STUDY ON REDUCING UNIT POWDER CONTENT OF HIGH－FLUIDITY CONCRETE BY CONTROLLING POWDER PARTICLE SIZE DISTRIBUTION

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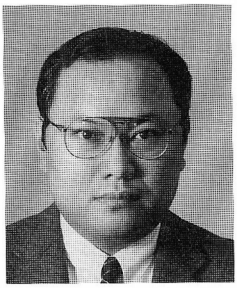
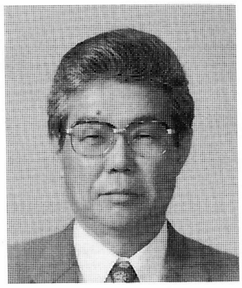

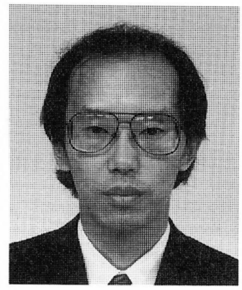

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This study aims to reduce the unit powder content of high-fluidity concrete by controlling the size distribution of the powder particles. The ranges of mortar viscosity and mortar yield value which satisfy the requirements for high fluidity, non-segregation, and ability to pass between bars are clarified. The physical characteristics of powder which reduce unit powder content were also clarified. Based on the results, a new cementitious powder which can produce high-fluidity concrete with low unit powder content is proposed.

Key words: *high fluidity, non-segregating property, ability to pass between bars, Blaine fineness, distribution constant, yield value, viscosity, unit powder content*

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1. INTRODUCTION

High-fluidity concrete features both high fluidity and resistance to segregation. There are two main means of providing resistance to segregation: high powder volume and a viscosity-controlling admixture. The high powder type contains more than 600 kg/m^3 of powder, such as blast furnace slag and limestone powder, giving the resulting mortar high viscosity and good resistance to segregation. The admixture type contains water-soluble polymers such as acrylics and cellulose polymers to provide higher mortar viscosity. Yet increasing resistance to segregation by these two methods may lead to problems. With the high powder type, These problems are increased drying shrinkage due to the higher powder content [1], autogenous shrinkage due to hardening [2], and increased heat of hydration [2]. With the viscosity-controlling admixture, the comparatively greater volume of water and powder required, higher cost, and issues of compatibility with other admixtures [3] are problematic.

The goal of this study was to produce high-fluidity concrete by improving powder quality rather than increasing the powder content above that used in conventional concrete ($\leqq$ 400 kg/m^3) or using a viscosity-controlling admixture. In the past, many studies have investigated increasing concrete fluidity by improving powder quality--such as through rounding of cement particles [4], improving grading [5], and reducing the amount of C3A +C4A F [6]. These methods, however, were aimed at reducing the yield value rather than increasing viscosity as required to produce high-fluidity concrete. This study aimed at reducing the yield value while also increasing the viscosity of mortar by controlling the powder grading distribution and at reducing the unit powder and water content of high-fluidity concrete.

2. STUDY PROCEDURE

Figure 1 shows a flow chart of the study procedure. The goal was to find a powder which would meet all the requirements of high-fluidity concrete, including good fluidity, resistance to segregation, and ability to pass between bars, as well as have a unit powder content of 400 kg/m^3 or under.

High-fluidity concrete was treared as a two-phase model comprising coarse aggregate and mortar. Experiments were carried out to determine the correlation between mortar yield value and viscosity and concrete fluidity, segregation resistance, and the ability to pass between bars. Based on the results, the ranges of mortar yield value and viscosity meeting all requirements were determined. The minimum powder content required to meet mortar yield value and viscosity range requirements was calculated for powders with varying Blaine fineness (BF) and n-value (NV) (calculated using Rosin-Rammler equation distribution constant (DC)). Using this procedure, the range of grading characteristic values which yield high-fluidity concrete with unit cement and water volumes of 370 kg/m^3 and 150 kg/m^3 was clarified. High-fluidity concrete was mixed with such cement, and its fluidity, segregation resistance, and ability to pass between bars were evaluated. This concrete satisfied all requirements, demonstrating it is possible to produce high-fluidity concrete having a powder content similar to that of conventional concrete and containing no viscosity-controlling admixture.

Target	Proportion	Unit powder content:	≦ 400 kg/m^3
	Performance	Slump flow: Segregation index (SI value): Height difference for test of ability to pass between bars:	≧ 500 mm ≦ 5% ≦ 20 cm

Model	Consider high-fluidity concrete as two-phase model comprising coarse aggregate and mortar.

Study volume of coarse aggregate in concrete, yield value of mortar portion, and range of viscosity to meet performance requirements.

Study correlation between lower limit of unit powder content necessary to meet mortar yield value and viscosity requirements with powder grading characteristics

Evaluate performance of high-fluidity concrete using powder made on an experimental basis

Fig. 1. Study procedure

3. COARSE AGGREGATE CONTENT, YIELD VALUE, AND VISCOSITY RANGE OF MORTAR IN HIGH-FLUIDITY CONCRETE

3.1 Outline of experiment

High-fluidity concrete was treared as a two-phase model comprising coarse aggregate and mortar. The yield value and viscosity of the mortar were kept within six levels by varying the amount of viscosity-controlling admixture added. Each of these mortars was then mixed with three ratios of coarse aggregate, giving 18 types of concrete in all. Each was evaluated for fluidity, resistance to segregation, and ability to pass between bars. Based on the results, the yield value and viscosity range required of high-fluidity concrete was calculated.

a) Materials used

The materials used in the experiment are described below. Table 1 shows the chemical composition of the ordinary Portland cement; Fig. 2 shows the fine aggregate grading curve; and Fig. 3 the coarse aggregate grading curve.

Cement: ordinary Portland cement (OPC; BF=3,210 cm^2/g; specific gravity=3.15; DC=1.06)

Fine aggregate: crushed sand (specific gravity=2.60; FM=2.92; solid volume=66.2%)

Coarse aggregate: crushed stone (specific gravity=2.64; max. size=20 mm; solid volume=59.8%)

Superplasticizer: ß-naphthalene sulfonic acid salt (NSF)

Air-entraining (AE) agent : rosin acid salt based anionic surfactant

Viscosity-controlling admixture: acrylic-based water-soluble polymer

Table 1 Chemical composition of ordinary Portland cement (OPC) (%)

Ig.loss	Insol	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	MnO	f-CaO	Total
1.6	0.3	61.6	20.1	5.0	3.0	1.1	2.0	0.38	0.43	0.26	0.06	0.17	0.6	96.00

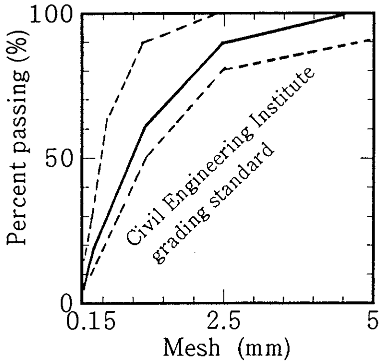

Fig. 2 Fine aggregate grading distribution curve

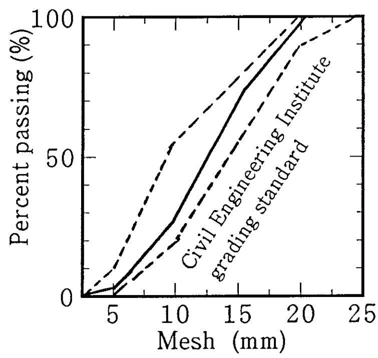

Fig. 3 Coarse aggregate grading distribution curve

b) Experimental conditions

Table 2 shows the composition of the mortar. This is the mortar portion of the standard proportions of high-fluidity concrete (unit powder content=450 kg/cm^2, unit water content=205 kg/cm^2). To this mortar, we added the viscosity-controlling admixture at six different levels ranging from 0 to 3.3% by weight of cement, 3% by weight of superplasticizer , and 0.03% of air-entraining agent to control the amount of air in the concrete to 4% ±1%.

Table 2 Mortar proportions

Proportions by wt. (%)			Viscosity controlling admixture (% by wt. cement)	NSF added (%)	AE agent added (%)
Cement	Water	Fine aggregate			
28.0	12.7	59.3	0, 0.88, 1.32, 1.76, 2.20, 3.30	3.0	0.033

Figure 4 shows the yield value and viscosity of the six types of mortar as measured using a rotation viscosimeter. Both viscosity and yield value (η_{pl} and τ_f in the figure, respectively) increase linearly as the percentage of viscosity-controlling admixture (ρ in the figure) increases. Table 3 shows the mix proportions of these concretes.

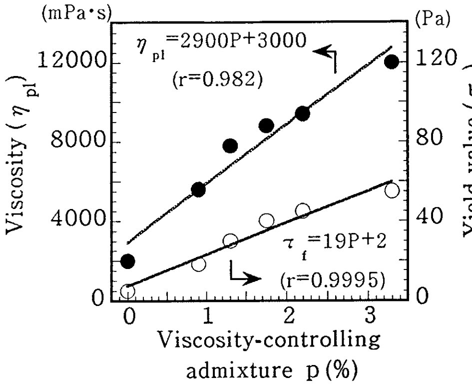

Fig. 4 Mortar yield value, viscosity

Table 3 Concrete proportioning conditions

No.	Coarse aggr. vol. (%)	S/a (%)	W/C (%)	Volume (kg/m^3)				Viscosity-controlling admixture (HF) (% by wt. cement)	NSF added (%)	AE agent added (%)
				Cement	Water	Coarse aggr.	Fine aggr.			
3-1	24.5	60.0	45.5	450	205	955	646	0, 0.88, 1.32, 1.76, 2.20, 3.30	3.0	0.033
3-2	29.5	53.8		420	191	892	778			
3-3	34.5	48.1		390	178	829	910			

c) Items evaluated

Fluidity

The slump flow, or diameter of the slump test base after release of the slump cone, was measured. This was used to evaluate the fluidity of the concrete. The concrete was evaluated as having high fluidity if the measured value exceeded 500 mm [2].

Resistance to segregation

The concrete was gently poured from a two-liter container over a five-millimeter mesh and left for five minutes. The amount of mortar passing through the screen was weighed and the segregation index (SI) calculated by the following formula [7]:

$$SI = \frac{\text{Wt. of mortar passing through screen}}{\text{Wt. of mortar in 2 liters of concrete}} \times 100\ (\%) \quad (1)$$

The mortar was evaluated as having adequate resistance to segregation when SI was ≦ 5% [8].

Ability to pass between bars

Concrete was poured into the left side of the container shown in Fig. 5 until it reached the top; the gate was opened and the concrete permitted to pass between the bars into the right side of the container until movement stopped the difference in concrete depth in the left and right sides of the container was measured. In this kind of test, the concrete behaves in one of two ways: either it passes between the bars or it clogs the space between the bars immediately after the gate opens. In this test, concrete with a final height difference of 20 cm or less was evaluated as having sufficient ability to pass between bars.

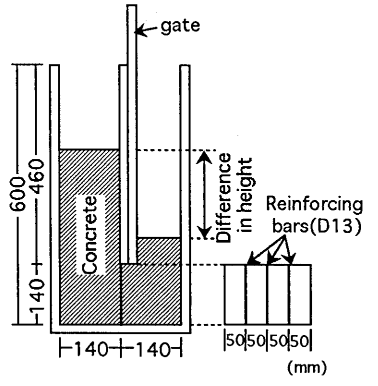

Fig. 5 Method of evaluating ability to pass between bars

3.2 Experimental results and determination of yield value and viscosity range

a) Fluidity evaluation results

The slump flow value was measured when the concrete stopped moving. It is considered to be determined by the concrete yield value [9]. When treating concrete as a two-phase material, the yield value is determined by the volume of coarse aggregate and the mortar yield value [10].

Figure 6 shows the relationship between concrete slump flow and mortar yield value for varians coarse aggregate volumes (X_V). It is clear that concrete slump flow and fluidity decrease as the mortar yield value and coarse aggregate volume increase. The concrete demonstrated high fluidity in the range where the maximum coarse aggregate volume was 34.5% and the mortar yield value was 50 Pa or less.

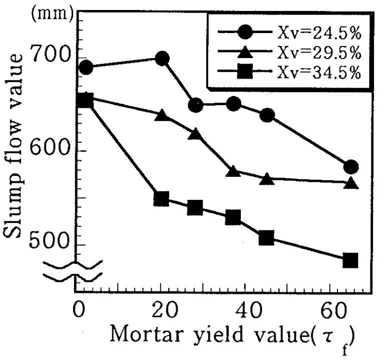

Fig. 6 Relationship between concrete slump value and mortar yield value

b) Segregation resistance result

Figure 7 shows the relationship between mortar yield value and the concrete's SI. For each mixture, SI decreases sharply as the mortar yield value increases (solid line in figure) and remains at around 0 when τ_f reaches a certain value (dotted line). SI decreases because the amount of mortar adhering to the coarse aggregate increases as τ_f increases. It is known from past studies that separation--such as sinking of the coarse aggregate--does not occur if SI is 5% or less [8]. Therefore, according to the figure, concrete demonstrates adequate resistance to segregation when the minimum coarse aggregate volume is 24.5% and the mortar yield value is in the range 20 Pa or higher.

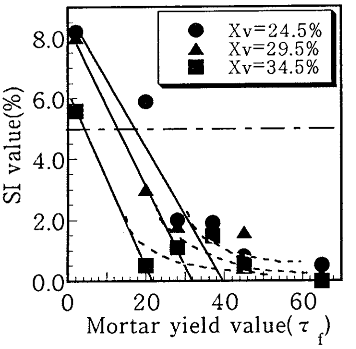

Fig. 7 Relationship between mortar yield value and concrete SI value

c) Ability to pass between bars

Factors affecting concrete's ability to pass between bars may include the bar clearance, the coarse aggregate volume (X_V), the maximum size of coarse aggregate, and the mortar viscosity [11]. In this study, we evaluated the percentage of coarse aggregate able to pass between bars under specific conditions: a net clearance between bars of 37 mm, a value adopted by several laboratories for such tests [12], and a maximum coarse aggregate size of 20 mm as generally used. Figure 8 shows the relationship between mortar viscosity and height difference. In this test, the concrete behaved in one of two ways: either most of the concrete passed between the steel bars to give a height difference of 10 cm or less, or it clogged the spaces between the bars and a height difference of 30 cm or more remained. Most concrete passed between the bars when the coarse aggregate volume was 24.5%, except when clogging occurred with the minimum viscosity. At 34.5%, the concrete clogged the bars under all conditions. Under the intermediate condition, 29.5% coarse aggregate , only concrete in the range of 7,000~9,000 mPa•s viscosity passed between the bars; it failed to pass between the bars when the viscosity was above or below this range.

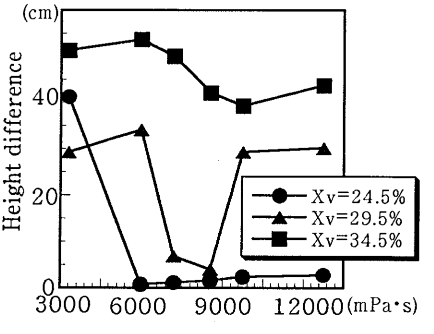

Fig. 8 Relationship between mortar viscosity and height difference

This clarifies that the range of mortar viscosities over which concrete will pass between the bars varies with the coarse aggregate volume. When the net clearance between the bars varies, the relationship between coarse aggregate volume and mortar viscosity required to provide passing ability is also thought to vary.
Given that the net clearance between bars of 37 mm used in this experiment is a very stringent condition, it should be possible to find conditions under which concrete passes between bars when the mortar viscosity is in the range 6,000~12,000 mPa•s; and since this mortar viscosity range equates approximately to the range of yield values (20~50 Pa) needed to meet the high-fluidity and passing ability requirements shown in Figure 4, we decided to adopt this range of mortar viscosity for our study.
This discussion demonstrates that mortar with a yield value in the range 20~50 Pa satisfies the requirements for high fluidity and resistance to segregation for a coarse aggregate volume range of 24.5~34.5%. It also demonstrates that mortar with a viscosity in the range 6,000~12,000 mPa•s satisfies the requirement for ability to pass between the bars.

4. RELATIONSHIP BETWEEN MINIMUM UNIT POWDER CONTENT NEEDED TO MEET MORTAR REQUIREMENTS AND POWDER GRADING DISTRIBUTION

In this section, the powder grading characteristics required to achieve the mortar yield value and viscosity obtained in Section 3 with a unit powder content of 400 kg/cm^2 or less are studied.

4.1 Research method

Two characteristics were chosen to indicate the powder distribution conditions: BF and NV as calculated by the Rosin-Rammler equation. The grading distribution, as required to calculate NV, was obtained by dispersing the powder in ethanol (ethyl-alcohol) and illuminating it with a laser beam. Powders with various values of BF and NV were used, with and without the addition of a viscosity-controlling admixture, and it was ascertained whether mortar yield value and viscosity fell within the high-fluidity concrete (20~50 Pa and 6,000~12,000 mPa•s respectively); tests were then carried out for each level of unit powder content, as shown in Table 4. The minimum unit amount of powder was determined and required the minimun water content was also determined.

Table 4 Range of study

Unit powder content	Range of study							Remarks
	No viscosity-controlling admixture			Viscosity-controlling admixture				Constant unit coarse aggr.
	Unit water	Fine aggr.	NSF added	Unit water	Fine aggr.	NSF added	Viscosity-controlling admixture	
(kg/m^3)	(kg/m^3)	(kg/m^3)	(%)	(kg/m^3)	(kg/m^3)	(%)	(%)	(kg/m^3)
550	165~230	768~937	1.0~3.0	---	---	---	---	
500	150~230	809~1017	1.0~3.0	---	---	---	---	
450	150~230	850~1058	1.0~3.0	160~235	838~1032	2.0~3.0	1.0~3.0	
425	145~230	871~1092	1.0~3.0	155~235	858~1066	2.0~3.0	1.0~3.0	
400	140~220	918~1126	1.0~3.0	150~230	892~1100	2.0~3.0	1.0~3.0	739
375	135~220	938~1159	0.7~2.5	140~220	938~1146	1.0~2.5	1.0~2.5	
350	130~210	985~1193	0.7~2.5	135~215	972~1180	1.0~2.5	1.0~2.5	
325	125~200	1031~1226	0.7~2.0	130~210	1005~1214	1.0~2.0	1.0~2.5	

4.2 Outline of experiment

a) Materials used

The OPC used in Section 3 and limestone powder (specific gravity=2.70) were used for the experiment. The limestone was crushed to BF=2,200~10,000 cm^2/g using a ball mill. The limestone powder and OPC were mixed at a ratio of 1:1 by weight to make 51 types of powder with BF=3,500~7,500 cm^2/g and NV=0.7~1.1, as shown in Fig. 9. The viscosity-controlling admixture, superplasticizer, and fine aggregate were the same as used in Section 3 .

b) Experimental Conditions

Mortar proportioning was controlled by the mortar portion (powder, water, fine aggregate) to give a coarse aggregate volume in the concrete of 28.0%. In other words, we checked whether the ranges of yield value and viscosity specified in Section 3 were attainable by controlling the volume of water and superplasticizer added to powders of unit weight as shown in Table 4. The volume of fine aggregate was varied with the amount of water since the coarse aggregate content was set at 28.0% by volume. The percentage of viscosity-controlling admixture was also controlled in the tests where it was used.

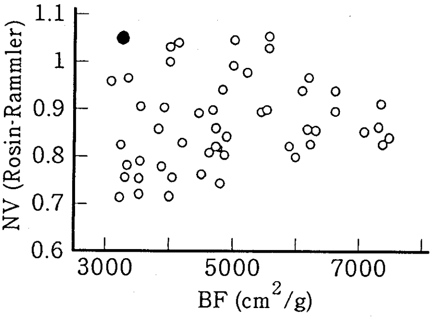

Fig. 9 BF and NV of powder
(black dot indicates BF and NV for OPC)

The reasons for setting the coarse aggregate volume at 28.0% are given below.

① At 28.0%, it is possible to satisfy all the requirements--for high fluidity, resistance to segregation, and ability to pass between the bars--by setting the yield value and viscosity of the mortar portion within the appropriate range.

② At the 29.5% level used in Section 3, there is only a very narrow range of viscosity over which the requirement for ability to pass between the bars is met, so we reduced the coarse aggregate volume slightly to 28.0%.

The mortar was mixed for two minutes using a 2-liter mixer. The mortar yield value and viscosity were then measured using a rotation viscosimeter.

4.3 Results

For the range of proportions shown in Table 4, the mortar yield value and viscosity without addition of a viscosity-controlling admixture were measured, and the minimum amount of powder necessary to satisfy the conditions (yield value=20~50 Pa and viscosity=6,000~12,000 mPa•s) were found; these amounts are shown in Fig. 10.

This experiment confirmed that it is possible to make high-fluidity concrete with a unit powder content of 370 kg/m^3 if BF=≦3,500 cm^2/g and NV calculated by the Rosin-Rammler equation is 0.8~0.9. Further, it is also possible to make high-fluidity concrete with a unit water volume of 150~162 kg/m^3 when BF is in the range 4,500~5,200 cm^2/g. The results when a viscosity-controlling admixture was added are shown in Fig. 11. These results confirmed that high-fluidity concrete can be made with a unit powder content of 350 kg/m^3 when BF= ≧ 3,500 cm^2/g and NV=0.8~0.9. The results showed that use of a viscosity-controlling admixture permitted a slightly greater reduction in unit powder content than when a viscosity controlling admixture was not used. Further, it is possible to use a unit water content of 150~162 kg/m^3 when BF=3,500~5,200 cm^2/g.

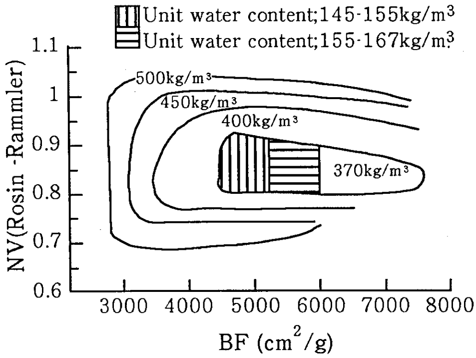

Fig. 10 Relationship of minimum powder content to BF and NV with no viscosity-controlling admixture

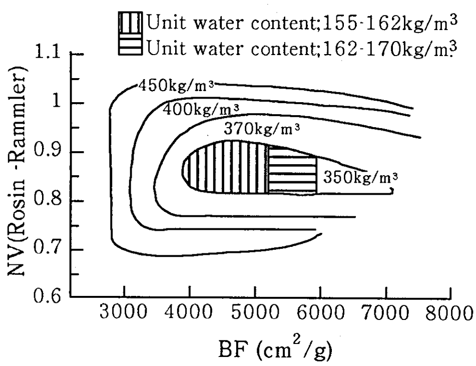

Fig. 11 Relationship of minimum powder content to BF and NV with viscosity-controlling admixture added

4.4 Conclusion

Based on this study, it is concluded that the unit powder content can be reduced by 25% or more compared with conventional mixes containing 500 kg/m^3 or more of powder if a powder with BF=4,500~5,200 cm^2/g and NV=0.8~0.9 is used; it is also possible to make high-fluidity concrete containing this powder without using a viscosity-controlling admixture.

5. EVALUATION OF CONCRETE PERFORMANCE

High-fluidity concrete was manufactured using powder with the grading distribution range studied above, thus reducing the unit water and powder contents, and its performance was evaluated.

5.1 Outline of experiment

a) Materials used

Concrete was manufactured using OPC and the following powders.

No. 1: Powder with BF=4,500~5,200 cm^2/g and NV=0.8~0.9, where the unit powder content and water volume are minimized.

No. 2: Powder with BF=5,200~6,000 cm^2/g and NV=0.8~0.9, where the unit powder content is minimized but the unit water volume is slightly above the minimum.

No. 3: Powder with BF=3,500~4,500 cm^2/g and NV=0.8~0.9, where the unit powder content and water volume are slightly above the minimum.

The grading distribution was controlled by using cements crushed in a ball mill to different BF values. The grading distribution of the OPC (No. 4) was not controlled. Table 5 shows the BF and NV values of these powders. The fine aggregate, coarse aggregate, and superplasticizer were the same as those used in Section 3.

b) Conditions

Concrete proportioning conditions are shown in Table 5. The coarse aggregate volume was 28%, as set in Section 4. The unit water volume and percentage of superplasticizer were determined on the basis of preliminary test results. Proportions of No. 4 are the same as No. 1 for the purposes of comparison. The unit water volumes appearing in this section are slightly higher than in Section 4 to offset any possible influence of early hydration resulting from the use in this section of 100% OPC.

Table 5 Powder grading distribution characteristics and concrete proportioning characteristics

Grade	Grading distribution characteristics		Concrete proportioning conditions				
			Unit weight (kg/m^3)				NSF
	BF	NV	Cement	Water	Fine	Coarse	added
No.	(cm^2/g)				aggregate	aggregate	(%)
1	4,720	0.88	370	159	1,105	739	2.3
2	5,680	0.89	370	165	1,090	739	2.3
3	3,630	0.88	400	174	1,041	739	2.5
4	3,210	1.06	370	159	1,105	739	2.3

c) Test items evaluated

The yield value and viscosity of the mortar portion were measured, and overall concrete performance was evaluated using the following tests (as described in Section 3): 1) Fluidity evaluation; 2) segregation resistance evaluation; 3) test to evaluate ability to pass between bars.

5.2 Test results

Table 6 shows the yield value and viscosity of each mortar, as well as the concrete slump value, SI, and difference in height as measured in the test to evaluate the ability to pass between bars. All mortars containing grading-controlled OPC met the yield value and viscosity requirements. Concrete made with these mortars exhibited a slump flow of 500 mm or over, an SI of 5% or less, and a difference height of 20 cm or less; thus the performance requirements for high-fluidity concrete were satisfied, even when unit powder amount was 400 kg/m^3 or less. In particular, even when No. 1 OPC with BF of 4,500~5,200 cm^2/g and NV of 0.8~0.9 was used, it was possible to make concrete meeting the requirements for high fluidity, resistance to segregation, and ability to pass between the bars with a unit powder content and water volume of 370 kg/m^3 and 159 kg/m^3, respectively. On the other hand, when using conventional OPC No. 4, none of the requirements were met. In this case, it is thought that if the percentage of superplasticizer added for higher fluidity is increased, SI would rise and significant segregation would occur.

Table 6 Mortar yield value and viscosity and results of concrete performance evaluation

Grade No.	Mortar characteristics		Concrete performance evaluation items		
	Yield value (Pa)	Viscosity (mPa•s)	High fluidity Slump flow (mm)	Resistance to segregation SI (%)	Ability to pass between bars Height difference (cm)
1	42	6,000	570	3.8	7.5
2	38	6,300	580	3.3	6.8
3	35	7,000	580	4.0	4.3
4	74	18,000	400	8.7	48.2

6. CONCLUSION

With the goal of making high-fluidity concrete using a unit powder amount similar to that in ordinary concrete (400 kg/cm^2 or less), a study of cement materials was carried out, in which the grading distribution was controlled to allow lower than conventional unit powder content and water volume. As a result of the study, the following information was gained:

1) It is possible to make high-fluidity concrete with a unit powder content and water volume of 370 kg/m^3 and 159 kg/m^3, respectively, using OPC with a grading distribution controlled such that BF=3,500~5,200 cm^2/g and NV=0.8~0.9.
2) In high-fluidity concrete, the ranges of mortar yield value and viscosity that meets all requirements for high fluidity, segregation resistance, and ability to pass between bars are from 20~50 Pa and 6,000~12,000 mPa·s, respectively.
3) BF and NV values which give mortar yield values and viscosities with in the range described in (2) above are as follows.
   a)No viscosity-controlling admixture added: BF=4,500~5,200 cm^2/g; NV=0.8~0.9.
   b) Viscosity-controlling admixture added: BF=3,500~5,200 cm^2/g; NV=0.8~0.9.

The use of a viscosity-controlling admixture reduces the required unit powder content slightly. This study was carried out using a single kind of fine aggregate, superplasticizer, and viscosity-controlling admixture. However, our past work indicates that the relationship between mortar viscosity and yield value varies according to the mineral composition of the cement, the major ingredient of the superplasticizer, and the type of admixture [14]. Therefore, if viscosity can be increased with no increase in yield value through the optimum application of these effects, it will be possible to further reduce the minimum necessary unit powder content and water volume. We plan to carry out further studies in this area.

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