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THE DEFORMATION OF FRESH CONCRETE PUMPED THROUGH PIPELINES

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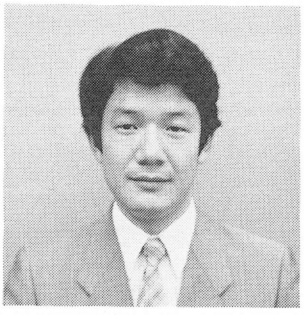

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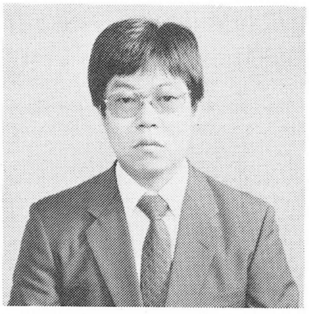

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SYNOPSIS

The mechanism of blockade of fresh concrete in pumping and the factors causing blockade are discussed. In the series of experiments, the blockade of concrete in the tapered pipe was artificially produced and analyzed using a separable pipe. From the experimental results, it is confirmed that the arching of coarse aggregates which results in the stiffening of concrete due to squeezing of segregated water in mortar primarily produces the blockade of concrete in pipe.

Accordingly the authors took the degree of segregation of coarse aggregates in pipe as "deformation" into account. And it is recognized that the particle-size distribution of coarse aggregates along the pipe is the practical index to estimate the deformation of fresh concrete.

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1. INTRODUCTION

In recent construction industry concrete pumping has been widely diffused and it has been very effective in shortening construction period and saving labors. Due to the diffusion of concrete pumping, researches for horizontally and vertically long distance pumping have been advanced. The method to plan concrete pumping is that a pump machine and pipelines and chosen according to the pumping capacity calculated from the pumping duty[1]. But the criteria to prevent the blockade of concrete is not clarified because of uncertainty of the mechanism of blockade of fresh concrete pumped through pipelines. Therefore for the purpose of preventing the blockade, the trend is to increase sand-aggregate ratio, unit weight of water and cement. These cause the increase of shrinkage and result in cracks, lack of durability and bad appearance. To prevent these unfavorable influences, it is required to establish how to estimate the concrete pumpability.

To estimate the concrete pumpability, it is necessary to evaluate the flowability, the deformation, and segregation resistance of pulsating flow. The flowability is the degree of concrete plug slipping near pipe wall and this criteria has been considerably established in recent researches [2,3]. The deformation is the degree of facility of relative movement between particles of concrete in a tapered pipe or a bent pipe and this has been little developed in spite of its important influence to the blockade of concrete. The segregation resistance of pulsating flow is the maintenance of the flowability and the deformation of pumped concrete subjected to pulsating flow in which pressure and speed change regularly and this also been little developed.

There are two theories about the mechanism of blockade of concrete in pumping. One is that segregation of water or cement paste makes a layer with high density of aggregates and high resistance zone exceeding the pump capacity and then blockade occurs[2]. The other one is that firstly coarse aggregates, secondly fine aggregates, and thirdly cement compose the arching and finally water segregation occurs and then blockade is completed[4]. But there exist few experiments to support these theories. Therefore the mechanism of blockade and the factors causing blockade are discussed in this research using the indices of the deformation of fresh concrete in pumping.

2. CONCRETE PUMPING EXPERIMENT

2.1 Apparatus

The apparatus for the concrete pumping experiment is as shown in Fig.1. This apparatus consists of a hydraulic cylinder which operates a piston head of stroke 1 m. There connected a 1 m straight pipe of inner diameter 155 mm and the piston head moves through inside the straight pipe. At the top of this straight pipe there connected a tapered

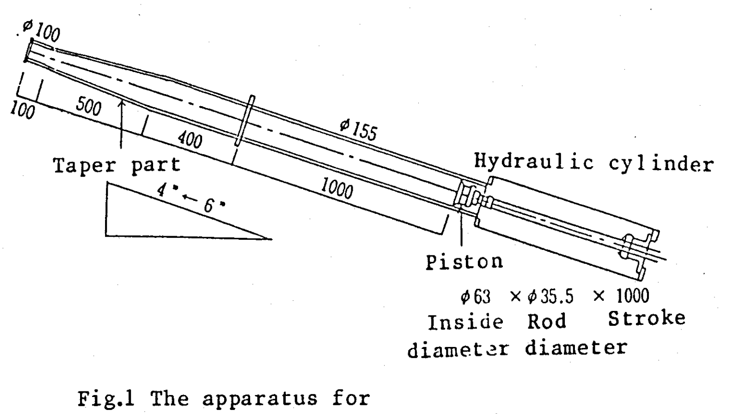

Fig.1 The apparatus for the concrete pumping experiment

pipe as shown in Fig.2. It has a 40 cm straight part of inner diameter 155 mm and a 50 cm tapered part of inner diameter 155 to 100 mm. This tapered pipe can be separated into two pieces to take out the undisturbed sample of the concrete at blockade area and the tapered angle is large enough for the occurence of the blockade. But it can be recognized that the concrete condition at blockade area is just the same as that occurs in a usually used tapered pipe.

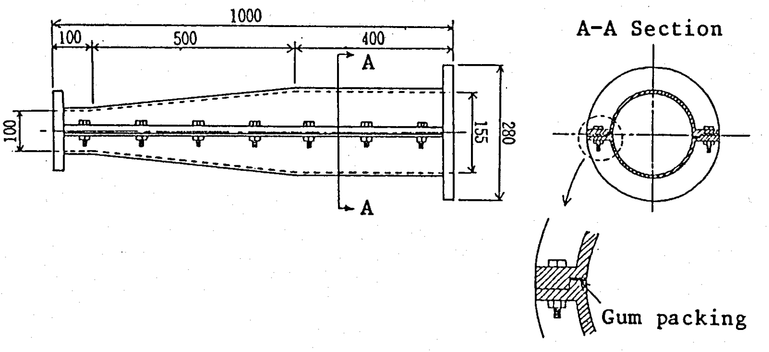

Fig.2 The tapered pipe (unit:mm)

2.2 Procedures

Concrete pumping experiment was performed according to the following procedures.

1)Set the piston head back and connect the 1 m straight pipe.
2)Put the concrete into the 1 m straight pipe using a stick with a disk of 9 cm diameter.
3)Set the tapered pipe and put the concrete into 40 cm straight part of the tapered pipe using the same stick.
4)Forward the piston head at a speed of 13 cm/s and send the concrete through the tapered pipe.

The blockade of concrete was confirmed by the following conditional criteria.

a)When the hydraulic pressure of the pump rises suddenly up to more than 150 kgf/cm^2. In pumping it is normally between 20 and 30 kgf/cm^2 but at the moment of blockade it rises suddenly up to more than 150 kgf/cm^2.
b)When the concrete in the pipe under the pressure (more than 150 kgf/cm^2) completely stopped moving and segregated water squeezed out from top of the pipe.

In this research three series of experiments were performed ; the first and second series for clarifying the mechanism of blockade of concrete and the factors causing blockade, and the third series for estimating the deformation of concrete in pumping. The summary of these three series of experiments are as follows.

Series 1 --- The objective of the first series is to recognize the real state of the blocked concrete. After confirming the blockade by the conditional criteria as mentioned above, the tapered pipe is separated into two pieces. Observation of concrete along the pipe, mix proportion analysis at each part of the pipe, screen analysis of coarse and fine aggregates at each part of the pipe, and analysis of the change of W/C along the pipe were performed. Three batches of fresh concrete were used for each mix; one for the observation and mix proportion analysis, one for the compressive strength test pieces at each part of the pipe, and one for the unit weight test at each part of the pipe. By measuring slump and air content for each batch, it was confirmed that the three batches of fresh concrete were in the same condition.

Series 2 --- The objective of the second series is to clarify the factors causing blockade. At the moment of condition a) mentioned above (namely "at the moment of blockade"), the piston was returned back for the pressure of concrete to be 0. The tapered pipe was separated into two pieces and observation of blocked concrete and analysis of the water-cement ratio W/C along the pipe were performed.

Series 3 --- The objective of the third series is to estimate the deformation of fresh concrete. Using concrete which causes no blockade (namely send under constant hydraulic pressure between 20 and 30 kgf/cm^2), the tapered pipe was separated into two pieces after pumping and the analysis of particle-size distribution of coarse aggregates along the pipe was performed.

Before the commencement of these series of experiments, the method on how to estimate the accurate mix proportion was examined. Water-cement ratio(W/C), sand-cement ratio(S/C), sand-aggregate ratio(s/a), and unit weight of concrete are necessary to calculate the mix proportion. The flow chart for the mix proportion analysis in this research is as shown in Fig.3. W/C and S/C are analyzed by back titration method [5] and s/a is determined by washing analysis. Unit weight of concrete is calculated by aerial- and submerged-weight of hardened concrete in the pipe after blockade. Analytical accuracy of this method is ± 2 % for W/C and ± 0.05 for S/C.

2.3 Materials and Mix proportion

Cement is normal Portland cement. Fine aggregate is Fuji-river sand and coarse aggregate is the mixed of Fuji- and Ohi-river gravel. Their physical characteristics are as shown in Table 1. Air entrained-water reducing agent as admixture and general service water is used. A tilting mixer is used and the mixing time is three minutes

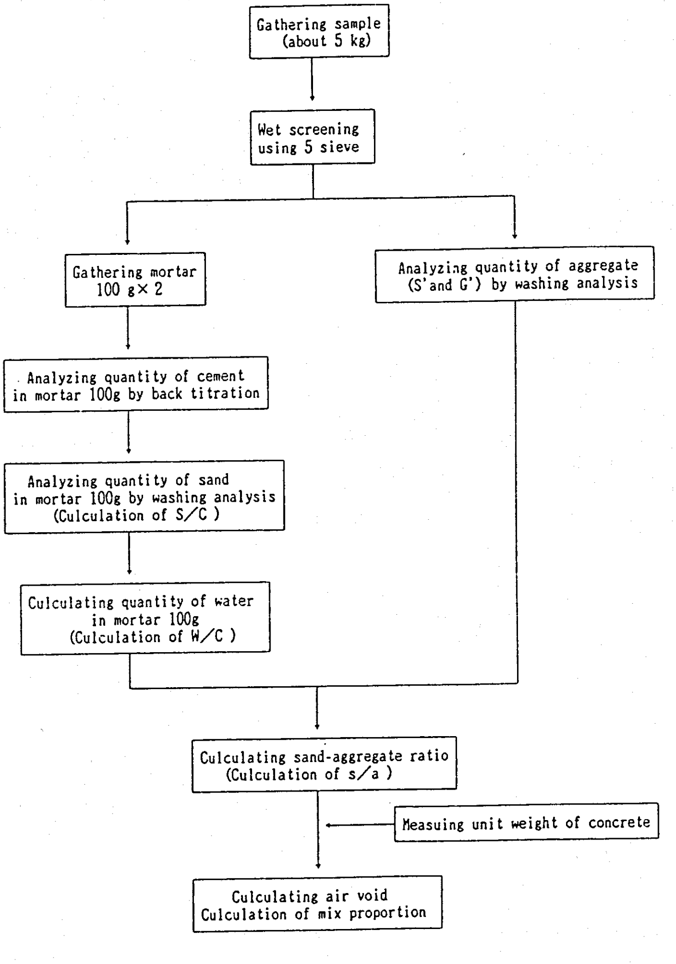

Fig.3 The flow chart for the mix proportion analysis

Table 1. Physical characteristics of cement and aggregate

Physical characteristics of cement

Specific gravity	Fineness (Blain) (cm²/g)	Setting time (hr-min)			Soundness	Flow (mm)	Strength (kgf/cm²)					
		Amount of water (%)	Initial	Final			Flexural			Compressive		
							3days	7days	28days	3days	7days	28days
3.15	3300	28.0	2-40	3-45	O.K.	250	36	52	70	148	247	420

Physical characteristics of fine aggregate

Kind	Specific gravity	Water absorption (%)	Granding (retaining % by weight)						Fineness modulus
			5.0mm	2.5	1.2	0.6	0.3	0.15	
Fuji river	2.62	2.08	0	7	38	63	82	97	2.87

Physical characteristics of coarse aggregate

Kind	Maximum size (mm)	Specific gravity	Water absorption (%)	Granding (retaining % by weight)						Fineness modulus
				25 mm	20	15	10	5	2.5	
Fuji river A	15~5	2.65	1.31	0	0	0	27	95	100	6.22
Ohi river B	25~10	2.65	0.64	0	20	54	100	100	100	7.20
Mix A:B =1:1	25~5	2.65	—	0	10	27	64	98	100	6.72

Table 2. Mix proportion

Mix No.	M.S. (mm)	Design slump (cm)	Design air (%)	W/C (%)	s/a (%)	Unit weight (kg/m³)			
						W	C	S	G
1	25	8 ± 1	4 ± 1	53.6	41	150	280	775	1127
2	25	—	4 ± 1	53.6	36	150	280	680	1223
3	25	—	4 ± 1	53.6	49	150	280	926	975
4	25	—	4 ± 1	98.2	43	167	170	833	1116
5	25	—	4 ± 1	53.6	36	165	308	685	1182
6	25	—	4 ± 1	70.0	44	150	214	855	1101
7	25	12 ± 1	4 ± 1	53.6	42	160	299	776	1084
8	25	—	4 ± 1	53.6	47	160	299	868	990
9	25	17 ± 1	4 ± 1	53.6	43	170	317	777	1041
10	25	—	4 ± 1	53.6	48	170	317	867	950
11	25	—	4 ± 1	53.6	53	170	317	957	859
12	25	—	4 ± 1	53.6	58	170	317	1048	767
13	25	—	4 ± 1	53.6	39	170	317	704	1114

after putting all materials into mixer. Mix proportions used in this research are as shown in Table 2. Slump of mix No.1 is 8 cm and W/C of it is 53.6 % and it causes no blockade. Mix No.2 and No.3 are that only s/a of mix No.1 is changed. The unit weight of cement is remarkably small, that is poor mix, in mix No.4 and No.6. The viscosity of mortar in concrete is very low in mix No.5 having low value of S/C. All of the mix from No.2 to No.6 cause blockade. Mix No.7 and No.9 have optimum s/a with unit weight of water 160 kg/m^3 and 170 kg/m^3 respectively. Optimum s/a is defined as that it makes consistency maximum as long as the concrete is workable. Mix No.8 is that only s/a of mix No.7 is changed and also mix No.10, No.11, No.12, and No.13 are that only s/a of mix No.9 is changed.

3. THE MECHANISM OF BLOCKADE

3.1 Objective

There are two theories about the mechanism of blockade of fresh concrete in pumping but there exist few experiments to support these theories. Thus, the authors tried to clarify the state of blocked concrete by Series 1 and to estimate the factors causing blockade by Series 2. The objective of this section is to investigate the mechanism of blockade from the results of Series 1 and Series 2.

3.2 The State of Blockade Concrete (Series 1)

Photo.1 shows the state of blocked concrete where cement paste around aggregates are washed out by the movement of segregated water (named "blockade area") and segregated water is conspicuous. Between these areas there is a clear boundary (named "blockade boundary"). Moreover, in a case of blockade, when the pipe is separated into two pieces, it is observed that the completely segregated cement paste with high W/C has flowed out especially from blockade area and that only water adheres to pipe wall and especially very little water adheres to the pipe wall of blockade area. But mortar and/or cement paste adhere to the pipe wall in the case of mix No.1 which causes no blockade.

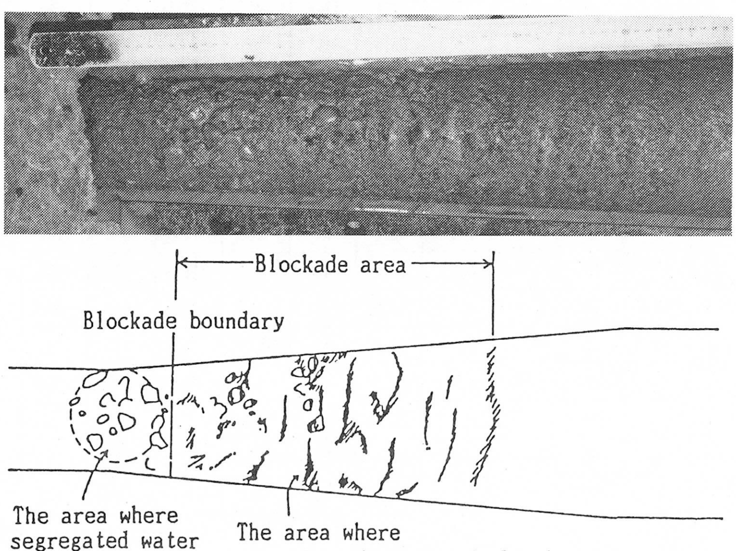

Photo.1. The state of blockade concrete

The results of mix proportion analysis of mix No.1, No.2, and No.4 are as shown in Fig.4. Each unit weight along the pipe is almost constant in the case of mix No.1 which causes no blockade. On the other hand, in the case of mix No.2 and No.4 which cause blockade, there is a tendency that more coarse aggregates and less fine aggregates are recognized in blockade area and that the unit weight of water and cement along the pipe is less than that of mix proportion. It is considered that, as mentioned above, because of the segregation of cement paste, the unit weight of water and cement decreases. Mix No.3 and No.5 show the same tendency as mix No.2 and No.4.

Then the screen analysis of aggregates was performed for examining the particle-size distribution of coarse aggregates at the area where the mix proportion analysis was performed. From these results, the particle-size distribution of coarse aggregates are dispersive but that of fine aggregates are not dispersive for all mix proportions. Accordingly, it is considered that only coarse aggregates compose the arching during pumping and fine aggregates simply fill up the gaps between coarse aggregates. Particle-size of coarse aggregates which causes the arching was then examined. The distribution of coarse aggregates along the pipe for each particle-size are as shown in Fig.5. Vertical axis of Fig.5 is the percentage of the weight of coarse aggregates for each particle-size (G') to the unit weight of coarse aggregates (G). The distribution of coarse aggregates along the pipe for each particle-size is almost uniform in the case of mix No.1 which causes no blockade. On the other hand, there exist more coarse aggregates over 15 mm and less coarse aggregates under 15 mm at blockade area in the case of mix No.2 which causes blockade. Mix No.3 shows the same tendency. It is considered that coarse aggregates over 15 mm compose the arching in the case of mix No.2 and No.3. But in spite of the blockade in the case of mix No.4, the distribution of coarse aggregates along the pipe for each particle-size is very little dispersive and mix No.5 shows the same tendency. It is concluded that mortar and coarse aggregates do not form as one body and all particle-size of coarse aggregates compose the arching because mix No.4 is poor mix concrete and S/C of mix No.5 is very low and consequently the viscosity of mortar of both concrete is very low.

Finally, the irregularity of W/C along the pipe analyzed with back titration method was confirmed by the compressive strength test results. W/C and the compressive strength along the pipe of mix No.1, No.2, and No.4 are as shown in Fig.6. The

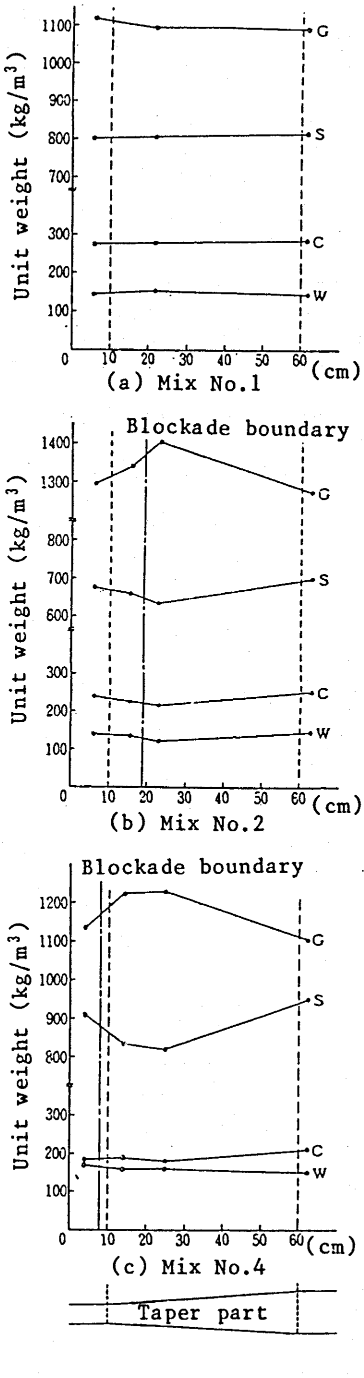

Fig.4. The results of mix proportion analysis

test pieces were made of concrete from the area where segregated water is conspicuous, from the blockade area, and from straight pipe area of inner diameter 155 mm. The size of each test piece is ϕ10x20 cm. The compressive strength tests were performed after standard curing age of 28 day. The value of W/C are almost uniform along the pipe in the case of mix No.1 which causes no blockade but not in the case of mix No.2 and No.4. Mix No.3 and No.5 show the same tendency as mix No.4. There are two patterns about the irregularity of W/C along the pipe; one is as shown in Fig.6(b), and the other is as shown in Fig.6(c). These two patterns are considered to be based on the difference of dewatering characteristics of each concrete. When the fresh concrete contains large size coarse aggregates or has a high unit weight value of coarse aggregates in the pressure bleeding test, it can not be dewatered sufficiently because of the arching effects of coarse aggregates[6]. Mix No.2 seems to be corresponding to this theory. In the case of mix No.2, the arching of coarse aggregates at blockade area is considered to obstruct the segregated water to go through the blockade area to the straight pipe with a inner diameter of 100 mm. Therefore W/C at the blockade area is the largest one along the pipe.

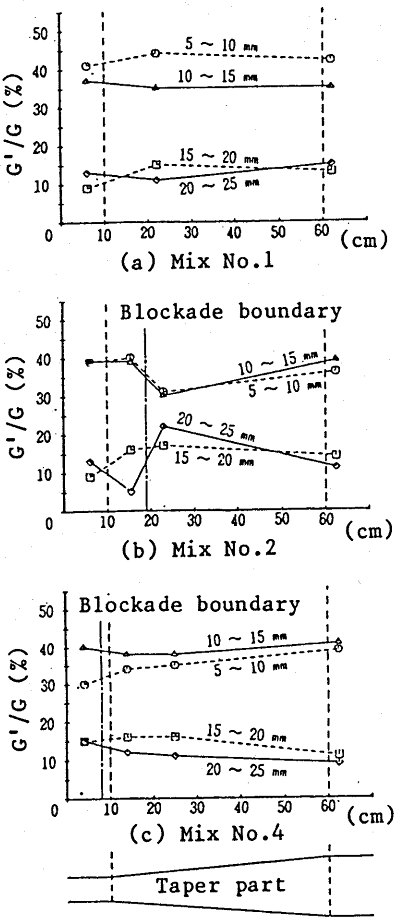

Fig.5 The distribution of coarse aggregates along the pipe

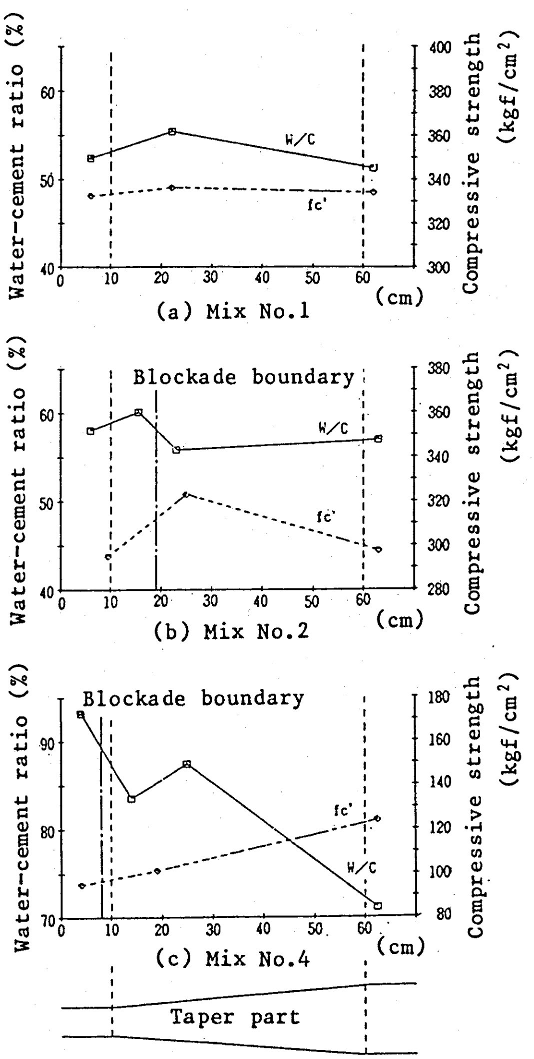

Fig.6 W/C and compressive strength along the pipe

3.3 The Factors Causing Blockade (Series 2)

When the pressure is lowered down to 0 at the moment of blockade, the blocked concrete is observed to be uniform as shown in Photo.2. Segregated cement paste doesn't flow out when the pipe is separated into two pieces and mortar or cement paste adheres to the pipe wall as in the case of mix No.1 which causes no blockade.

The irregularity of W/C along the pipe at the moment of the blockade was examined using the compressive strength at each area in the pipe. Because the blockade boundary was not clear, the test pieces were taken out corresponding to Series 1. Compressive strength tests were performed after standard curing age of 28 day. At the forward area from the blockade boundary, at the blockade area, and at the straight pipe area with inner diameter of 155 mm, the compressive strength was respectively 324, 320, and 312 kgf/cm^2 for mix No.3 and was respectively 168, 176, and 172 kgf/cm^2 for mix No.6. From these results it is considered that there is no irregularity of W/C along the pipe at the moment of the blockade.

At the moment of the blockade, as mentioned above, water or cement paste dose not segregate yet and the quality of mortar in the concrete along the pipe is considered to be uniform. Therefore it is concluded that the factor causing the blockade is the arching effect of the coarse aggregates and that water or cement paste segregate afterward.

3.4 The Mechanism of Blockade

From the results and the considerations in 3.2 and 3.3, the mechanism of blockade in the case of the occurrence of relative movement between each particles in the fresh concrete (for example in a tapered pipe) can be described as follows.

(1)First the arching of coarse aggregates starts forming and then the layer with high density of coarse aggregates is constituted. At this moment there is no difference of the quality of mortar in the concrete along the pipe (from the results of Series 2).
(2)Water or cement paste with high W/C passes though aggregates and flows out to the lower pressured area.
(3) Finally the blockade area with low W/C and high density of coarse aggregates is completed.

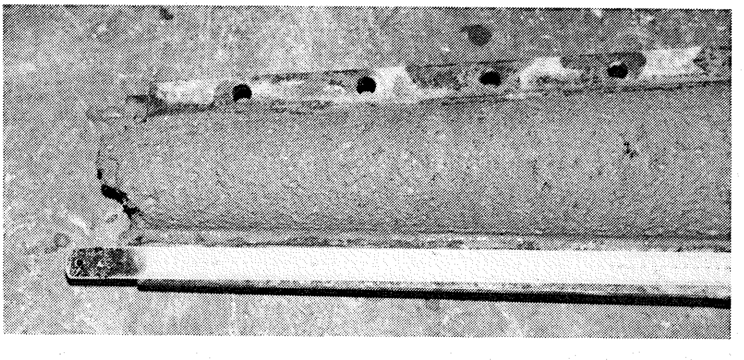

Photo.2 The concrete state at the moment of blockade

The mechanism of the arching of coarse aggregates can be described as following two items. One is that each particle flows against high friction and smooth relative movement is obstructed because of the lack of unit water part of which is absorbed by fine aggregates and cement and result in the increase of friction between aggregates. Subsequently the arching occurs. This is corresponding to mix No.3. The other is that some of the coarse aggregates are left behind because of lack of effective mortar to carry coarse aggregates and the arching occurs. This is corresponding to mix No.2, No.4, and No.5. In the case of mix No.4 and No.5 coarse aggregates and effective mortar do not form as one body because of the low viscosity of mortar in the concrete. This can be explained that because of too much water to reduce the friction between particles, the layer of water prevents coarse aggregates and effective mortar to form as one body. Then it can be concluded that the blockade begins in the state (1) and completes in the state (2) and secondarily water or cement paste segregates and that what particle-size of the coarse aggregates causes the arching depend on the viscosity of mortar in the fresh concrete.

4. THE DEFORMATION OF FRESH CONCRETE

4.1 Objective

Because the factor causing the blockade is the arching of coarse aggregates, it is expected that when the deformation of concrete is not superior, even if it can be sent by pump, the distribution of coarse aggregates along the pipe for each particle-size is not uniform. Thus objective of this section is to estimate the deformation of concrete using the degree of turbulence of the distribution of coarse aggregates(Series 3). The relationships between mix proportions used in Series 3 are as shown in Fig.8 corresponding to each mix No.

4.2 The Deformation of Fresh Concrete (Series 3)

The distribution of coarse aggregates along the pipe for each particle-size is as shown in Fig.7 (mix No.9, No.11, No.12, and No.13). In the case of mix No.9, the distribution of coarse aggregates is considerably irregular in spite of its optimum s/a. There is the same tendency in the case of mix No.10. The distribution of coarse aggregates is almost uniform in the case of mix No.11. In the case of mix No.12 the distribution of coarse aggregates is similar to that of mix No.2 shown in Fig.5(b) and this suggests that the potentiality of the blockade is very high. But in the case of mix No.13 the distribution of coarse aggregates is almost uniform as mix No.11. This is not because the deformation of concrete is very bad but coarse aggregates and effective mortar do not form as one body due to the low viscosity of mortar in the concrete as mix No.4 shown in Fig.5(c).

From the examination mentioned above and the results of mix No.1, No.7, and No.8, under this experimental conditions, the pumpable area for the concrete to be sent through this tapered pipe is as shown in Fig.8. The area in Fig.8 is separated into the following four areas.

(a)The area where the deformation of concrete is superior.
(b)The area of high potentiality of the blockade because it is located near the upper limit of pumpable curve.
(c)The area where the viscosity of mortar is low because of the low S/C of mortar in the concrete and therefore coarse aggregates and mortar do not form as one body.
(d)The area where s/a is smaller than that of the area(a) and the distribution of coarse aggregates along the pipe for each particle-size is not uniform.

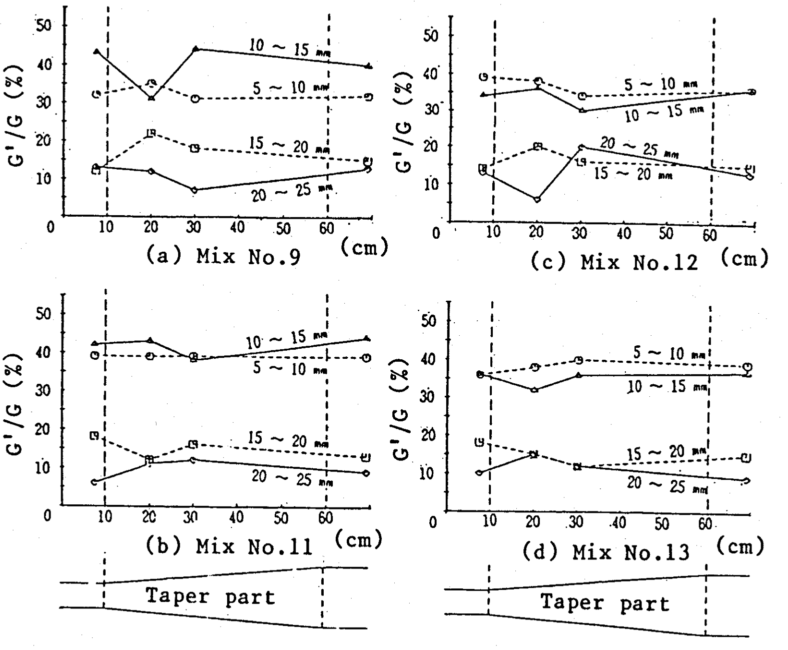

Fig.7 The distribution of coarse aggregate along the pipe

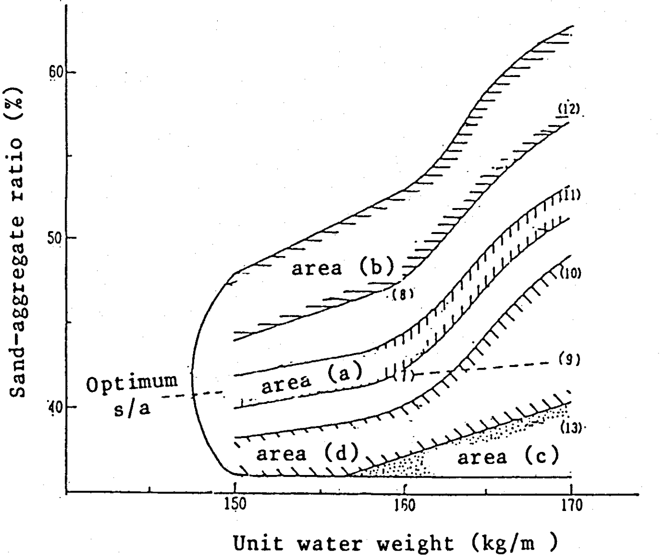

Fig.8 The deformation of fresh concrete

The pumpable limit curve in Fig.8 is decided by many experiments to determine the pumpability of concrete of various mix proportions.

From Fig.8 and under these experimental conditions, the deformation of concrete is superior what the sand-aggregate ratio s/a is almost optimum in the case that the unit weight of water is almost 150 - 160 kg/m^3, that is, the slump is about 8 - 13 cm. But s/a should be considerably higher than the optimum in the case that the unit weight of water is more than 160 kg/m^3, that is, the slump is more than 13 cm. This can be explained as follows. Yield value of concrete becomes generally lower and shearing deformation of concrete becomes better as the unit weight of water increases. But in the case that the shearing deformation is so good, the fresh concrete is considered to segregate during its pumping. In these experiments the limit of the unit weight of water is around 160 kg/m^3 to prevent such segregation. Consequently more higher value of s/a than the optimum is necessary to keep the deformation of concrete superior when the unit weight of water is more than 160 kg/m^3.

Concrete pumpability becomes bad suddenly in the case that the unit weight of water is less than 150 kg/m^3, that is, the slump is less than 8 cm. This value is considered to be the minimum unit weight of water which causes no blockade under these experimental conditions. To clarify this cause, more detailed researches concerning the relationships between coarse aggregates and mortar are necessary.

5. CONCLUSIONS

In this research the mechanism of blockade and the factors causing the blockade are clarified on the basis of the deformation of concrete in pumping which is most influential to the blockade. And the deformation of concrete is discussed using the factors causing the blockade. The conclusion in this research are as follows.

(1)By the results of analysis of concrete at the moment of blockade, the difference of the quality of mortar in the concrete along the pipe is not recognized. From this it is clarified that the factor causing blockade of concrete is not the segregation of water or cement paste but the arching of coarse aggregates. And by the results of analysis of the concrete which caused the blockade, the mechanism of the blockade in the case of causing relative movement between the particles in the concrete as in a tapered pipe is concluded as follows.

(a)Each coarse aggregates flock together gradually to result in the arching and the layer with a little high density of coarse aggregates is constituted.
(b)Water or cement paste with high W/C flows out by passing through coarse aggregates.
(c)The blockade area where W/C is small and the density of coarse aggregates is high is completed.

(2)Because the principal factor which causes the blockade of concrete is the arching of coarse aggregates, it is considered that an effective method to estimate the deformation of concrete is to examine the distribution of coarse aggregates along the pipe for each particle-size. By the results of this method and under these experimental conditions, the deformation of concrete is superior when s/a is almost optimum in the case that the slump is about the 8 - 13 cm. But s/a should be considerably higher than the optimum in the case that the slump is more than 13 cm because the shearing deformation of concrete in pumping is better than the upper limit of resistance of the segregation. The upper limit of resistance of the segregation is subjected to the viscosity of mortar in the concrete. If S/C of mortar in the concrete is about less than 2.3, even if W/C is 53.6%, the behavior of coarse aggregates and the mechanism of blockade is similar to those of poor mix concrete.

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