SELF-COMPACTING CONCRETE

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SUMMARY

Self-compacting concrete was first developed 1988 in order to achieve durable concrete structures. Since then, various investigations have been carried out and the concrete has been used in practical structures in Japan, mainly by large construction companies. Investigations for establishing a rational mix-design method and self-compactability testing methods have been carried out to make the concrete the standard one.

Keywords*: self-compacting concrete, development, self-compactability of fresh concrete, mix-design, testing methods for self-compactability, superplasticizer.*

DEVELOPMENT OF SELF-COMPACTING CONCRETE

For several years beginning in 1983, the problem of the durability of concrete structures was a major topic of interest in Japan. 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. One solution for the achievement of durable concrete structures independent of the quality of construction work is the employment of self-compacting concrete, which can be compacted into every corner of a formwork, purely by means of its own weight and without the need for vibrating compaction (**Fig. 1**). The necessity of this type of concrete was proposed by *Okamura* in 1986. Studies to develop self-compacting concrete, including a fundamental study on the workability of concrete, have been carried out by *Ozawa* and *Maekawa* at the University of Tokyo [**1**].

The prototype of self-compacting concrete was first completed in 1988 using materials already on the market (**Fig. 2**). The prototype performed satisfactorily with regard to drying and hardening shrinkage, heat of hydration, denseness after hardening, and other properties [**1**] [**2**]. This concrete was named “High Performance Concrete.” and was defined as follows at the three stages of concrete:

(1) Fresh: self-compactable

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(2) Early age: avoidance of initial defects
(3) After hardening: protection against external factors

At almost the same time, "High Performance Concrete" was defined as a concrete with high durability due to low water-cement ratio by Professor Aitcin et. al [**3**]. 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 our proposed concrete to "Self-Compacting High Performance Concrete."

SELF-COMAPCATBILITY OF FRESH CONCRETE

Mechanism for Achieving Self-Compactability

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 of reinforcing bars. *Okamura* and *Ozawa* have employed the following methods to achieve self-compactability (**Fig. 3**) [**4**]:

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

The frequency of collision and contact between aggregate particles can increase as the relative distance between the particles decreases and then internal stress can increase when concrete is deformed, particularly near obstacles. It has been revealed that the energy required for flowing is consumed by the increased internal stress, resulting in blockage of aggregate particles. Limiting the coarse aggregate content, whose energy consumption is particularly intense, to a level lower than normal proportions is effective in avoiding this kind of blockage.

Highly viscous paste is also required to avoid the blockage of coarse aggregate when concrete flows through obstacles (**Fig. 4**). When concrete is deformed, paste with a high viscosity also prevents localized increases in the internal stress due to the approach of coarse aggregate particles. High deformability can be achieved only by the employment of a superplasticizer, keeping the water-powder ratio to be very low value.

The mix-proportioning of the self-compacting concrete is shown and compared with those of normal concrete and RCD (Roller Compacted concrete for Dam) concrete (**Fig. 5**). The aggregate content is smaller than conventional concrete which requires vibrating compaction. The ratios of the coarse aggregate volume to its solid volume (***G***/***Glim***) of each type of concrete are shown (**Fig. 6**). The degree of packing of coarse aggregate in SCC is around 50% so that the interaction between coarse aggregate particles when the concrete deforms may become small. In addition, the ratios the fine aggregate volume to its solid volume (***S***/***Slim***) in the mortar are shown in the same figure. The degree of packing of fine aggregate in SCC's mortar is around 60% so that the shear deformability when the concrete deforms may be limited. On the other hand, the viscosity of the paste in SCC is the highest of the other types of concrete due to the lowest water-powder ratio (**Fig. 7**). That is effective in inhibiting segregation.

There are three purposes for self-compactability tests relating to practical purposes.

Test (1): To check self-compacable or not to the structure
Test (2): To adjust mix-proportion when the self-compctability is not sufficient
Test (3): To characterize materials

As Test (1), so-called U-test or Box-test (**Figs. 8, 9 and 10**) having the obstacle with higher requirement is recommended [**5**]. U-test was developed by the *Taisei*-group. In this test, the degree of compactability can be indicated by the height that the concrete reaches after flowing through an obstacle. Concrete with the filling height of over 300 mm can be judged as self-compacting. Box-test is more suitable for detecting concrete with higher possibility of segregation between coarse aggregate and mortar.

If the concrete is judged to be having insufficient self-compactability with test (1), the cause has to be detected quantitatively so that the mix-proportion can be adjusted. Slump-flow and funnel tests (**Fig. 11**) have been proposed for testing the deformability and viscosity respectively and the indices were also defined as $\boldsymbol{\Gamma c}$ and $\boldsymbol{Rc}$.

$\Gamma c = (Sfl_1\ Sfl_2 - Sfl_0^2)/Sfl_0^2$, Sfl_1, Sfl_2: measured flow diameter; Sfl_0: Slump cone's diameter

$Rc = 10/t$, t (sec): measured time (sec) for concrete to flow through the funnel

Flow and funnel tests for mortar or paste have been proposed to characterize materials used in self-compacting concrete, e.g. powder material, sand, and superplasticizer. The testing methods for the mortar properties were also proposed and the indices for the deformability and viscosity were also defined as Γm and Rm (**Figs. 12** and **13**) [**6**].

$\Gamma m = (d_1\ d_2 - d_0^2)/d_0^2$, d_1, d_2: measured flow diameter; d_0: flow cone's diameter

$Rm = 10/t$, t (sec): measured time (sec) for mortar to flow through the funnel

Larger Γm indicates higher deformability and smaller Rm indicates higher viscosity. Characterizing methods for materials were proposed by using the indices of Γm and Rm [**3.4**].

Factors of Self-Compactability in Terms of Testing Results

Factors composing self-compactability were described in terms of the test results of fresh concrete or mortar below.

(1) Influence of Coarse Aggregate Depending on Spacing Size

It is not always possible to predict the degree of compaction into a structure by using the test result on the degree of compaction of the concrete into another structure, since the maximum size of coarse aggregate is close to the minimum spacing between reinforcing bars of the structure. For example, the relationship between coarse aggregate content in concrete and the filling height of the Box-type test, the standard index for self-compactability of fresh concrete, is shown (**Fig. 14 and 15**). The relationship between the filling height through obstacle R1 and that through R2 varied depending on the coarse aggregate content. That test result shows that the influence of coarse aggregate on flowability of fresh concrete largely depends on the size of the spacing of the obstacle. It can be said that self-compactability of fresh concrete has to be treated as solid particles in addition to as liquid.

(2) Role of Mortar as Fluid in Flowability of Fresh Concrete

Sufficient deformability of mortar phase in concrete is required so that concrete can be compacted into structures by its self-weight without need for vibrating compaction. In addition, moderate viscosity as well as deformability of the mortar phase is required so that the relative displacement between coarse aggregate particles in front of obstacles when concrete is to flow through it can be reduced and then segregation between coarse aggregate and mortar can be inhibited. The necessity for the viscosity was confirmed by Hashimoto's visualization test.

The indices for mortar's deformability ***Γm*** and viscosity ***Rm*** were proposed by using mortar flow and funnel test results. The relationship between mortar's deformability and viscosity and self-compactability of fresh concrete is shown on condition that the coarse aggregate content is fixed (**Fig. 15**). It was found that the optimum combination of deformability and viscosity of mortar for achieving self-compactability of fresh concrete exists [**7**].

(3) Role of Mortar as Solid Particles

In addition to the role as liquid mentioned above, mortar plays a role as the solid particles. This property is so-called "pressure transferability", which can be apparent when the coarse aggregate particles approach to each other and mortar in between coarse aggregate particles is subjected to the normal stress (**Fig. 16**). The degree of the decrease in the shear deformability of the mortar largely depends on the characteristics of the physical characteristics of the solid particles in the mortar (**Fig. 17**).

For example, the difference in the relationships between mortar's and concrete's funnel speeds due to the different fine aggregate content in mortar are shown (**Fig. 18**). It was found that the relationship between mortar's and concrete's flowability cannot always be unique due to the difference in the characteristics of the solid particles in mortar even if the characteristics of the coarse aggregate and its content in concrete are the same.

A simple evaluation method for the stress transferability of mortar was proposed by using the ratio of the funnel speed of concrete with glass beads as the standard coarse aggregate (***Rcs***) to the speed of mortar (***Rm***) (**Fig. 19**). The higher stress transferability corresponds to the smaller value of ***Rcs/Rm***. The relationships between fine aggregate content in mortar and ***Rcs/Rm*** are shown (**Fig. 20**). The difference in the characteristics of the solid particles in mortar can be reflected by the value of ***Rcs/Rm***. The relationship between ***Rcs/Rm*** and the filling height of Box-type test, the index for self-compactability of fresh concrete, is shown (**Fig. 21**). It was found that the relationship was unique despite of the differences in the fine aggregate content in mortar or the characteristics of sand or powder particles [**8**].

(4) Influence of Coarse Aggregate -Content, Shape & Grading-

The influence of coarse aggregate on the self-compactability of fresh concrete, especially flowability through obstacle, can be equal despite of the shape of the coarse aggregate particle's shape on condition that the ratio of coarse aggregate content to its solid volume in concrete is the same (**Fig. 22**) (Matsuo, et. al., 1994). However, the influence of the grading

of coarse aggregate has also to be considered if the spacing of the obstacles is very close to the maximum size coarse aggregate. For example, the relationships between the size of the concrete funnel's outlet and the flow speed through it depends on the fineness modulus of coarse aggregate FM even if the property of the mortar phase is the same (**Fig. 23 and 24**). It was found out that the flow speed of the concrete through the funnel with the outlet width of 55 mm was largely influenced by the grading of the coarse aggregate.
The true nature of global environmental problems is a result of economic society systems due to the explosion of industrialization since the Industrial Revolution, in which mass production, mass consumption and mass disposal have been pursued. Such systems have caused the destruction of ecological system due to the use of land, natural resource and energy depletion, and water pollution, the emission and diffusion of hazardous substances and greenhouse gases, waste excretions, etc. Mankind has realized that these impacts exceed its allowable limit.

RATIONAL MIX-DESIGN METHOD

Self-compactability can be largely affected by the characteristics of materials and the mix-proportion. A rational mix-design method for self-compacting concrete using a variety of materials is necessary. *Okamura* and *Ozawa* have proposed a simple mix-proportioning system assuming general supply from ready-mixed concrete plants [**4**]. The coarse and fine aggregate contents are fixed so that self-compactability can be achieved easily by adjusting the water-powder ratio and superplasticizer dosage only.

(1) Coarse aggregate content in concrete is fixed at 50% of the solid volume.
(2) Fine aggregate content is fixed at 40% of the mortar volume.
(3) Water-powder ratio in volume is assumed as 0.9 to 1.0, depending on the properties of the powder.
(4) Superplasticizer dosage and the final water-powder ratio are determined so as to ensure self-compactability.

In the mix-proportioning of conventional concrete, the water-cement ratio is fixed at first from the viewpoint of obtaining the required strength. With self-compacting concrete, however, the water-powder ratio has to be decided taking the self-compactability into account because self-compactability is very sensitive to this ratio. In most cases, the required strength does not govern the water-cement ratio because the water-powder ratio is small enough for obtaining the required strength for ordinary structures unless the most of powder materials in use is not reactive.

The mortar or paste in self-compacting concrete requires high viscosity as well as high deformability. This can be achieved by the employment of a superplasticizer, which results in a low water-powder ratio for the high deformability.

CONCLUSIONS

Since both a rational mix-design method and an appropriate acceptance testing method at the job site have almost been established for self-compacting concrete, it is considered that the main obstacles for making self-compacting concrete widely used have been solved. The next task is to distribute the technique for manufacturing and construction of self-compacting concrete rapidly. Rational training and qualification systems for engineers should be introduced. In addition, new structural design and construction systems making full performance of self-compacting concrete should be introduced.

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

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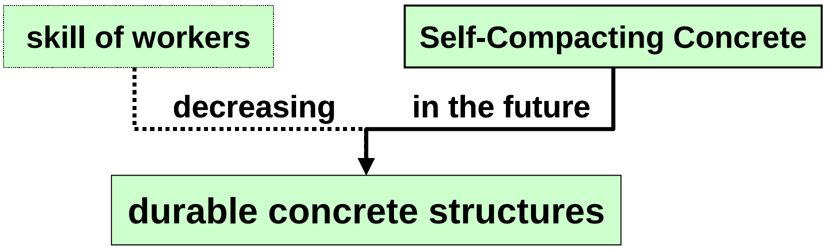

Fig. 1 Necessity for Self-Compacting Concrete

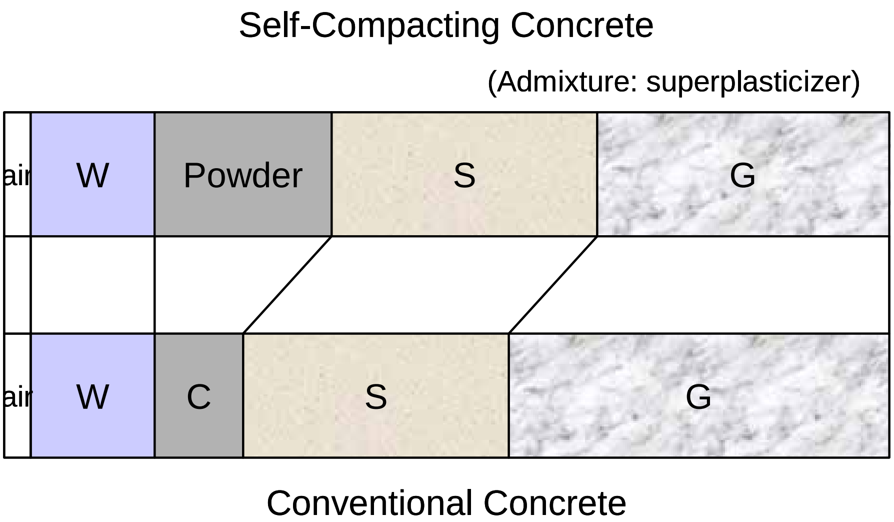

Fig. 2 Comparison of mix-prpoprtioning

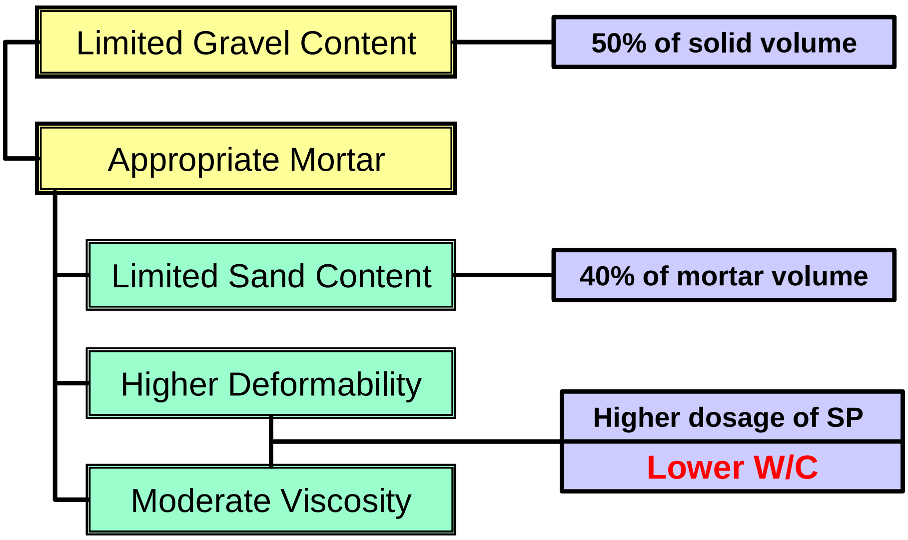

Fig. 3 Methods to achieve self-compactability of fresh concrete

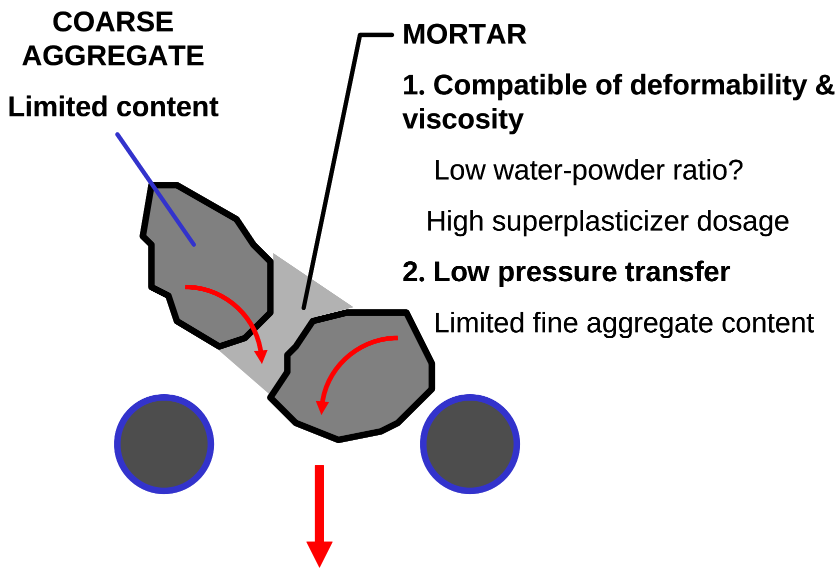

Fig. 4 Mechanism for achieving self-compactability

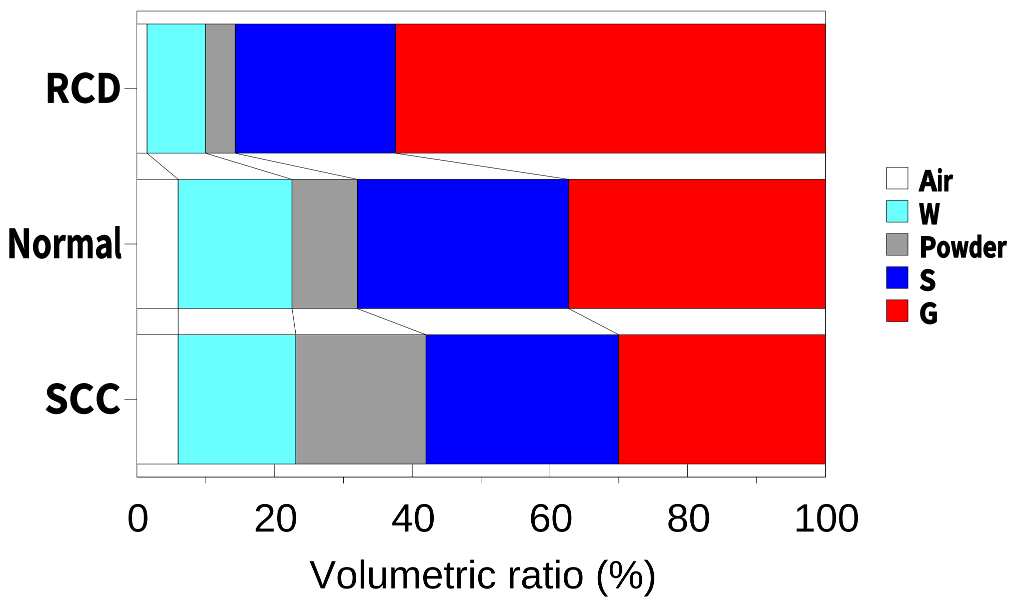

Fig. 5 Comparison of mix-Proportioning of SCC with other types of conventional concrete

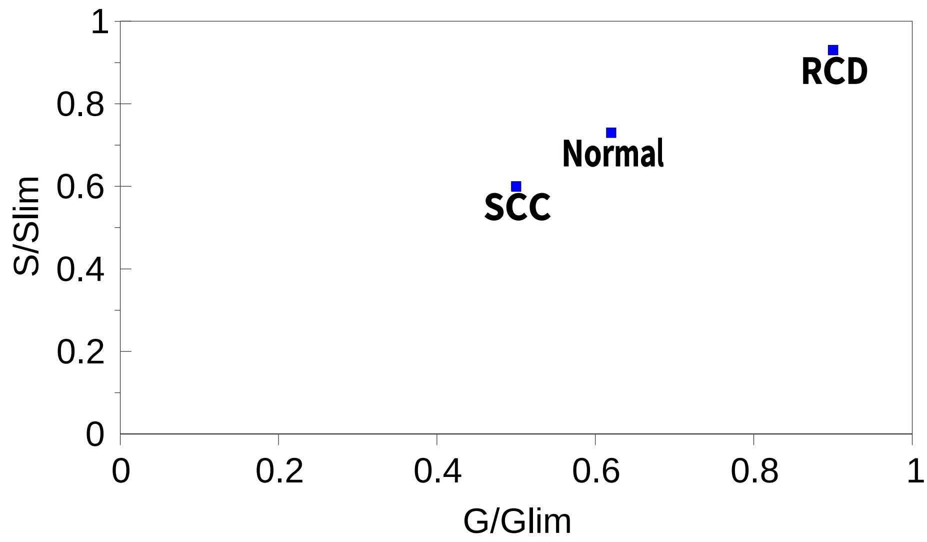

Fig. 6 Degree of aggregate's compaction to concrete or mortar -Coarse aggregate in concrete and fine aggregate in mortar

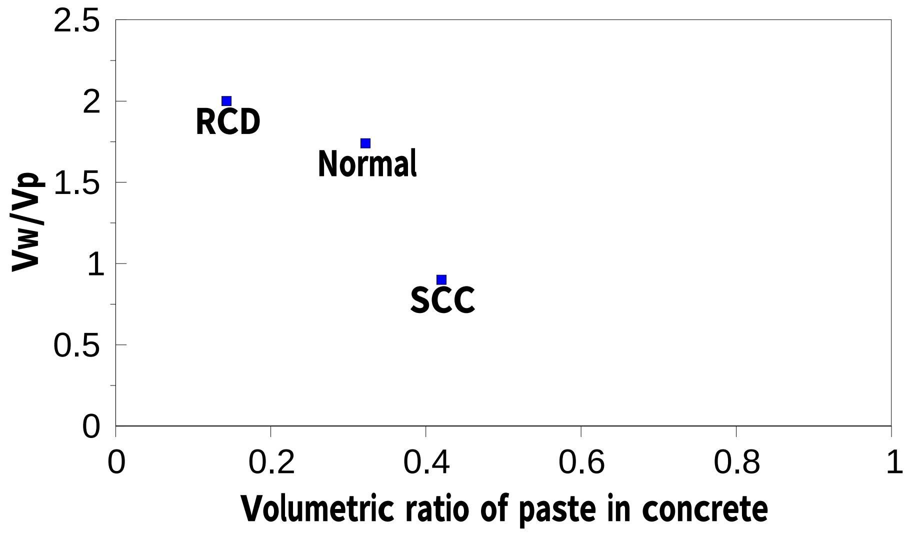

Fig. 7 Relationship between paste volume and water-powder ratio

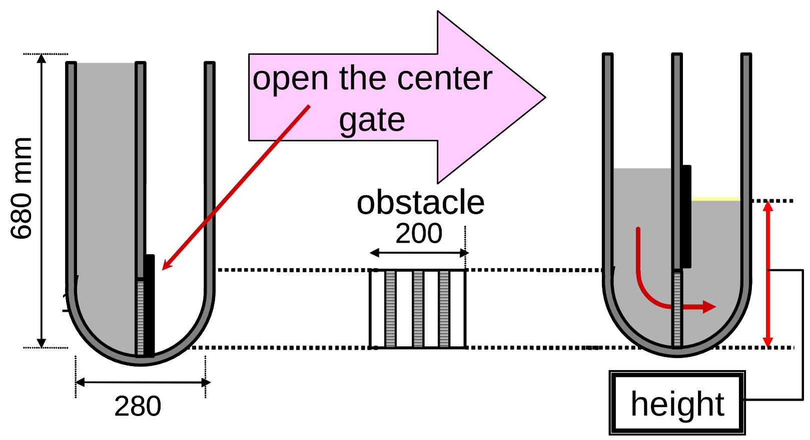

Fig. 8 U-test

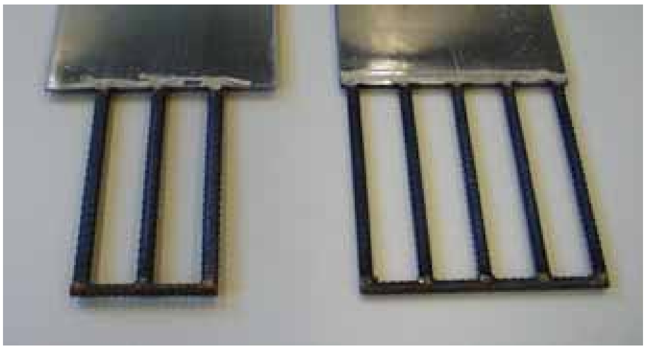

Fig. 9 Box-test **Fig. 10 Obstacles for box-test**

Fig. 11 V-funnel

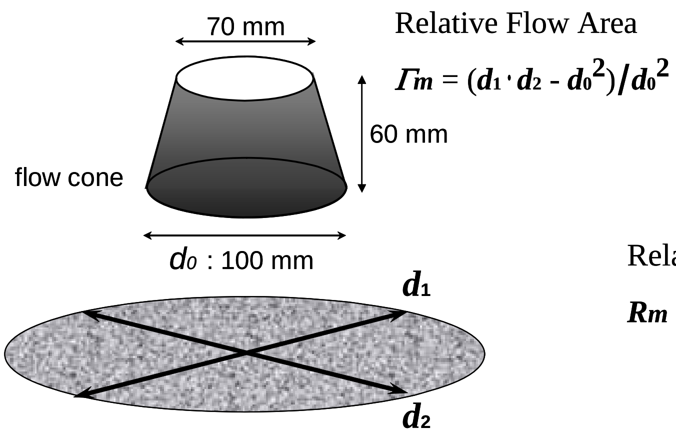

Fig. 12 Flow test for mortar

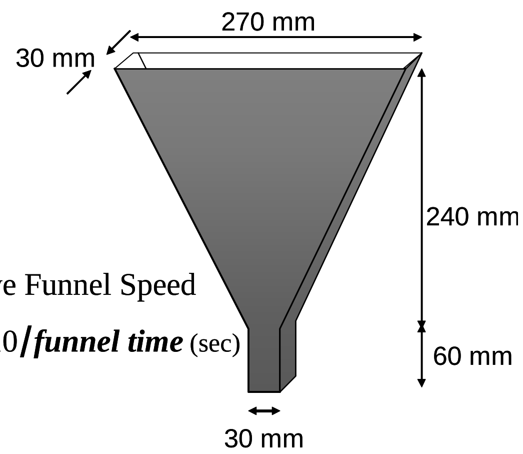

Fig. 13 Funnel test for mortar

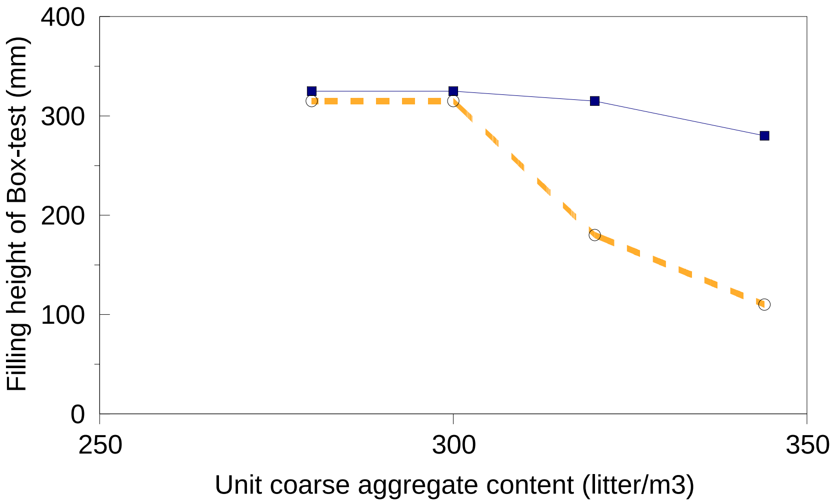

Fig. 14 Influence of coarse aggregate content on self-compactability

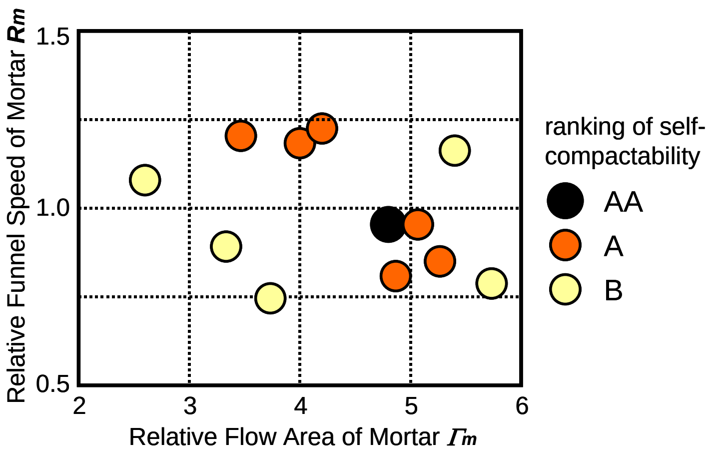

Fig. 15 Relationship between mortar’s flowability and self-compactability of concrete

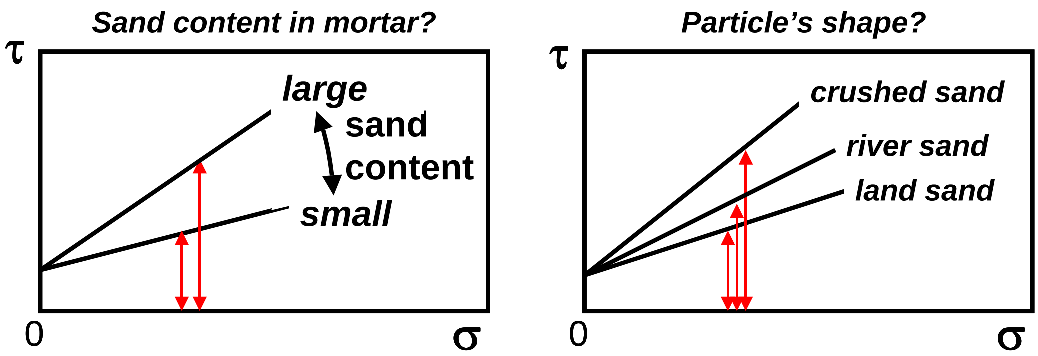

Fig. 16 Normal stress generated in mortar due to approaching coarse aggregate particles

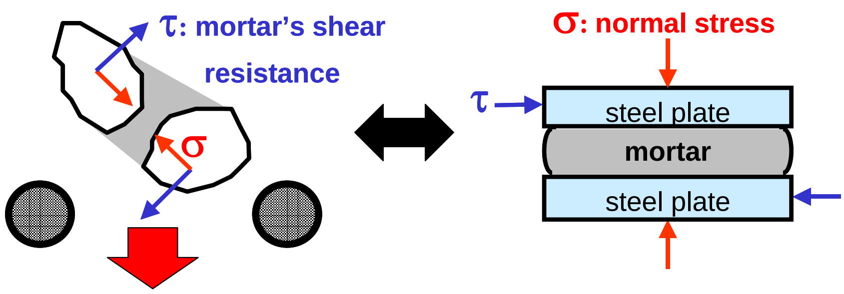

Fig. 17 Degree of increase in shear deform resistance τ due to σ depending on physical characteristics of solid particles

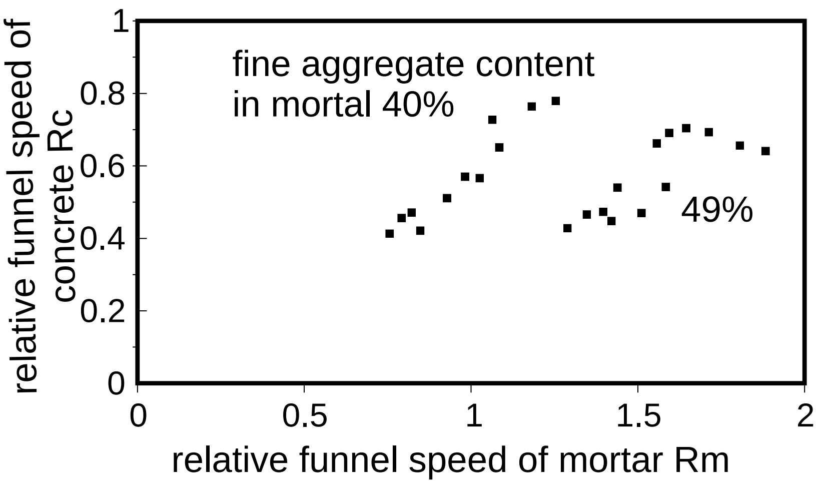

Fig. 18 Relationship between mortar's and concrete's flowability (V65 funnel)

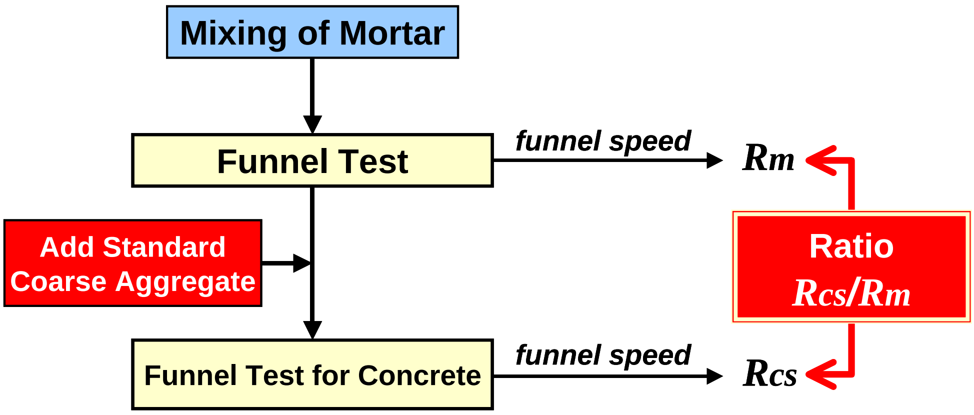

Fig. 19 A Simple Evaluation Method for Stress Transferability of Fresh Mortar

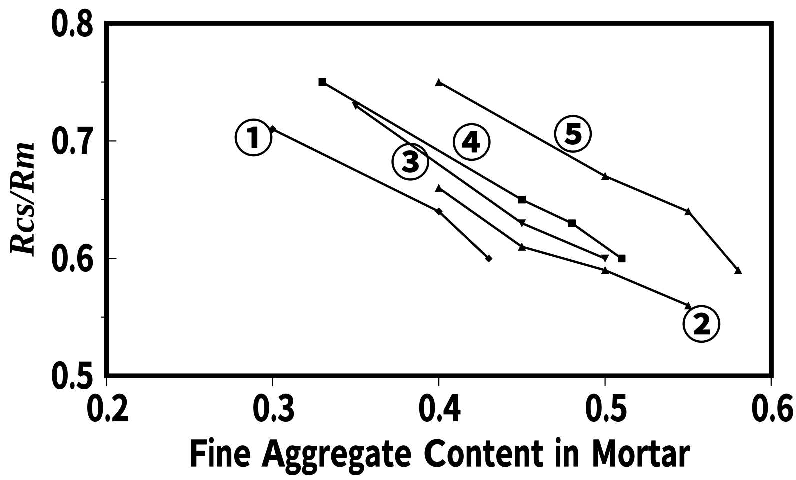

Fig. 20 Relationships between Fine Aggregate Content in Mortar and *Rcs/Rm*
[**1:** OPC+Crushed Sand(CS), **2:** Fly Ash (FA)+CS, **3:** FA+River Sand(RS), **4:** OPC + RS, **5:** OPC+Land Sand(LS)]

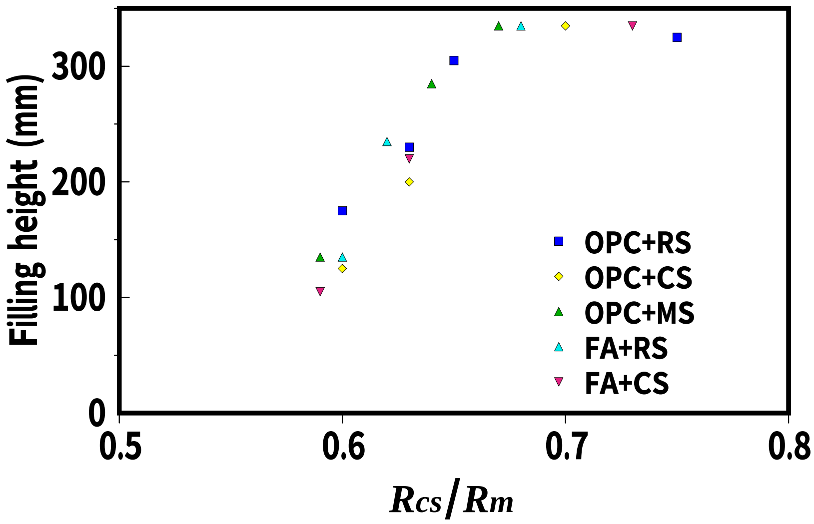

Fig. 21 Unique Relationship between *Rcs/Rm* and degree of self-compactability

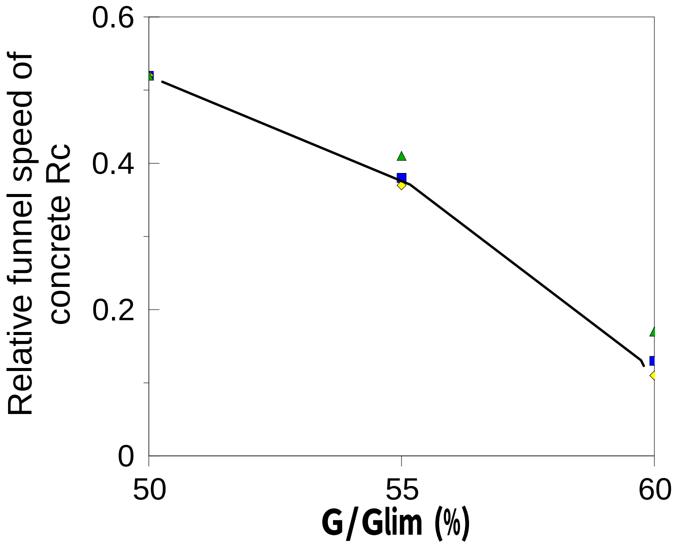

Fig. 22 Unique Relationship between G/G*lim* and flowability despite of difference in gravel shape

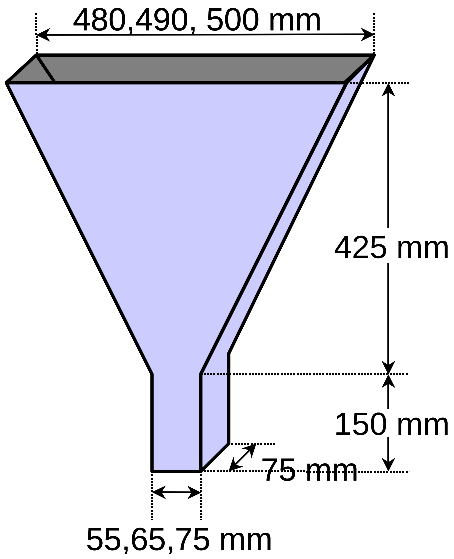

Fig. 23 Funnel for concrete with three types of outlet

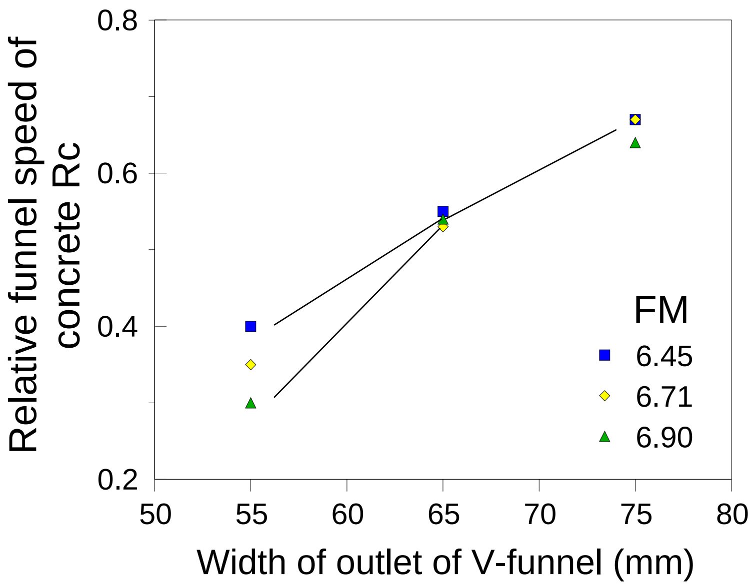

Fig. 24 Dominance of gravel grading for flowability through small spacing