test, the volumetric ratio(Vg/Vm) was constant during pumping. Thus, the change in mortar properties with elapsed time was the only parameter. If the findings of the laboratory test were valid, it was predicted that the blocking would occur in the bent pipe but not in the tapered pipe. This was because the blocking in the tapered pipe depended on the volumetric ratio(Vg/Vm), whereas the blocking in the bent pipe was caused by the increase in modulus of rigidity of fresh concrete, which was expected due to the change in properties of mortar with the lapse of time.

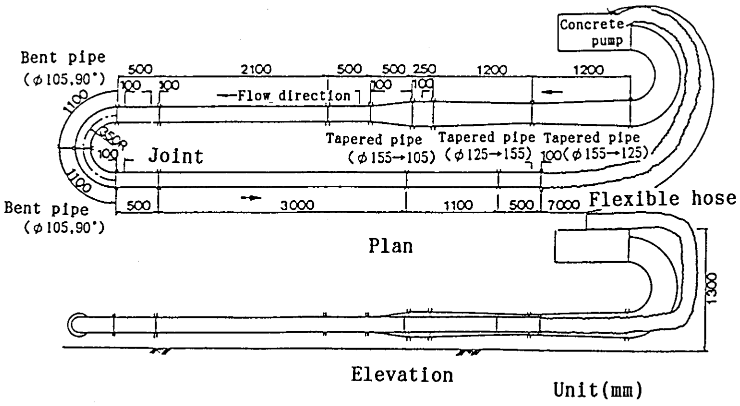

Fig.11 Overall view of pipeline

Table 2 Specifications of the concrete pump

Cylinder diameter(mm) * Stroke length(mm)		Delivery capacity (m^3/h)	Delivery pressure (N/cm^2)	Delivery length (m)			Hopper capacity (m^3)
				¢155mm	¢125mm	¢105mm	
¢205 *1400	Low pressure	10--110	Max.461	125* 740	105*520	73*310	0.45
	High pressure	10-- 78	Max.720	205*1160	180*800	140*480	

Delivery length: vertical length(m) * horizontal length(m)

Table 3 Material properties

Cement	Ordinary portland cement	Specific gravity:3.16
Fine Aggregate	Natural Sinano-gawa river sand	Specific gravity:2.60 Fineness modulus:2.66
Coarse Aggregate	Natural Sinano-gawa river gravel	Specific gravity:2.71 Fineness modulus:6.95

Maximum size of coarse aggregate is 25mm.

Table 4 Mix proportion of actual concrete

Slump (cm)	Air (%)	W/C (%)	S/C (%)	Vg/Vm (%)	s/a (%)	Unit weight(kgf/m^3)				
						W	C	S	G	AD
8.0±1	4.5±1	50.0	2.1	81.0	39.0	142	267	744	1241	2.7

Vg/Vm : Volumetric ratio of aggregate to mortar.
AD : AE-reducing admixture of lignosulphonate type and air-entraining agent.

4.2 Test Program

The overall view of the pipeline and the location of the concrete pump are shown in Fig.11. The total length of the pipeline was 19.5m and the horizontal equivalent length was 70.5m. The pump was a piston-type and the specifications of the concrete pump are shown in Table 2. The concrete used in this test was AE concrete. The materials and the mix proportions are indicated in Tables 3 and 4, respectively. Ready-mixed concrete was used and it was transported by a truck agitator and poured into the hopper of the concrete pump.

4.3 Testing Method

Concrete was circulated in a closed pipeline circuit at three different speeds, 10, 30, and 50m^3/h. The speed was chosen as an experimental parameter. At each speed, the number of piston strokes was held constant at 50 so as to make the total volume of concrete flowing in the pipeline equal in each case. Here, it was assumed that the increase in the concrete temperature through the pipe was identical because the volume of concrete flow was the same. Before and after the circulation of concrete, the slump, the air content and the concrete temperature were measured. This process was repeated until the blockade was generated.

Table 5 Test results of fresh concrete

Series Number	Measurement time (min.)	Slump(cm)		Air(%)		Conc.temp.(ºC)		State of pumping
		Pumping	Static	Pumping	Static	Pumping	Static	
1st	0.0	19.0	20.5	4.2	4.0	8.5	9.5	Stable
2nd	25.0	16.5	20.6	3.2	3.7	9.8	8.5	Stable
3rd	50.0	12.5	21.5	2.9	2.7	12.0	8.5	Stable
4th	75.0	8.0	18.0	1.9	3.1	13.7	8.3	Unstable
5th	100.0	4.5	19.0	1.5	1.9	15.5	7.5	Unstable

Measurement time is the elapsed time from the beginning of pumping.
'Static' represents the concrete which was stored in a bucket separately from the concrete for pumping.
Blockage occurred in the bent portion of the pipeline just after the sixth series had started.

4.4 Test Results and Discussion

Table 5 indicates the test results of slump, air content and concrete temperature. In the first series, the measured slump was about 20cm in spite of the fact that the specified slump was 8cm. The test was conducted in the middle of winter in Niigata Prefecture, in the northern part of Japan. It took more than one hour to transport the ready-mixed concrete to the test field. The outside temperature was much lower than the field room temperature(5.0 ºC).

It was also considered that the main cause of slump loss was the change in the mortar properties caused by friction between concrete and the wall of the pipe, because the mechanisms of slump loss during circulation and the increase in concrete temperature appeared to be relatively similar to each other. Furthermore, the slump and temperature of concrete under the static condition were constant throughout the series of tests. The decrease in air content before and after pumping was also reported by other researchers[14].

Judging from the change in the pressure gage of the pump and the movement of the piston, the states of pumping were stable in series 1 through 3, but were unstable in series 4 and 5. As soon as the sixth series started, the blockade occurred in the bent portion of the pipe and circulation was not possible any longer. The blocking process was different from that in the tapered pipe where it occurred abruptly due to the arching by coarse aggregate particles; instead, the concrete in the bent pipe became stiff as a whole. Also, it was confirmed that the blocking was not caused in the tapered pipe when the rest of the concrete was discharged.

Therefore, the deterioration of mortar properties was assumed to reduce the deformability of fresh concrete flowing in the bent pipe, resulting in the blockade. In contrast, in the tapered pipe, the blockade was not caused by the constant volumetric ratio(Vg/Vm) of the fresh concrete in the pipeline.

5. CONCLUSIONS

The objective of this research was to elucidate the required characteristics for fresh concrete flowing in deformed pipes.

The experimental study was conducted using a visualization technique which was developed by the authors. The deformability of model concrete was measured and evaluated by calculating the strain rate which was an index for the solidity of fresh concrete. Next, a field test was conducted so as to examine the applicability of the findings in the laboratory tests.

The following is concluded from this study.

(1)In the case of tapered pipe, near the outlet of the pipe, large compressive strain was observed in the direction from the wall to the center of the pipe, and tensile strain was parallel to the axis of the pipe. The larger the volumetric ratio of coarse aggregate to mortar (Vg/Vm), the greater were those strains.

(2)In the case of bent pipe, concrete in the inside of the curved portion flowed faster than that in the outside of the curved portion. Thus, large shear strain was generated. The shear strain rate was espesially large in the outside of the curved portion. This tendency was not influenced by either the viscosity of mortar or the volumetric ratio(Vg/Vm).

(3)In the tapered portion, collision, spinning and sliding of coarse aggregate particles occurred conspicuously because the distance among aggregates decreased due to the narrowing of pipe section. Therefore, it is imperative to reduce those actions and to restrain the internal stress of fresh concrete as much as possible. The main factor in this case was the volumetric ratio(Vg/Vm).

(4)In the bent portion, large shear deformation took place in the outside of the curved portion. Thus, it is indispensable that the resistance against shear deformation is controlled to be smaller than the maximum pressure supplied by the pump. The factor influencing the deformability was the change in mortar properties.

(5)In order to examine the applicability of the findings in the laboratory test, the field test was conducted by circulating a constant volume of fresh concrete through a pipeline containing tapered and bent portions. Since the blockade occurred only in the bent portion of the pipe, the slump loss of the fresh concrete must induce the blockade. Furthermore, the constant value of Vg/Vm ratio prevented any blockade in the tapered pipe. Hence, the findings on the deformability in this experimental study using the visualization technique could be applied to actual concrete.

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