

Fundamental Properties of Low-Viscosity Self-Compacting Concrete with a Superplasticizer Containing an Innovative Viscosity-Modifying Admixture

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ABSTRACT

A technology with which it is possible, without causing segregation, to economically upgrade ordinary concrete to self-compacting concrete that has superior fluidity with a high deformation velocity at low viscosity and superior self-compactability is proposed through the utilization of a newly developed superplasticizer containing an innovative viscosity-modifying admixture. The basic characteristics of this technology are evaluated using laboratory tests and full-scale tests. The results confirmed that while the low-viscosity self-compacting concrete using that superplasticizer has a low viscosity, it also has good segregation resistance and self-compactability, which are expected to lead to a reduction in labor and rationalized, more energy-efficient rapid construction. It was also found that the hardened properties of the concrete are almost identical to those of ordinary concrete having the same water-cement ratio.

Keywords. Viscosity-Modifying Admixture, Self-Compacting Concrete, Low Viscosity, Superplasticizer, Self-Compactability

INTRODUCTION

Self-compacting concrete not only improves the reliability of concrete structures from the perspective of quality and durability through superior self-compactability; it also significantly contributes to a reduction in labor and yields a rationalized, more energy-efficient construction, which in turn enables more rapid construction. In the drive for sustainable development, the role that self-compacting concrete should play in the construction industry is extremely important because of the need for further improvement in the durability of concrete structures and more energy-efficient construction as an environmentally friendly measure. However, there are problems with self-compacting concrete. These include the following: 1) self-compacting concrete costs more compared with ordinary concrete; 2) the use of mineral admixtures and viscosity modifying admixtures

is restricted by plant equipment; and 3) workability is reduced (for example, the pumping pressure is high because of the high viscosity, and finishing is difficult because there is little bleeding).

Therefore, the authors propose a technology with which it is possible to economically upgrade ordinary concrete to self-compacting concrete by utilizing a newly developed superplasticizer containing an innovative viscosity-modifying admixture and which does not cause the normal strength concrete to segregate. The resulting concrete will have: a) superior fluidity with a high deformation velocity at low viscosity and b) self-compactability. This self-compacting concrete using a superplasticizer containing a viscosity-modifying admixture has been adopted as the surfactant system of viscosity-agent-type self-compacting concrete in "Recommendations for Mix Design and Construction of Self-Compacting Concrete - 2012" by the Japan Society of Civil Engineers.

In this paper, the fundamental properties of low-viscosity self-compacting concrete with a superplasticizer containing an innovative viscosity-modifying admixture are discussed.

OUTLINE OF EXPERIMENT

Phase 1. Table 1 shows the materials used in the experiment. Table 2 shows the mix proportion and test items. An evaluation of the basic characteristics of the low-viscosity self-compacting concrete (SDC) using the new superplasticizer containing viscosity-modifying admixture (SP-SDC) was conducted alongside ordinary concrete (OC) with a slump of 21 cm and using conventional superplasticizer for comparison. Further, SP-SDC is a unique, newly developed viscosity-modifying admixture mixed with a polycarboxylic ether compound that is the main component of the superplasticizer.

Table 1. Materials

	Symbol	Kind	Physical properties and main components
Water	W	Tap water	-
Cement	C	Ordinarily portland cement (N)	Density: 3.16g/cm ³
		Portland blast-furnace slag cement type B (BB)	Density: 3.04g/cm ³
Mineral admixture	LP	Limestone powder	Density: 2.71g/cm ³
Fine aggregate	S	Land sand (Oi-gawa River system)	Density in saturated surface-dry condition: 2.59g/cm ³ , Fineness modulus: 2.70
Coarse aggregate	G	Crushed hard sand-stone from Ome	Density in saturated surface-dry condition: 2.66g/cm ³ , Maximum size: 20mm
Chemical admixture	SP	Superplasticizer	Polycarboxylic ether compound
	SP-SDC	Superplasticizer containing innovative viscosity-modifying admixture	Complex of polycarboxylic ether compound and viscosity-modifying polymer

Table 2. Mix proportion of concrete and test items

Kind of concrete	Symbol	Target slump / slump flow	Target air content (%)	Cement	W/C (%)	s/a (%)	Unit absolute volume of coarse aggregate (m ³ /m ³)	Unit water content (kg/m ³)	Chemical admixture
Ordinary concrete	OC	Slump 21cm	4.5	N	45.0 50.0 40.0	47.8 48.7 46.5	0.343	175	SP
				BB	45.0	47.4			
Low-viscosity self-compacting concrete	SDC	Slump flow 600mm	4.5	N	45.0 50.0 40.0	50.5 51.4 49.3	0.325		SP-SDC
				BB	45.0	50.2			

The mix proportion of SDC was based on the mix proportion of OC with the unit water content and unit cement content fixed for each water-cement ratio (W/C) and the unit absolute volume of coarse aggregate given as $0.325 \text{ m}^3/\text{m}^3$ to obtain self-compacting properties equivalent to Rank 2 that is defined in “Recommendations for Mix Design and Construction of Self-Compacting Concrete – 2012.”

The properties of the concrete were measured using the following methods:

- Slump: in accordance with JIS A 1101:2005;
- Slump flow: in accordance with JIS A 1150:2007;
- Flow time to total spread of 500 mm: in accordance with JSCE-F 516-2011;
- Air content: in accordance with JIS A 1128:2005;
- Bleeding: in accordance with JIS A 1123:2012;
- Time of setting: in accordance with JIS A 1147:2007;
- Compressive strength: in accordance with JIS A 1108:2006;
- Drying shrinkage (length change): in accordance with JIS A 1129-3:2010; and
- Freeze-thaw resistance: in accordance with JIS A 1148:2010 (method A).

Phase 2. The low-viscosity self-compacting concrete using the new superplasticizer containing viscosity-modifying admixture proposed by the authors is aimed at achieving self-compacting properties equivalent to Rank 2. In this study, the authors investigated the effect of different mix proportion conditions on the self-compacting properties. The materials employed are shown in Table 1 and the mix proportion and test items are shown in Table 3.

In Series 1, the study items were the water-cement ratio (W/C) and unit absolute volume of coarse aggregate. A study of the effect of different mix proportion conditions on the self-compacting properties of SDC was conducted. In Series 2, a study of the effect of variation in the percentage of surface moisture of fine aggregate (i.e., a change in the real unit water content) on the fluidity and self-compacting properties of SDC was conducted, and a comparison with conventional powder-type self-compacting concrete (SCC) was made.

The properties of the concrete were measured using the following methods:

- Slump: in accordance with JIS A 1101:2005;
- Air content: in accordance with JIS A 1128:2005;
- Flowability (funnel method): in accordance with JSCE-F 512-2011 (V_{75} funnel);
- Compactability: in accordance with JSCE-F 511-2011, obstacle R2, U-shape, Box-shape

Phase 3. The fresh concrete properties of SDC produced at a ready-mixed concrete plant in the city were evaluated. In addition, the self-compacting properties, segregation resistance and workability were evaluated using modeling forms that simulated real-scale structures. The materials used at the aforementioned ready-mixed concrete plant and shown in Table 4 were used. The mix proportion was based on ordinary concrete with a water-cement ratio

Table 3. Mix proportion of concrete and test items

Series	Kind of concrete	Symbol	Target slump flow	W/C (%)	Quantity of material per unit volume of concrete (kg/m^3)			Unit absolute volume of coarse aggregate V_g (m^3/m^3)	Chemical admixture	Setting error of percentage of surface moisture of fine aggregate (%)
					W	C	LP			
1	Low-viscosity self-compacting concrete	SDC	600mm	40.0 45.0 50.0	175	438 389 350		0.290, 0.320 0.350	SP-SDC	
2	Powder-type self-compacting concrete	SCC	600mm	45.0	170	378	172	0.320	SP	-1.0, -0.5 ± 0 +0.5, +1.0
	Low-viscosity self-compacting concrete	SDC		40.0 45.0 50.0	175	438 389 350			SP-SDC	

(W/C), unit water content, and unit cement content fixed, and the unit absolute volume of coarse aggregate given as $0.315 \text{ m}^3/\text{m}^3$ to ensure a self-compacting properties equivalent to Rank 2 (Table 5).

The concrete was mixed in two batches of 1.5 m^3 at the ready-mixed concrete plant in the city, producing a total of 3 m^3 . The concrete was then loaded onto a truck agitator with a 5 m^3 capacity and transported to the test site. The fresh concrete measurements were made immediately after the concrete was produced at the ready-mixed concrete plant (after 0 minutes) and after arrival at the test site (after 60 minutes).

A wall modeling form (Figure 1) was used in the evaluation of self-compactability. A concrete pump truck was used to place the concrete in the form and the compacting status of the concrete was verified. The OC was placed with vibration using an internal vibrator (vibration was applied 10 seconds after the start of concrete placement). The SDC was placed without vibration.

Table 4. Materials

	Symbol	Kind	Physical properties and main components
Cement	C	Ordinarily portland cement (N)	Density: $3.16\text{g}/\text{cm}^3$
Fine aggregate	S1	Land sand from Sagamihara	Density in saturated surface-dry condition: $2.60\text{g}/\text{cm}^3$, Fineness modulus: 3.10
	S2	Mountain sand from Ichihara	Density in saturated surface-dry condition: $2.58\text{g}/\text{cm}^3$, Fineness modulus: 1.69
Coarse aggregate	G	Crushed limestone from Chichibu	Density in saturated surface-dry condition: $2.70\text{g}/\text{cm}^3$, Maximum size: 20mm
Chemical admixture	SP	Superplasticizer	Polycarboxylic ether compound
	SP-SDC	Superplasticizer containing innovative viscosity-modifying admixture	Complex of polycarboxylic ether compound and viscosity-modifying polymer

Table 5. Mix proportion of concrete

Kind of concrete	Symbol	W/C (%)	s/a (%)	Unit absolute volume of coarse aggregate (m^3/m^3)	Quantity of material per unit volume of concrete (kg/m^3)					Chemical admixture	
					W	C	S1	S2	G	Kind	Dosage (%)
Ordinary concrete	OC	46.2	48.9	0.337	175	379	629	209	910	SP	0.80
Low-viscosity self-compacting concrete	SDC		52.3	0.315			673	223	851	SP-SDC	1.40

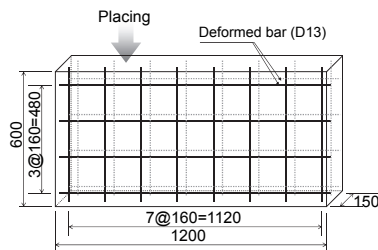


Figure 1. Wall modeling form

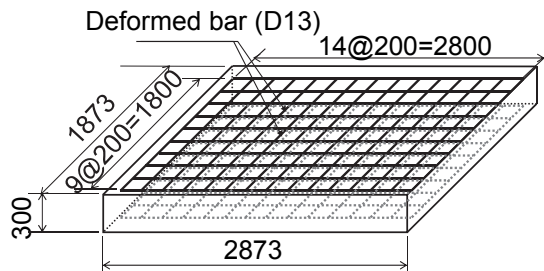


Figure 3. Slab modeling form

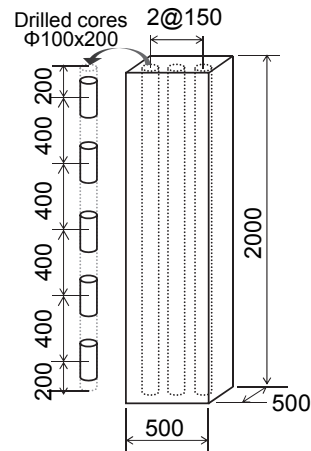


Figure 2. Pillar modeling form

The segregation resistance was evaluated using a pillar model (Figure 2). The concrete was placed in the upper level of the form using a concrete pump vehicle and was removed from the form at an age of 7 days, then air-cured outside. At a material age of 28 days, 3 cores of concrete (10 cm in diameter) were extracted vertically from the upper surface of the concrete and each core was cut height wise into 5 core test pieces. The core compressive strength and coarse aggregate area ratio were measured. The coarse aggregate area ratio was measured using image analysis of splits in the surface of the core test pieces.

The workability was evaluated using a slab modeling form (Figure 3). The concrete was placed in the form directly from the truck agitator and the operation times required to complete placement for OC and SDC were measured.

RESULTS AND DISCUSSION

Phase 1. The dosage of chemical admixture used to obtain the specified fluidity is shown in Figure 4. The symbol is expressed as “W/C - kind of cement” in the figure. The SDC mix proportion is made up of the same unit water content and unit cement content as the OC. The dosage of SP-SDC used was approximately 1.5 to 2 times more compared with SP by increasing the target fluidity from 21 cm slump to a slump flow of 600 mm. Figure 5 shows the flow time to total spread of 500 mm. Figure 5 also includes the measurement results for the conventional viscosity agent-type self-compacting concrete for which a test was implemented separately using the same mix proportion. The Flow time to total spread of 500 mm for SDC was 4.0 to 5.3 seconds, compared with 7.6 to 9.0 seconds for SCC. It was confirmed that the viscosity was low and the deformation velocity was high. The authors concluded that the pressure loss during pumping is reduced and construction can be executed more quickly. Moreover, a sufficient segregation resistance was observed when the spread of slump flow was visually monitored.

The measurement results for bleeding are shown in Figure 6. A high bleeding-inhibiting effect was not identified for SDC as it was observed for SCC, but because the bleeding

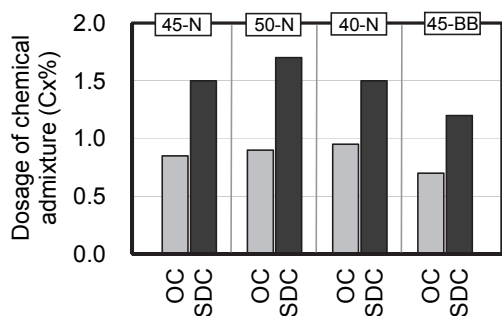


Figure 4. Dosage of chemical admixture

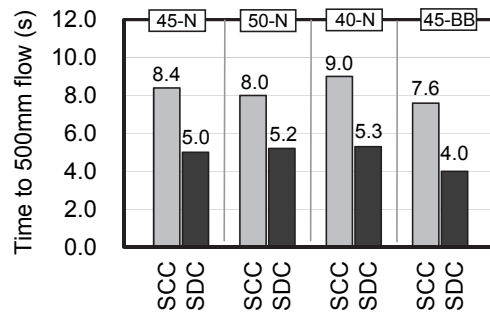


Figure 5. Flow time to total spread of 500 mm

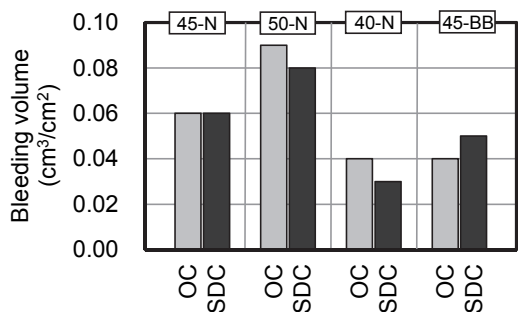


Figure 6. Bleeding volume

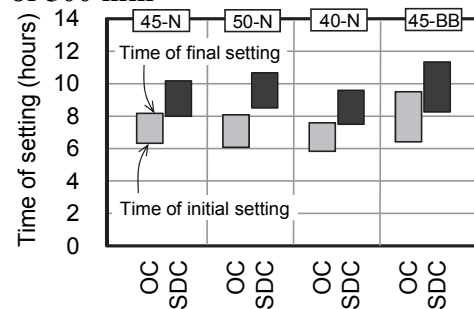


Figure 7. Time of setting

volume is almost the same as for OC, it is thought that the same finishability as that achieved with ordinary concrete can be guaranteed. Moreover, as shown in Figure 7, the time of setting tended to be approximately 90 to 120 minutes longer due to the dosage of admixture used being 1.5 to 2 times greater than the dosage used for OC.

The compressive strength results are shown in Figure 8. The compressive strength of SDC was almost identical to the compressive strength of OC irrespective of the mix proportion and material age. Furthermore, as shown in Figure 9 and Figure 10, SDC exhibited almost identical behaviour to OC with regards to rate of length change. The absolute value of shrinkage strain was less than 800×10^{-6} . The evaluation results for resistance to freezing and thawing are shown in Figure 11. A high freeze-thaw resistance was obtained for all mixes by incorporating an air content of approximately 4.5%.

Phase 2. The dosage of admixture (SP-SDC) used to obtain the specified fluidity is shown in Figure 12. The dosage used tends to increase gradually in accordance with an increase in W/C. With the W/C of 45% at the center of the test items designated as the datum, the dosage used changed by approximately -3% at a W/C of 40% and by approximately +10% at a W/C of 50%, respectively. Further, the dosage of admixture used decreased with an increase in the unit absolute volume of coarse aggregate.

The relationship between unit absolute volume of coarse aggregate and the fill height in the compactability test at a W/C ratio of 45% is shown in Figure 13. The relationship between the W/C ratio and the fill height at each aggregate volume condition is shown from Figure 14 to Figure 16. The target aggregate volume for Rank 2 of self-compacting concrete using a viscosity agent is shown as 0.30 to 0.33 m^3/m^3 , but at 0.290 to 0.320 m^3/m^3 (which are smaller than the upper limit value) the fill height using a U-shaped container sufficiently meets at least the minimal required value of 300 mm. In contrast, when the aggregate volume is 0.350 m^3/m^3 , the self-compacting performance is reduced. Further, as Chikamatsu *et al*

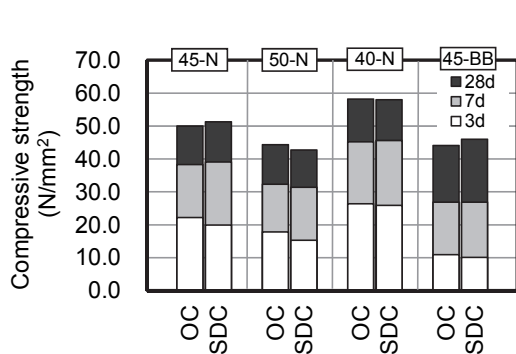


Figure 8. Compressive strength

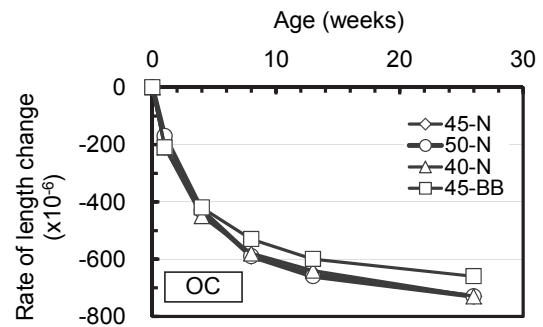


Figure 9. Rate of length change (OC)

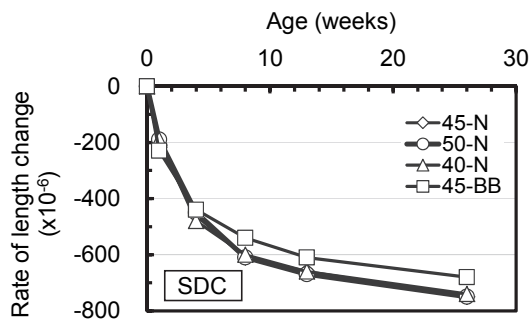


Figure 10. Rate of length change (SDC)

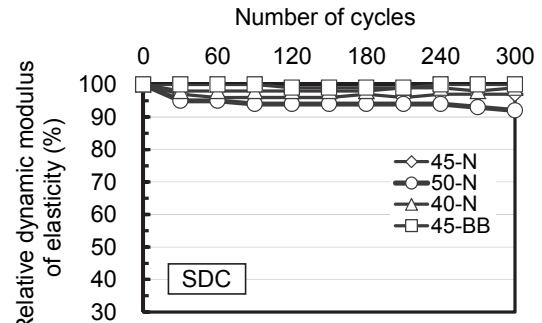


Figure 11. Relative dynamic modulus of elasticity

found, the evaluation of compacting performance using a Box-shaped container has a tendency to show inferior in comparison to a U-shaped container (Figure 17) and when the W/C ratio is 50%, in other words, when the unit cement content is small, even when the aggregate volume is 0.290 or 0.320 m³/m³, it tends to be impossible to obtain sufficient self-compacting performance.

Figure 18 shows the relationship between the setting error of percentage of surface moisture of fine aggregate and the slump flow. The slump flow for SDC increased by approximately 50mm at a change in the percentage of surface moisture of -1.0%, and decreased by approximately 100 mm at a change in the percentage of surface moisture of +1.0%, irrespective of the W/C. However, the increase and decrease is more restrained than for the

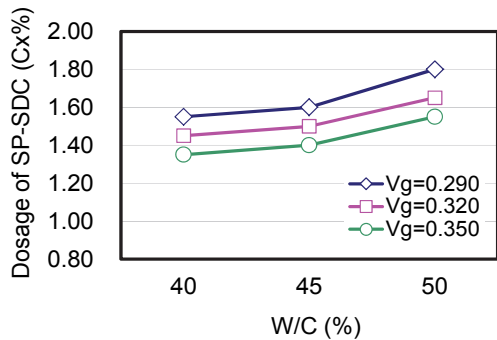


Figure 12. Relationship between W/C and dosage of SP-SDC

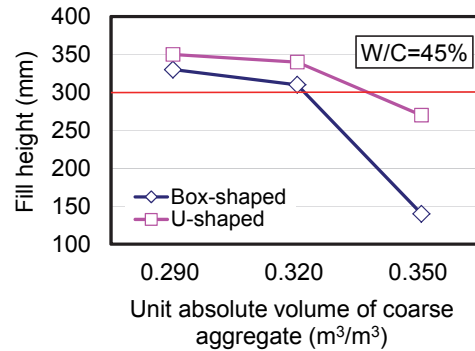


Figure 13. Relationship between unit absolute volume of coarse aggregate and fill height

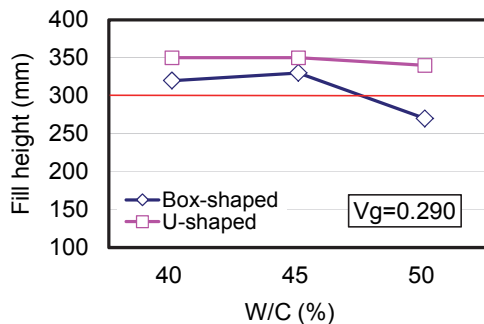


Figure 14. Relationship between W/C and fill height (Vg=0.290)

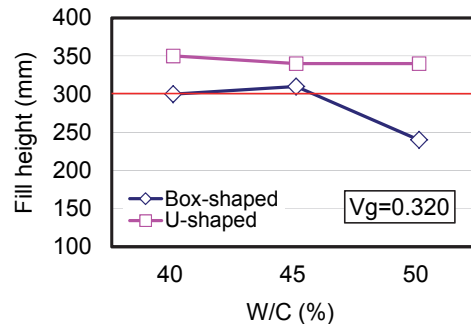


Figure 15. Relationship between W/C and fill height (Vg=0.320)

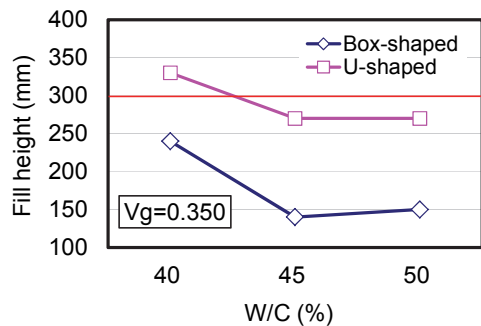


Figure 16. Relationship between W/C and fill height (Vg=0.350)

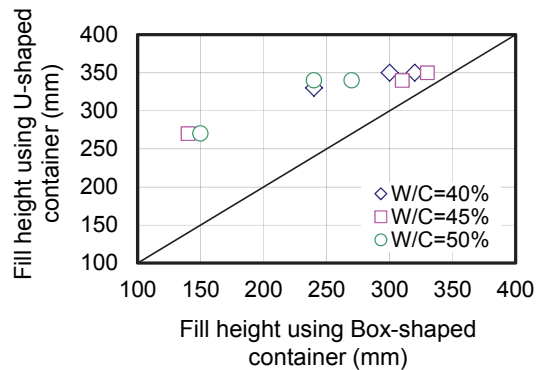


Figure 17. Relationship between fill height using Box-shaped container and U-shaped container

SCC implemented for comparative purposes. The authors identified that SDC is less susceptible to the effect of a change in the percentage of surface moisture. The relationship between setting error of percentage of surface moisture of fine aggregate and flow-through time of V_{75} -funnel is shown in Figure 19. The relationship between setting error of percentage of surface moisture of fine aggregate and fill height using Box-shaped container and U-shaped container is shown in Figure 20 and in Figure 21. At a W/C of 50%, the flow-through time of V_{75} -funnel and the fill height using Box-shaped container are susceptible to the effect of the change in the percentage of surface moisture and have a tendency to fluctuate easily, but at W/Cs of 45% and 40%, the variation was identified as being more restrained than the variation for SCC.

Phase 3. Table 6 shows the results of the measurement of the fresh concrete properties. For both Series 1 and Series 2, the slump flow retention is favorable for SDC. The time to a 500 mm flow is approximately 3 seconds, and the time to the end of the flow is approximately 25 seconds from immediately after mixing to 60 minutes after mixing. Low viscosity is obtained, as in the laboratory test, and segregation is not visually apparent.

The conditions when concrete is placed into a wall modeling form are shown in Figure 22. In the case of OC, before vibration the concrete in the bottom of the placement location was still until 10 seconds had passed and then after that the entire form was filled evenly with the

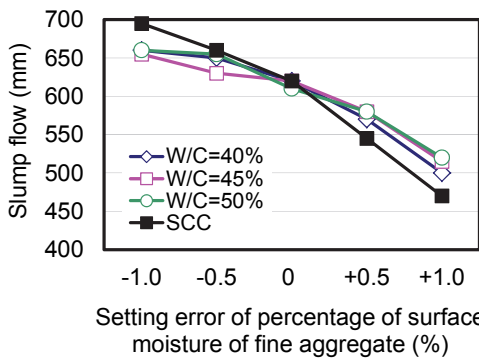


Figure 18. Relationship between setting error of percentage of surface moisture of fine aggregate and slump flow

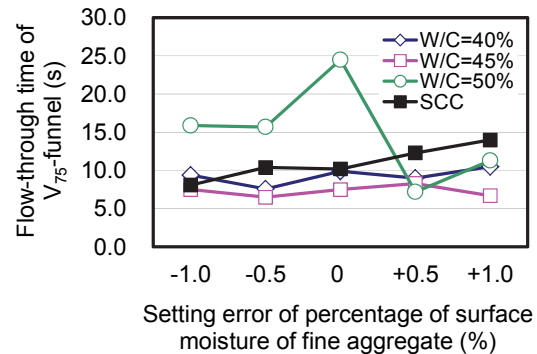


Figure 19. Relationship between setting error of percentage of surface moisture of fine aggregate and flow-through time of V_{75} -funnel

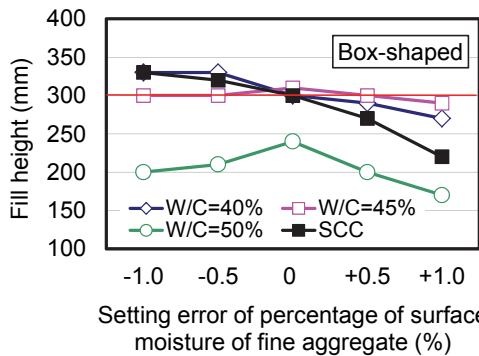


Figure 20. Relationship between setting error of percentage of surface moisture of fine aggregate and fill height using Box-shaped container

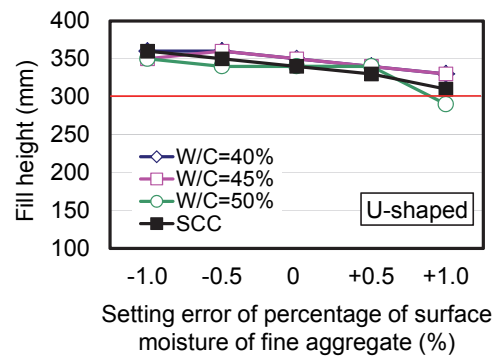


Figure 21. Relationship between setting error of percentage of surface moisture of fine aggregate and fill height using U-shaped container

concrete by vibration from the internal vibrator. On the other hand, SDC exhibited high self-compacting performance without vibration.

The compressive strength distribution for the core test pieces taken from the pillar is shown in Figure 23. The coarse aggregate distribution is shown in Figure 24 and in Figure 25. The compressive strength and distribution of coarse aggregate are the same for OC and SDC at all positions. Issues of coarse aggregate sedimentation and uneven distribution due to low viscosity were not identified. The conditions when concrete is placed into a slab modeling

Table 6. Test result of fresh concrete

Series	Kind of concrete	Elapsed time (min.)	Testing location	Slump (cm)	Slump flow (mm)	Time to 500mm flow (s)	Time to the end of the flow (s)	Air content (%)	Concrete temperature (°C)
1	OC	0	Plant	22.5	-	-	-	4.2	18.0
		60	Test site	21.0	-	-	-	4.6	18.0
	SDC	0	Plant	-	640	2.5	24.0	4.5	18.0
		60	Test site	-	610	3.0	24.7	4.8	18.0
2	OC	0	Plant	21.5	-	-	-	4.5	12.0
		60	Test site	22.0	-	-	-	4.8	13.5
	SDC	0	Plant	-	665	3.5	24.3	4.2	13.0
		60	Test site	-	680	3.7	25.7	4.5	13.5

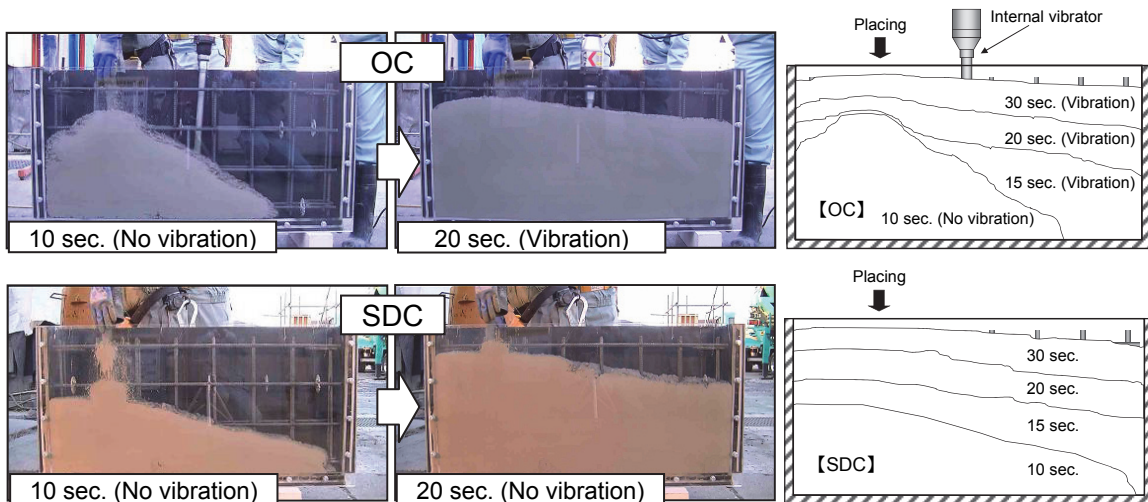


Figure 22. Filling situation in wall modeling form

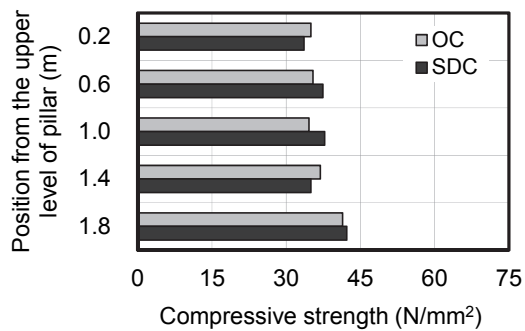


Figure 23. Distribution of compressive strength of pillar

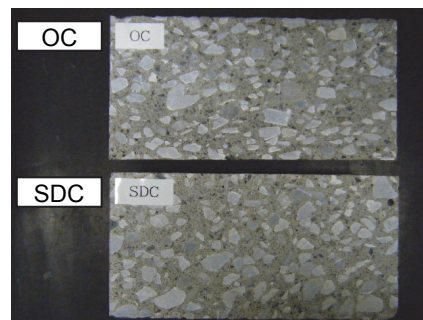


Figure 24. Distribution of coarse aggregate in drilled core

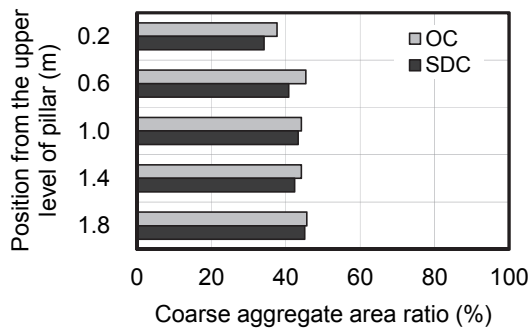


Figure 25. Distribution of coarse aggregate of pillar

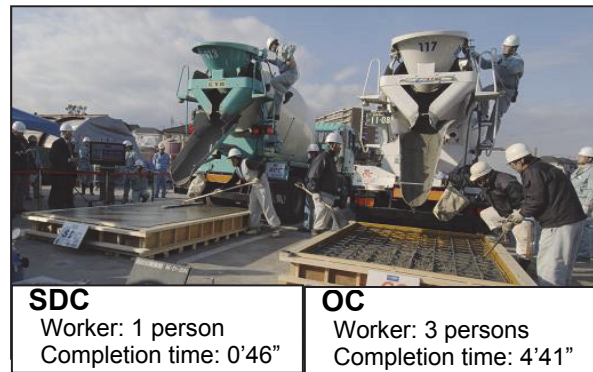


Figure 26. Placing situation to slab modeling form

form are shown in Figure 26. In comparison with OC for which 3 workers (2 workers for spreading and smoothing and 1 for operating the vibrator) and 4 minutes 41 seconds are required for placing the concrete, only 1 worker is required for spreading and smoothing the concrete; moreover, the operation is completed in 46 seconds with SDC and a superior workability is obtained compared with OC.

CONCLUSIONS

The basic properties of the low-viscosity self-compacting concrete (SDC) with a newly developed superplasticizer containing an innovative viscosity-modifying admixture were evaluated. The following conclusions are drawn within the limit of the present study.

- 1) While possessing low viscosity, SDC has sufficient segregation resistance. It is hoped that this concrete will have improved placeability, and that its hardened properties will be almost the same as those of ordinary concrete having the same water-cement ratio.
- 2) By selecting the appropriate mix proportion, SDC self-compacting properties corresponding to those of Rank 2 can be obtained.
- 3) It was confirmed that compared with powder-type self-compacting concrete, SDC is less affected by variation in the proportion of surface moisture on the fine aggregate.
- 4) The evaluation of SDC's fillability using a wall modelling form revealed that SDC has good fillability in the absence of vibration. The evaluation of SDC's segregation resistance using a pillar form test piece indicated that SDC has a segregation resistance equivalent to that of ordinary concrete (OC). The evaluation of SDC's placeability using a slab modelling form revealed that SDC has good placeability.

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