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Application of Super Workable Concrete to Reinforced Concrete Structures with Difficult Construction Conditions

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Synopsis: Recently in Japan, "Super Workable Concrete", that has higher flowability and filling capacity, has attracted attention as being effective in rationalization of concrete execution. It can be applied for simplifying placing work while securing high quality of reinforced concrete structures. Especially, in case of heavily reinforced structures, it is highly applicable beause of its excellent filling capacity or less consolidation effort.

The authors have been occupied with studying improvement of workability of some special concretes for several years, such as Anti-Washout Underwater Concrete , Expansive Grouting Concrete for inverted placement and Ultra High-Strength in-site concrete, and have consequently succeeded in developing Super Workable Concrete, suitable for rapid placing or perfect filling without consolidation. The authors also have established a new evaluating method for segregation resistance of mortar and aggregate, that is useful to design mix proportion, or keep high quality of Super Workable Concrete in site.

Recently, opportunities to apply Super Workable Concrete to several actual structures with difficult construction conditions have arisen. One is a LNG(liquefied nitrogen gas) storage inground tank, that has much complicated reinforcement at the junction of base mat and side wall, another is a thin and tall reinforced concrete wall, that must be placed from upper point, 6-8 m in hight.

This paper describes the basic properties of Super Workable Concrete, the new method of quality control, and a summary of applications to reinforced concrete structures mentioned above.

Keywords: Durability; flowability; mix proportioning; placing; quality control; reinforced concrete; segregation; viscocity; workability.

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INTRODUCTION

Recently in Japan, as concrete structures have become large in scale, or of more complicated shape, or smaller in thickness of members accompanying with high strength concrete, placing or consolidation becomes more difficult to perform, and at worst, it may bring about decrease in durability of concrete structures. On the other hand, socially speaking, skillful working staffs for concrete execution have become fewer or aged, so rationalization of concrete placing and consolidation have been demanded in site. For these reasons, study and development of superior concrete in flowability and filling capacity (1) have been advanced, by researchers of construction companies or universities (2).

The authors also have been studying more workable on-site concrete for years, and have finally succeeded in developing"Super Workable Concrete",suitable for rapid concrete placing or improvement of placeability. Super Workable Concrete, which can be placed without compaction or vibration, is expected to be effective for rationalization or automation of concrete execution.

In order to design mix proportion of Super Workable Concrete,it is important to evaluate segregation resistance quantitatively, but evaluation methods have not been established yet. So the authors have been studying evaluation methods for segregation resistance, and have devised a simple evaluation method using a large funnel, measuring flow-out time.

Recently, opportunities to apply this new concrete to several actual concrete structures with difficult construction conditions have arisen as follows,

1) LNG storage inground tank with heavy reinforcement,
2) thin and tall wall placed from higher point.

This paper describes the experimental results of mix test, shows new technics, such as combining method of cementitious materials, design concept of mix proportions of Super Workable Concrete, evaluating method for segregation resistancere, and refers to some results of real-scale model placement and special application for actual constructions mentioned above.

STUDY OF WORKABILITY

Workability of Super Workable Concrete

It is thought that workability of Super Workable Concrete is mainly consist of "flowability"(or deformability) and "segregation resistance"(that is obviously affected with viscosity), those are most dominant properties to obtain good filling capacity (1). Flowability is generally estimated by slump (or "slump-flow" that is defined as an average diameter of concrete sample after slump test), but it has not established how to estimate segregation resistance yet (here, segregation means separation of mortar and coarse aggregate). Accordingly, the authors decided to devise a new estimation method, that seemed to be most important item to evaluate workability of Super Workable Concrete, and have been studying several types of testing methods for segregation resistance (3). After all, the authors reached a new evaluating method, using a large funnel, shown in Fig.1, measuring flow-out time of cocrete by stop watch.

Segregation resistance is estimated by the mean flow-out rate at lower straight duct in Fig.1, that is an average of three measurements. Fig.2 shows the relationship of slump-flow and flow-out time of three typical mixtures, those are extremly different in unit powder content (here,"powder" means cement, mineral admixtures and inactive fillers), or water-powder ratio, that affects viscosity. It is obvious that flow-out time of these three mixtures are different, and that of each mix is almost constant when slump-flow may change. Thus, this testing method is proved to be able to evaluate some property independent to flowability, and be useful for judgement of apparent viscosity or segregation resistance of Super Workable Concrete.

It is also known that the degree of fluctuation of three measured values shows the degree of trend of segregation. Fig.3 is an example which shows the influence of unit coarse aggregate volume on flow-out time. When unit aggregate volume becomes as large as 380ℓ/m^3, coarse aggregate is condensed at bottom of funnel during flowing, so collision or blocking may often happen, and the degree of fluctuation of three measured values may increase, consequently with an increase of mean flow-out time. Similarly, when segregation resistance of mix is extremly low, collision or blocking happens partially, so concrete flow becomes unstable and the degree of fluctuation becomes remarkable. Thus, new evaluating method is very simple and easy, and it seems to be effective to judge segregation resistance of Super Workable Concrete.

Flowability and Cementitious Powder

In order to obtain higher flowability (or expanded slump-flow), it is generally known that an increase in unit water content or dosage of water-reducing agent (or superplasticizer) is designed. But, excessive increase of water causes less durability or cracking in reinforced concrete structure, and excessive dosage of superplasticizer causes delay of setting time or slow development of early strength. So additional coutermeasures mentioned below are usually adopted.

In order to grasp a influence of mineral admixtures or mix proportioning on flowability or segregation resistance, 4 series of tests shown in Table 1 were carried. Then materials used for concrete are shown in Table 2 (aggregates are S-1 and G-1) .

Fig.4 shows the relationship of mineral admixture content and slump-flow, under constant condition of unit powder, water and aggrgate volume and dosage of superplasticizer. It is obvious that flowability of concrete may change remarkably, when ordinary portland cement is partially replaced with fly ash or granulated blast-furnace slag powder, and that combination of these two admixtures, 30% of fly ash and 50% of slag powder by volume, shows the highest flowability. Thus, combination of proper percentage of cementitious powders can remarkably improve the flowability of concrete.

Fig.5 shows the relationship of unit powder volume and slump-flow, under constant condition of unit water and aggregate volume. It is obvious that flowability of concrete may increase in accordance with increase of unit powder volume, and the change between 120-140 ℓ/m^3 is seemed to be relatively large. Fig.6 shows the relationship of unit powder volume and dosage of superplasticizer(SP-N, see Table 2), under the condition maintaining the same slump-flow. In this result, when unit powder content decrease, dosage of superplasticizer increase, and it becomes too much especially under than 140 ℓ/m^3 of powder volume. Thus, considerably smaller volume of unit powder causes excessive addition of superplasticizer, so there may be some proper range of unit powder volume for a given flowability.

Filling Capacity and Segregation Resistance

As mentioned above, flow-out rate test with a funnel can evaluate the characteristic concerning with segregation resistance, and when viscousity is high enough to maintain a stable flow, the lower flow-out rate indicates higher segregation resistance. But, when viscousity becomes low enough to be unable to maintain a stable flow, the lower rate and large fluctuation indicate a happening of segregation of mortar and coarse aggregate at the narrow gaps, and blocking may happen at worst. When unit coarse aggregate volume becomes excessively large as shown in Fig.3, similar phenomenon may happen. Thus, segregation resistance of concrete as passing through the narrow gaps (between reinforcements) seems to be affected with both viscousity of mortar (or cement paste) and coarse aggregate volume (4). Accordingly, filling capacity of Super Workable Concrete, especially to a narrow gaps or among much reinforcing bars, may be affected with flowability (or deformability), viscousity and aggregate volume, then the first property can be evaluated by slump-flow, the others are thought to be evaluated by flow-out rate test or analogous methods.

The evaluating method for segregation resistance, such as flow-out rate test with a funnel, can be also used for evaluation of passing capacity through narrow gaps, as mentioned above. If no blocking (or no segregagaon) may happen at this test, it must be thought that workability of concrete is relatively better as passing rate is faster (5). Namely, too much high resistance to segregation is not always needed for Super workable Concrete, as it may resist a smooth flow, and flow rate becomes seriously low. In other words, it seems to be right that proper range of segregation resistance of mix may exist in accordance with a space of reinforcing bars or placing conditions.

<u>Segregation Resistance and Cementitious Powder</u>

Fig.7 shows the influence of mineral admixtures on flow-out rate, using fly ash and blast-furnace slag powder. In this case, unit powder volume, unit water content and aggregate volume are constant, with maintaining same slump-flow (60 ± 3cm) by superplasticizer. Mean flow-out rate gradually increases in accordance with an increase of replacement by fly ash. It also increases by replacing with slag powder, but influence of increase of replacement by slag powder seems to be little. In this result, replacement by 40% of fly ash may obtain as twice fast as ordinary portland cement only, and replacement with a combination of 50% of slag powder and 30% of fly ash can perform as fast as 2.5 times of flow-out rate. Thus, it is possible to control the viscousity of Super Workable Concrete by using different type, shape or grading of cementitious powders without affecting flowability badly.

Fig.8 shows the influence of replacement by silica fume and limestone powder on the flow-out rate, in constant condition of total volume of fly ash, silica fume and limestone powder. In this result, replacement of 1/6 of fly ash by silica fume shows the highest flow-out rate, and it can performs as 3 times fast as ordinary portland cement only. Thus, small percentage of silica fume can reduce the viscosity, and improve the passing capacity through narrow opening.

When enough volume of cementitious powder to obtain good segregation resistance cannot be maintained in order to reduce heat of hydration in cases of mass concrete, inactive powders such as limestone powder may be used by partially replacement of cement. As is shown in Fig.8, segregation resistance does not change when fly ash is partially or totally replaced by limestone powder. In this case, difference in particle shape may not influence on segregation resistance practically, under the condition of constant slump-flow.

Fig.9 shows the relationship of unit powder volume and the flow-out rate, under constant condition of unit water, coarse aggregate volume and slump-flow. In this result, flow-out rate decreases in accordance with increase of unit powder volume within a range of more than 120ℓ /m^3, namely with increase of powder-water ratio. Thus, segregation resistance is mainly affected by powder-water ratio, and it can be roughly estimated as a difference of flow-out rate measured by funnel test.

Fig.10 shows the relationship of cement-water ratio and flow-out time, using the ternarry low-heat cement with 35% of ordinary portland cement, 45% of slag powder and 20% of fly ash. Under the condition of same cement content, it is clear that flow-out time shows direct relation to cement-water ratio, and each line has a same incline, so flow-out time may catch a change of cement-water ratio sensitively.

APPLICATION TO LNG STORAGE TANK

Reason for Application

In the study of execution planning of a LNG (liquefied nitrogen gas) storage inground tank, it was pointed out that the junction of base slab and side wall had much reinforcing bars (see Fig.11), so that improvement of filling capacity of concrete was needed, because of difficulty in consolidation with internal vibrator. Then the authors proposed to apply Super Workable Concrete to this place, and have been studying for selecting a most suitable mix proportion, having good flowability and proper segregation resistance.

Restrictive Conditions of Concrete Materials

Because of the restrictive conditions of equipment at the ready mixed concrete factory used for construction, special cement or other mineral admixtures, or inactive fillers must not be used, so the same type of cement used for general construction may be adopted, only with combination of a slump retaining type of superplastisizer. The other materials are same as general. Concrete materials are shown in Table 2 (as Cement: TL, Fine Aggregate: S-2, Coarse Aggregate: G-2).

Selection of Mix Proportion

In order to perform good filling capacity, many types of mixtures have been tested. Especially to obtain good flowability and segregation resistance, 130-175 ℓ /m^3 of unit cement volumes, and 145-165 ℓ /m^3 of unit water volumes are combined to be related by measuring slump-flow, flow-out time and some passing ability through narrow gaps, which is evaluated with a special apparatus shown in Fig.12, as an uniformity of concrete after flowing. This test may evaluate some segregation resistance as a passing ability through two wire meshes with 45 mm of opening space, by judging passing weight of concrete and aggregate contents change in concrete.

As a result, it was found that mixtures with 130 ℓ/m^3 of unit cement volume showed a tendency to segregation at passing ability test, when slump-flow was extended to 55 cm, so more than 145 ℓ/m^3 of unit cement volume was thought to be needed. Thus, representative mixtures were selected as more than 145ℓ/m^3 of unit cement volume, with less than 0.37 in water-cement ratio, and more than 45% in sand percentage.

Modification of Mix Proportion for Supposed Fluctuation at Plant

At the ready mixed concrete plant, production of concrete is affected by the fluctuation of material qualities or batching errors, especially by a fluctuation of real water content because of change of surface moisture content of aggregates. So additional experimental study was carried for grasping a degree of influence. As a result (6), it was found that mixtures with 145ℓ/m^3 of unit cement volume is more sensitive to the fluctuation of surface moisture content of fine aggregate, and it showed a tendency to segregation when slump-flow was extended to as 60 cm by increasing fluctuation of real water content.

After mix test in lab, real test mixing at concrete plant was carried out, by using a 2.5 m^3 of forced mixing type mixer. As a result, dosage of superplasticizer became 0.3-0.4 % higher than that of lab test, so unit water content had to be increased as a degree of 5-10 kg/m^3 for maintaining almost the same dosage. Additionally, designed slump-flow immediately after mixed is modified as 50 $\pm$5 cm, considering the tendency of a little increase after mixing. According to the modification of mix proportion, flow-out time became about 2 sec. shorter than that of lab test.

Experimental Placing of Real-Size Model with Heavy Reinforcement

The heavily reinforced model used for experimental placing is shown in Fig.11, having almost the same reinforcements or steel pipes of actual structure. Concrete was transported to job site by agitator trucks, pumped through 5 inches pipe in diameter for about 100 m, and poured from the point of about 1.8 m in height, near left end of model (see Fig.11). The pumping rate was roughly controlled as $5m^3/h$ (only the second truck) and 30 m^3/h (the other trucks), then transporting time was about 5-10 min.

Fig.13 shows the result of changes in air content, slump-flow and flow-out time, according to elapsed time. Mix proportions of comparing concrete mixes are shown in Table 3, one is a normal concrete with 12cm of slump, and the others are Super Workable Concretes, Type A having 160ℓ/m^3 of unit cement volume, Type B having 175ℓ/m^3. Concrete temperature was in the range of 17$\pm$2 ℃.

As a result, decrease of air content of Super Workable Concrete for early 30 minutes seemed to be a little larger than normal concrete, but after more than 30 minutes, it was not so serious as normal concrete. Slump-flow of Super Workable Concrete shows almost the same tendency of a gradually increase as shown in lab test. Super Workable Concrete A showed an increase in slump-flow continuously till 110 minutes of time elapsing, with a excess of a proposed limitation (55cm) to control segregation. Super Workable Concrete B showed the least fluctuation in slump-flow among these three mixtures.

Flow-out time of Super Workable Concrete B was almost constant although time elapsed, but that of A showed a gentle increase after more than 60 minutes. This increse seems to depend on an occurrence of slight segregation during flow-out test, according to excessively extended slump-flow and lower viscosity.

Fig.14 shows the results of passing ability test using a apparatus shown in Fig.12, as a relationship of slump flow and passing concrete weight, or coarse aggregate content of concrete after flowing into each space. As a result, it is clear that passing ability through narrow gaps of Super Workable Concrete B, evaluated with both passing weight and coarse aggregate content, is better than that of A, especially at higher slump-flow as 50-55 cm. At this test, Super Workable Concrete A showed a tendency to segregation, and separation of aggregate and mortar occurred at each mesh, so blocking happened and concrete flow was limitted, and passing concrete weight was reduced. The difference of passing ability between Super Workable Concrete A and B is thought to depend on some subtle difference of segregation resistance, estimated as about 1 sec. of difference in flow-out time.

Fig.15 shows the recording results of concrete surface of model placing among much reinforcing bars as shown in Fig.11. Measurement of concrete surface was carried out per half volume of each agitator truck, about 1 m^3. In this case, normal concrete was vibrated to flow with two high-frequency internal vibrators at the point shown in Fig.15, but the incline of normal concrete surface was as steep as 3/10 - 6/10. The incline of surface of Super Workable Concrete, having more than 50 cm of slump-flow, was as gentle as 1/20-3/20 and seemed to be almost flat. Filling capacity of Super Workable Concrete was also proved to be good enough to pass through narrow gaps of reinforcements and to perform perfect grouting around reinforcing bars or steel pipes even though without consolidation or vibration.

Fig.16 shows the results of compressive strength of cylindrical test pieces and cored samples from model placement. The compressive strength of Super Workable Concrete B is highest, according to lowest value of water-cement ratio. Bad influence of pumping on strength cannot be observed, and strength of concrete placed without consolidation shows almost the same value of standard-made test pieces. Accordingly, it is clear that no bad influence of less compaction or rodding on strength is exist.

Fig.17,18 shows severally the effect of flowing distance on compressive strength, and static modulus of elasticity, then value is defined as a rate against each total average. As a result each of these figures shows almost the same tendency, that reduction rate of Super Workable Concrete A after 2.0 m flow is indeed more than 10%, although that of Super Workable Concrete B is as small as negligible. This difference is thought to depend on the difference of segregation resistance. As a result of aggregate percentage survey with cored samples by image analysis, reduction of aggregate content percentage because of sedimentation at upper part after 2.0 m flow was observed.

As a conclusion of this experimental placing, it was found that qualities of placed Super Workable Concrete B is better than that of Super Workable Concrete A or normal concrete, so best mix proportion used in site is selected as Super Workable Concrete B.

Application to Heavily Reinforced Base Mat of Inground Tank

As a base mat exists in about 45 m under ground level (see Photo.1) the improvement of vetical transporting pipe line is needed as attached with S type bended pipe in order to control segregation during falling. Two systems of pumps and transporting lines were used, each shared in half area of horizontal circle pipe line (as 180 °, see Photo.2), connected with gate valves (see Photo.3) at each 3.75m pitch. Distribution of Super Workable Concrete was performed as a manual controlling of opening or closing, in order to restrict a excessive long-distance flow, that might cause segregation of aggregate as passing through reinforcing bars. In this case flowing distance was roughly limited within 10 m, and placement depth was controlled as a 50 cm layer, with making three layers in base mat.

Average placing rate was about 65 m^3/h with 2.0 m^3 of mixing per one batch at plant, and peformed maximum placing rate was 92 m^3/h with 2.5 m^3 of full capacity mixing. In site, concrete temperature was in the range of 25 $\pm$2.5 ℃, slump-flow was in the range of 51 $\pm$4 cm, and flow-out time was in the range of 6.7 $\pm$1 sec, so it seemed to be under good quality control.

In this construction, as a ternary low-heat blended cement and some naphthalene series of superplasticizer were used, initial setting time of concrete in 20℃ room became as long as 27 hours. Accordingly, time for finishing of concrete surface was remarkably different from usual finishing, so rough finishing was carried immediately after end of placing, and re-finishing was carried about 20 hours later.

After all, it was proved that Super Workable Concrete was suitable for placing to heavily reinforced structure or rapid execution of large structure, without vibrating noises. In this application, materials were restricted as only a combination of ternary low-heat cement and superplasticizer, but it was certified that high quality of reinforced concrete structure could be obtained by selecting an appropriate cement content or cement-water ratio, and being produced under exact control of materials or proportioning, using such as a funnel test.

APPLICATION TO THIN & TALL WALL

Reason for Application

In construction of a new building of Acoustic Researching Laboratory in Obayashi Corporation Technical Research Institute, the authors were requested to execute a thin and tall wall with 20 cm in thickness and 6 to 8 m in height. But because of double reinforcement and closed form, pumping tube cannot be incerted, so concrete must be placed from high level as top of form, but segregation cannot avoid occuring. Then, the authors decided to apply Super Workable Concret, and experimental study to select a mix proportion with high segregation resistance have been carried out.

Selection of Mix Proportion

In order to perform a good filling capacity or uniformity after placed by falling, many types of mixtures have been tested. Especially to obtain high segregation resistance not to disperse aggregate after falling, as much as 200 kg/m^3 of limestone powder was proposed to be used as a part of powders, then the flow-out time became more than 10 sec.

Continuously, small scale of model falling test using a 2.7 m in height of reinforced-form model was carried out. As a result, the lost volume as bonded with reinforcing bars was least in case of Super Workable Concrete. In this case(7) it was also found that the extent of scattering of aggregate reduced in accordance with increase of flow-out time (or viscosity), and that uniformity of concrete was improved by using Super Workable Concrete having more than 55 cm of slump-flow and more than 10 sec. of flow-out time, with less than 330ℓ/m^3 of unit aggregate volume.

Experimental Placing of Model Wall having 6 or 8 m in Height

In order to confirm a filling capacity and uniformity, experimental placing to model wall (as shown in Fig.19) was carried out before actual placing to structures. As a result of experimental placing with 6 m wall in height, it was found that Super Workable Concrete showed better filling capacity than usual superplasticized concrete, and that badly segregated parts (as rock pocket) observed in usual superplasticized concrete could not be occured in Super Workable Concrete at all (as shown in Fig.20), even after falling 6 m. Continuously, 8 m model wall in height was placed by using Super Workable Concrete. Mix proportion was shown in Table 4, and test results of fresh concrete was shown in table 5.

Fig.21 shows the change of placing level, and it is clear that concrete surface becomes almost flat although open area or increased reinforcement exist. In this placement, concrete pressure was measured, and the measured lateral pressure shows the triangular distribution as a liquid (as shown in Fig.22). It seems to