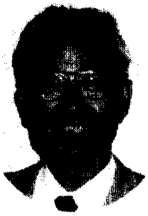
Self-Compacting High Performance Concrete
자기충전성 고성능 콘크리트



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1. Concept of Self-Compacting High Performance Concrete

Concrete is one of essential structural materials. However, careful placing by skilled workers on site is vital for constructing durable and reliable structures. Reduced durability resulting from improper placement is a major defect of concrete.

In order to improve the reliability of concrete, it is necessary to develop a concrete which is not affected by workmanship during placing, or in other words, a self-compacting concrete requiring no consolidation. In addition, the concrete should be such that the heat of hydration of the cement used is low and the shrinkage caused by hardening and drying is small in order to minimize the early-age defects. It should also possess sufficient resistance to carbonation as well as to the mobility of such corrosive factors for reinforcing steel as oxygen and water to be durable for a long period of time. The authors define a concrete possessing all of these properties here as Self-Compacting High Performance Concrete(Fig. 1).

1. Self-Compactability
   - high deformability
   - high segregation resistance
2. Little initial defect
   - high cracking resistance
3. High durability
   - small permeability

Fig. 1 Definition of self-compacting high performance concrete

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Self-Compacting High Performance Concrete produces durable and highly reliable concrete structures, saves labor during placing, eliminates consolidation noise. Many of new construction methods and materials that have recently been developed will find wider applications with enhanced effects, if they are combined with self-compacting concrete. For instance, it could be a scenario of a new integrated technology to place self-compacting concrete by using branch pipes in built-in forms impregnated with resin and fitted with steel reinforcement fabricated and assembled at a plant. Self-compacting concrete is an important element technology that provides the basis for future concrete technology(Fig. 2).

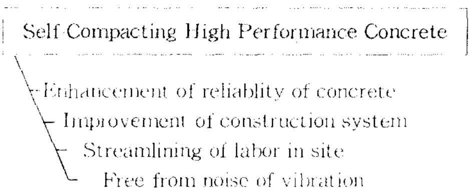

Fig. 2 Advantages of self-compacting high performance concrete

In 1986 at a concrete seminar sponsored by the Cement Association of Japan, Okamura advocated the development of a concrete requiring no consolidation, which is not affected by the workmanship in order to improve the reliability of concrete structures[1]. He pointed out that the durability and reliability of concrete is questioned though it is a durable material. One of the major causes for this is that consolidation work in the procedure of concreting is greatly affected by the human factor, requiring skill and experience. If a concrete requiring no consolidation is developed, the reliability of concrete structures must be greatly improved. He also stated that it is necessary to develop a well-balanced concrete, improving properties other than strength as well.

Concrete consists of water, cement, aggregates and a small amount of chemical admixtures. Aggregates account for approximately 70% of the total volume. The amount of water required for the chemical reaction is only 1/4 of the weight of cement. As far as the quality of hardened concrete is concerned, it is important to use the minimum amount of water required for producing concrete suitable for placing. It follows that careful consolidation is required in order to compact the concrete, which basically is an assortment of particles of various sizes and specific gravities, in the forms without causing segregation. In fact, however, the quality of concrete is affected in various ways by consolidation work, in which the human factor is critical. Consequently, the authors concluded that the most effective approach to a higher reliability of concrete is to make consolidation work redundant, and launched the development of consolidation-free self-compacting concrete.

The groundwork for self-compacting concrete had been laid. Supper plasticizers were on the market and antiwashout underwater concrete, which is a kind of underwater self-compacting concrete, was available. In the beginning the authors considered that a new admixture might be necessary for realizing self-compacting concrete. While requesting Prof. Uriu, an expert of polymer chemistry, to develop the new admixture, the authors explored the possibilites by combining various materials on the market. Attempts were made to produce a concrete with a high slump and little segregation by balancing a supper plasticizer with a viscosity agent, but it appeared impossible to realize the concrete by this method. Consequently, the authors returned to the starting point, and began reconstructing the concept of self-compactability by conducting fundamental experiments to investigate the basic properties of fresh concrete.

2. Concept of Self-Compactability

2.1 Control of segregation

The self-compacting concrete requires not only high flowability but also excellent resistance to segregation(Fig. 3). Concrete of low slump cannot be filled in a place where reinforcement is congested because of its insufficient flowability. An increase in the slump by an inceased unit water content will not improve the self-compactability, because particles of coarse aggregate are blocked by such obstacles as reinforcement. To obtain the self-compactability, it is necessary not only to increase the flowability, but also to control the blockage of the flow by the particles of coarse aggregate occurring near obstacles.

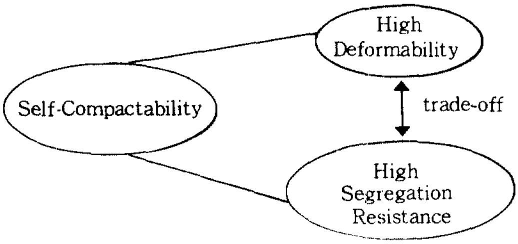

Fig. 3 Method of realizing self-compactability

2.2 Mechanism of coarse aggregate blockage during flowing

To control the blockage of coarse aggregate particles near obstacles, the authors attempted to clarify its mechanism, applying the technique of visualized experiments developed by Hashimoto(Fig. 4)[2]. As a result, it was confirmed that coarse aggregate particles coagulate, where the concrete flow is narrowed down, arch with one another and block the flow. It was also revealed that the coagulation of coarse aggregate particles is inhibited when the viscosity of mortar is increased. The same result was obtained where the flow is divided. When the viscosity of mortar is low, the deformation of the coarse aggregate phase is not uniform, and localized violent contact and crash between the particles were found to occur. When the viscosity is high, however, the localized deformation was restricted. Instead, the deformation of the coarse aggregate phase occurred uniformly.

Segregation during flowing is augmented not only by the difference in the specific gravities but also by crash and contact friction between coarse aggregate particles. To control segregation, it is very effective to increase the viscosity of the mortar or paste.

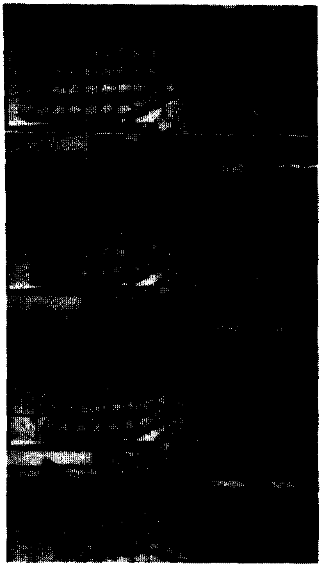

Fig. 4. Visualized test : Blockage of coarse aggregates around a tapered portion

2.3 Effects of particles of aggregates on self-compactability

An experimental study on the effects of the particles of aggregates on the self-compactability of fresh concrete revealed that the blockage of the flow by the arching of the particles of aggregates occurs whenever the average distance between the particles is less than a certain threshold value, and the threshold value changes with the properties of the paste phase(Fig. 5)[3]. It was also found that when the ratio of the representative diameter of the region where the concrete passes to the average diameter of aggregate is 10 or smaller, the ratio is in a linear relation with the critical aggregate content of causing blockage of the flow(Fig. 6).

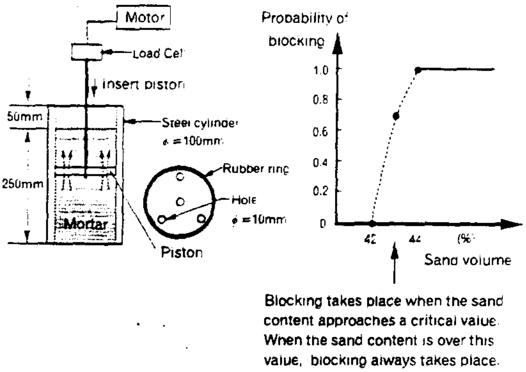

Fig. 5 Influence of aggregate content on blocking of concrete(Mortar is an imitation of concrete and sand is regarded as coarse aggregate)

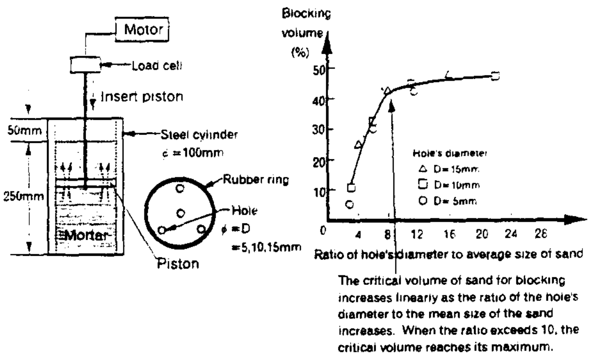

Fig. 6 Influence of ratio of hole's diameter to average size of sand on blocking of concrete

2.4 Effects of paste on friction resistance between aggregate particles

The difference in the transfer of stress by crash and contact friction between coarse aggregate particles also has marked effects on the self-compactability of concrete. As a result of a direct shear test on paste pressed between two steel plates(Fig. 7), it was made clear that the stress transfer mechanism between two solid bodies is determined by the combination of the so-called friction mechanism and adhesion mechanism, depending on the properties of the paste[3]. The adhesion mechanism is more advantageous as the stress transfer mechanism, because under this mechanism shear resistance is not increased by the increase in the direct stress between the particles of the aggregate when they approach one another.

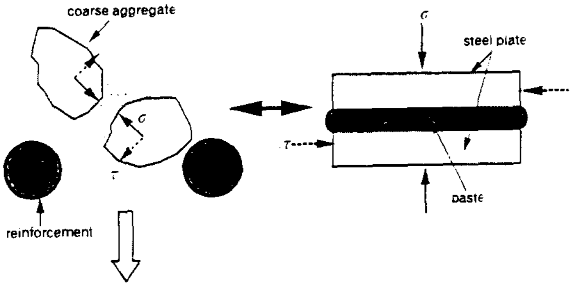

Fig. 7 Comparison of fresh mortar/paste around re-bars and between steel plates

The stress transfer mechanism between solid bodies is governed by the amount of free water and the viscosity of the paste, which are affected by the water-powder ratio, type of powder, and dosages of the superplasticizer and viscosity agent. The balance between the friction and adhesion mechanisms varies depending on these factors. There is a point where the combined effects of both mechanisms result in minimum shear resistance(Fig. 8). If this point is successfully obtained, the transferred shear force between particles of aggregate can be effectively reduced, and thus coagulation of the particles and blockage of the flow can be prevented.

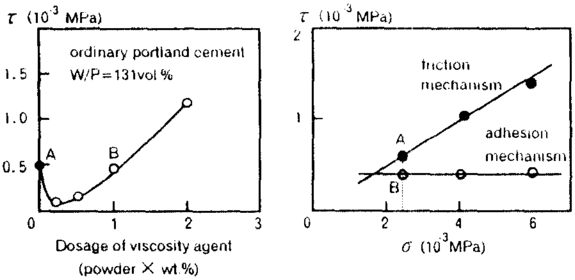

Fig. 8 Balance between friction and adhesion mechanisms on shear transfer in paste

3. History of Development

Having constructed the concept from the above results, the authors commenced attempts to actually produce self-compacting concret. In the summer of 1988, they successfully completed the prototype of self-compacting high performance concrete by combining materials on the market[4]. This prototype proved to have a practically satisfactory performance with regard to drying and hardening shrinkage, heat of hydration, denseness after hardening and other properties.

The prototype is proportioned to have a slightly lower coarse aggregate content and a slightly higher powder content than conventional air-entrained concrete. When compared with the mix proportions of antiwashout underwater concrete, this has a similar aggregate content and a smaller water content. Its slump flow is designed to remain unchanged for 90 min after mixing by the use of a superplasticizer of the low slump loss type. A superplasticizer is a material essential for enhancing the flowability without increasing the unit water content.

In addition to normal portland cement, fly ash, ground granulated blast-furnace slag and an expansive agent are employed as powders. Fly ash is used for enhancing the flowability without increasing the unit water content and the heat of hardening . Fine ground granulated blast-furnace slag contributes to adjusting the grading of normal portland cement, as well as to imparting adequate viscosity. The expansive agent is for compensating the early-age shrinkage. A small dosage of a viscosity agent is also added to impart adequate viscosity to the concrete.

After having succeeded in developing the prototype, the authors conducted an open experiment, inviting more than 100 engineers, on the campus of the University of Tokyo(Fig. 9). Naturally the experiment created a sensation among the guests. Some of the engineers who supervise construction sites wished to use the concrete immediately. However, the authors had a lot more to do.

Fig. 9 Open experiment in July, 1989

A number of experiments to confirm the self-compactability have been reported. The concrete has been used for actual constructions. Precast concrete plants start to manufacture products by using self-compacting concrete on a commercial basis. New forms of construction, such as composite construction of steel plates and self-compacting concrete, are being constructed. For the commercialization of the concrete in its real sense, however, there still remain subjects to be studied. Therefore, great care is currently exercised when applying this concrete, such as obtaining confirmation by construction experiments and strict production control of ready-mixed concrete. Real commercialization will have been accomplished when these concerns have become redundant and a new system is established, in which self-compacting concrete can be purchased anytime over the phone and highly reliable and durable structures are assured.

3.1. Cement

The self-compactability depends greatly on the properties of powders, and the properties of powders are a critical factor governing the durability of hardened concrete. Consequently, it is necessary to develop cements for this type of concrete excellent in self-compactability and in durability after hardening. A committee was organized in the Cement Association of Japan, aiming for the development of such cements. The committee has proposed that the cement be based on moderate-heat portland cement, yet has not proceeded to the establishment of a quality standard. Lately low-heat portland cements have been developed.

3.2 Mix proportion

At present no established system is available for designing the proportions of concrete which is outside the scope of conventional slump tests. Therefore, the establishment of a theory for mix proportion of self-compacting concrete is necessary. A system of evaluating the self-compactability is also required with respect to actual structures, because this concrete is useless unless it is judged or guaranteed in advance to be self-compactable. The authors have suggested a method to make a mix design of self-compacting concrete(5).

3.3 Production

The quality of self-compacting concrete is determined at the time of production, and cannot be improved during placing. It is therefore necessary to construct a system to ensure the production and control of concrete of the required quality. To ensure stable supply, the highest present production system at ready-mixed concrete plants should be required.

Since the self-compactability is achieved with a low water content relative to the powder content, fluctuation of the water content must be minimized and the mixing time should be slightly extended so as to make the most of its performance. It will require a production system whereby the surface moisture can be controlled accurately and mixing efficiency is good. Such a production system is feasible by combining existing state-of-the-art technologies. A production system with 2-stage mixing is a possiblity to produce uniform quality by automatically controlling the fluctuations of materials, especially surface moisture of fine aggregate. The upper mixer detects fluctuations of surface moisture by the load on the mixer, and the lower mixer corrects it, stabilizing the output quality. Such a system may improve the mixing efficiency as well.

The Research Committee on Concrete Production System of the Japan Concrete Institute published the results of a study on new systems of producing high-quality concrete rationally. If the concrete is produced by this system, the quality of concrete produced could be assured by ready-mixed concrete manufacturers. The Small Business National Corporation adopted, as one of the subjects of technology development for 1991, an energy-saving system for manufacturing concrete products, and has been formulating a concept design of an energy-saving concrete production system. This will pave the way for full-automatic control concrete plants and the streamlining of production lines in precast concrete plants.

4. Effects of Propagating

4.1 Modernization of construction by the streamlining of concreting systems

Self-compacting high performance is a material which can bring about a drastic change in the concreting system premised on consolidation. Because this concrete is consoli- dation-free, concreting systems can be streamlined, and require less manpower, leading to the modernization of concreting. It is expected to lead to the development of an comprehensive rational concreting system, including formwork, reinforcement, shoring, and structural design, if all goes well.

The state of the construction industry in Japan is beginning to change radically. Construction engineers and workers are in short supply. Construction under extraordinary conditions is increasing and the demand for structures of higher performance is growing. Self-compacting concrete enables structures of high reliability to be constructed without being affected by workmanship and brings about the benefit of radical rationalization of construction systems on construction sites.

Because of the need for consolidation during placing, construction using conventional concrete is restricted in many ways. Restriction on the height of a lift of placing. Necessity to construct the scaffolding for consolidation work and necessity for separate placing of the bottom and walls of box-section members. If consolidation is unnecessary, construction systems can be streamlined without being disturbed by such restrictions. The possibility of new construction forms will become stronger. For instance, steel-concrete sandwich construction, which has been impracticable due to problems in placeability, mainly in concrete placing, could be realized. A construction method, in which concrete is just pumped into built-in forms which are assembled with steel reinforcement fabricated and constructed in a plant, is possible if consolidation is not required. The develpment of construction systems is anticipated, which are to be rationalized in a variety of aspects, such as the reduction in the number of workers on site, reduction in the number of skilled workers required, constant number of workers required throughout the construction period, shortened construction period, non-interference of the elements, and improved safety.

Self-compacting concrete will make a key contribution to the modernization of construction, if comprehensive construction systems covering materials, production, and quality control are formulated and rationalization and labor saving are attempted in those systems.

4.2 Noise abatement and modernization of precast concrete plants

Reduction of consolidation noise is a nagging concern for precast concrete plants and construction sites in urban areas. The noise is not only an environmental problem for people in the neighborhood, but also an issue of industrial hygiene for the workers. Needless to say, the problem disappears if vibratory consolidation is excluded from the procedure. It is not simply exclusion of consolidation work, but an opportunity to radically review production lines etc. and carry out further modernization.

4.3 Durability design

The performance required of concrete structures is generally divided into 3 element : safety, durability, and functionality. It is the task of concrete engineers to formulate a structural design, material design, and scheme of execution to satisfy these required elements so as to ensure the quality of the structure. It has been difficult to evaluate accurately the durability of structures, because durability is highly sensitive to the factor of construction work, which largely consists of uncertain elements.

Use of a self-compacting concrete must facilitate the evaluation of durability, because fluctuations due to workmanship at the time of concrete placing are eliminated. This demands a system of quantitatively grasping the durability, a durability checking system, such as those used in structural design for checking safety. Such a system enables not only quantitative checking of durability, but also the material design of concrete based on the durability.

Material design by this durability checking system will be carred out as follows. The cross-sectional shapes and reinforcing bar arrangement are determined by a structural design from such conditions as safety and functionality, and the construction system is determined by a scheme of execution. A concrete material design is formulated, so as to satisfy the required durability under these conditions. Material design consists of selection of materials and mix design to realize self-compactability. Then the durability of the concrete of the determined materials and composition is checked by the durability checking system for whether the requirements are satisfied under the given environmental conditions. As a result of this checking, it is to be used if the con crete passes. If not, the procedure is to be repeated again from the material selection. Self-compacting concrete satisfying the required durability is designed.

Thanks to the development of various admixtures, a wide selection of materials are available, and concrete can now easily be furnished with a variety of properties which could have hardly been possible with conventional materials. In these circumstances, the conventional material design methods naturally become irrelevant. The authors reviewed the capabilities required of concete, established a durability checking system, and reconstructed the material design methods by returning to the fundamentals of concrete.

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