Ferguson Lecture for 1996

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Self-Compacting High-Performance Concrete

by Hajime Okamura

It was a great pleasure and privilege for me to be named a Ferguson Lecturer, because about 30 years ago I studied under Prof. Ferguson at the University of Texas at Austin. Two papers,[1,2] published by ACI, were the fruit of my time spent with Prof. Ferguson.

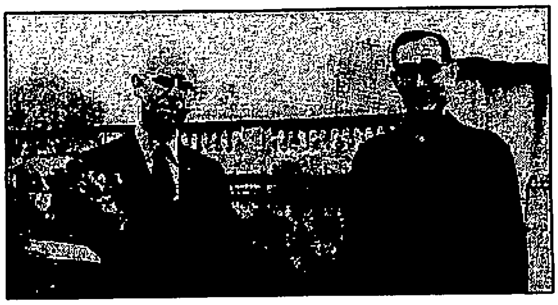
These research works involved computation using a program created by Prof. Breen.[3] His program, in which the nonlinearity of material and geometry was adopted, was at the forefront in its field at the time.

In the wake of Prof. Breen's work, we conducted research at the University of Tokyo.[4] Our two-dimensional FEM program simulates the nonlinear behavior of reinforced concrete under reversed cyclic load (Fig. 1). The success of the simulation derives from the accurate constitutive model of reinforced concrete that we were able to create.

Development of self-compacting high-performance concrete

Self-compacting concrete is mix that can be compacted into every corner of a formwork, purely by means of its own weight and without the need for vibrating compaction. In spite of its high flowability, the coarse aggregate is not segregated.

A model formwork was used to observe how well self-compacting concrete can flow through obstacles (Fig. 2). Concrete is placed into the right-hand tower, flows through the obstacles and rises in the left-hand tower. The obstacles were chosen to simulate the confined zones of an actual structure. The self-compacting concrete on the left can rise to almost the same level as on the right.



Prof. Ferguson (L) with Prof. Kokubu.

Similar experiments of this type were carried out over a period of about one year, and the applicability of self-compacting concrete for practical structures was verified. This research was started at the suggestion of Prof. Kokubu, another of my supervisors and an honorary member of ACI.

For several years beginning in 1983, the problem of the durability of concrete structures was a major topic of interest in Japan, and was even viewed as a major problem facing Japanese society. Sufficient compaction by skilled workers is required in order to realize durable concrete structures. 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. I therefore realized that the development of self-compacting concrete would be necessary to guarantee durable concrete structures in the future.

At first, we thought it would be easy to create this new con-

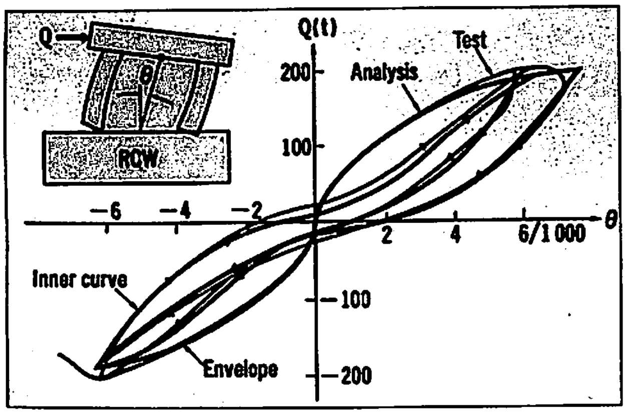


Fig. 1 — An example of finite element analysis (FEM).

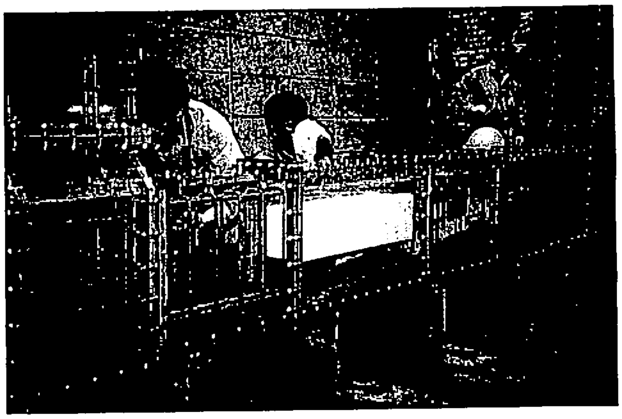


Fig. 2 — Model formwork simulating actual structures.

crete because antiwashout underwater concrete was already in practical use. Antiwashout underwater concrete is cast underwater and segregation is strictly inhibited by adding a large amount of a viscous agent made of water-soluble polymer; this prevents the cement particles from dissolving in the surrounding water. However, it was found that antiwashout underwater concrete was not applicable for structures in air for two reasons: first, entrapped air bubbles could not be eliminated due to the high viscosity; and second, compaction in the confined areas of reinforcing bars was difficult. Therefore, we started to investigate the workability of concrete.

This visualization experiment was developed by Prof. Hashimoto of Gumma University[5] (Fig. 3). The use of a transparent polymer material in place of the mortar allows us to observe the movement of coarse aggregate. The result of the experiment showed that blockage of the flow through a narrow cross section occurs as a result of contact between coarse aggregate. To prevent this, a moderate viscosity is necessary.

When concrete flows between reinforcing bars, the relative location of the coarse aggregate is changed. This relative displacement causes shear stress in the paste between the coarse aggregate, in addition to compressive stress. For concrete to flow through obstacles smoothly, shear stress should be small enough to allow the relative displacement. To better

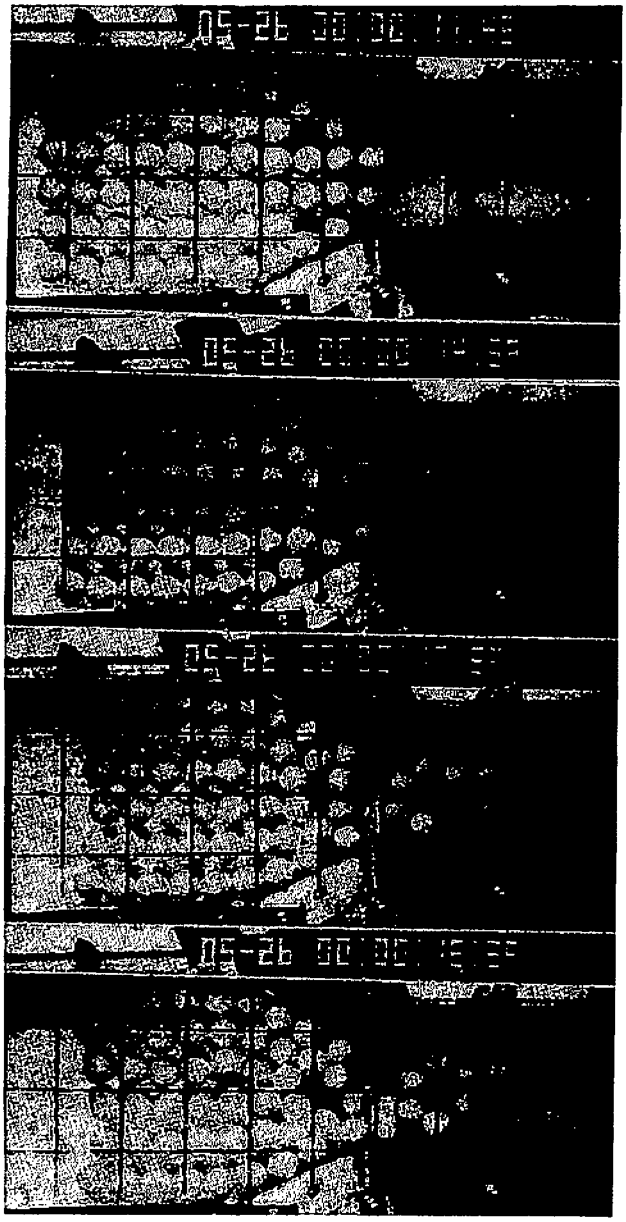


Fig. 3 — Visualization experiment.

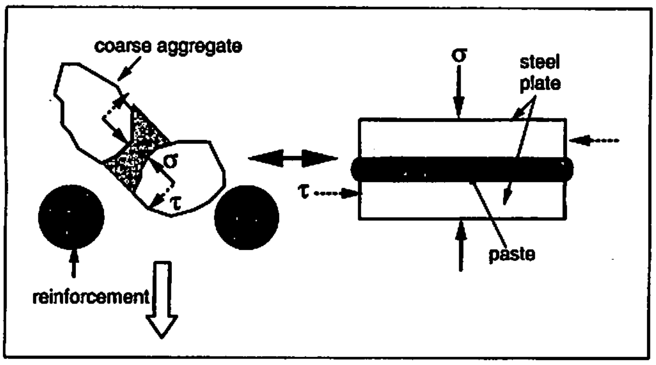


Fig. 4 — Stress generation due to relative displacement between aggregate.

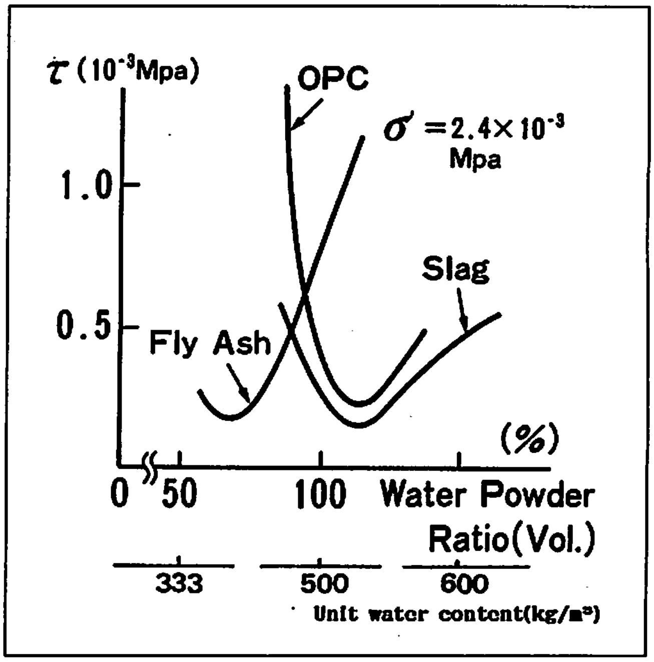


Fig. 5 — Relation between water-cement ratio and shear stress of paste.

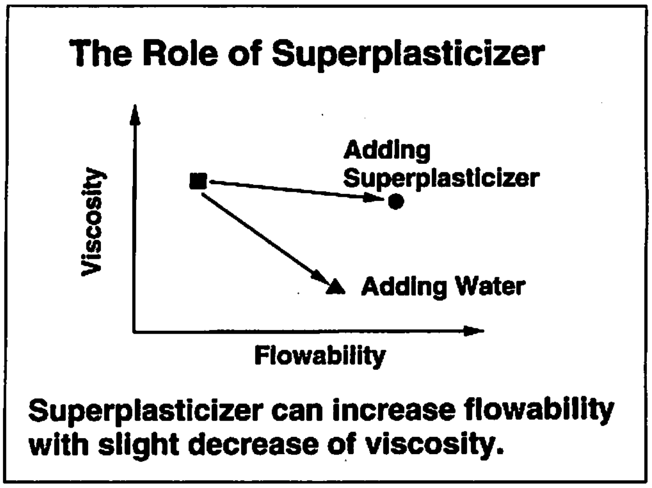


Fig. 6 — Effect of superplasticizer.

understand this type of shear stress, we carried out an experiment to simulate its generation; the experiment involved a pair of steel plates with paste between them (Fig. 4). The experimental results indicate that the shear force required for relative displacement largely depends on the water-cement ratio (*w/c*) of the paste. From this we derived an optimum *w/c* to minimize the generation of shear stress (Fig. 5).

However, while manipulating the *w/c* leads to improved flowability of the cement paste, it also leads to decreased viscosity. For the achievement of self-compactibility, therefore, a superplasticizer is indispensable. With a superplasticizer, the paste can be made more flowable with little concomitant decrease in viscosity (Fig. 6). An optimum combination of *w/c* and superplasticizer for the achievement of self-compactibility can be derived for fixed aggregate content concrete (Fig. 7).

As we have seen, blockage in a narrow section is directly due to the contact within the aggregate. If the coarse aggregate contact exceeds a certain limit, then blockage will occur in spite of the moderate viscosity of the mortar. The limiting value of coarse aggregate is around 50 percent of the solid volume.

Similarly, if the fine aggregate content exceeds a certain figure, direct contact between sand particles results in a decrease in deformabilty, again in spite of the moderate viscosity of the paste. The limit value of fine aggregate content in mortar is around 40 percent of the mortar volume (Fig. 8).

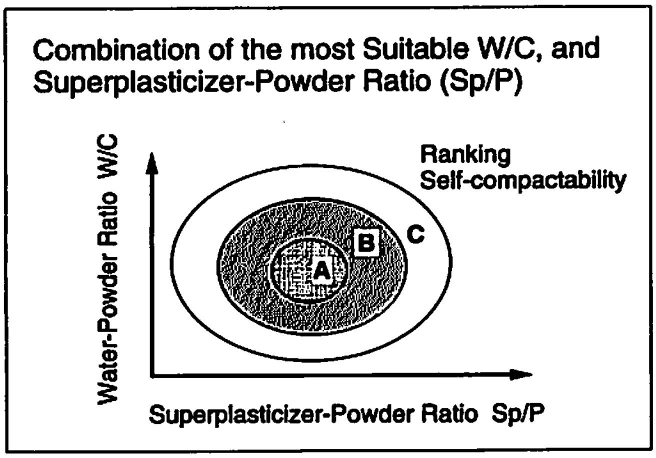


Fig. 7 — Optimum combination of superplasticizer dosage and water-cement ratio.

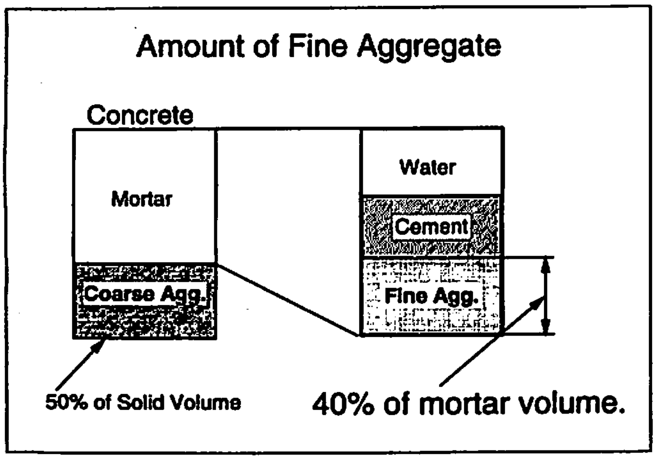


Fig. 8 — Proper fine aggregate content for self-compacting concrete.

We have proposed a simple mix proportioning system:

1. Coarse aggregate content is fixed at 50 percent of the solid volume.
2. Fine aggregate content is fixed at 40 percent of the mortar volume.
3. Water-cement ratio in volume is assumed as 0.9 to 1.0 depending on the properties of the cement.
4. Superplasticizer dosage and the final *w/c* are determined so as to ensure the self-compactibility.

Among the many test methods proposed for evaluating self-compactibility, the U-type test proposed by Taisei group[6] would seem, at this stage, to be the most appropriate (Fig. 9). In this test, the degree of compactibility can be indicated by the height that the concrete reaches after flowing through the obstacle.

Present situation

In the summer of 1988, Ozawa, now associate professor at University of Tokyo, succeeded in developing self-compacting concrete for the first time.[7] The year after that, an open experiment on this new concrete was held at the University of Tokyo, in front of more than 100 researchers and working engineers. As a result, intensive research was begun in many places, especially in the research institutes of large construction companies and at the University of Tokyo.

In 1991, researchers from 13 general contractors spent a year in our laboratory to study self-compacting high-performance concrete. In 1993, we published a book on the subject.[8] The number of presentations on self-compacting concrete at the annual meeting of the Japan Concrete Institute increased rapidly to 30 in 1992, a figure that has remained constant since then.

Akashi Straights Bridge

The use of self-compacting concrete in actual structures has been gradually increasing over the last few years. The Akashi Straits Bridge, now under construction, will be the longest suspension bridge (1990 m [6530 ft]) in the world. Self-compacting concrete was used in the construction of the two anchorages of the bridge (Fig. 10). A new construction system, which makes full use of the performance of self-compacting concrete, was introduced for this project.

The concrete was mixed at the batch plant beside the site, and was then pumped out of the plant. It was transported 200

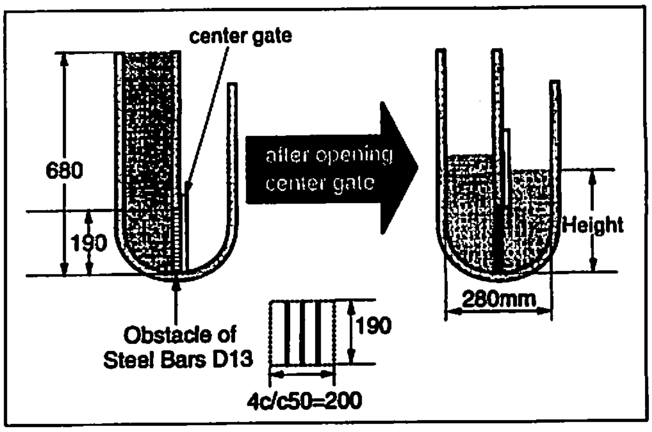


Fig. 9 — Self-compactibility evaluation test.

m (656 ft) through pipes to the actual casting site. At the casting site, the pipes were arranged in rows 3 to 5 m (10 to 16 ft) apart. The concrete was cast from gate valves located at regular 5 m intervals along the pipes (Fig. 11). These valves were automatically controlled so that a level surface of the cast concrete could be maintained.

The maximum size of the coarse aggregate in the self-compacting concrete used at this site was 40 mm (1.6 in.). The concrete fell as much as 3 m (10 ft), but segregation did not occur, despite the large size of coarse aggregate.

In the final analysis, the use of self-compacting concrete shortened the anchorage construction period by 20 percent, from 2.5 to 2 years.

Fig. 11 — Concrete being cast from gate valve.

Liquefied natural gas tank

Self-compacting high-performance concrete is slated for the wall of a large LNG tank (Fig 12). Adoption of self-compacting high-performance concrete will mean that:

1. The number of lifts will decrease from 14 to 10, as the height of one lift of concrete can be increased.
2. The number of concrete workers will decrease from 150 to 50.
3. The construction period of the structure will decrease from 22 months to 18 months.[9]

Since the degree of compaction of the self-compacting concrete used in a structure depends directly upon the quality of the concrete itself, with no possibility of skilled workers compensating for poor quality, it is vital that we have a manufacturing system capable of producing self-compacting concrete of the required quality. At this stage, I recommend a method to guarantee the self-compactibility of all the concrete placed in site. If the concrete flows through the apparatus at the site before pumping (Fig. 13), the concrete is considered self-compactible for the structure.

Self-compacting concrete can greatly improve construction systems previously based on conventional concrete requiring vibrating compaction. Vibratory compaction, which can easily cause segregation, has been a kind of obstacle to the rationalization of construction work.

Once this obstacle has been eliminated, concrete construction can be rationalized and a new construction system, including formwork, reinforcement, support, and structural design, can be developed. For example, Fig. 14 illustrates a so-called sandwich structure; here concrete is filled into a steel shell. I should stress that this sort of structure, part of which has already been completed in Kobe, could not have been achieved without the development of self-compacting concrete.

We hope and trust that self-compacting concrete will one

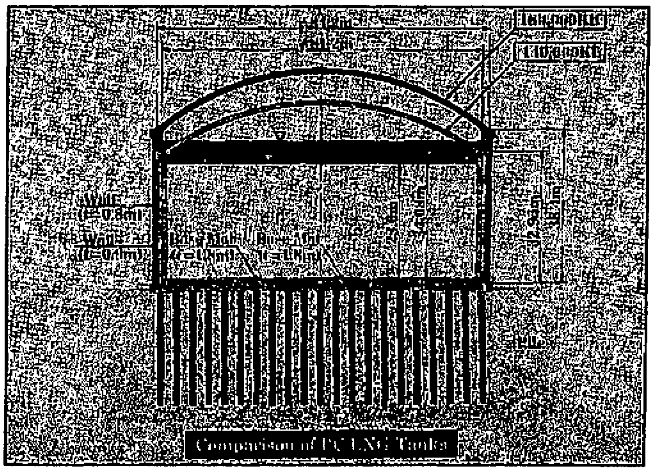


Fig. 12 — LNG tank.

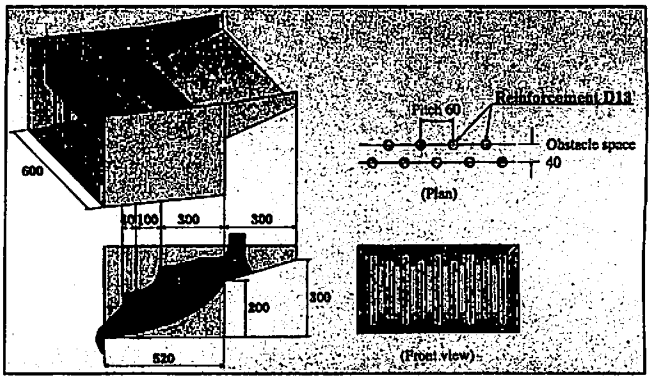


Fig. 13 — Apparatus to guarantee *self-compactibility*.

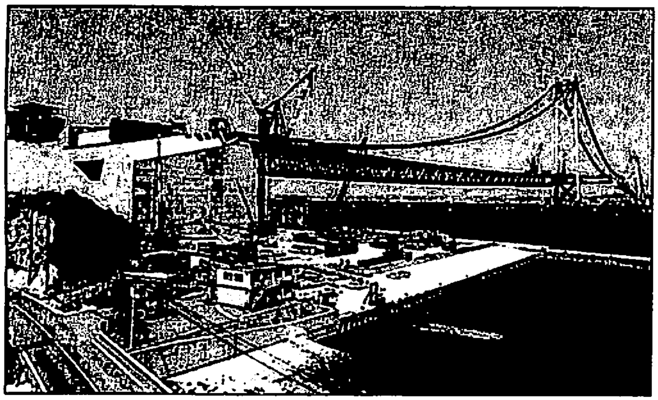


Fig. 10 — Akashi Straits Bridge and anchorage.

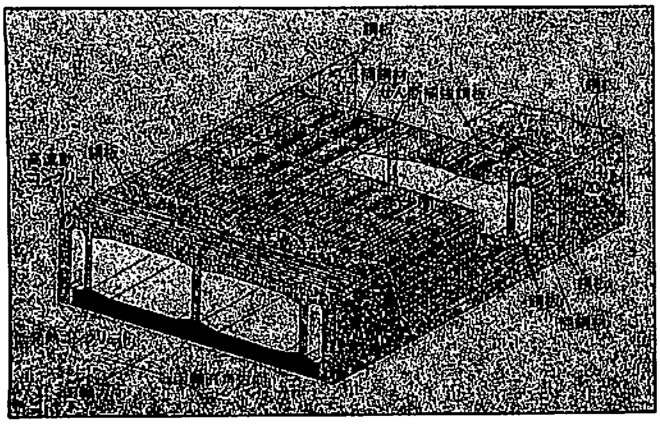


Fig. 14 — Sandwich structure.

day become so widely used that it will be seen as the "standard concrete" rather than as a "special concrete." When that happens, we will have succeeded in creating durable and reliable concrete structures requiring very little maintenance work.

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Selected for reader interest by the editors.

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