

HISTORY AND DEVELOPMENT OF HIGH-PERFORMANCE CONCRETE IN JAPAN

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ABSTRACT :

The history of Japan's high-performance concrete was summarized in this paper. The development of Japan's high-performance concrete was started with the proposal for self-compacting concrete (SCC) by Okamura in 1986 and the completion of its proto type in 1988. Japan's self-compacting concrete was inevitable high-performance/high-strength concrete due to its low water to cement/binder ratio. Because of its high cost due to high unit binder content, SCC has not been common in Japan with the share of around 0.1%. Following the situation, the authors have just developed an air-enhanced SCC in which self-compactability can be enhanced by finer entrained air resulting in a unit binder content of less than 400 kg/m³.

KEYWORDS: high performance concrete, self-compacting concrete, self-compactability, flowability, air-enhanced self-compacting concrete

1. Introduction

The definition of HIGH-PERFORMANCE CONCRETE in Japan is unique in the world. "High-performance concrete" is almost equal to high-strength concrete with high durability. That is, high-performance is referred to the performance of concrete after hardening without considering the difficulty in compaction work. On the other hand, Okamura defined "high-performance" regarding the perfect compaction to be assured in spite of the lack skilled workers. That concept has been Japan's original and it lead to the development of self-compacting concrete in 1988 by Maekawa and Ozawa [1]. The history of Japan's SCC, proposed and developed as "high-performance concrete" was summarized in this paper.

2. Self-Compacting High-Performance Concrete

2.1 Characteristics

Self-compacting high-performance concrete is a high performance concrete that can be compacted into every corner of a formwork, purely by means of its own weight, without the need for vibrating compaction (Fig. 1). This concrete is defined at the three stages of concrete as follows:

- (1) Fresh: self-compactable
- (2) Early age: avoidance of initial defects
- (3) After hardening: resistance against external factors.

Self-compactability of SCC is measured in order to ensure that SCC can fully flow into all area in formwork and it can be perfectly compacted by its own weight. The apparatus used for evaluating self-compactability is Box test as shown in Fig. 1. The desirable SCC is concrete that can flow through the obstacle in box test and finally reaches the filling height of 250mm-300mm.

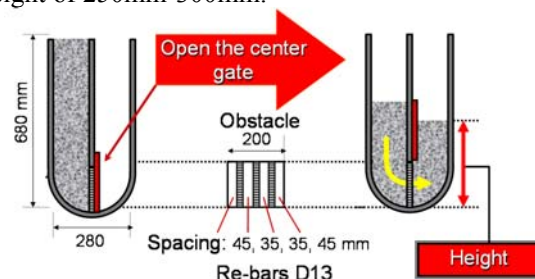


Figure 1 Test for self-compactability

2.2 History of Development

To make durable concrete structures, sufficient compaction by skilled workers is required. However, the gradual reduction in the number of skilled workers in Japan's construction industry has led to a similar reduction in the quality of construction work. A solution for the achievement of durable concrete structures independent of the quality of construction work is the employment of self-compacting concrete. The necessity of this type of concrete was proposed by Okamura in 1986. Studies to develop self-compacting concrete (SCC), including a fundamental study on the workability of concrete, were carried out by Ozawa and Maekawa at the University of Tokyo. The prototype of self-compacting concrete was first completed in 1988 using materials already available in the market. The prototype performed satisfactorily with regard to drying and plastic shrinkage, heat of hydration, denseness after hardening, and other properties. At almost the same time, "High-Performance Concrete" was defined as a concrete with high durability due to low water-cement ratio by Aitcin et.al. Since then, the term high performance concrete has been used around the world to refer to high durability concrete. Therefore, Okamura has changed the term for Japan's SCC to "Self-Compacting High Performance Concrete."

2.3 Mechanism for the Technology

Self-compactability of fresh concrete owes a lot to flowability through obstacle (Fig. 2). The method for achieving self-compactability involves not only high deformability of paste or mortar, but also resistance to segregation between coarse aggregate and mortar when the concrete flows through the confined zone such as around reinforcing bars. Okamura and Ozawa have employed the following methods to achieve the self-compactability:

- (1) Limited aggregate content
- (2) Low water-powder ratio
- (3) Use of superplasticizer

Highly viscous paste is required to avoid the blockage of coarse aggregate when concrete flows through obstacles. When concrete deforms, paste with a high viscosity also prevents localized increases in the internal stress due to the approach of coarse aggregate particles (Fig. 3). High deformability can be achieved by the employment of a superplasticizer, keeping the water-powder ratio very low, resulting in high-performance after hardening. Poly-carboxylate type of superplasticizer is suitable for self-compacting high-performance concrete (Fig. 4).

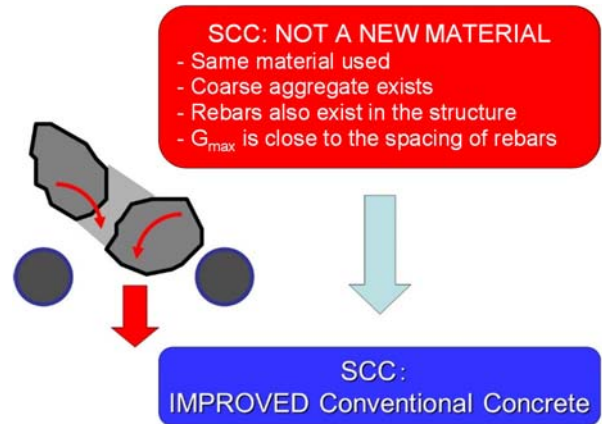


Figure 2 Self-compactability owing to flowability through obstacles characterizing self-compactability of fresh concrete

Only W/P & SP/P to be adjusted by Testing with G & S fixed.

G	S	W	S	P
50% of solid volume	40% of mortar volume	Moderate deformability & viscosity		
can be fixed with material parameters		to be fixed by trial mixing		

G: coarse aggregate, W: water, P: powder
S: fine aggregate, SP: superplasticizer

Figure 3 Rational mixdesign method for self-compacting high-performance concrete

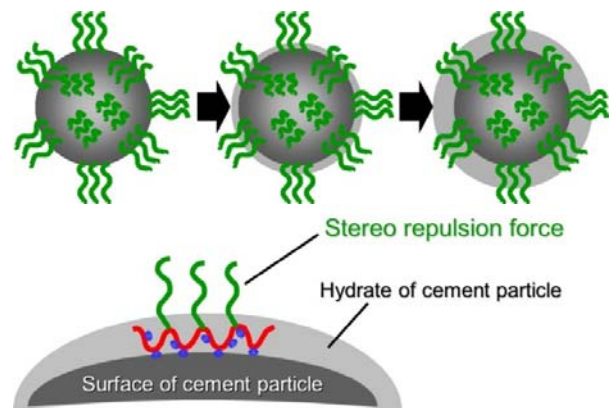


Figure 4 Poly-carboxylate type of superplasticizer suitable for self-compacting high-performance concrete

2.4 Practical Applications

Self-compacting high-performance concrete has been used in many actual structures since 1990. Currently, the main reasons for the employment of

self-compacting high-performance concrete can be summarized as follows:

(1) To shorten construction period (Fig. 5). Fig. 5 shows Akashi-Kaikyo bridge, the suspension bridge with the longest span in the world (1,991 meters). The anchorage structure of Akashi-Kaikyo was one of the applications of self-compacting concrete. By using SCC, construction period of the anchorage structure could be reduced from 2.5 years to 2 years.

(2) To assure compaction in the structures: especially in confined zones where vibrating compaction is difficult (Fig. 6 and 7). Self-compacting concrete was used for RC structures of LNG tank which belong to Osaka Gas Company (Fig. 6) in order to ensure that high level of compaction could be achieved. The concrete structures storing dangerous material needs high strength and durability for safety matter which directly relates to the compactness of concrete. Accordingly, SCC can effectively solve this problem. In addition, SCC was also applied to concrete structure with congested reinforcement bar as shown in Fig. 7. Although concrete member consists of high amount of reinforcement bar, SCC can flow and will be perfectly compacted without any vibration as long as the maximum aggregate size is not bigger than the spacing between reinforcement bars.

(3) To eliminate noise due to vibration: effective especially at concrete products plants e.g. precast concrete factory. Also, self-compacting high-performance concrete is applied to tunnel lining for preventing the cold joint (Fig. 8). Sometimes, the placement of concrete might be delay or two steps casting is necessary. These actions form cold joint in concrete structures. The full compaction of two batches of concrete is impossible under vibration. Accordingly, SCC is applied to this case to make more homogenous condition of concrete structures.



Figure 5 Anchorage of Akashi-kaikyo Bridge



Figure 6 LNG on-ground tank



Figure 7 High pier of bridge and confined zone of reinforcing bars



Figure 8 Self-compacting casted into an arch crown of a tunnel

However, the share of SCC in Japan has been less than 0.1% and it still remains a “special concrete.”

3. Air-enhanced Self-Compacting Concrete

3.1 Bubble-lubricated SCC: Breakthrough for SCC applications

Although Japan's SCC is claimed as an innovative high performance material that contributes to structural reliability, its cost is approximately double that of the ordinary concrete because of its high unit cement content, and this has been an obstacle to its adoption in ordinary structures that do not require high levels of strength. According to one survey, the

necessity for high-strength concrete with the compressive strength of over 60 N/mm² was only 5% in Japan. Japan's SCC is inevitable a high-strength concrete due to its very low water to cement ratio of around 0.3 for preventing segregation at fresh stage.

Using technologies for the quantification of self-compaction factors and technologies for the evaluation of chemical admixtures as its tools, the authors have found solutions for these challenges (Fig. 9). The key is the introduction of air bubbles (air entrainment) to improve the freeze-thaw resistance of concrete. Air entrainment is used in designing the mix proportions of concrete, as these air bubbles act like ball bearings for greater deformability in fresh concrete, increasing its performance (Fig. 10). In this way, the proportions are kept about the same as ordinary concrete, using only ordinary cement as the powder, with unit cement content of less than 370 kg/m³ and unit water content of approximately 165 kg/m³ (Table 1, Fig. 11). Meanwhile, the level of self-compaction is about the same as that of conventional SCC (Fig. 12 & Fig. 13). This material is called air-enhanced self-compacting concrete (abbreviated as air-SCC). A prototype was completed in 2013 [2]. The strength of air-SCC was quite similar to that of normal concrete with W/C of 55% (Fig. 14).

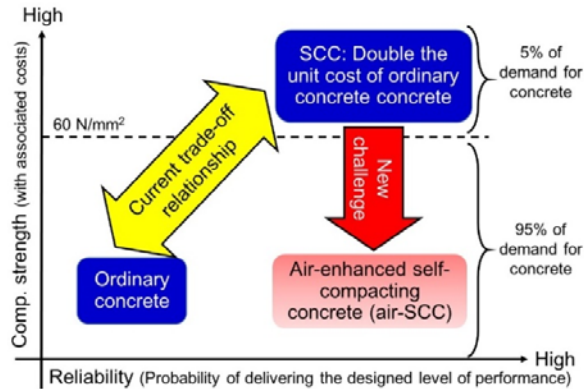


Figure 9 Concept of development of air-SCC

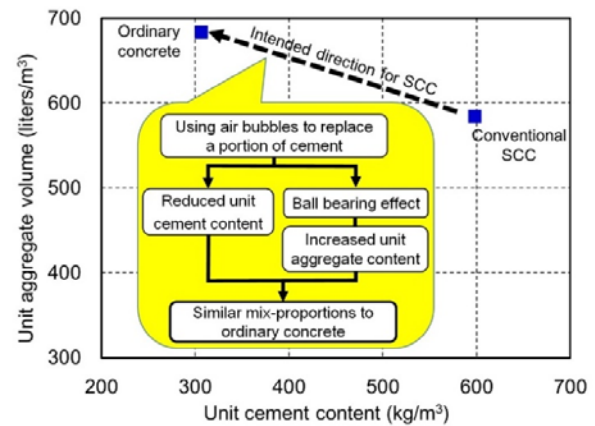


Figure 10 Intended direction for SCC by making use of entrained air

Table 1 Mix-proportion of air-enhanced SCC

Air	W/C	Unit mass (kg/m ³)			
		W	C	S	G
10%	45%	166	369	929	729

Cement: Ordinary portland cement (density: 3.15 g/cm³)

Fine aggregate: Crushed limestone sand (density: 2.68 g/cm³)

Coarse aggregate: Crushed limestone (density: 2.70 g/cm³)

Superplasticizer: Grenium 6500

Air-entraining agent: "Masterair" 101

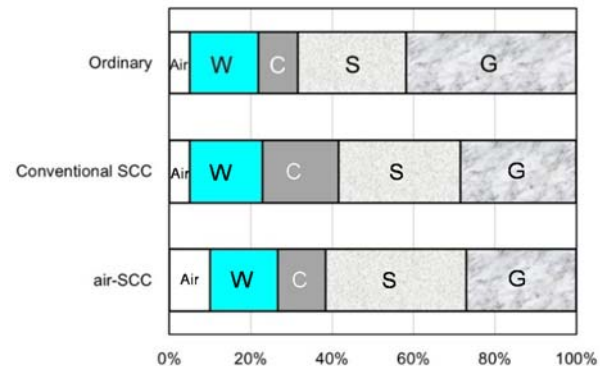


Figure 11 Comparison of components in each type of concrete by volume



Figure 12 Slump flow of air-SCC



ภาพ Figure 13

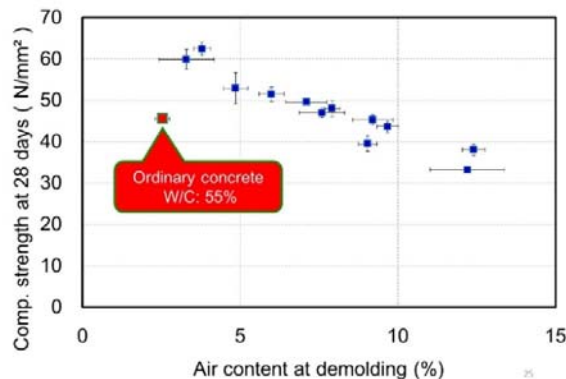


Figure 14 Higher air content resulting in lower strength at the rate following the previous research

Air-SCC is a material that can improve the reliability of general structures. This highly reliable concrete material can keep costs low while delivering the same strength as ordinary concrete after hardening (Fig. 15).

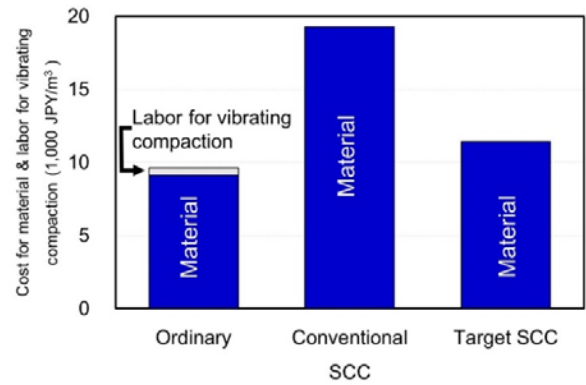


Figure 15 Reduction in cost of air-SCC compared with conventional SCC

3.2 Mechanism of Air-enhanced Self-Compactability

Air bubbles in air-enhancing self-compacting concrete cannot be entrained with a simple mixing procedure in which all the materials are to be poured into the mixer at the same time and mixed 120 seconds [3]. With such a simple mixing procedure, the level of self-compactability specified by JSCE was not achieved with the air content of as much as 15% (Fig. 16).

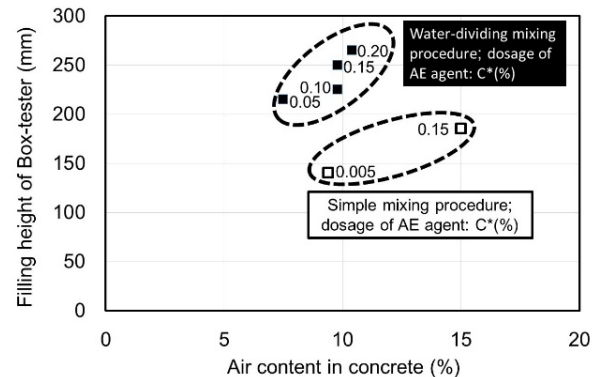


Figure 16 Effective mixing procedure for higher level of self-compactability in spite of lower air content

The authors have found one mixing procedure so called “water-dividing method” for entraining air for enhancing self-compactability, in which cement, fine aggregate, coarse aggregate, 50% of water and superplasticizer are poured into the mixer at first and mixed 60 seconds and then AE agent and the other 50% of water are poured and mixed 60 seconds [4]. The distribution of the diameter of air bubbles of the two types of concrete with different level of self-compactability (filling height of box-tester of 250 mm and 140 mm respectively) with almost the same air content of around 10% was obtained with the linear-traverse method (Figs 17 & 18). The distribution was quite different from each other. It is possible that finer

air bubble was effective in enhancing self-compactability of fresh concrete.

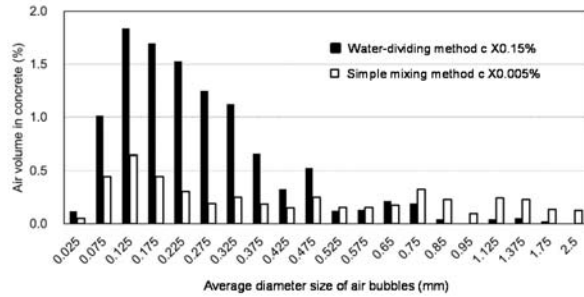
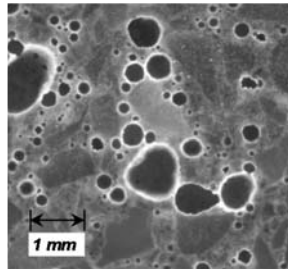
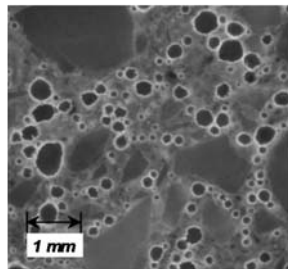


Figure 17 Water-dividing mixing procedure generating finer air bubbles with almost the similar total air content in concrete of around 10% (black bars: water-dividing mixing & dosage of AE agent: cX0.15%; white bars: standard mixing procedure & dosage of AE agent: cX0.005%)



a) Air bubbles by simple method



b) Air bubbles by water-dividing method

Figure 18 Example photos of air bubbles in mortar specimens

3.3 Current research on air-SCC

The authors have developed an air-enhanced self-compacting concrete. The unit cement content has been reduced to around 370 kg/m^3 , almost similar to that of the ordinary concrete requiring vibrating compaction.

The minimum air content for achieving the level of self-compactability specified in the standard of Japan Society of Civil Engineers (JSCE) was around 10% in concrete at this moment. The authors

are investigating for entraining finer air bubbles so that air content of the self-compactability may be reduced to around 5% (Fig. 19). The purpose is to increase the aggregate content or to promote strength with keeping the similar self-compactability to that of the current SCC now.

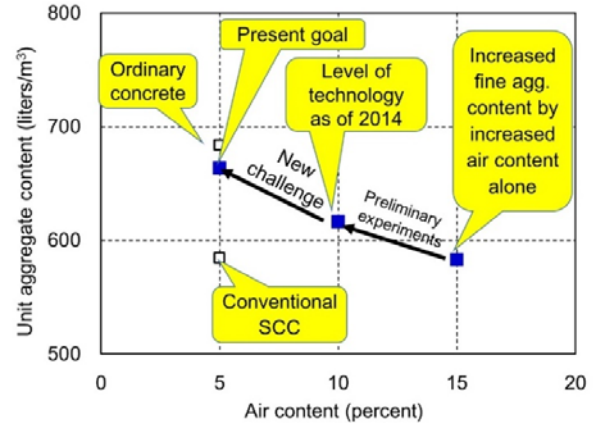


Figure 19 Present goal of air-SCC as a research

4. Summary

The history of Japan's SCC, originally proposed and developed as high-performance concrete was summarized. Despite the fact that Self-compacting high performance concrete offers various advantages in both at fresh (self-compactable) and hardened stage (high strength and durability), it has mostly been applied to special structures. The authors have understood that high-performance is not always welcome due to the cost for construction. Sufficient consumption is necessary for construction material despite its required strength and other performances.

A new type of self-compacting concrete (SCC) was developed based on the concept that reducing unit cost to be similar to conventional concrete and maintaining level of self-compactability as similar as SCC by application of entrained air. This new SCC with low unit cement content and air content of approximately 10% called air-SCC has been achieved by effective mixing procedure. The air-SCC possesses compressive strength similar to that of normal concrete with unit cement content of approximately 370 kg/m^3 . Moreover, unit cost of this concrete is slightly higher than that of conventional concrete. The air-SCC is alternative concrete material for structures requiring high level of compaction with moderate compressive strength.

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