SELF-COMPACTING EVALUATION OF SELF-COMPACTING CONCRETE BY INSPECTING ALL CONCRETE PLACED FOR LNG UNDERGROUND STORAGE TANK

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Self-compacting concrete (SCC) was adopted for the lower sidewall of an LNG underground storage tank at the TOKYO GAS Ohgisima terminal. Internal space was very limited because of the many embedded devices for prestressing and piles of reinforcing bars being assembled. It was important to use a concrete with extremely good compactibility characteristics. Compactibility was evaluated in mock-up tests. Using equipment for testing all concrete placed, quality control during actual placing was carried out with self-compactibility evaluated mainly in terms of ability to pass through constrictions. It was necessary for the test equipment to allow judgment of flowability and viscosity as well as constriction-passing performance. To obtain better determinations of flowability and viscosity, we experimented with various modifications to the test equipment. By testing all concrete being placed using the equipment, we were able to execute high-quality concrete for the sidewall.

Key Words: *self-compacting concrete, all available quantity inspection devices, barrier, constriction passing performance, flowability, viscosity*

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1. INTRODUCTION

In adopting high-flowable concrete with self-compactibility characteristics (self-compacting concrete: SCC) in the sidewall of an LNG underground storage tank, a mix proportion was specified that guaranteed the designated quality. Self-compactibility was verified by conducting placement tests using a mock-up. Self-compacting concrete requires no vibration compaction, so quality is determined at the time of manufacture. Consequently, concrete that fails to meet the specified standard must be excluded before placement. Using a test setup to inspect all concrete before placement was considered a possible means of achieving this. Test methods for self-compactibility evaluation(prototype) have so far been shown capable of judging constriction-passing performance where the obstructions are mainly reinforcing bars[1]. It has been recommended that the quality of SCC should be checked upon unloading, with the first three to five deliveries being checked and then once for every 50 m^3 of concrete [2]. For the sidewall of this LNG underground storage tank, a large quantity of concrete was to be placed per lift with raw material supplied simultaneously from six ready-mixed concrete plants. This would mean a very large number of tests. It was necessary to verify whether SCC flowability and viscosity could be determined for all concrete placed rather than by sample tests. To test feasibility, concrete was placed on a trial basis using a test rig. In order to determine SCC flowability and viscosity, it was necessary to temporarily control the dynamic force of concrete flowing into the test rig so that only the self-weight of the concrete acted on the measuring equipment [3]. An existing test rig with reinforcing bar obstructions for testing constriction – passing performance was modified to allow inspection of all concrete placed.

In the experiment, new obstacles were installed in the test rig to allow performance to be easily judged under the action of self-weight only. The location and size of these obstructions and the slump-flow were the experimental parameters. With appropriate location and sizing of obstacles, it was possible to detect concrete that had low flowability and high viscosity. By employing the modified test rig to continuously monitor quality during construction, the number of sample tests for quality control was reduced. As a result, good

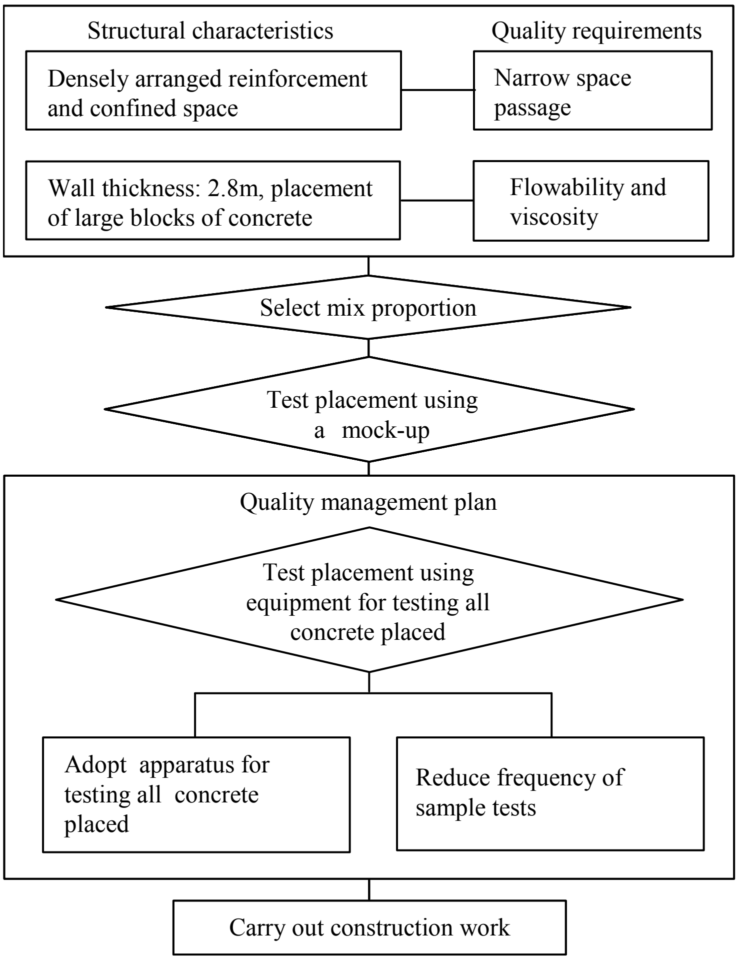


Fig.1 Flow of SCC placement steps

concrete was placed with reduced labor. A flow chart of the SCC placement procedure for the LNG underground storage tank is shown in Fig. 1.

2. OUTLINE OF LNG UNDERGROUND STORAGE TANK

The TL12 LNG underground storage tank at the Ohgishima Terminal of Tokyo Gas is a reinforced concrete cylindrical structure. It has an internal diameter of 70.8 m, a liquid depth of 51.0 m, and a capacity of 200,000 kl. The main structure consists of a concrete bottom slab, sidewall, and the roof.

The bottom slab has a design concrete strength of 24 N/mm^2, a thickness of 8.0 m, and a concrete volume of 36,120 m^3. The sidewall has a design concrete strength of 60 N/mm^2, a thickness of 2.8 m, and a concrete volume of 37,194 m^3. Of this volume, lifts 1 through 3 are of SCC for a volume of 7,355 m^3. Lifts 2 through 9 consisted of 150-mm-thick concrete segments as an embedded formwork. This is the first LNG underground storage tank with a bottom slab rigidly connected to the sidewall. Prestressing steel amounting to 199 tons was used in lifts 1 through 3 for the part of the sidewall rigidly connected to the bottom slab. In lift 1, where the connection was made to the bottom slab, shear was expected to be severe, so a large number of reinforcing bars were used and the slab was haunched. Workers were unable to enter the placement area because of the resulting reinforcement arrangement. In view of this, SCC was deemed necessary for lifts 1 through 3. The first lift was 2.0 m, while the second and third lifts were 4.0 m each. Figure2 gives an outline of the tank.

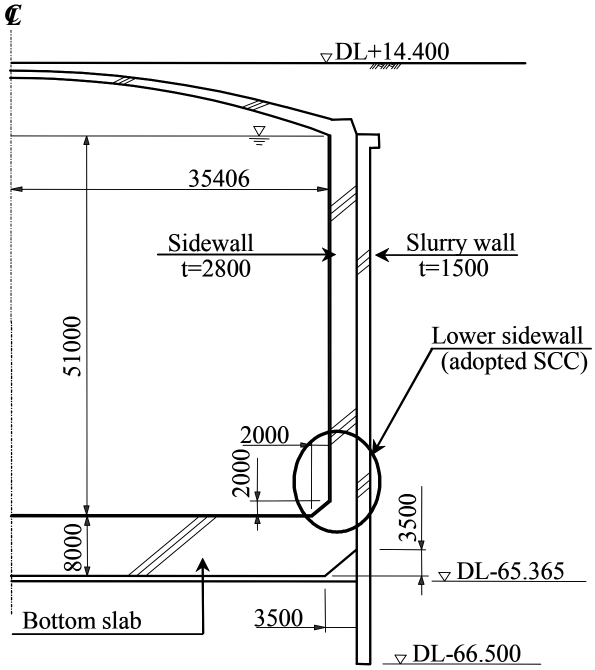


Fig.2 LNG underground storage tank

3. CONCRETE QUALITY

3.1 Quality requirements

In placing concrete, a smaller number of lifts is desirable for economical reasons, because fewer structural joints are required and the number of steps is reduced. However, structural limitations and work efficiency limit the amount of concrete that can be placed in one lift, so multiple lifts are employed. In this case, the sidewall concrete was placed in nine lifts based on a construction plan. In lifts 1 through 3, double rows of D51 reinforcing bars were arranged as the main reinforcement near the inside and outside surfaces of the wall (Fig.3). The reinforcing bars overlapped at lift joints. To ensure concrete placement in such a confined space, SCC was adopted. A self-compactibility grade of 1[2] was specified as a requirement because the minimum reinforcement spacing was 78 mm and there was 400 kg/m^3 of reinforcing steel. Each lift (lifts 1-3) consisted of 1,900 to 2,700 m^3 of concrete. With only a confined work space available in the structure, self-compactibility was required. The structure was large, so large quantities of concrete were expected to be placed per lift. The target slump was set at 60 to 70 cm [2] to achieve first-grade self-compactibility. The target funnel flow time required to satisfy first-grade self-compactibility is said to be 9 to 20 seconds [2]. The target funnel flow at site was set at 9 to 15 seconds to prevent excessive viscosity and facilitate construction. The SCC quality requirements for the sidewall are listed in Table 1.

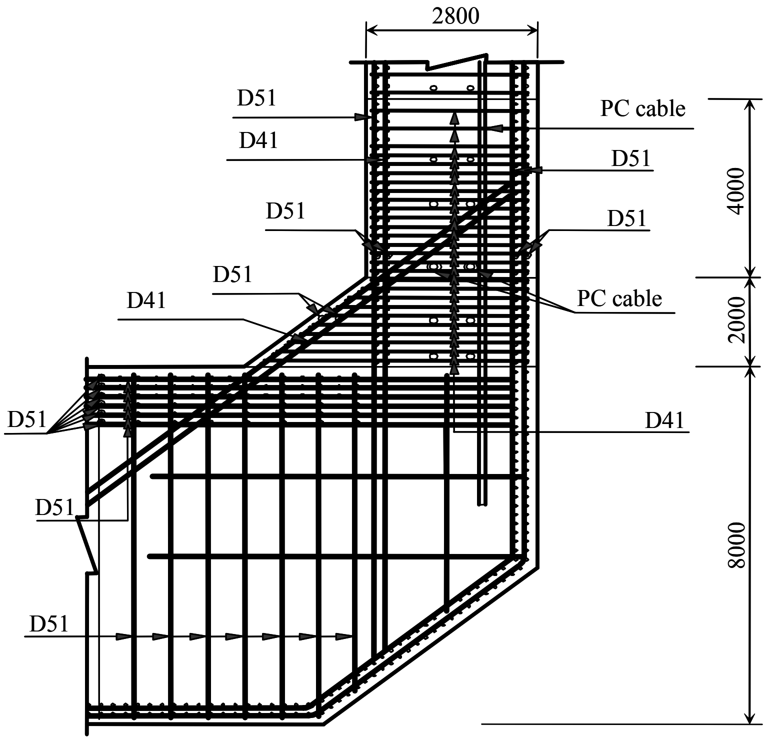


Fig.3 Reinforcement arrangement for lower sidewall

3.2 Concrete mix proportion

High-strength concrete with a design strength of 60 N/mm^2 was required for the sidewall. Powder-type high-flowability concrete was used. Low-heat portland cement with a density of 3.24g/cm^3 was premixed with fine calcareous powder with a Blaine specific surface area of approximately 7,000 cm^2/g as partial replacement for the cement to secure the designated quantity of fine particles. A polycarboxylic acid air-entraining and superplasticizing agent was employed as a chemical admixture. Mountain sand from Kimitsu City in Chiba Prefecture and crushed limestone with a maximum diameter of 20 mm (density: 2.70 g/cm^3; water absorption: 0.6%; fineness modulus: 6.70 at a typical plant) were used as the fine and coarse

Table 1 Mix design specification

Maximum size of coarse aggregate (mm)	Specified design strength (N/mm^2)	Filling height of U-type compaction test (cm)	Slump flow (cm)	Air content (%)	O-funnel time (sec)
20	60	≧30	65±5	4±1	9～15

aggregates, respectively.

Large quantity of concrete had to be placed at once, so supplies were obtained from six ready-mixed concrete plants at the same time. The water-cement ratio, unit quantity of water, and volume of coarse aggregate were set uniformly at all plants. Fine aggregate from the same source was used at all plants to ensure stable quality. The concrete materials and mix proportions are shown in Table 2 and 3, respectively.

4. TEST PLACEMENT USING MOCK−UP

4.1 Test outline

In order to verify the self-compactibility of the selected mix proportion, concrete was placed into a mock-up. Compaction was visually inspected through the transparent formwork, and samples were collected at various points and the coarse aggregate was washed for analysis to verify self-compactibility. The mock-up represented the first lift in the sidewall, where the reinforcing bars were most dense. Double rows of D51 reinforcing bars were arranged both vertically and horizontally, and there were also lap joints at some points.

Table 2 Properties of various materials

Classification	Material
Cement	Low heat Portland cement Density ρ:3.24, Blaine:3230cm^2/g
Admixture	Limestone powder Density ρ:2.70, Blaine:7280cm^2/g
Chemical admixture	Air entraining and superplasticizing agent: A poly carboxylic acid type
Fine aggregate	Mountain sand : Surface dry density ρ:2.60 g/cm^3 Water absorption:1.3%,F.M:2.66
Coarse aggregate	Crushed stone : Surface dry density ρ:2.70 g/cm^3 Water absorption:0.6%,F.M:6.70

※For fine and coarse aggregate, data obtained at a typical plant are listed.

Table 3 Mix proportion (Typical plant)

W/C (%)	W/P (%)	Volume of coarse aggregate in concrete (ℓ/m^3)	Unit quantity (kg/m^3)					Chemical admixture (P×%)
			W	C	Admixture (Limestone powder) LF	S	G	
38.0	94.1	300	160	421	108	858	810	1.3 ~ 1.7

※P = C + LF

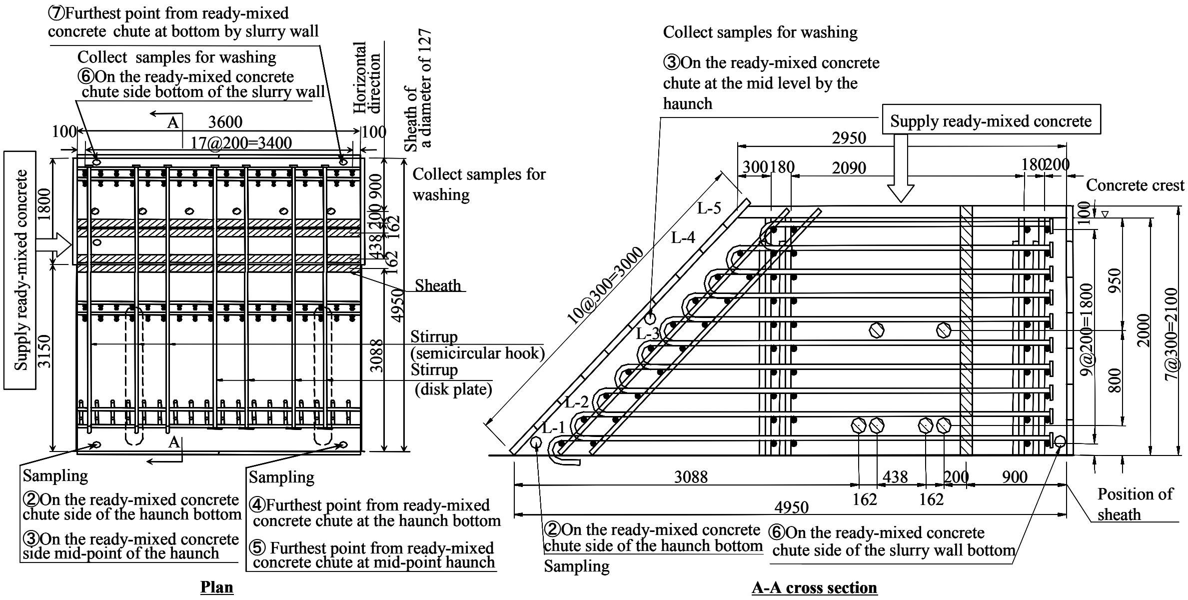


Fig.4 Outline of mock-up

Sheaths and steel anchor bars were embedded in the formwork. The interior of the first lift was haunched at an angle of 45 degrees. Figure 4 shows the shape of the full-scale model formwork. A truck agitator chute was used to place concrete in the full-scale mock-up.

4.2 Test results

a) Result of placement

Concrete of the mix proportion used at a typical plant was adopted in the test. The properties of the fresh concrete were represented by a slump of 63 to 68 cm, a funnel flow time of 12 to 14 seconds, an air content of 3.8 to 4.5%, and a temperature of approximately 19℃. The concrete diffused throughout the formwork across the intersections of reinforcing bars and prestressing cable sheaths. The gradient of the concrete surface during placement was 1/10 to 1/20. In the sixth layer, concrete was placed two hours after the placement in the previous lift to examine the effect of cold joints.

b) Analysis of washed coarse aggregate

Samples were collected from the concrete being placed and washed to measure the content of coarse ***aggregate. Samples were taken from the concrete cover, where aggregate was less likely to be transported. For analysis of the washed samples, 4 kg of sampled concrete was passed through a 5-mm sieve, and the weight of the remaining aggregate was measured. For the concrete cover, the content of coarse aggregate fluctuated slightly from 28.0% to 33.5%, more than 80% of the design content of 34.5%. Table 4 shows the results of coarse aggregate analysis of the concrete cover where the coarse aggregate content of the sampled concrete was considerably low.

Table 4 Result of analysis of washed coarse aggregate

Sample position	Weight of specimen (kg)	Weight of aggregate (kg)	Percent of aggregate weight (%)	Ratio to design value (%)
①Ready-mixed concrete chute (fifth layer)	4.0	1.36	34.0	98.6
②On the ready-mixed concrete chute at the bottom by the haunch (first layer)	4.0	1.14	28.5	82.6
③On the ready-mixed concrete chute side at the mid level by the haunch (third layer)	4.0	1.12	28.0	81.2
④Furthest point from ready-mixed concrete chute at the bottom by the haunch (first layer)	4.0	1.34	33.5	97.1
⑤Furthest point from ready-mixed concrete chute at the mid level by the haunch (third layer)	4.0	1.20	30.0	87.0
⑥On the ready-mixed concrete chute side at the bottom by the slurry wall (first layer)	4.0	1.20	30.0	87.0
⑦Furthest point from ready-mixed concrete chute side at the bottom by the slurry wall (first layer)	4.0	1.18	29.5	85.5
Average	—	—	30.5	88.4
Design value	4.0	1.38	34.5	—

c) Condition at formwork removal

The formwork was removed about one month after the concrete was placed. Air pockets were found on the haunch surface in the fourth and fifth layers. Depressions probably due to air entrapment in the concrete were observed at layer boundaries. At five locations, these depressions were chipped vertically. The maximum depression depth was found to be 15 mm. No layer boundaries were found beyond that depth. It was considered that improved compactibility might be achieved at the haunch surface in actual construction work by tapping on the surface of the formwork.

After removal of the formwork, concrete was chipped. Internal compaction was verified while the formwork was being dismantled. The internal concrete suffered no voids or honeycombing either at the intersections of reinforcing bars or near the prestressing cable sheaths or steel anchor bars. Neither layer boundaries nor cold joints were found in the area where concrete layers overlapped. The interval between concrete placement in the fifth and sixth layers was more than two hours. At the time of placement of the sixth layer, the crest of the fifth layer had hardened to a point where footprints remained as 1 to 2 cm depressions. Still no cold joints were detected. The state of the concrete surface on different sides after removal of the formwork is shown in Figs. 5 through 8.

4.3 Discussion of test

Test concrete placement into the full-scale mock-up is summarized below.

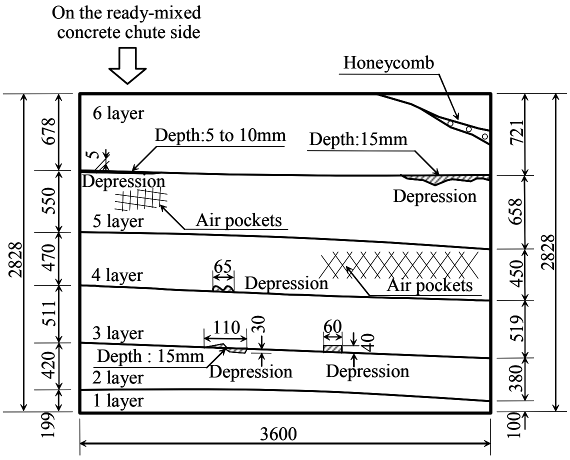


Fig.5 Concrete surface after formwork removal (haunch seen from opposite side)

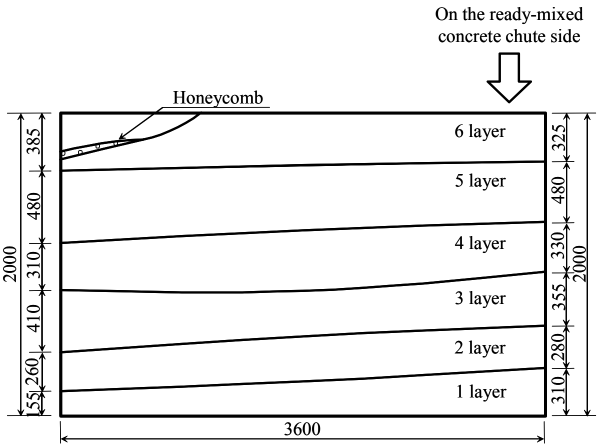


Fig.6 Concrete surface after formwork removal (at sidewall)

-The properties of the fresh concrete were satisfactory. The concrete was properly transported across the reinforcement and sheathing.

-The gradient of the concrete surface during placement was 1/10 to 1/20. The planned lateral flow over a length of approximately 7 m was considered possible.

-Analysis of washed coarse aggregate revealed that the coarse aggregate content was better than 80% of the design content at points where samples were taken. The aggregate content did not reach 100% of the design content because the coarse aggregate settled once concrete movement stopped and because the samples were taken in the upper layers. Placing concrete in several layers may result in coarse aggregate settling from the upper to lower layers. Generally, the filling of coarse aggregate was well balanced.

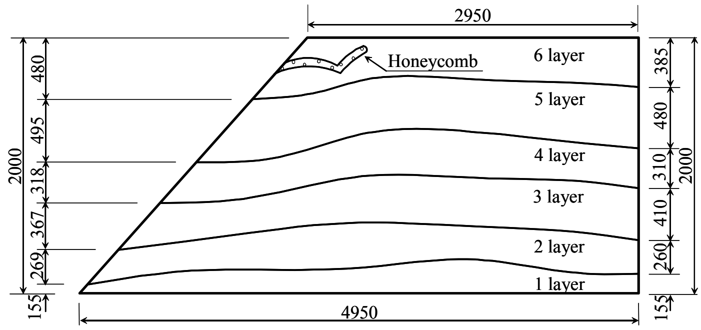


Fig.7 Concrete surface after formwork removal (gable at furthest point)

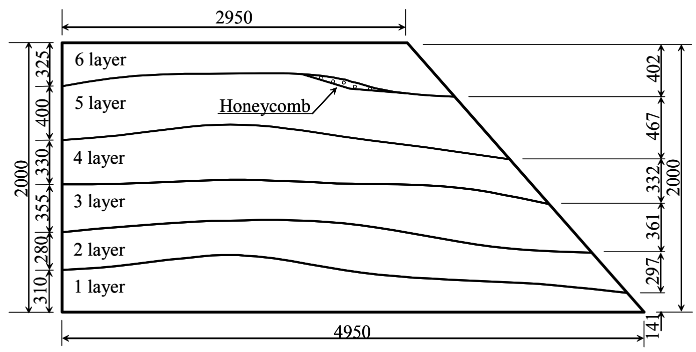


Fig.8 Concrete surface after formwork removal (gable on ready-mixed concrete chute side)

-Post-hardening investigations found no large areas that were not filled with concrete. Depressions were detected in the formwork at the haunch, and these may have occurred because air was not fully removed.

Removing air using form vibrators was considered a possible remedy.

<u>5. STUDY OF FEASIBILITY OF TESTING ALL CONCRETE PLACED</u>

<u>5.1 Improvement of test equipment</u>

The test equipment used as the basis for evaluating self-compactibility was a box-type system with obstacles consisting of reinforcing bars[4]. In its original form, concrete is evaluated for self-compacting quality by its passage through the obstacles without any additional force. This equipment was originally developed for implementation as a sampling technique, with self-compactibility evaluated from flowability and viscosity as determined from passage of samples past the obstacles. Where large amounts of concrete are placed, however, the number of samples rises rapidly and quality control becomes a complex issue. Further, placing large amounts of concrete requires concrete to pass into the test equipment at a higher flow rate. This interferes with judgment of compactibility due to the dynamic forces arising from high flow rates in the equipment.

To overcome these problems, an attempt was made to improve the basic test equipment. The aim of the improvements was as follows.

(1) To be able to judge flowability and viscosity as well as constriction-passing performance, and to reduce the frequency of the usual sampling inspections.

(2)To meet the speed requirements of the placing plan.

Four variants of the test equipment were investigated, including the original. Concrete

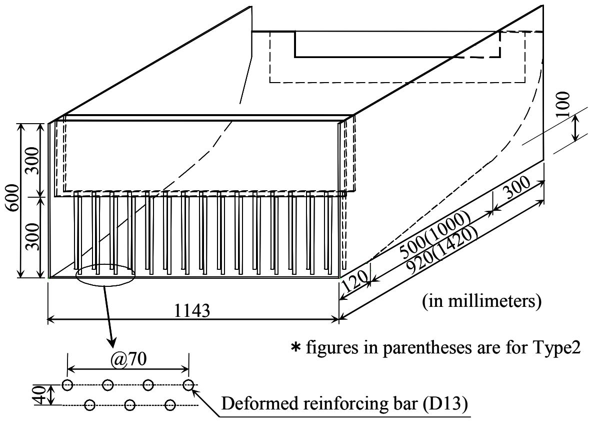


Fig.9 Test equipment for self-compactibility evaluation No.1,2 (prototype and type with increased internal horizontal extent)

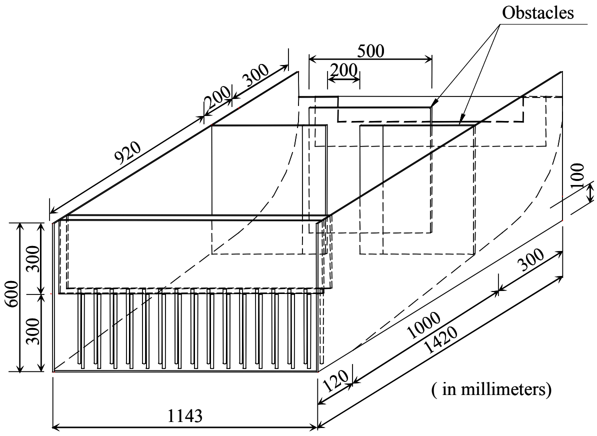


Fig.10 Test equipment for self-compactibility evaluation No.3 (type with obstacles)

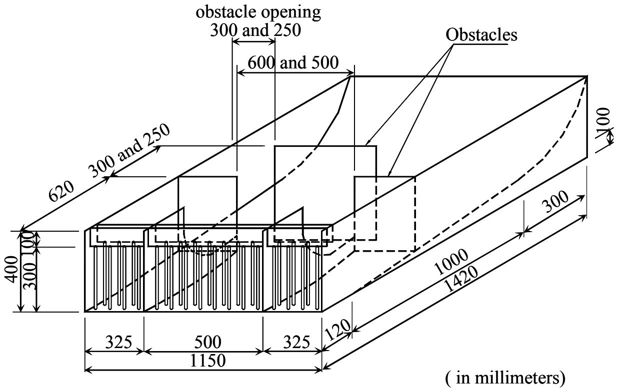


Fig.11 Test equipment for self -compactibility evaluation No.4(improved type with obstacles)

was passed through the variants, and performance was observed. Passage time was also measured.

Type 1: original (Fig.9)

Type 2: type with extended horizontal internal extent (Fig.9)

Type 3: type with obstacles (Fig.10)

Type 4: improved type with obstacles (Fig.11)

In type 2, the horizontal extent of the equipment was lengthened to improve passage time while slowing down the concrete flow.

In type 3, dynamic force was introduced by causing the concrete to impact against obstacles added to the Type 2 design.

Type 4 had obstacles in different positions, and the flow width was increased after passage through obstacles to secure greater inflow of concrete. All variants were in height, and they were set up to allow two agitator trucks to unload simultaneously.

Concrete was fed into the test equipment. The passage of concrete through the equipment was observed and the passage time measured. The concrete passage rate was calculated as follows:

$$v=(L/t) \times (1/V) \qquad (1)$$

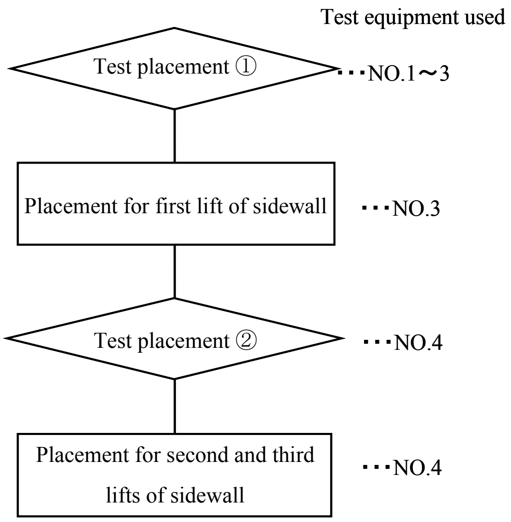


Fig.12 Procedure for test placement using test equipment

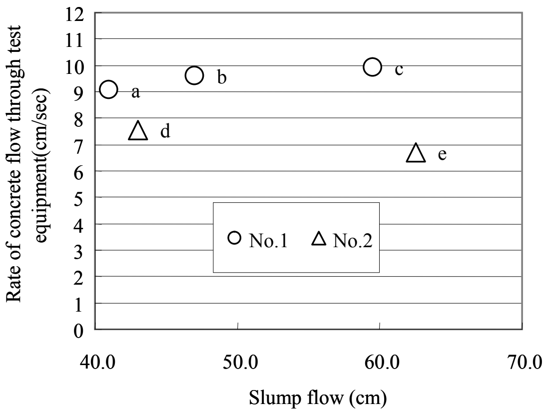


Fig.13 Relationship between flow rate in test equipment and slump flow (No.1, 2)

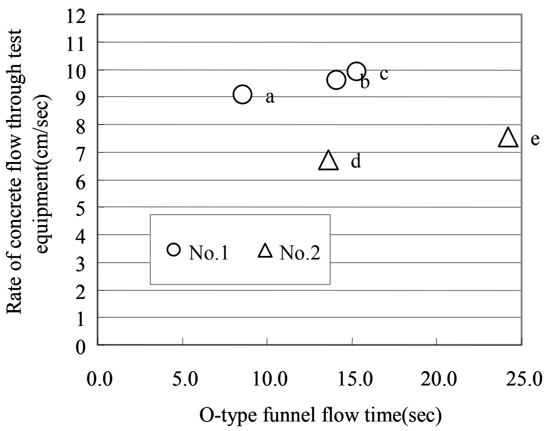


Fig.14 Relationship between flow rate in test equipment and O-type funnel flow time (No. 1, 2)

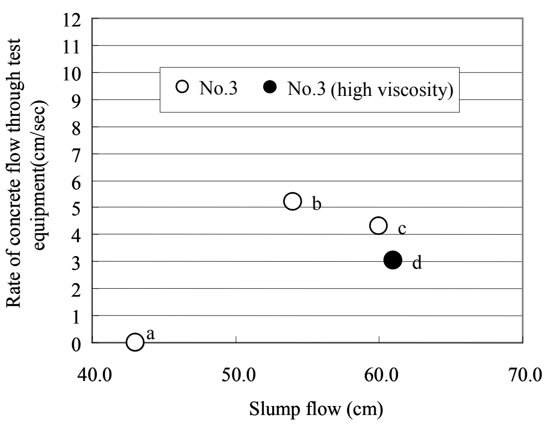


Fig.15 Relationship between flow rate in test equipment and slump flow (No.3)

where,

v: Rate of concrete passing through test equipment (cm/sec)

L: Length of passage through test equipment (cm)

t: time required for 1 m^3 of concrete to pass through the test equipment (sec)

V: Volume of test equipment (m^3)

Tests were carried out using concretes with slump flow, an indicator of flowability, of 45 cm, 55 cm, and 60 cm. Slump flow was varied by changing the unit volume of water. Figure 12 is a flow chart of the test placement procedure.

5.2 Test results

a) Types 1 and 2

Concrete passed both the original and the type with extended internal horizontal extent (Fig. 9) in nearly the same time regardless of slump flow or funnel flow time. Concrete of all mix proportions from an agitator truck fully passed the test equipment.

With both these designs, dynamic force acts on the concrete as it enters the test equipment from an agitator truck. As a result, flowability and viscosity could not be clearly determined, and it was not possible to judge performance. Figure 13(a)through (e) correspond to their counterparts in Fig.14.

b) Type 3

In the test equipment with obstacles, concrete was blocked by the obstacles in the case of 45cm of slump flow. However, there was no difference in passage speed, and all concrete passed through the equipment in the case of 55cm slump flow the lower limit.

Even though flowability was good, passage speed was shower when the concrete viscosity was high. The rate of concrete passage through the test equipment correlated with the funnel flow time. Moreover, the U-type filling height did not reach 30cm where blockage occurred. Figure 15 (a) through (e) correspond to their counterparts in Figs.16 and 17.

c) Type 4

The rate of concrete passing test equipment Type 4 (Fig. 11) was higher as the slump flow increased, and lower as the funnel flow time increased. In the same way as with Type 3, concrete was blocked by the obstacles in the case of 45cm of slump flow. Though the passage speed slowed, all concrete passed through the equipment in the case of 55cm slump flow, which was the lower limit. Moreover, the U-type filling height did not reach at 30cm where blockage occurred. The opening of the obstacles was 30cm and 25cm in the experiment. The figures show that concrete tended to pass easily in case of the 30cm opening, except from case where the slump flow was either 65 cm or 55 cm. Where the slump was 55 cm, there was a difference of only 0.9 cm/sec in the rate of concrete passing through equipment with obstacle spacing of 30 cm and 25 cm. (Figures 18 through 20 (a)through (d) correspond to their counterparts in Figs. 18 through 20.)

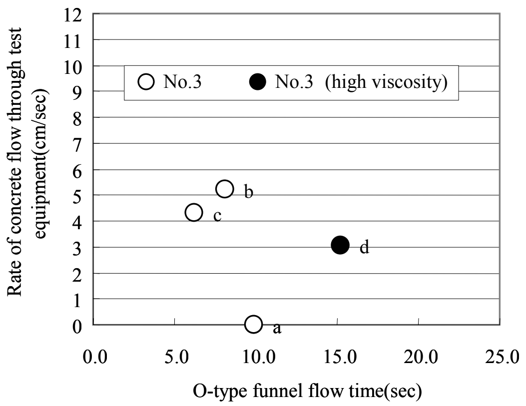


Fig.16 Relationship between flow rate in test equipment and O-type funnel flow time (No.3)

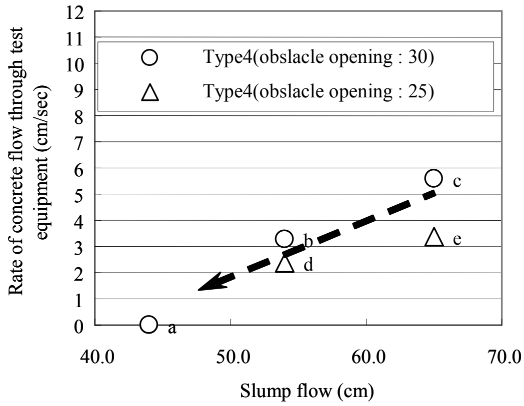


Fig.18 Relationship between flow rate in test equipment and slump flow (No.3)

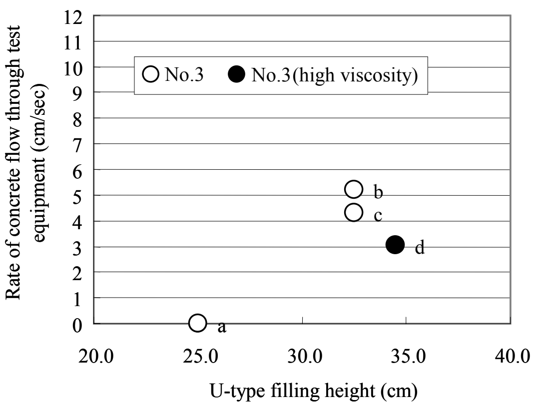


Fig.17 Relationship between flow rate in test equipment and U-type filling height (No.4)

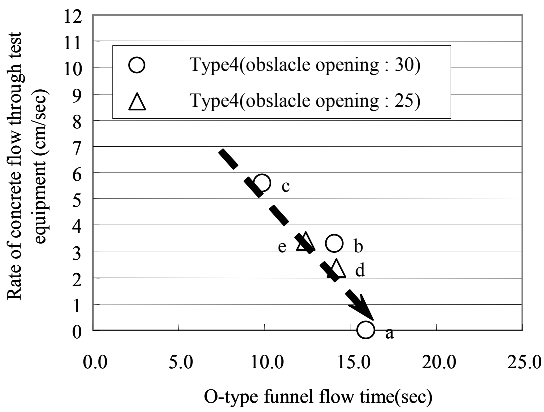


Fig.19 Relationship between flow rate in test equipment and O-type funnel flow time (No.4)

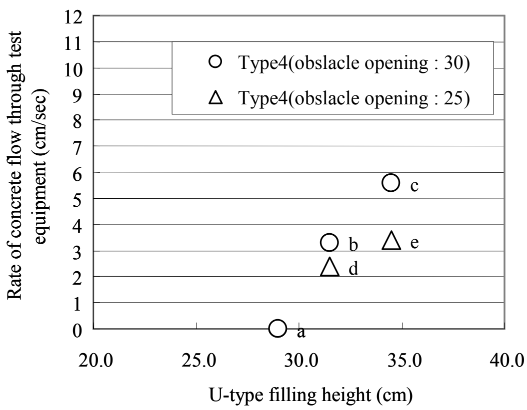


Fig.20 Relationship between flow rate in test equipment and U-filling height (No.4)

5.3 Discussion of tests

Test placement using equipment variants designed for testing all concrete placed is summarized below. Table 5 shows the ratings of the test equipment.

-Determining flowability and viscosity was difficult using the existing design (Type 1) and the type with extended internal horizontal extent (Type 2).

-Installing obstacles enables identification of low-flowability concrete.

-Increasing the rate of concrete supplied from the agitator truck allows the designated rate of placement to be achieved.

6. ASSESSMENT OF APPLICABILITY OF TEST EQUIPMENT

6.1 Quality control method

Concrete quality is conventionally controlled through sample testing according to the size or importance of the structure, with test items and frequencies specified accordingly. As a result, concrete not designated for testing is accepted without measurement and nonstandard concrete may be placed. Here, an assessment is carried out on various equipment designs for a quality control method in which all concrete is tested, with the aim of eliminating below-standard concrete before placement. Using test equipment fitted with obstacles made it possible not only to check the concrete`s ability to pass constrictions, but also to detect concrete of extremely low flowability or excessively high viscosity. Changes in concrete characteristics could be detected by monitoring the rate of concrete flow through the test equipment. To support the testing of all concrete, the passage of concrete through the test equipment was constantly monitored in the control room using a video camera. Fully determining flowability and viscosity using the test equipment was difficult, so conventional sampling was also implemented. The frequency of sampling tests was reduced by half (during construction of lifts 2 and 3 of the sidewall) because field engineers were constantly monitoring concrete characteristics n the test equipment. The concrete being placed was monitored from acceptance to completion of placement. A system was put into place to allow quality control personnel on site to communicate with the ready-mixed concrete plant for reporting of irregularities in concrete characteristics. A flow chart of the quality control process for lifts 1 through 3 of the sidewall is shown in Fig. 21.

6.2 Results of construction management

For lift 1 of the sidewall, test equipment Type 3 (with obstacles spaced 30 cm apart) was used for quality control for the following reasons:

(1) As a result of primary test placement, it was found that Type 3 made it possible to identify low-flowability concrete before placement.

(2) Concrete with a slump approximately at the designated lower limit traveled slowly through the equipment but was able to pass the disruptive steel bars obstacles. Visual observations were carried out during construction, and sample tests were also employed.

Table 5 Ratings of test apparatus in test placement

Apparatus	Flowability and viscosity	Concrete placement speed	Overall rating
No.1	C	A	C
No.2	C	A	C
No.3	B	B	B
No.4	B	A	A

A : Highly satisfactory, B : Satisfactory, C : Difficult to determine

Quality control at plant	Personnel assignment	Lift No.	Quality control on site	Personnel assignment
・Surface moisture in fine aggregate：Once in two hours ・Surface moisture in coarse aggregate： Once each in the morning and afternoon ・Slump flow /Air content/ Concrete temperature/ O-type funnel flow time： When three vehicles arrive at the plant for the first time, and when 50m³ and 100m³ of concrete have been supplied. Subsequently, each time 100m³ of concrete is supplied and whenever required. ・Chloride content：Once each in the morning and afternoon	One person at each plant.	1	・Apparatus for testing all concrete： Monitoring and recording using a video camera. ・Slump flow /Air content/ Concrete temperature： When three vehicles arrive at the plant for the first time, and when 50m³ and 100m³ of concrete have been supplied. Subsequently, each time 100m³ of concrete is supplied and whenever required. ・Sampling specimens for compression strength tests： When the first vehicle arrives, 50m³ and 100m³ of concrete has been supplied and subsequently, each time 100m³ of concrete is supplied.	Centralized control： Two persons Sampling tests： Two persons At the nozzle： Eight persons
・Surface moisture in fine aggregate：Once in two hours ・Surface moisture in coarse aggregate： Once each in the morning and afternoon ・Slump flow /Air content/ Concrete temperature： When three vehicles arrive at the plant for the first time, 75m³ of concrete have been supplied and whenever required. ・Chloride content：Once each in the morning and afternoon	One person at each plant. Plant mainly responsible for quality control.	2	・Equipment for testing all concrete： Monitoring and recording using a video camera. ・Slump flow /Air content/ Concrete temperature/ O-type funnel flow time： When the first vehicle arrives, 150m³ of concrete has been supplied and whenever required. ・Sampling specimens for compression strength tests： When the first vehicle arrives, and 150m³ of concrete has been supplied.	Centralized control： Two persons Sampling tests： One person At the nozzle： Four persons
・Surface moisture in fine aggregate：Once in two hours ・Surface moisture in coarse aggregate： Once each in the morning and afternoon ・Slump flow /Air content/ Concrete temperature/： When three vehicles arrive at the plant for the first time, 75m³ of concrete have been supplied and whenever required. ・Chloride content：Once each in the morning and afternoon	None. Quality control by plant.	3	・ Equipment for testing all concrete： Monitoring and recording using a video camera. ・Slump flow /Air content/ Concrete temperature/ O-type funnel flow time： When the first vehicle arrives, 150m³ of concrete has been supplied and whenever required. ・Sampling specimens for compression strength tests： When the first vehicle arrives, and 150m³ of concrete has been supplied.	Centralized control： Two persons Sampling tests： One person At the nozzle： Four persons
・Chloride content：Once each in the morning and afternoon ・Quality control for other factors is based on the control standards of each plant.	None. Quality control by plant.	Next -phase	・Equipment for testing all concrete： Monitoring and recording using a video camera. ・Slump flow /Air content/ Concrete temperature/ O-type funnel flow time： When the first vehicle arrives, 150m³ of concrete has been supplied and whenever required. ・Sampling specimens for compression strength tests： When the first vehicle arrives, and 150m³ of concrete has been supplied.	Centralized control： Two persons Sampling tests： One person At the nozzle： Four persons

Fig.21 Procedure for quality control for lifts 1 through 3 of the side wall

(3) Passage through the steel bars obstacles was a guarantee of self-compactibility. In the test, the obstacle spacing was set at 20 cm. An obstacle spacing of 30 cm was selected for actual construction because a relatively large quantity of concrete was likely to be accepted given the planned placement rate.

The concrete was placed using eight concrete pumps. The test equipment was located between the concrete pumps and the agitator trucks. Moreover, video cameras were installed, and a technical expert was always on hand to observe concrete passage on monitors in the control room. Thus, the concrete being supplied was centrally controlled. Changes in concrete characteristics could be identified easily, and effective quality control was realized. During lift 1 of the sidewall, on-site sample testing was carried out for slump flow. A slump flow below the designated lower limit was detected twice in 54 sample tests. Concrete that passed a sample test but passed slowly through the test equipment was considered to have a high viscosity and was discarded. The mix proportion, based on actual material weights at the time of production, was checked and the results reflected in the next production batch.

During lifts 2 and 3 of the sidewall, the quantity of concrete placed was almost 1,000 m^3 greater than for lift 1. Approximately 2,700 m^3 of concrete was placed continuously for each lift, so it was necessary to reduce construction time. The Type 4 test equipment was used for quality control during these lifts. Two agitator trucks were made simultaneously available at the site, in contrast with the alternate use for lift 1. Tests showed that there was no significant difference in flowability for equipment with obstacle spacings of 25 cm and 30 cm, so the obstacles were spaced at 30 cm because this allowed more concrete to be supplied.

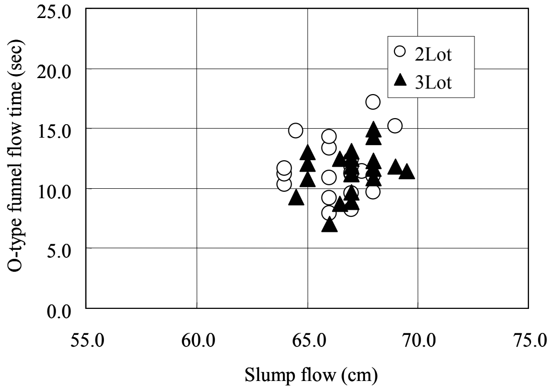
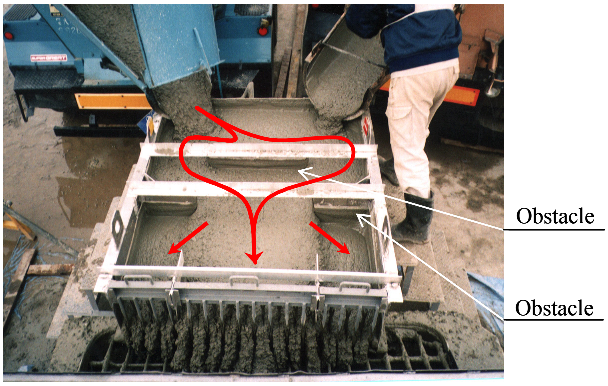


Fig.22 Result of sampling inspection at construction site (in lifts 2 and 3)



Photograph.1 The process of quality control using test equipment

Concrete was placed using the same method as for lift 1. For quality control, the frequency of sample tests was reduced based on the experience with lift 1. The method of quality control using the test equipment was the same as for lift 1.

Passage through constrictions, flowability, and viscosity were checked using this equipment for testing all the concrete placed. As a result, the sample tests played an auxiliary role and their frequency could be reduced. During lifts 2 and 3 of the sidewall, no concrete was found to be outside the specifications, either in testing using the test equipment or in the sample tests. Figure 22 shows the on-site quality control results for lifts 2 and 3. Photograph 1 shows quality control in progress using the test equipment.

7. CONCLUSION

In this study, we examined whether flowability and viscosity could be judged in addition to self-compactibility using equipment usually used for self-compactibility testing. Obstacles were installed in the standard test equipment, and attempts made to evaluate flowability and viscosity in experiments with the obstacle opening as a parameter. It was found that concrete outside the standard limits could be detected because flowability was lost in the test equipment. The experiment indicated a tendency for the passage time through the test equipment to increase as flowability fell and viscosity rose.

By using the equipment to test all concrete being placed, quality control of self-compacting concrete can be assured and low-quality concrete eliminated. Constant monitoring of the passage of concrete through the test equipment by engineers using video images facilitates understanding of changes in concrete characteristics.

Though it proved difficult to judge flowability and viscosity quantitatively, it was possible to detect signs of change by observing the concrete as it passed through the test equipment. A system was put into place for centrally controlling construction at the site using the test equipment and immediately reporting irregularities to the concrete plant. Thus, effective quality control became possible.

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