Development of Low-Elasticity High-Ductility Fiber-Reinforced Cementitious Composite for Use in PC Girder Connecting Slabs

Ryo Ooyagi[1], Hideaki Taniguchi[2], Wataru Sasaki[3], Masanori Higuchi[4], Noriyuki Shiina[5] and Takeshi Oshiro[6]

[1]*Osaka Branch, Sumitomo Mitsui Construction Co., Ltd., 4-7-28 Kitahama, Chuo-ku, Osaka 541-0041, Japan. oyagiryo@smcon.co.jp*
[2]*Technology Development Center, Sumitomo Mitsui Construction Co., Ltd., 518-1 Komagi, Nagareyama City, Chiba 270-0132, Japan. hitaniguchi@smcon.co.jp*
[3] *Technology Development Center, Sumitomo Mitsui Construction Co., Ltd., 518-1 Komagi, Nagareyama City, Chiba 270-0132, Japan. wsasaki@smcon.co.jp*
[4] *Technology Development Center, Sumitomo Mitsui Construction Co., Ltd., 518-1 Komagi, Nagareyama City, Chiba 270-0132, Japan. masanorihiguchi@smcon.co.jp*
[5] *Osaka Branch, Sumitomo Mitsui Construction Co., Ltd., 4-7-28 Kitahama, Chuo-ku, Osaka 541-0041, Japan. nseena@smcon.co.jp*
[6]*West Nippon Expressway Company Limited, 1-6-20 Dojima, Kita-ku, Osaka 530-0003, Japan. t.oshiro.aa@w-nexco.co.jp*

ABSTRACT

The construction project of Daini-Keihan Road Tanabe Parking Area employed slab connection system in which adjacent prestressed concrete girders were connected with each other using slabs only. Due to the structural characteristics of this slab connection system, it was decided to use a material with a lowest possible modulus of elasticity, high ductility and improved crack dispersion performance. This paper describes the performance requirements for materials to be used in the connecting slabs under concentrated sectional force, and reports the quality and performance of low-elasticity high-ductility fiber-reinforced cementitious composite developed for this purpose.

Keywords. Slab connection system, Slabs, High ductility, Low elasticity, Self-compactability

1. DEVELOPMENT OF LOW-ELASTICITY HIGH-DUCTILITY FIBER-REINFORCED CEMENTITIOUS COMPOSITE

The precast girders to be erected in this project varied in girder height and cross-sectional shape due to location restrictions on the piers (Figure 1). The authors developed a slab connection system shown in Figure 2 in order to make the girders continuous and minimize the use of expansion joints for reduced maintenance requirements. This system uses thin slabs of a constant length to connect simple girders with each other in an attempt to reduce the sectional force to a level where the connecting member can be designed as a slab. However, sectional force was estimated to be considerably large at some locations where the slab was in contact with a long span like at the top of pier P1 in Figure 1. It was impossible to design the slab for such locations as an ordinary reinforced concrete slab. Therefore, the authors decided to develop a material with a lower modulus of elasticity than that of ordinary concrete, high ductility and good crack dispersion performance for the regions subjected to a large cross sectional force.

2. PERFORMANCE REQUIREMENTS

Table 1 shows the performance requirements for materials to be used in the connecting slabs. Ordinary concrete can have a low modulus of elasticity when designed to a low compressive strength. However, it is almost impossible with ordinary concrete to achieve a design strength of 30 N/mm^2 and a static modulus of elasticity of 20 kN/mm^2 at the same time. In addition, since the slabs were intended for the use under concentrated sectional force, concentrated cracking or propagation of cracks could affect safety or durability of the connecting members. There was also a risk of possible initiation of large cracks in the slabs under restraint by the main girders during construction. Therefore, the new material was required to have high ductility and improved crack dispersion performance, with volumetric change characteristics equivalent to those of ordinary concrete. At the same time, it had to be capable of being manufactured and constructed by using conventional equipment and methods for ordinary concrete, in consideration of the total area of application and the quantity of placement in this project. As a result, the low-elasticity high-ductility fiber-reinforced cementitious composite (hereinafter referred to as "low-elasticity high-ductility FRCC") was developed to meet these performance requirements as a kind of high performance fiber reinforced cement composite with multiple fine cracks (HPFRCC) (Japan Society of Civil Engineers, 2007).

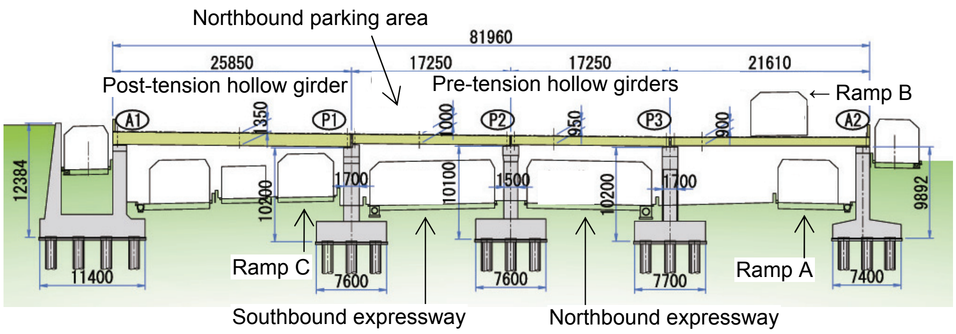

Figure 1. Side View of a Bridge (Example)

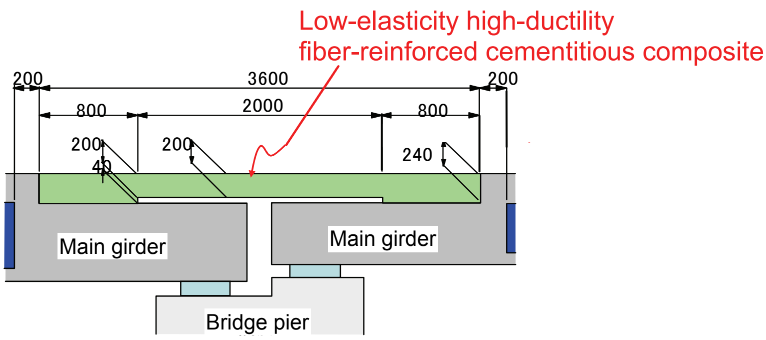

Figure 2. Slab Connection System

Table 1. Performance Requirements of Materials

Items	Performance requirements
Compressive strength	Should satisfy design strength of 30 N/mm^2 or above (at the age of 28 days).
Static modulus of elasticity (Young's modulus)	Should not be larger than design Young's modulus of 20 kN/mm^2.
Crack dispersion performance and ductility	Should have high ductility and good dispersion performance in consideration of possible reduction in durability of members due to concentrated cracking or crack propagation.
Volumetric change (shrinkage, coefficient of thermal expansion)	Should be equivalent to that of ordinary concrete.
Manufacture	Should be capable of being manufactured by using usual equipment at ready-mixed concrete plants, with specified quality achieved.
Transportation	Should be capable of being transported on an agitator truck, with specified quality maintained after the transportation.
Placement	Should have high fluidity and good self-compactability (because satisfying above performance requirements made compaction by vibration difficult).

3. QUALITY AND CHARACTERISTICS OF THE LOW-ELASTICITY HIGH-DUCTILITY FRCC

3.1 Materials and Mix Proportions

Table 2 shows the mix proportions of the low-elasticity high-ductility FRCC. The premixed powder contains portland cement, limestone powder and expansive admixture, added with water reducing powder admixture, shrinkage reducing powder admixture, natural sand and other contents. The premixed powder is easy to handle and measure at a standard-equipped ready-mixed concrete plant, only requiring a vacant cement silo for storage. High strength vinylon fibers (fiber length: 12 mm) were added at 2% as the short fibers (Taniguchi et al., 2009).

Table 2. Low-elasticity High-ductility Fiber-reinforced Cementitious Composite Mix Propotions

Water to cementitious material ratio (%)	Sand to cementitious material ratio (%)	Air content (%)	Short fiber content (%)	Contents (kg/m^3)		
				Water	Premixed powder	Short fibers
48.4	44.8	3.0	2.0	361	1643	25.6

3.2 Self-compactability and Fluidity

In order to satisfy various performance requirements described in Table 1, the low-elasticity high-ductility FRCC was designed to achieve high self-compactability (rank 1 by JSCE; the highest level for high-fluidity concrete) and high fluidity (slump flow of 500 mm or above at the time of placement). Photo 1 shows the views of fill test and slump flow measurement.

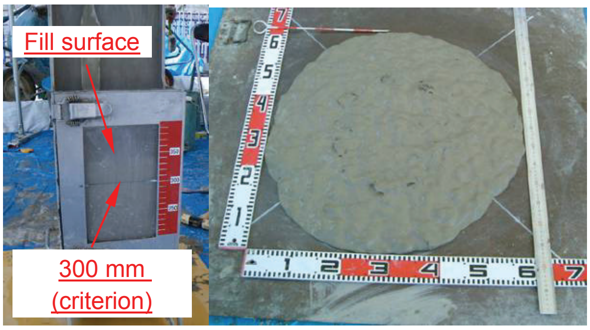

Photo 1. Views of Fill Test and Slump Flow Measurement

3.3 Compressive Strength and Static Modulus of Elasticity

Figure 3 shows compressive strength and static modulus of elasticity, respectively, of the low-elasticity high-ductility FRCC against the age. Values of normal concrete with design strength of 30 N/mm^2 are also shown for reference. As shown in the diagrams, the low-elasticity high-ductility FRCC was found to have similar strength development characteristics to normal concrete, with substantially low Young's modulus achieved (about 18 kN/mm^2 at the age of 28 days).

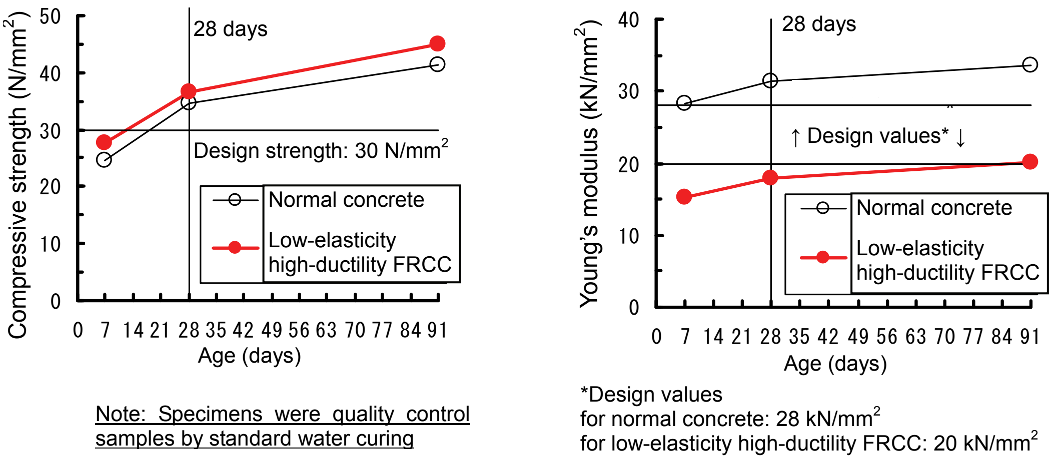

Figure 3. Compressive Strength and Static Modulus of Elasticity vs. Age

3.4 Crack Dispersion Performance and Ductility

Figure 4 shows the load-displacement curve of the low-elasticity high-ductility FRCC obtained from the flexural strength test. Those of normal concrete and short fiber-reinforced concrete (using vinylon fiber products intended for use with concrete) (Taniguchi et al., 2008) are also shown for comparison purposes. Bending fracture proceeded rapidly in normal concrete without fiber reinforcement once the cracking load was reached. Short fiber-reinforced concrete exhibited a rapid decrease in load at the occurrence of flexural cracking but then showed large deformation as the vinylon fibers carried the load. In contrast, the low-elasticity high-ductility FRCC exhibited no major decrease in load after the cracking load was reached. Load increased with displacement which increased to about 5 to 6 mm until failure. The maximum load and displacement of the low-elasticity high-ductility FRCC were significantly higher than those of the short fiber-reinforced concrete. The area enclosed by a load-displacement curve and the horizontal axis represents the ductility of the material.

The ductility of the low-elasticity high-ductility FRCC was obviously higher than those of the other materials. Photo 2 shows cracks observed in the samples after the bending test. A number of fine cracks were distributed in the low-elasticity high-ductility FRCC, while cracks in normal concrete were locally concentrated.

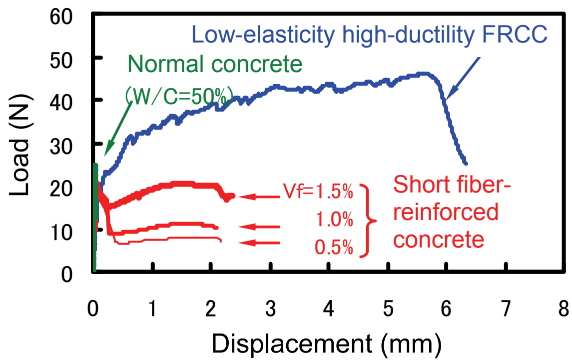

Figure 4. Load-Displacement Curves by Bending Tests

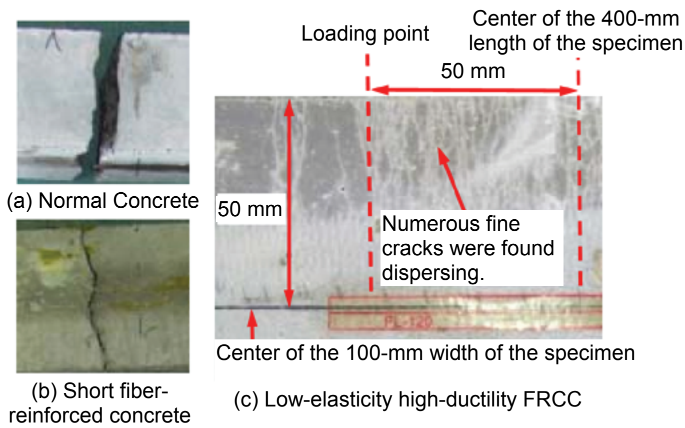

Photo 2. Cracks Caused during Bending Tests

3.5 Volumetric Change

Figure 5 shows the drying shrinkage test results of the low-elasticity high-ductility FRCC. Drying was started at the age of 7 days, and the test was carried out in compliance with JIS A1129. The diagram also shows the values of normal concrete (water content: 175 kg/m^3) calculated by the shrinkage strain prediction equation specified in the Standard Specifications for Concrete Structures (Japan Society of Civil Engineers, 2008) for reference. Drying shrinkage strain in the low-elasticity high-ductility FRCC was found to be very similar to that in ordinary concrete. Autogenous shrinkage strain was found to be as small as $\pm 50\times10^{-6}$, and coefficient of thermal (linear) expansion was 9.5 to 9.7×10^{-6}/°C which was almost equal to the standard value commonly used in concrete design (10×10^{-6}/°C).

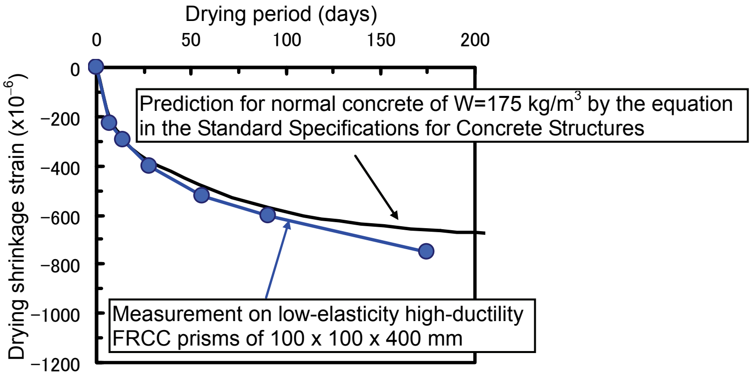

Figure 5. Drying Shrinkage Test Results

4. HANDLING AND CONSTRUCTION PROPERTIES TEST

The low-elasticity high-ductility FRCC manufactured at a ready-mixed concrete plant was transported to the site and placed in test pieces imitating the connecting slabs, and its quality change and construction properties were investigated.

4.1 Time Control from Transportation to Completion of Placement

A usual agitator truck was used for transportation. It took about 25 minutes to carry the product from the plant to the site. Table 3 shows the relationship between the time elapsed from water addition and the quality of the low-elasticity high-ductility FRCC displaced from the agitator truck. Although both fill height and slump flow decreased with the time from water addition, fill height was found to be within the range of self-compactability of rank 1 (300 mm or above) until about 120 minutes from water addition. Fill height was expected to be 300 mm when slump flow was around 450 mm as shown in Figure 6. In order to obtain slump flow of 500 mm or above, it was decided to implement strict time control from water addition to completion of placement in actual construction. It was demonstrated that quality of the low-elasticity high-ductility FRCC was maintained at specified levels after transport on a usual agitator truck, despite its properties significantly different from those of ordinary concrete.

Table 3. Quality Change with Time in the Low-elasticity High-ductility Fiber-reinforced Cementitious Composite

Test items	Time elapsed from water addition			
	30 minutes	70 minutes	90 minutes	120 minutes
U-shaped fill height (mm)	--	314	314	309
Slump flow (mm)	615 x 560	565 x 515	550 x 500	560 x 470
Air content (%)	2.6	3.2	2.4	--
Compressive strength (N/mm^2)	37.2	35.9	35.3	--
Young's modulus (kN/mm^2)	15.9	15.3	15.7	--

Note: No measurement was taken where "--" is shown.

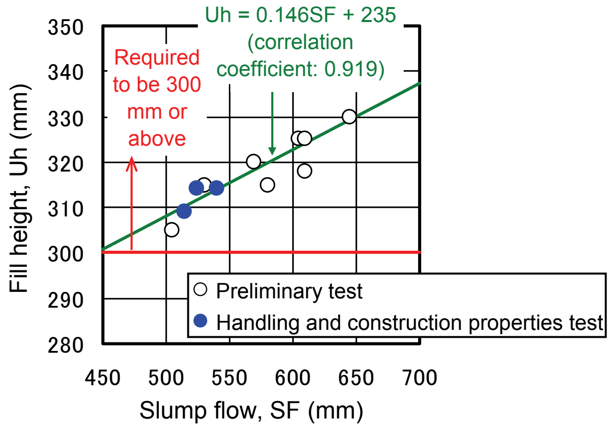

Figure 6. Relationship between Slump Flow and Fill Height

4.2 Construction Properties

Placement, finishing and curing methods were examined through preparation of the test pieces imitating the actual slabs. Photo 3 shows the full view of a test piece, and Photo 4 shows the flow condition during placement. The bottom flow of the mix was not overtaken by the upper flow during placement, with the leading edge constantly in contact with the floor of the test piece form, and the mix was densely packed around the reinforcing steels. It was confirmed that proper construction was achieved by the proper control described above, without causing significant decrease in workability, separation or "overtaking" in the flow of the mix. The surface was successfully finished by using metal trowels together with finishing additives after leveling with wood blocks or timbers. Moisture curing was carried out for five days, using curing mats.

Table 4 shows the compressive strength and Young's modulus (static modulus of elasticity) measurement results on the quality control samples after sealed curing at the site and nine core samples taken from the test pieces. Compressive strength values of the core samples were almost equal to that of the quality control samples. Although Young's modulus of the core samples was about 10% smaller than that of the quality control samples, all of the nine core samples satisfied the design value described in Chapter 2, with little variation between them. The test pieces were cut using a concrete cutter for inspecting the inside. The mix was found densely packed around the reinforcing steels as shown in Photo 5. These results demonstrated that the low-elasticity high-ductility FRCC had satisfactory self-compactability and fluidity and proved the validity of the construction method used in the test.

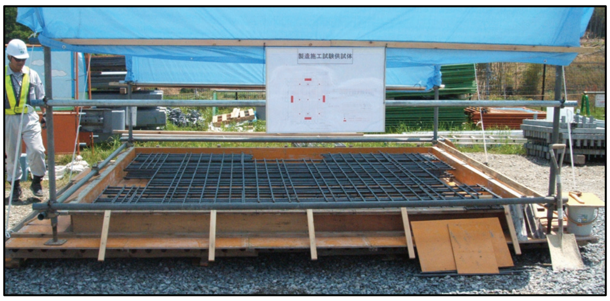

Photo 3. Full View of the Slab-imitating Test Piece

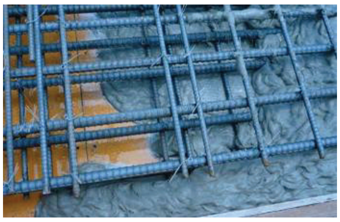

Photo 4. Flow Condition within the Test Piece Form

Table 4. Strength Test Results on Quality Control and Core Samples

	Quality control samples (sealed-cured at the site)	Core samples			
		Average	Maximum	Minimum	Standard Deviation
Compressive strength (N/mm^2)	35.5	35.9	37.2	33.1	1.2
Young's modulus (kN/mm^2)	15.1	13.7	14.2	13.4	0.3

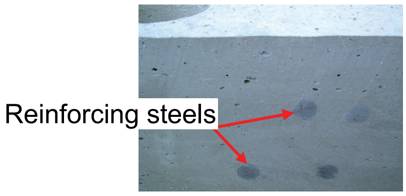

Photo 5. Compaction around Reinforcing Steels

5. CONCLUSION

The slab connection system combined with the low-elasticity high-ductility FRCC adopted in the current project enabled rationalization of the structure and improvement of work efficiency during construction. The proposed technique will have a wide range of applicability, from new construction to renewal work on existing bridges. With the actual data obtained from the current project, application of this system is expected to increase in future.

REFERENCES

Japan Society of Civil Engineers. (2007). *Recommendations for design and construction of high performance fiber reinforced cement composite with multiple fine cracks (draft)*, Concrete Library No. 127, Tokyo (in Japanese).

Japan Society of Civil Engineers. (2008). *Standard Specifications for Concrete Structures-2007, Design*, Tokyo, 45-47.

Taniguchi, H., Mikami, H., Asai, H, Higuchi, M. and Fujita, M. (2008). "Development of Ductile Fiber Reinforced Concrete -- Basic Physical Properties of PVA Fiber Reinforced Concrete." *Reports of Technical Research and Development Center of Sumitomo Mitsui Construction Co., Ltd.*, No. 6, 73-82 (in Japanese).

Taniguchi, H., Higuchi, M., Shiba, A. and Sasaki, W. (2009). "Development of Various Ductile Fiber Reinforced Mortar." *Reports of Technical Research and Development Center of Sumitomo Mitsui Construction Co., Ltd.*, No. 7, 39-44 (in Japanese).