APPLICATIONS OF SELF-COMPACTING CONCRETE IN JAPAN, EUROPE AND THE UNITED STATES

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ABSTRACT

Japan has used self-compacting concrete (SCC) in bridge, building and tunnel construction since the early 1990's. In the last five years, a number of SCC bridges have been constructed in Europe. In the United States, the application of SCC in highway bridge construction is very limited at this time. However, the U.S. precast concrete industry is beginning to apply the technology to architectural concrete. SCC has high potential for wider structural applications in highway bridge construction.

This paper covers the applications of SCC in Japan and Europe. It discusses the potential for structural applications in the U.S. and the needs for research and development to make SCC technology available to the bridge engineers.

Keywords: Self-compacting concrete, SCC, Mix design, Flowability, Segregation Resistant, Testing methods, Slump flow test, Workability, Strength, Durability, Form pressure,

INTRODUCTION

The application of concrete without vibration in highway bridge construction is not new. For examples, placement of seal concrete underwater is done by the use of a tremie without vibration, mass concrete has been placed without vibration, and shaft concrete can be successfully placed without vibration. These seal, mass and shaft concretes are generally of lower strength, less than 34.5 MPa and difficult to attain consistent quality. Modern application of self-compacting concrete (SCC) is focused on high performance – better and more reliable quality, dense and uniform surface texture, improved durability, high strength, and faster construction.

Recognizing the lack of uniformity and complete compaction of concrete by vibration, researchers at the University of Tokyo, Japan, started out in late 1980's to develop SCC. By the early 1990's, Japan has developed and used SCC that does not require vibration to achieve full compaction. More and more applications of SCC in construction have been reported in Japan as shown in Fig. 1. As of the year 2000, the amount of SCC used for prefabricated products (precast members) and ready-mixed concrete (cast-in-place) in Japan was about 400,000 m^3.

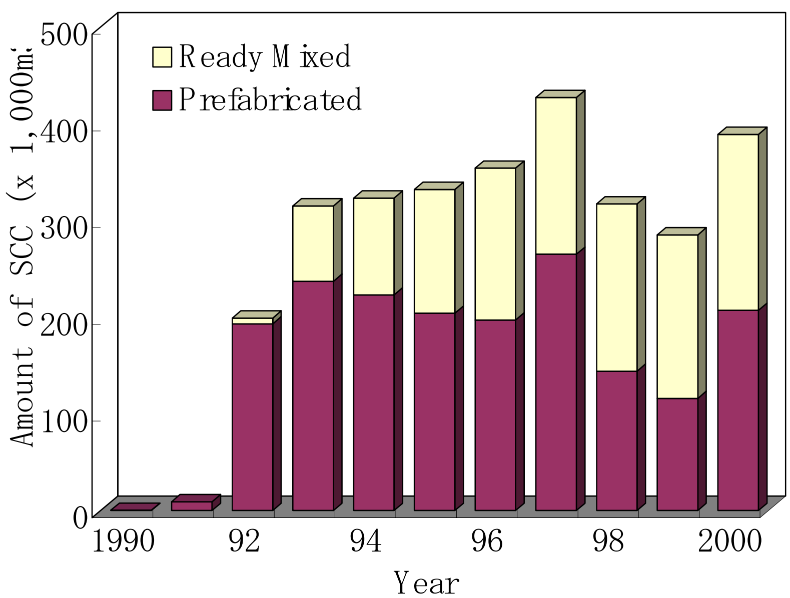


Fig. 1 Amount of SCC Placement in Japan[1]

SCC offers many advantages for the precast, prestressed concrete industry and for cast-in-place construction:

- Low noise-level in the plants and construction sites.
- Eliminated problems associated with vibration.
- Less labor involved.
- Faster construction.
- Improved quality and durability.
- Higher strength.

Several European countries were interested in exploring the significance and potentials of SCC developed in Japan. These European countries formed a large consortium in 1996 to embark on a project aimed at developing SCC for practical applications in Europe. The title of the project is "Rational Production and Improved Working Environment through using Self-compacting Concrete." In the last six years, a number of SCC bridges, walls and tunnel linings have been constructed in Europe.

In the United States, SCC is beginning to gain interest, especially by the precast concrete industry and admixture manufacturers. The precast concrete industry is beginning to apply the technology to commercial projects when specifications permit. The applications range from architectural concrete to complex private bridges.

DEVELOPING SCC MIXES

SCC mixes must meet three key properties:

1. Ability to flow into and completely fill intricate and complex forms under its own weight.
2. Ability to pass through and bond to congested reinforcement under its own weight.
3. High resistance to aggregate segregation.

The SCC mixes are designed and tested to meet the demands of the projects. For example, the mix for mass concrete is designed for pumping and depositing at a fairly high rate. SCC was used in the construction of the anchorages of the Akashi-Kaikyo Suspension Bridge. The SCC was mixed at a batch plant at the job site and pumped through a piping system to the location of the anchorages 200 m away. The SCC was dropped from a height of as much as 5 m without aggregate segregation. For mass concrete, the maximum size of coarse aggregates may be as large as 50 mm. The SCC construction reduced the construction time for the anchorages from 2.5 years to 2 years. Similarly, SCC mixes can be designed and placed successfully for concrete members with normal and congested reinforcement. The coarse aggregate size for reinforced concrete generally varies from 10 mm to 20 mm.

EXAMPLES OF SCC MIXES

When designing an SCC mix, a suitable mix is selected among "Powder- type" by increasing the powder content, "VMA-type" using viscosity modifying admixture and "Combined-type" by increasing powder content and using viscosity agent in consideration of structural conditions, constructional conditions, available material, restrictions in concrete production plant, etc. Examples of SCC mixes are given in the following tables to provide a feel for how SCC mixes differ from normal concrete mixes and from each other based on the specific needs of a project. In comparison to the conventional concrete, all three types work with an increased amount of superplasticizer.

Table 1 shows typical SCC mixes in Japan. Mix J1(Powder-type) is an example of SCC used in a LNG tank, Mix J2(VMA-type) is an example of SCC used for a massive caisson foundation of a bridge, and Mix J3(Combined- type) is an example of SCC used in usual reinforced concrete structures.

Table 1 Examples of SCC Mixes in Japan[2]

Ingredients	Mix J1 (Powder-type)	Mix J2 (VMA-type)	Mix J3 (Combined- type)
Water, kg	175	165	175
Portland Cement Type, kg	530***	220	298
Fly Ash, kg	70	0	206
Ground Granulated Blast Furnace Slag, kg	0	220	0
Silica Fume, kg	0	0	0
Fine Aggregate, kg	751	870	702
Coarse Aggregate, kg	789	825	871
*HRWR, kg	9.0	4.4	10.6
**VMA, kg	0	4.1	0.0875
Slump Flow Test – Diam. of Spread, mm	625	600	660

Notes: * HRWR = High-range water reducing admixture.
** VMA = Viscosity-modifying admixture
*** Mix J1 uses low-heat type Portland cement.

Table 2 Examples SCC Mixes in Europe[3]

Ingredients	Mix E1	Mix E2	Mix E3
Water, kg	190	192	200
Portland Cement Type, kg	280	330	310
Fly Ash, kg	0	0	190
Limestone Powder, kg	245	0	0
Ground Granulated Blast Furnace Slag, kg	0	200	0
Silica Fume, kg	0	0	0
Fine Aggregate, kg	865	870	700
Coarse Aggregate, kg	750	750	750
*HRWR, kg	4.2	5.3	6.5
**VMA, kg	0	0	7.5
Slump Flow Test – Diam. of Spread, mm	600-750	600-750	600-750

Notes: *HRWR = High-range water reducing admixture.
**VMA = Viscosity-modifying admixture

Table 3 Examples of SCC Mixes in the U.S.[4]

Ingredients	Mix U1	Mix U2	Mix U3

Water, kg	174	180	154
Portland Cement Type, kg	408	357	416
Fly Ash, kg	45	0	0
Ground Granulated Blast Furnace Slag, kg	0	119	0
Silica Fume, kg	0	0	0
Fine Aggregate, kg	1052	936	1015
Coarse Aggregate, kg	616	684	892
*HRWR, ml	1602	2500	2616
**VMA, ml	0	0	542
Slump Flow Test – Diam. of Spread, mm	710	660	610

Notes: *HRWR = High-range water reducing add mixture.
**VMA = Viscosity-modifying admixture

PROPERTIES OF FRESH SCC

The main characteristics of SCC are the properties in the fresh state. SCC mix design is focused on the ability to flow under its own weight without vibration, the ability to flow through heavily congested reinforcement under its own weight, and the ability to obtain homogeneity without segregation of aggregates.

Several test methods are available to evaluate these main characteristics of SCC. The tests have not been standardized by national or international organizations. The more common tests used for evaluating the compacting characteristics of fresh SCC in accordance with the draft standards of the Japan Society of Civil Engineers are described below.

TEST METHODS FOR FRESH SCC

The Slump Flow Test
This is a test method for evaluating the flowability of SCC, where the slump flow of SCC with coarse aggregates having the maximum size of less than 40 mm is measured (See Fig. 2). The basic equipment is the same as for the conventional slump test. However, the concrete placed into the mold is not rodded. When the slump cone has been lifted and the sample has collapsed, the diameter of the spread is measured rather than the vertical distance of the collapse.

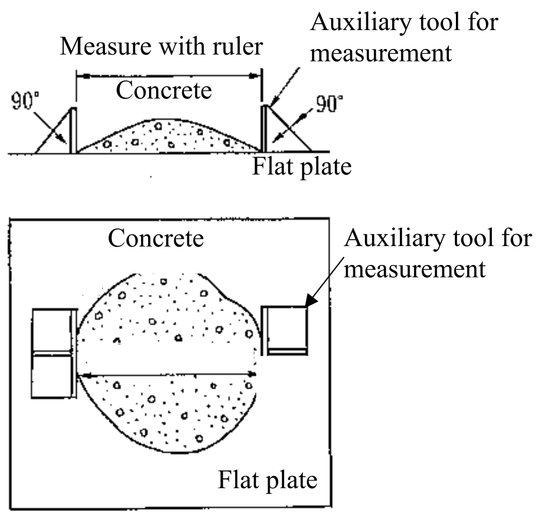
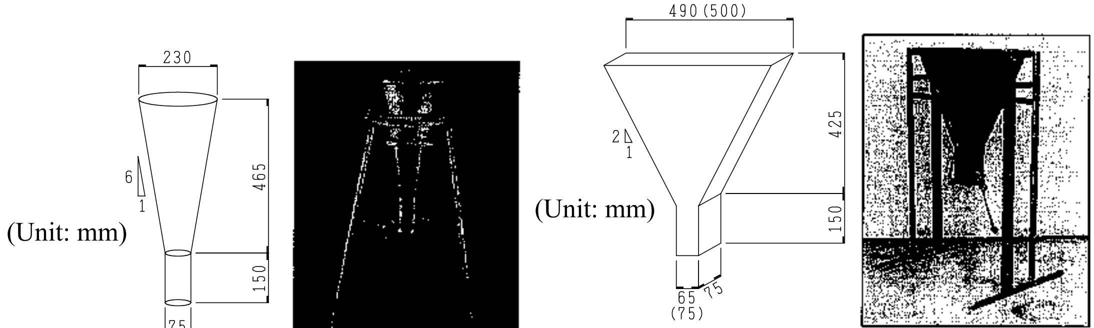


Fig. 2 Slump flow test [2]

Funnel Test

A test method for evaluating the material segregation resistance of SCC, using a funnel as shown in Fig. 3, where the efflux time of SCC with coarse aggregates having the maximum size of less than 25 mm is measured.



(a) O-shaped funnel

Figure in ( ) applies when the outlet size is 75 mm.

(b) V-shaped funnel

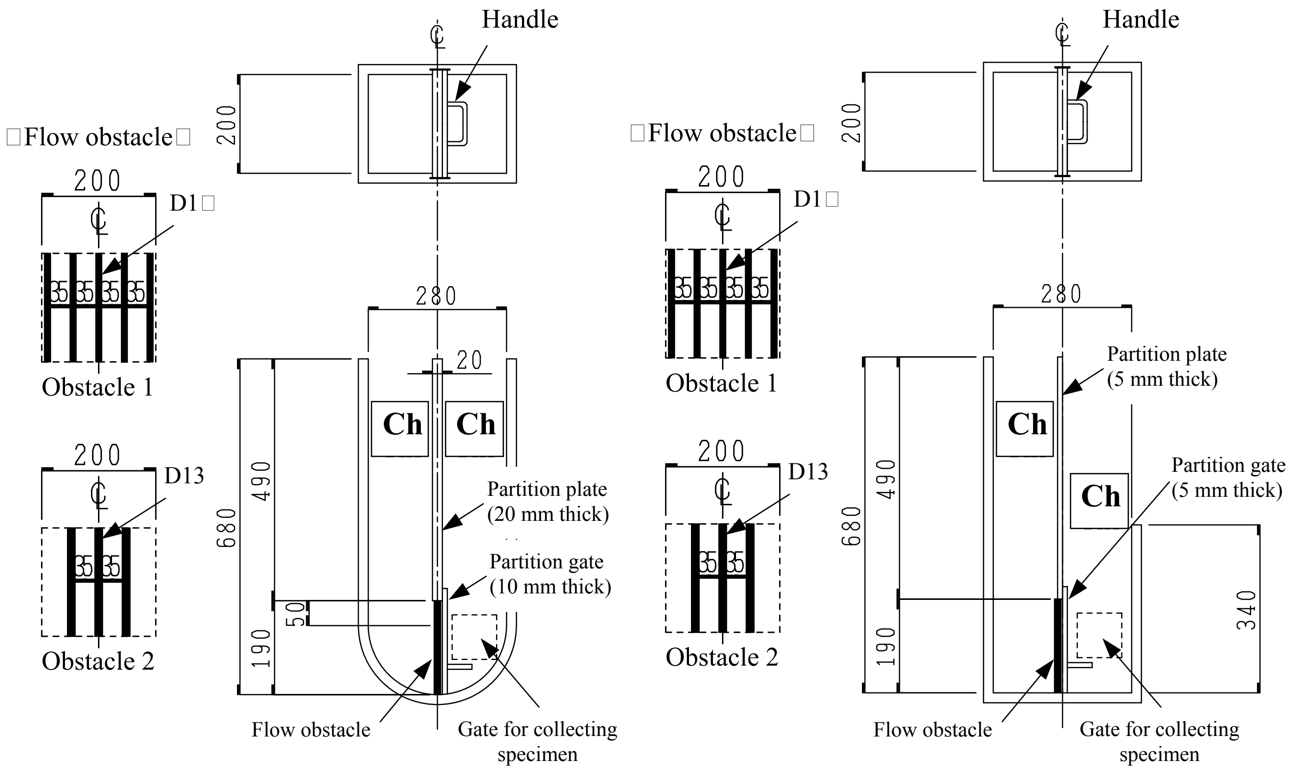
Fig. 3 Shape, dimension and overview of funnel [2]

T50 Test

A test method for evaluating the material segregation resistance of SCC, where the 500-mm flow reach time is measured in the slump flow test above, that is, the time for the flow to reach 500 mm is measured in the slump flow test. SCC should give T50 = 2 – 5 seconds.

U-Type and Box-Type Tests

These are methods for testing flowability of SCC through an obstacle with coarse aggregates having the maximum size of less than 25 mm (Fig. 4 and Photo 1). Time and height to be filled in the chamber B and amount of aggregate passed through the obstacle are measured for self-compactability.



(a) U-type Test (b) Box-type Test

Fig. 4 Shape of Filling Unit and Flow Obstacle [2]

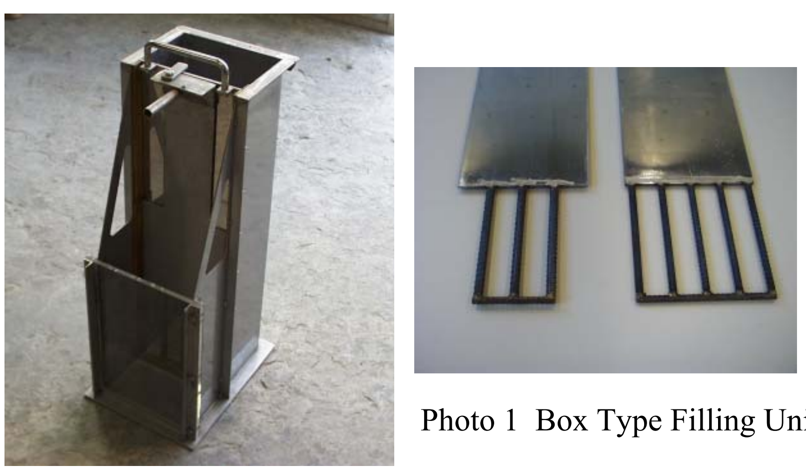


Photo 1 Box Type Filling Unit and Flow Obstacle

PROPERTIES OF HARDENED SCC

STRUCTURAL PROPERTIES

The basic ingredients used in SCC mixes are practically the same as those used in the conventional HPC vibrated concrete, except they are mixed in different proportions and the addition of special admixtures to meet the project specifications for SCC. The hardened properties are expected to be similar to those obtainable with HPC concrete. Laboratory and field tests have demonstrated that the SCC hardened properties are indeed similar to those of HPC. Table 3 shows some of the structural properties of SCC.

Table 3 Structural Properties of SCC[2]

Items	SCC
Water-binder ratio (%)	25 to 40
Air content (%)	4.5-6.0
Compressive strength (age: 28 days) (MPa)	40 to 80
Compressive strength (age: 91 days) (MPa)	55 to 100
Splitting tensile strength (age:28 days) (MPa)	2.4 to 4.8
Elastic modulus (GPa)	30 to 36
Shrinkage strain (x 10^{-6})	600 to 800

Compressive Strength

SCC compressive strengths are comparable to those of conventional vibrated concrete made with similar mix proportions and water/cement ratio. There is no difficulty in producing SCC with compressive strengths up to 60MPa.

Tensile Strength

Tensile strengths are based on the indirect splitting test on cylinders. For SCC, the tensile strengths and the ratios of tensile and compressive strengths are in the same order of magnitude as the conventional vibrated concrete.

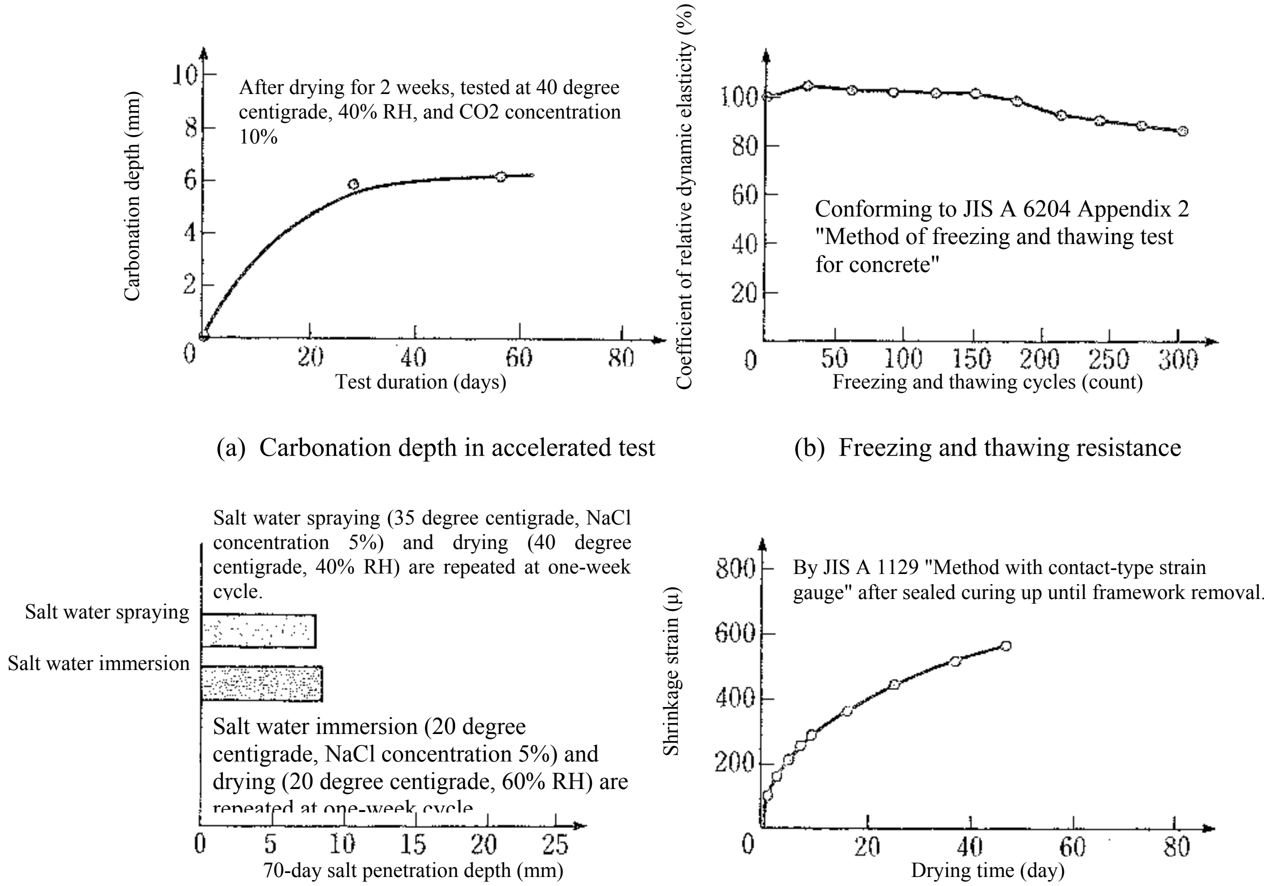
Bond Strength

Pull-out tests have been performed to determine the strength of the bond between concrete and reinforcement of different diameters. In general, the SCC bond strengths expressed in terms of the compressive strengths are higher than those of conventional concrete.

Modulus of Elasticity

SCC and conventional concrete bear a similar relationship between modulus of elasticity and compressive strength expressed in the form $E/(f_c)^{0.5}$, where E = modulus of elasticity, f_c = compressive strength. This is similar to the one recommended by ACI for conventional normal weight concrete.

DURABILITY CHARACTERISTICS



(a) Carbonation depth in accelerated test

(b) Freezing and thawing resistance

(c) Salt penetration depth in accelerated test

(d) Drying shrinkage characteristic

Concrete used for the test: Unit volume of water: 172 kg/m3, water-cement ratio: 33.5 wt.%, air content: 4.5%, moderate-heat Portland cement, sand from Fuji River, crushed stone from Oume, test started after 28 days of curing.

Fig. 7 Examples of Durability Characteristics of "Power-Type" SCC [5]

CASE STUDIES

1. RITTO BRIDGE, JAPAN

The Ritto Bridge is a PC extra-dosed bridge with corrugated steel webs on the New Meishin Expressway in Japan (Fig. 8). The highest pier is 65-meter high. High strength concrete and reinforcements, of which specified compressive strength and yield strength are 50 MPa and 685 MPa respectively, were applied to the construction of the pier to meet the earthquake resistance. Arrangement of reinforcement was very dense; therefore SCC was chosen to obtain good workability for the pier construction.

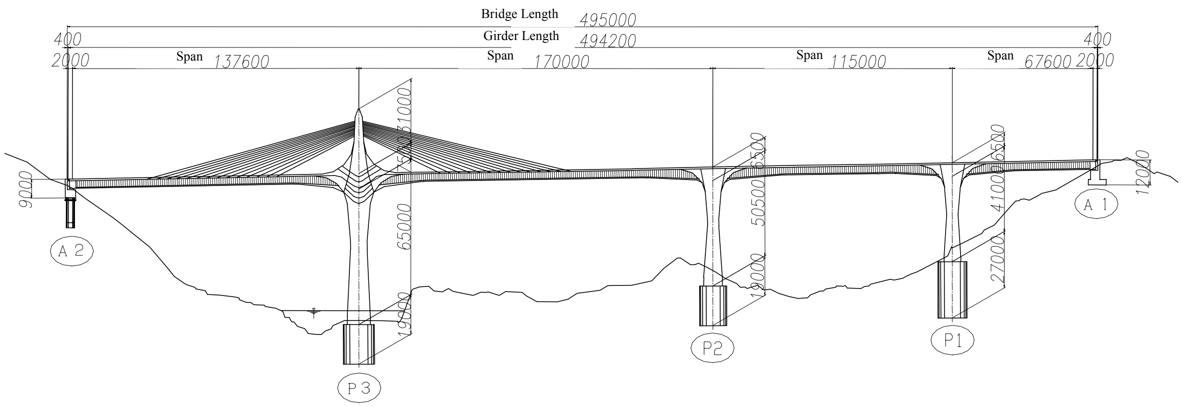


Fig. 8 Elevation and Cross Section (A-Line bound for Tokyo)

Requirements for the SCC are shown in Table 5 according to the recommendations of JSCE [2] and Japan Highway Public Corporation (JH).

Table 5 Requirements for high strength self-compacting concrete[6]

Testing Items	Unit	Spec.
Fresh concrete		
Slump Flow	(mm)	600 or 650
Flow time until 500mm	(sec.)	3 to 15
U type filling capacity	(mm)	min.300
V type Funnel flow time	(sec.)	8 to 15
Air content	(%)	4.5
Chloride ion content	(kg/m^3)	max.0.3
Hardened concrete		
Compressive strength	MPa	50

In-house trial mixes, plant trial mixes and mock-up tests were carried out, and mix proportions of the SCC were developed. The final mix proportion and test results of fresh and hardened concrete are shown in Table 6.

Table 6 Mix proportion and test results [6]

Mix proportion (In-house trial mix)										
Design Compressive Strength (MPa)	Water Cement Ratio (%)	Maximum Aggregate size (mm)	Slump Flow (mm)	Air Content (%)	Unit weight(kg/m^3)					
					Cement	Water	Fine Aggregate	Coarse Aggregate		HRWR
								20mm	13mm	
50	33.0	20	600 650*	4.5	470	155	868	505	336	6.11

Test result									
Testing Time from Mixing Complete	Slump Flow (mm)	Flow Time 500mm (sec.)	Flow Time Stop (sec.)	U Type Filling (mm)	V Type Funnel (sec.)	Air Content (%)	Concrete Temp (degree Centigrade)	Compressive Strength (MPa)	
								7days	28days
5	630	6.1	34.0	338	11.8	4.3	19.0	41.1	74.0

Target of slump flow was 600mm with allowable variation of 50mm at the beginning of the construction. After the 7th segment, target slump flow was revised to 650mm because flow-ability of concrete at the nozzle of the pumping pipe decreased. Photo 2 shows condition of concrete flowing, and Fig. 7 shows quality control results of slump flow. Slump flow was almost stable within the control values.

Photo 2 Condition of Concrete Flowing [4]

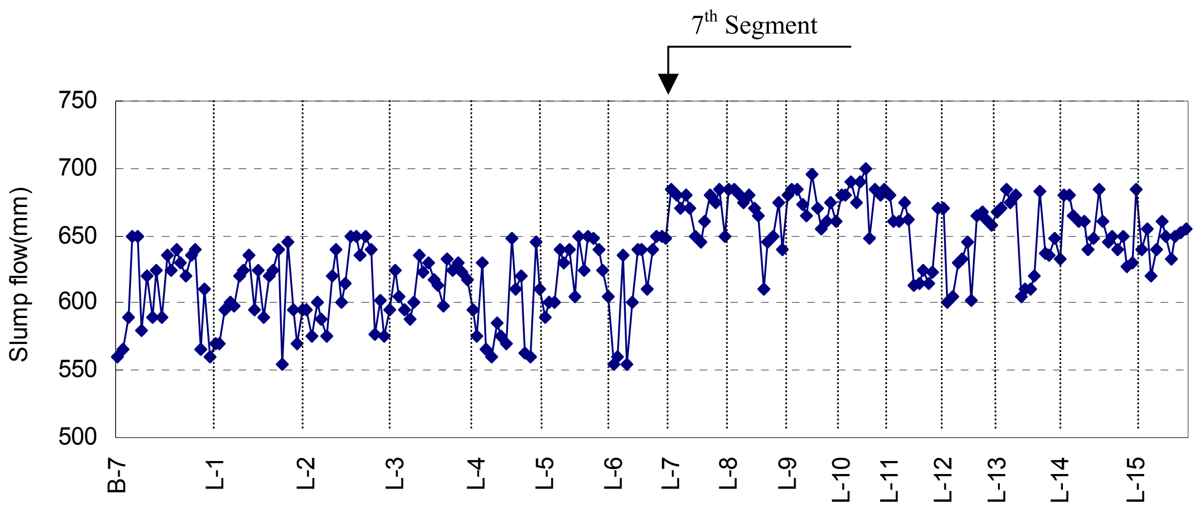


Fig. 7 Quality control results of slump flow[6]

2. HIGASHI-OOZU VIADUCT, JAPAN

Precast, prestressed T-girders were used for main girders of the Higashi-Oozu Viaduct. In the beginning of the fabrication, the conventional concrete with slump of 80mm was planned. However, it was found that conventional concrete was not capable of forming suitable surface of the girder because of girder dimensions. And also, complaints associated with noise and vibration were occurred from neighbors of the plant. Under the situations, SCC was chosen to fabricate the girders.

Table 7 shows results of quality control of the SCC. Results of fresh concrete and compressive strength are almost stable, and they satisfied the target values.

Table 7 Results of quality control of SCC[7]

	Fresh Concrete Test			Compressive Strength (MPa)			
	Slump Flow (mm)	V Type Funnel (sec.)	Air Content (%)	At Stripping	At the Age of 1 Day	7 Days	28 Days
Target value	650	12	2.0	30MPa or more		50MPa or more	
Number of Data	39	39	39	39	19	35	34
Mean Value	665	12.1	1.8	41.2	39.7	62.4	71.0
Maximum Value	695	14.0	2.5	54.2	44.5	69.5	80.5
Minimum Value	620	9.0	1.2	33.5	33.5	58.0	64.9
Standard Deviation	20	1.5	0.3	5.5	2.7	3.0	4.7

For the decision of the mix proportion, "Powder-Type" SCC using Fly ash (20%) was chosen in consideration of concrete properties, location of the plant and cost performance. Table 8 shows the mix proportion of the SCC.

Table 8 Mix proportion of SCC [7]

W/B (%)	F/B (%)	Unit weight (kg/m^3)					SP (B*%)
		Water	Binder		Fine Aggregate	Coarse Aggregate	
			Cement	Fly Ash			
30.5	20	175	457	118	840	744	1.0

Table 9 shows cost comparison with conventional concrete and the SCC. Material cost increased 4%, labor cost decreased 33%, and total cost decreased approximately 7%. It is the main reason that fly ash of low cost can be obtained and the SCC was manufactured in the prestressed concrete factory (PC factory). Expenses for trial mixes and making specimen are not included in the SCC cost. However, they are gradually decreasing. It is possible that SCC is used for reducing the fabrication cost in the PC factory.

Table 9 Comparison of Cost Performance [5]

	Conventional Concrete	SCC
Material	100	104.1
Labor	100	67.2
Total	100	92.5

Photo 3 shows the condition of concrete filling. As shown in the photo, it is judged that SCC was filled in good condition.

Photo 3 Condition of Concrete

Observations

It was observed that precast, prestressed T-girders by SCC manufactured in the PC factory showed good cost performance if some conditions are satisfied. However, in many cases, SCC in Japan is still regarded as special concrete because of its cost performance and difficulty of quality control, although it is apparent that SCC offers many advantages to PC factory or cast-in-place concrete. Therefore, for advanced expansion of SCC, it is significant to establish a new system that evaluates other values, such as life-cycle-cost and environmental issues.

3. THE SODRA LANKEN PROJECT, SWEDEN

The Sodra Lanken Project (SL) is the largest ongoing infrastructure project in Sweden. The overall cost of the SL is estimated to around 800 million USD. The SL will provide a six kilometer four lane west - east link in the southern parts of Stockholm. The SL project includes seven major junctions, with bridges, earth retention walls, tunnel entrances and concrete box tunnels. The overall length of the rock tunnels are16.6 kilometers. They are partly lined with concrete. The concrete volume used in the project amounts 225,000 cubic meters.

The duration of the SL project is estimated to last 6 years (1998 – 2004). Up to today, roughly 15,000 m^3 of SCC has been used in the SL project. The Swedish National Road Administration, Production and Maintenance (SNRA, P&D), Borlage, Sweden, has used over 4,000 m^3. The experiences with SCC are generally good. SCC has primarily been used in connection with constructions difficult to compact by normal vibration and high demands on aesthetics, for examples, in concrete rock lining, underground installation structures, rock tunnel entrances, retention walls with negative inclination and relief structures.

Concrete Rock Lining With SCC

At a part of the project, the two parallel tunnels did not have a full rock cover at a section of about 20 meters. They were therefore partly excavated in artificially deep frozen moraine, partly blasted and excavated. The only possible way to stabilize the tunnels with their partly lacking and partly very thin rock cover was by concrete arches.

The task was to achieve a strong solid structure, tight against soil- and water pressure and with a good durability. At an early stage it was decided to use SCC in the two arches. The reason for this was the complicated structure with dense reinforcement and very uneven rock surfaces. Besides, the formwork of the upper section of the arches had to be closed at the gables and bottom with no possibility for concrete workers to get inside it and compact the concrete manually.

Previous experiences of using SCC at small walls in the same tunnel system had been quite encouraging. The concrete had been pumped in to the formwork through one or more valves, mounted on the formwork. A steel lid afterwards closed the openings in the valves. An especially notable advantage casting this way, was the very good homogeneity and solid contact to the upper rock surface. The solid contact was not possible to achieve by the normal way of pumping and vibrating the concrete using openings in the formwork, later closed according to the progress of the cast.

Wall Sections

The wall sections of the arches were 5 meters high, 9 or 16 meters long and 0.8 meter thick. They were cast from fixed points of concrete release, 1.5 m from each gable (plus two points symmetrically in between, at the longer walls).

The concrete was pumped trough a 5” steel pipe coming from a mobile concrete pump. Right under the formwork, the steel pipe was bifurcated into two 4” rubber hoses by an Y-valve, each ending about half a meter over the top of the formwork, in a fixture. The end of the rubber hose was jointed to a soft 4” plastic hose. The soft hose was now and then hauled up according to the progress of the cast and cut of by a knife. The dropping height of the concrete could therefore be kept within the range of 0.7 to 1.5 meter.

The average casting time was 5 hours, roughly corresponding to a cast rate of 1 m/h. The relatively low cast rate was chosen in order to let the concrete develop a thixotropic structure, thereby limiting the form pressure to approximately 15 – 18 kPa [8].

A limited amount of active compaction (by vibration with hand hold pokers) was done at the intersection between the release points where the concrete flows met. This was only done if a longer period than 30 minutes had passed between the layers.

Quality Control Of The Delivered Concrete

All arriving concrete batches were checked for slump flow, and every 6th batch was checked for temperature . The first 3, and further on every 6th batch was also checked for air content. The concrete composition was as follows:

1. Cement - low alkali, sulphate resistant, low heat: 440 kg/m^3

2. Limestone powder. 0 – 250 ∝m: 160 kg/m^3
3. Natural rounded aggregates. 0 – 8 mm: 880 kg/m^3
4. Coarse aggregates, crushed. 8 – 16 mm: 720 kg/m^3
5. Water cement ratio: 0.38 (+/- 0.01).
6. 28 day cube strength: 70 – 80 MPa.
7. Slump flow range was 720 mm to 770 mm, with a target value of 740 mm.
8. Air content was kept within the range of 4 – 7 %.

At the start of each cast, the slump flows tended to swing up and down (mostly downwards). Values down to 450 – 500 mm were recorded, despite a short transportation time of only some 10 – 20 minutes. The explanation of the rapid decline of slump flow was due to an unbalance in the cement used. Therefore, several of the initial batches had to be corrected by adding superplasticizer (Glenium 51) to the agitating truck. With an approximate amount of half a liter of Glenium 51 per cubic meter of concrete, the slump flow was brought up about 200 mm. If the first addition was not enough, a second dosage would normally do it. On the average, about 30 % of arriving batches had to be corrected. To ensure an almost continuous flow of concrete into the formwork, two agitating trucks were arranged side by side to discharge the SCC as shown in Figure 8.

The advantage of this arrangement was the possibility to let the latest arrived truck to discharge about 300 liters of concrete into the flow of the previous truck, which already had been approved. Thereby, a representative sample could be taken out, without risking a bad influence on the pumped concrete significantly. Another advantage was adjusting of the consistency was possible, within the time span of discharging the previous truck. After this had been done, the latest arrived truck could start to discharge, directly at the spot.

Arch Sections

The second and more difficult part of this project was cast of the top arch sections (6 in all). Each arch section was between 8 and 9 meters long, with a span with of 12 meters. The only way to secure a complete filling of the cavity between the closed wooden formwork and the upper shotcreted rock surface was to pump the concrete into the formwork through valves or pipes. In this project, valves were chosen.

The quality control procedure was basically the same as for the walls. The target value for the slump flow was, however, adjusted upwards to 750 mm.

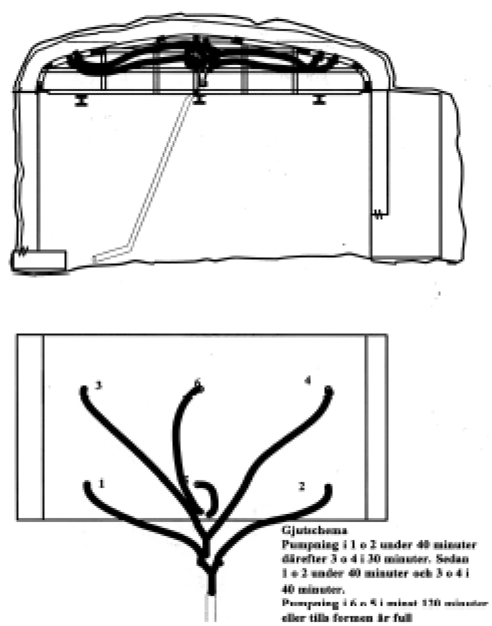


Fig. 8 Arrangement of Feeding Concrete

Six valves were mounted on the form as

shown in Figure 8. Four of the valves were placed about one meter above the bottom of the formwork, and about 2 meters from the gables.

The two remaining valves were placed at the top of the form, at the same distances from each other. The feeding system was the same as for the walls, with a 5" steel pipe connected to two 4" rubber hoses.

At the start of each cast, the SCC was simultaneously pumped in two of the lower valves for about 40 minutes. By manually shifting the 5" feeding pipe to a second split valve, concrete was redirected into the other two lower valves for about 40 minutes. Then the flow was shifted back again, and so on. When the concrete level had reached about 1.5 meters up on both sides, the flow was directed to the two upper valves by a third split valve.

The formwork was filled up to the top from those valves. Limited views of the flowing concrete were possible through holes in the formwork in the gables. Quite a lot time was spent observing the flow of the concrete inside the formwork. A trained eye could rather easily judge if the concrete is self-compacting just by watching it flow. At the arch castings the concrete nearly always showed a plain upper surface and sections within moving slowly towards the outer rims of the formwork.

In the final stages of the cast much attention was paid to deformations of the formwork, implicating an elevated concrete pressure due to a completely filled formwork. Normally, the cast was interrupted when concrete began to come out from overflow pipes ending in elevated parts of the rock roof. The cast rate was in the range of 16 – 22 cubic meters per hour. One person operated the pump, two concrete workers monitored the cast and intermittently with the help of a third person to shift the direction of concrete. The same arrangement for emptying the trucks used for the wall casts was also used for the arches. Each cast took an average 6 hours.

Observations

The result in respect of surface evenness and porosity was good both for the walls and the arches. Especially nice imprints of the wood structure were recorded at the gables of the walls and arches. In comparison with other arches cast with conventional technique in the SL project, it could be concluded that the homogeneity and quality was better for those cast with SCC. See Figure 9.

Fig. 8 Arrangement for continuous discharge

Fig. 9 View of the south arch

LESSONS LEARNED

SCC PRODUCTION

- Production of SCC requires more experience and care than the conventional vibrated concrete. The plant personnel would need training and experience to successfully produce and handle SCC. In the beginning, it may be necessary to carry out more tests than usual to learn how to handle SCC and gain the experience.
- Before any SCC is produced at the plant and used at the job site, the mix must be properly designed and tested to assure compliance with the project specifications. The ingredients and the equipment used in developing the mix and testing should be the same ingredients and equipment to be used in the final mix for the project.
- Most common concrete mixers can be used for producing SCC. However, the mixing time may be longer than that for the conventional vibrated concrete. SCC is more sensitive to the total water content in the mix. It is necessary to take into account the moisture/water content in the aggregates and the admixtures before adding the remaining water in the mix. The mixer must be clean and moist, and contains no free water.
- Admixtures for the SCC may be added at the plant or at the site. There is cost benefit in adding the admixtures at the site. Conventional ready-mix concrete can be bought at a lower cost than the cost of SCC bought from a ready-mix supplier.

TRANSPORTATION

- The truck drivers should be given oral and written instructions for handling SCC. The truck drivers must check the concrete drum before filling with SCC to make sure that the drum is clean and moist, but with no free water. Extra care must be taken for long deliveries. In addition to the usual information, the delivery note should show the following information:
    - Slump flow – target value and acceptable range.
    - Production time – time when it was produced.
    - Instruction for adding admixtures at the site, if allowed.
- The truck drivers should not be allowed to add water and/or admixtures during transit.

FORM SYSTEM

- All commonly used form materials are suitable for SCC. For surface quality of SCC, wood is better than plywood, and plywood is better than steel. More pores seem to form on the surface when the form skin is colder than the SCC. During cold weather placement of SCC, it may be necessary to insulate the formwork to maintain temperature and normal setting time. SCC is more sensitive to temperature during the hardening process than the conventional vibrated concrete.
- Due to the cohesiveness of SCC, the formwork does not need to be tighter than that for conventional vibrated concrete.

- Higher form pressures than normal were not observed even at high rate of concrete placement. However, it is recommended that the formwork be designed for hydrostatic pressure, unless testing has shown otherwise.

CASTING ON SITE

- A pre-SCC placement meeting with all personnel involved in the SCC placement would be beneficial. The SCC placement plan, including QC/QA, and the roles and responsibilities of the field personnel should be explained and understood.
- In addition to the normal testing, the slump flow, T50 and L-box tests are useful to check SCC at the job site before placement.
- SCC can flow horizontally a distance of 15 to 20m without segregation. A well-designed SCC may have a free fall of as much as 8m without segregation. However, it is recommended that the distance of horizontal flow be limited to 10m and the vertical free fall distance be limited to 5m.
- For deck slab of a bridge, it would be difficult for the SCC to flow too far. This could be handled by designing an SCC with a lower slump flow. With a lower slump flow, a bridge deck with a slope of 2% could also be accomplished.
- If an SCC placement is interrupted and the concrete has started to harden, it would be necessary to “wake up” the placed concrete by striking a stick or board into the concrete several times before starting the placement again.
- SCC takes some time before the hardening starts, especially during cold weather conditions. When it starts to harden, the process is very rapid, which can cause problems in leveling and treating large surface areas.

SURFACE FINISHING AND CURING

- Finishing and curing of SCC can follow the good practices of superplasticized high performance concrete. Surface of SCC should be roughly leveled to the specified dimensions, and the final finishing applied as necessary before the concrete hardens.
- SCC tends to dry faster than conventional vibrated concrete, because there is little or no bleeding water at the surface. SCC should be cured as soon as practicable after placement to prevent surface shrinkage cracking.

COLD JOINT

- When placing a new layer of SCC on old SCC, the bond between the old and new SCC is equal to or better than in the case of conventional vibrated concrete. Normal vibration will not destroy the concrete, such as in the case of placing conventional vibrated concrete on fresh SCC. This may be necessary when the surface slope is greater than practicable for SCC.

FEASIBLE PERFORMANCE SPECIFICATIONS

Based on the current state-of-the-knowledge, the following performance specifications for SCC are achievable through proper mix design and testing:

- Workability:
  - Slump flow > 600 mm
  - Remain flowable ≥ 90 minutes
  - Withstand a slope of 3%
  - Pumpable ≥ 90 minutes through pipes ≥ 100 m long
- Mechanical Properties:
  - 28-day compressive strength = Similar to HPC
  - Creep and Shrinkage = Similar to HPC
- Durability Parameter:
  - Freeze-thaw resistance ≥ HPC.

CLOSING REMARKS

SCC has high potential for greater acceptance and wider applications in highway bridge construction in the U.S.. An NCHRP Research Project has been initiated to develop design and construction specifications to supplement the AASHTO LRFD Bridge Design and Construction Specifications. The South Carolina State Department of Transportation (SCDOT) has received an Innovative Bridge Research and Construction (IBRC) grant to study the use of SCC in drilled shafts. This study consists of constructing 4 test shafts, 2 with SCC and 2 with normal SCDOT concrete mixes. These tests will help SCDOT determine the use of SCC in production drilled shafts. The Kansas State Department of Transportation (KSDOT) has received an IBRC grant to study the fresh and hardened properties SCC for use in Kansas prestressed concrete bridge girders. KSDOT will build a 3-span bridge, using SCC in all the prestressed concrete girders in one of the spans and the remaining prestressed girders will be constructed of Kansas standard concrete mixes. The bridge will be instrumented and monitored for five years to determine the performance of the bridge.

Japan and European countries have demonstrated by tests and applications the feasibility and benefits of SCC in highway construction. The advantages of SCC are already recognized by the concrete industry in the U.S. The Precast/Prestressed Concrete Institute (PCI) reports that a significant number of fabricators in the U.S. are already retooling to use SCC. Cast-in-place concrete construction in tight space and congested reinforcement, such as, drilled shafts, columns and earth retaining systems, can be accelerated by using SCC.

There will be a large payoff in not requiring vibration to achieve consolidation, and the low noise level to meet stringent environmental requirements in urban and suburban construction sites. Less labor and speedier construction will result in substantial cost savings, less traffic disruption and risk reduction. Better durability and high strength will allow the engineers to design and build bridges to last a century and beyond.

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