Planning and design of a pedestrian bridge made of low-shrinkage ultra-high-strength concrete (120 N/mm^2): Akihabara Pedestrian Bridge

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Summary

Akihabara pedestrian bridge, which connects Akihabara Station with surrounding buildings, is a 2span-continuous prestressed concrete bridge with 63.803m of total and 8.0m of effective width. Main girder of this bridge has π-form consisting of a upper deck and two webs, which are made of low-shrinkage, high-strength concrete with 120N/mm^2. This paper reports on the planning and design of the bridge, along with the test results of the concrete.

Fig.1 IT Center

Keywords: low-shrinkage, high-strength concrete; pedestrian bridge; precast member; cast-in-place

1. Introduction

Planned as part of the ongoing redevelopment of Tokyo's Akihabara area, the Akihabara Pedestrian Bridge will link up the railway station with the adjacent buildings. The bridge is a 63.803-meter-long [span lengths: 4.087m(cantilever)+25.762m+33.205m] two-span continuous prestressed concrete structure with an effective width of 8.0 m. The girder cross section consisting of an upper slab, webs and struts is π–shaped. The upper slab and webs are made of low-shrinkage, high-strength concrete of the specified design strength. The upper slab has been planned as a cast-in-place member, and the webs have been planned as precast members. This paper reports on the planning and design of the Akihabara Bridge, along with the results of tests conducted on the newly developed low-shrinkage, high-strength concrete used for the bridge.

The construction of the bridge will begin in June 2004, and the bridge is supposed to go into service in March 2006.

2. Planning

A competition for an urban redevelopment project for transforming "Electric Town" Akihabara into an information technology city of international importance began in December 2001 for an 18,000-square-meter tract of land owned by the Tokyo Municipal Government. As a result of the competition, a joint venture consisting of two companies including Kajima Corporation was chosen. By constructing two super-high-rise buildings and redeveloping the station area, a new "IT Center" (Fig.1) designed to attract people, promote cooperation between educational and industrial activities, and support information networking will open in March 2005.

Because the Akihabara Pedestrian Bridge will be built in front of the railway station and because the bridge is to become an approach to the IT Center, it was necessary to develop a bridge design that conjures a "latest technology" image. The pedestrian bridge will connect to the first floors of the super-high-rise buildings, and for the purpose of cost reduction, the first stories need to be made as low as possible. The first-story height, therefore, of 6.0 m was adopted. The pedestrian bridge, however, must have a clearance limit of 4.7 m because the bridge will pass over a road. Restrictions on the locations of bridge piers made it necessary to build a slender, two-span pedestrian bridge with a maximum span length of 33.2 m and a girder depth of 1.2 m (Fig.2,4). In order to support the 8.8-meter-wide bridge by the smallest possible piers, strut construction was adopted to form under-the-girder space with good visibility (Fig.3).

With the aim of making his bridge a reality, ultra-high-strength concrete that can be cast in place has been developed. This new material will expand the possibilities of concrete bridge design befitting the twenty-first century and meet various needs associated with concrete structures. With its architectural design befitting the name "IT Center," the Akihabara Pedestrian Bridge is expected to become a prelude to the era of a new type of concrete.

3. Design

3.1 Girder cross section

The girder cross section has been designed carefully so as to make the best use of the characteristics of the ultra-high-strength concrete. Figure 4 shows the cross-sectional shape of the girder. The components of this girder cross section are described below.

3.1.1 Upper slab

The upper slab is a member to which traffic loads are applied directly, so it was decided to use a more or less standard upper slab thickness. The upper slab will be cast in place with ultra-high-strength (120 N/mm2) concrete.

3.1.2 Lower slab

As shown in Figure 4, the bridge will not have a lower slab. The design that does not use a lower slab has been adopted because it will help to reduce girder weight and because we thought that if ultra-high-strength concrete is used, compressive forces acting on the lower edge of the girder can be resisted by the concrete in the lower part of the web. In place of a lower slab, struts are used to increase the lateral stiffness of the girder.

3.1.3 Web

The web is a precast member made of ultra-high-strength concrete. It was decided to make the web as thin as possible so that its weight can be reduced, and the member thickness of 20 cm has been adopted.

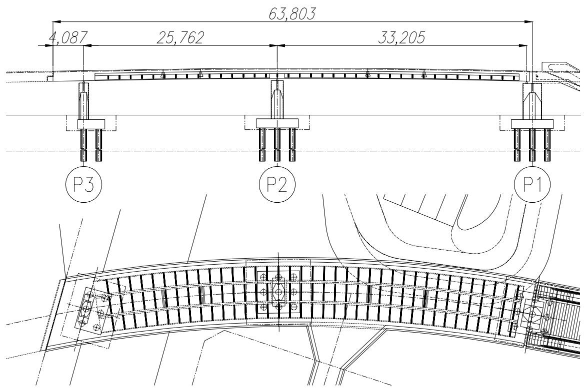

Fig.2 General drawing of the pedestrian bridge

Fig.3 Perspective of the pedestrian bridge

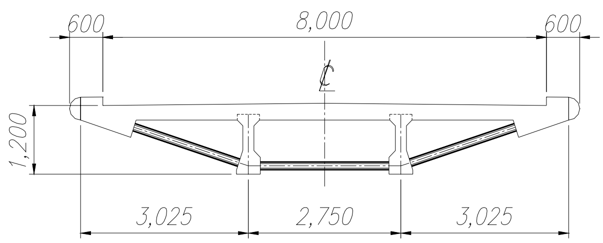

Fig.4 Girder cross section

3.1.4 Strut

As mentioned in the section concerning the lower slab, web pipe struts are used to achieve the required lateral stiffness of the web. Inclined struts are used to increase the lateral stiffness of the upper slab. Another important reason why the inclined struts are used is that inclined struts are more pleasing to the eye of pedestrians below.

Table 1 Allowable stress for concrete N/mm2

<table>
<tr><td colspan="2" rowspan="2">Allowable flexural compressive stress</td><td>A</td><td>43.0</td></tr>
<tr><td>B</td><td>42.0</td></tr>
<tr><td colspan="2" rowspan="3">Allowable flexural tensile stress</td><td>A</td><td>-2.0</td></tr>
<tr><td>B</td><td>0.0</td></tr>
<tr><td>C</td><td>-2.0</td></tr>
<tr><td colspan="2">Average shear stress
that can be resisted by concrete</td><td></td><td>0.7</td></tr>
<tr><td colspan="2" rowspan="2">Maximum value of average shear stress</td><td>E</td><td>6.0</td></tr>
<tr><td>F</td><td>6.8</td></tr>
<tr><td rowspan="4">Allowable diagonal tensile stress</td><td rowspan="2">B</td><td>E</td><td>1.3</td></tr>
<tr><td>F</td><td>1.6</td></tr>
<tr><td rowspan="2">C</td><td>E</td><td>2.5</td></tr>
<tr><td>F</td><td>3.0</td></tr>
</table>

A : Immediately after prestress application
B : Under design load
C : Under dead load
D : Under live load
E : Shear or torsion
F : Shear + torsion

3.2 Design values

Basically, the bridge has been designed in accordance with the Specifications for Highway Bridges (Japan Road Association), but the maximum value of the specified design strength of concrete is 60 N/mm2. Therefore, values obtained by extrapolating the specification values were used only for the allowable flexural compressive stress; for other parameters, values corresponding to the specified design strength of concrete of 60 N/mm2 were used. Table 1 shows the values to be used for the design of the bridge. Various tests including ultra-high-strength concrete beam tests are currently underway, so the values to be used for the design of the bridge will be reviewed after the results of those tests become available.

4. Low-shrinkage ultra-high- strength concrete (σck=120 N/mm2)

4.1 Autogenous shrinkage reduction method and mix design

In order to produce ultra-high-strength concrete at ready-mixed concrete plants at reasonable cost, materials that are commercially available and that are suitable for ultra-high-strength concrete were chosen as the basic materials for the ultra-high-strength concrete. Table 2 lists the materials used. As shown, premixed silica fume cement based on low-heat Portland cement is used as the cement material, and crushed stone and manufactured sand, which have excellent strength characteristics, are used as aggregates. A superplasticizer designed for ultra-high-strength concrete is used to achieve a water/cementitious material ratio of 17%. By so doing, basic mix proportions that make possible a compressive strength of 150 N/mm2 or more and high self-compacting property have been obtained.

Table 2 Materials used

Material used	Symbol	Type	Specifications
Cement	C	Silica fume cement	Density: 3.08 g/cm^3, specific surface area: 6,060 cm^2/g, silica fume content: 10–15%
Fine aggregate	S	Crushed andesite	SSD particle density: 2.66 g/cm^3, absorption: 1.30%, solid content: 66.1%, fineness modulus: 2.61
Coarse aggregate	G	Crushed andesite	SSD particle density: 2.66 g/cm^3, absorption: 1.25%, solid content: 63.1%, fineness modulus: 6.72
	JL	Artificial aggregate made of coal ash	SSD particle density: 1.80 g/cm^3, absorption: 17.8% (values for aggregate stored in water for 7 or more days after delivered)
Admixture	EX	Expansion-producin g admixture	Density: 3.20 g/cm^3, specific surface area: 3,500 cm^2/g
Chemical admixture	RA	Shrinkage-reducing agent	Lower-alcohol-based; density: 1.03 g/cm^3
	SP	Superplasticizer	Polycarboxylic acid based; ultra-high-range water reducer (liquid)

Table 3 Concrete mix proportions

Symbol	W/(C+EX) (%)	Air (%)	Unit content (kg/m3)						SP (C×%)	RA (C×%)	JL/(G+JL) Volume ratio(%)
			W	C	EX	S	G	JL			
B	17.0	1.5	155	912	-	613	798	-	1.5	-	-
JL20E10	17.0	1.5	155	902	10	613	638	101	1.5	-	20
JL20R05	17.0	1.5	155	912	-	613	638	108	1.5	0.5	20

EX : expansion-producing admixture, RA: shrinkage-reducing agent,
JL: artificial lightweight aggregate, SP: superplasticizer

It has been confirmed that the three admixtures listed below are effective in reducing autogenous shrinkage [2].

(i) Expansion-producing admixtures
(ii) Shrinkage-reducing agents
(iii) Artificial lightweight aggregate

Expansion-producing admixtures cause hydration so that the apparent volume increases and shrinkage of cement paste in the concrete is compensated. Expansion-producing admixtures, however, reduce concrete strength and also the fluidity of fresh concrete so that the self-compacting property of concrete is compromised and superplasticizer usage increases.

Shrinkage-reducing agents reduce the surface tension of pore water in hardened cement paste so that capillary tension, which causes autogenous shrinkage, is reduced. Slight delay in strength development, slight decrease in strength, and relatively high material costs are drawbacks of shrinkage-reducing agents.

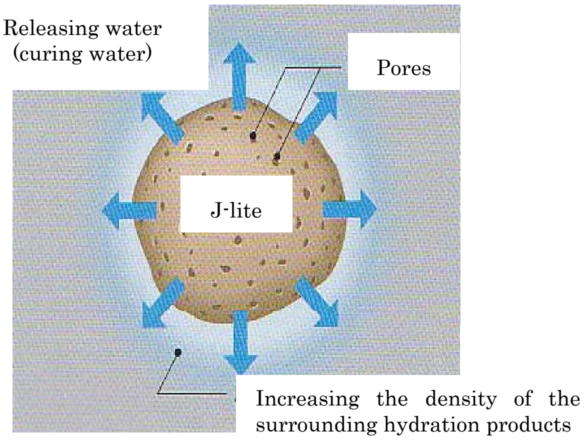

Fig.5 Self-curing effect

Artificial lightweight aggregates hold water that compensates autogenous shrinkage of hardened concrete caused by the hydration of cement so as to prevent reduction in humidity in capillary voids (self-curing effect; Fig.5). Ordinary artificial lightweight aggregates, however, are not strong enough for use in ultra-high-strength concrete. It was decided, therefore, to use a newly developed lightweight coal-ash aggregate (J-lite;Photo 1) that combines relatively high strength and high absorptivity.

Photo 1 Lightweight coal ash aggregate

The J-lite is a new type of material jointly developed by Kajima Corporation, Joban Joint Power Co., Ltd., and Nippon Mesalite Industry Co., Ltd. The J-lite has a compressive strength exceeding 1,000 N, more than twice the strength of conventional artificial lightweight aggregates (Kasai, Wami, Arai and Morita 2000). By adjusting the content of coal ash, the water absorption and compressive strength of aggregate can be controlled. Use of the J-lite to make ultra-high-strength concrete has made it possible to achieve sufficient concrete strength and reduce autogenous shrinkage without compromising the self-compacting property or causing an excessive increase in material cost.

Since, however, concrete strength decreases as the quantity of the J-lite used increases, it was decided to use different quantities according to the target compressive strength in conjunction with small quantities of other admixtures such as expansion-producing admixtures and shrinkage-reducing agents. Table 2 shows the concrete mix proportions considered. The following sections report the results of comparison of two mixes—one (JL20E10) in which 20% of coarse aggregate is replaced with the J-lite and 10 kg/m^3 of an expansion-producing admixture is used, and the other (JL20R05) in which a shrinkage-reducing agent is used in a quantity corresponding to 5% of the quantity of cement—with a basic mix (B) that is not designed to reduce autogenous shrinkage.

Photo 2 Slump flow test

4.2 Characteristics of low-shrinkage, ultra-high -strength concrete

4.2.1 Slump flow

Photo 2 shows an example of a slump flow test result. Since ultra-high-strength concrete contains a large quantity of powdery material, the viscosity of fresh concrete is higher than that of ordinary concrete. Because high viscosity makes vibrators less effective, it is necessary to enhance the self-compacting property of concrete. By using appropriate quantities of superplasticizers, a slump flow of 600 to 700 mm has been achieved. Thus, good flowability of concrete has been achieved without causing segregation of coarse aggregate and mortar.

4.2.2 Compressive strength and strain due to autogenous shrinkage

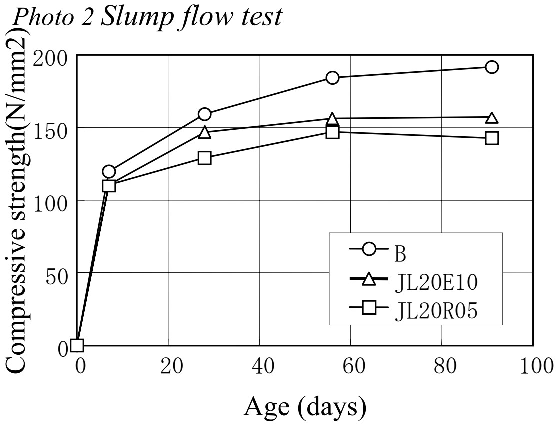

Fig.6 Compressive strength test results

Fig.6 shows the results of a compressive strength test on test specimens prepared by the standard curing method. Fig.7 shows the results of an autogenous shrinkage strain test. In the test, autogenous shrinkage strain was measured with low-stiffness-type strain gauges embedded in 100×100×400mm specimens, and shrinkage-induced strain was measured in a nondry condition.

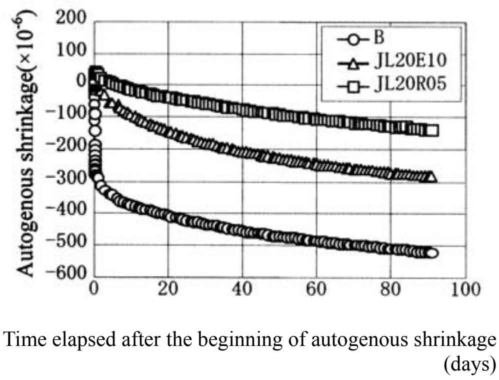

Fig.7 Autogenous shrinkage test results

The basic mix (B) specimens showed high compressive strengths, about 160 N/mm^2 at an age of 28 days and 190 N/mm^2 at an age of 91 days, but an autogenous shrinkage of as large as 520×10−6 was observed on day 91. The mixes designed to reduce autogenous shrinkage showed somewhat lower compressive strengths, but compressive strengths of about 150 N/mm^2 were obtained on and after day 56. Autogenous shrinkage strains in JL20E10 and JL20R05 at an age of 91 days were reduced to 280×10^{-6} and 140×10^{-6}, respectively.

Reducing autogenous shrinkage resulted in decreases in compressive strength of 20% or so, but autogenous shrinkage was reduced by as much as 50 to 70%. Rational mix proportions can be chosen by adjusting the usage of three types of shrinkage-reducing admixtures or using different combinations of those admixtures according to the desired level of compressive strength or autogenous shrinkage.

4.2.3 The effect of the J-lite on curing

Figure 8 shows the compressive strengths of mix B and JL20R05 achieved under different curing conditions. The basic mix (B) did not show significant differences between standard curing and sealed curing. Compressive strengths of 190 N/mm2 or so were achieved at an age of 91 days, but strengths achieved by air curing were only around 155 N/mm^2. The compressive strength of JL20R05 was lower (about 150 N/mm^2) than that of mix B for both standard curing and sealed curing, but similar levels of strength were obtained by air curing. This is thought to be due to the self-curing effect of artificial lightweight aggregate that has absorbed water. In other words, it is thought that the water contained in the J-lite not only reduces autogenous shrinkage; it also helps to reduce variation in strength development due to differences in humidity conditions in the curing environment.

The artificial lightweight aggregate used was highly absorptive of water. The dynamic modulus of elasticity, however, of the concrete mixes containing the artificial lightweight aggregate did not decrease even after 300 cycles of freeze–thaw testing. This indicates that the low-shrinkage, ultra-high- strength concrete is highly resistant to freeze–thaw cycles.

5. Conclusion

The construction of bridges using high-strength concrete has just begun. It is likely that in most cases high-strength concrete having strength of more than 100 N/mm2 is used in the form of precast members. The Akihabara Pedestrian Bridge is characterized mostly by the use of concrete having specified design strength of 120 N/mm2 both as precast members and as cast-in-place members. It is hoped that the technology used to build the bridge will greatly contribute to the progress of prestressed concrete bridge technology.

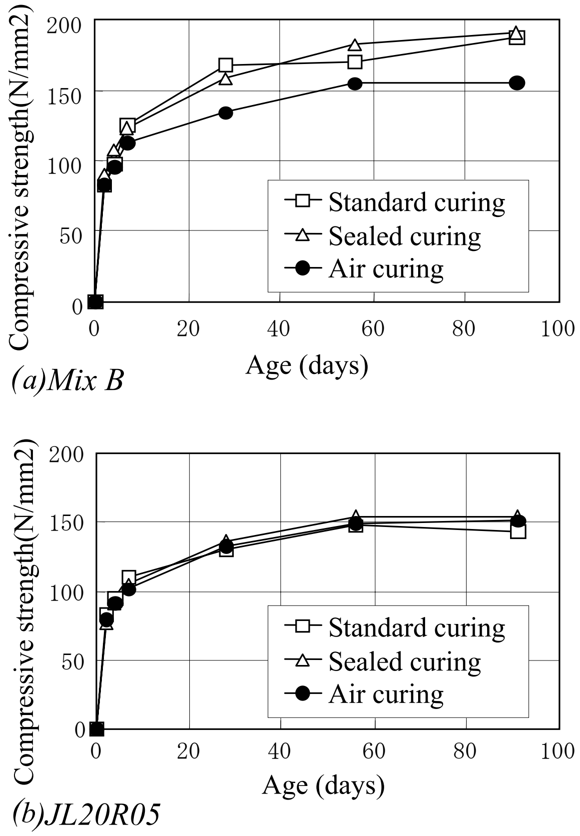

Fig.8 Compressive strength under different curing conditions

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