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A study of drying shrinkage for securing durability of PC bridges

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ABSTRACT

Recently, cracks have been found in a few prestressed concrete (PC) structures at early ages in Japan and it was determined that the cracks were caused by large drying shrinkage of concrete. In the current design standards, the relationship between the shrinkage strain of actual structures and that of small test specimens obtained by the Japanese Industrial Standards (JIS) test method has not been clarified.

Therefore, large test specimens whose sizes are the same as actual PC box girders were constructed and the drying shrinkage strain was measured over an extended period of time. These measurements provided an understanding of what happens in the actual structures, and a clue to solve the problem due to large drying shrinkage strain was gained. In addition, the validity of the measurements was verified by the analysis based on the moisture diffusion in concrete.

Keywords. Drying shrinkage, PC structure, Full-scale test specimen, Measurements over an extended period of time, Moisture diffusion

INTRODUCTION

Prestressed concrete (PC) structures do not permit cracking in service and feature excellent durability. However, damages including cracks were found recently in some PC superstructures in relatively early stages after completion, which has become an issue (Photo 1). As a result of various tests and analysis based on the moisture diffusion in concrete, it has been found that the cause of the damage is likely to be closely related to large drying shrinkage strains of concrete.

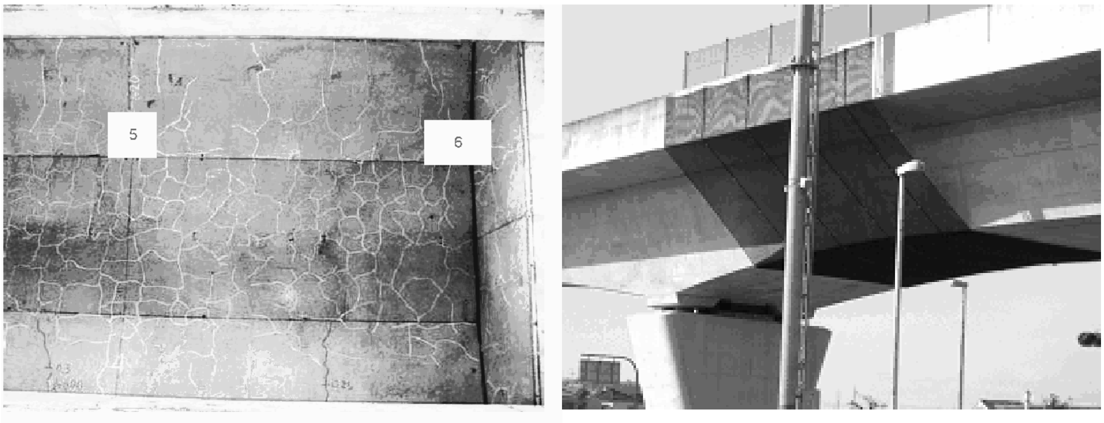

Photo 1. Examples of damage

Left: Cracks in (RC) slab Right: Measure against spalling of Concrete

One cause of the large drying shrinkage strains of concrete is recent quality degradation of coarse aggregate. Length change tests according to a Japanese Industrial Standards (JIS) test method (JIS A 1129) using test specimens (100×100×400 mm) made of coarse aggregate of the same origins as those of the damaged PC bridges sometimes show a final measured strain exceeding $1,000\times10^{-6}$. Meanwhile, the Japanese design standards (such as the Standard Specifications for Concrete Structures and Specifications, and Specifications for Highway Bridges) specify that a drying shrinkage strain to be used for design of PC bridges is roughly 150×10^{-6} to 200×10^{-6}, which is considerably different from the result of the JIS test. There are four possible reasons for the difference:

- The actual structures are composed of members larger than the test specimens (100×100×400 mm) used in the JIS test and internal moisture diffusion takes longer.

- The actual structures are exposed to rain and dew many times in service and the surfaces are damp, leading to longer periods for which drying is retarded.

- The actual structures have many steel products such as reinforcing bars in concrete, which resist shrinkage.

- Stress induced in the actual structures due to drying shrinkage is mitigated by creep and the drying shrinkage strain for design is decreased to simplify the design.

The damaged PC bridges were designed and constructed properly according to the design standards. Therefore, increase of the drying shrinkage strain for design should be considered for use of concrete with a large drying shrinkage strain in the future. However, the size of the shrinkage strain of the "standard concrete", which has been referred to by the design standards up to now, based on the JIS test, has not been made clear. For example, if the JIS test result for the "standard concrete" is defined as around 600×10^{-6}, the value for design can be increased according to the degree of any excess over 600×10^{-6} (e.g. for the JIS test result of 800×10^{-6}, the value for design may be $150\times10^{-6}\times800 / 600 = 200\times10^{-6}$).

Accordingly, for the purpose of identifying the relationship between the JIS test result and the drying shrinkage strain produced in actual structures, the authors created full-scale test specimens simulating an actual PC bridge and measured the drying shrinkage strain over an extended period of time. In addition, the validity of the measurements was verified by analysis based on the moisture diffusion in concrete. The following details the process.

DAMAGE IN ACTUAL STRUCTURES

Table 1. Compressive strength, Young's modulus and drying shrinkage strain

Origin of coarse aggregate	compressive strength (N/mm^2)	Young's modulus (kN/mm^2)	drying shrinkage strain (μ)
A	36.3	27.1	767×10-6
B	37.8	26.7	920×10-6

Outline and identification of cause by experiment. In order to study the cause of the damage produced in the actual structure shown in Photo 1, cores of 100 mm in diameter were sampled from a bridge that uses aggregate with the same origin as that used for the bridge in question to test neutralization and chloride ion content, and residual expansion by accelerated curing. As a result of these tests, it was clear that the cracks in the bridge was not caused by neutralization, chloride ion concentration or alkali-silica reaction of concrete.

Table 1 shows the result of tests on two types of concrete for the compressive strength and Young's modulus on the 28th day and the drying shrinkage strain on the 182nd day (26th week) of the drying period. One concrete uses the same coarse aggregate as that used for the bridges that suffered cracking (B origin) and the other the same as that used for other bridges that did not exhibit damage (A origin). Portland blast-furnace slag cement class B was used for these types of concrete and the design strength was 24 N/mm2.

There is not much difference between concrete with coarse aggregate from A and B in compressive strength on the 28th day. However, the Young's modulus is higher for the concrete with coarse aggregate from A and the drying shrinkage strain is larger for that with coarse aggregate from B. These results suggest that, for bridges constructed of concrete that uses coarse aggregate from B, the major cause of the crack damage is drying shrinkage strain.

Drying shrinkage analysis based on moisture diffusion in concrete. The authors analyzed the PC bridge damaged by drying shrinkage, focusing on moisture diffusion in concrete for reproducing damages. The following reports the results.

The bridge shown in Photo 2 uses the same coarse aggregate as that used for the damaged bridge shown in Photo 1. The bridge was damaged with cracking in the post-cast concrete section between the stationary staging and the incrementally launched section constructed earlier, because drying shrinkage in the post-cast section was significantly restrained by the existing sections on both ends. Among the cracks, those extending in the longitudinal direction, which is characteristic of cracks caused by external restraint, were dominant but non-directional cracking was also found here and there. Another characteristic point is that cracks occurred also in the sections constructed earlier, which were restraining bodies.

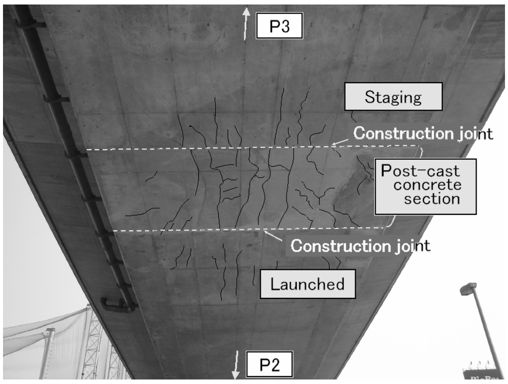

Photo 2. Cracking

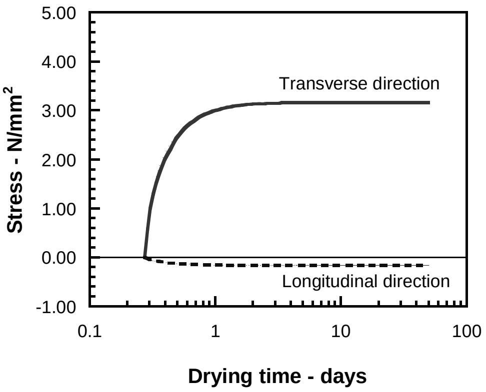

Figure 1. Change with time of stress in damaged part (point A: standard analysis)

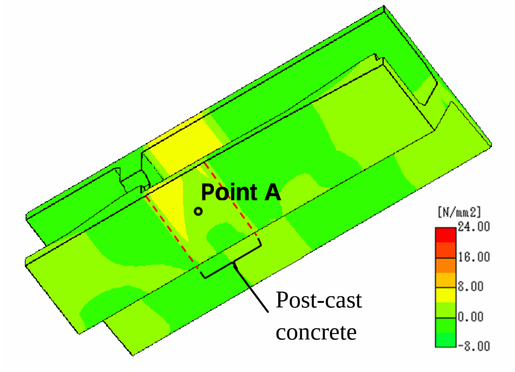

Figure 2. Distribution of stress in the lower surface of superstructure (standard analysis)

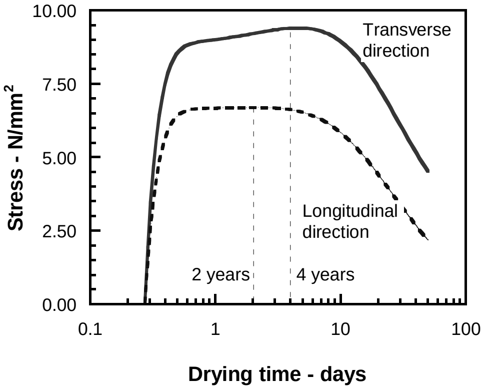

Figure 3. Change with time of stress in damaged part (point A: analysis with focus on moisture diffusion)

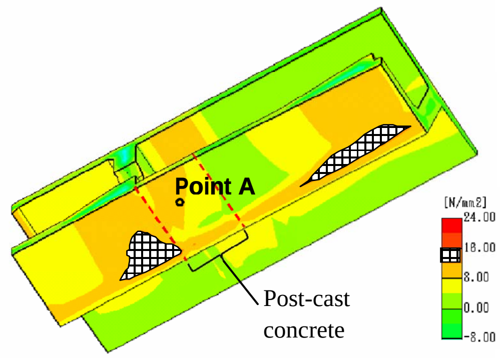

Figure 4. Distribution of stress in the lower surface of superstructure (analysis with focus on moisture diffusion)

Figures 1 and 2 show the results of analysis on the assumption that, as with the present design standards, the moisture distribution in the cross-section is uniform and the shrinkage strain in any element is also uniform. Figure 1 well depicts the high tensile stress in the transverse direction but shows little stress induced in the longitudinal direction. Hence cracking only in one direction is represented. The stress contours in Figure 2 also fail to show high stress in the existing sections before and after the post-cast section, giving results that are different from the actual damages.

In contrast, Figures 3 and 4 show the results of analysis on the assumption of moisture diffusion in the concrete according to the diffusion theory and with the moisture distribution in the cross-section taken into account. Figure 3 indicates that high stress is induced in the longitudinal direction and in the transverse direction, successfully reproducing non-directional cracking. It also shows when the stress peaks and is capable of evaluating internal restraint stress, which changes over time unlike the external restraint stress. In addition, Figure 4 shows high stress in the existing sections before and after the post-cast section, which very closely represents actual damage.

Photo 3. PC strutted rigid frame bridge

Photo 4. Full-scale specimens

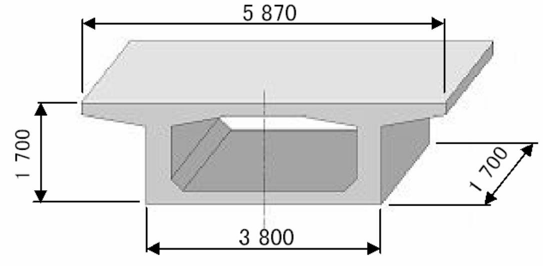

Figure 5. Dimensions of specimens

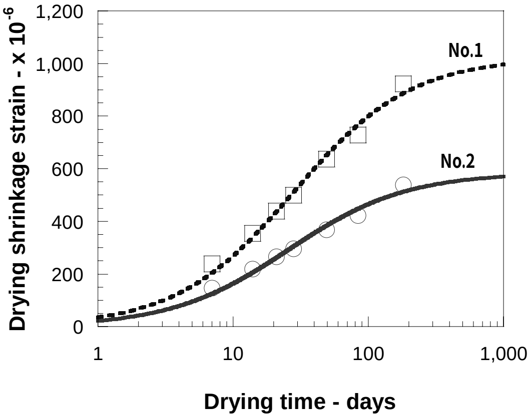

Figure 6. Results of length change test according to JIS

These results have clearly shown that the cause of the cracks in the structures in question originated from large drying shrinkage strains of the concrete. It has also been found that analysis on the assumption of moisture diffusion in the concrete according to the diffusion theory and with the moisture distribution in the cross-section taken into account allows the stress induced in members by drying shrinkage strains to be accurately represented.

FULL-SCALE TEST SPECOMENTS

Outline of test specimens. For the purpose of determining how the JIS test result can be reflected in design when concrete with a large drying shrinkage strain is used for the construction of a actual structure, the authors created full-scale test specimens simulating a PC bridge actually being constructed and measured the drying shrinkage strain over an extended period of time.

The bridge chosen as the subject of the test, which is an overbridge across an expressway, is a PC strutted rigid frame bridge with a box girder-shaped cross-section. For this bridge, the concrete available at the construction site was known to have a drying shrinkage strain close to $1{,}000\times10^{-6}$ and a study was conducted in advance by a committee composed of experts. As a result, it was determined that test specimens of the same size as for the bridge should be built to take measurements of the drying shrinkage strain over an extended period of time in parallel with the construction of the bridge. Photo 3 shows an overall view of the completed bridge, Photo 4 an overview of specimens and Figure 5 the dimensions of the specimens. For the actual construction of the bridge, coarse aggregate was delivered from a distant location

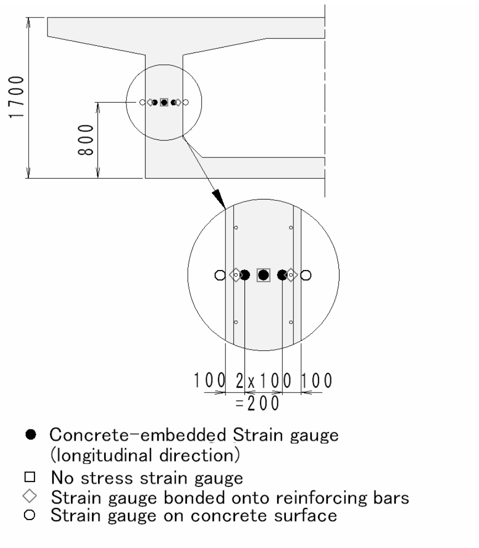

Figure 7. Measuring instruments

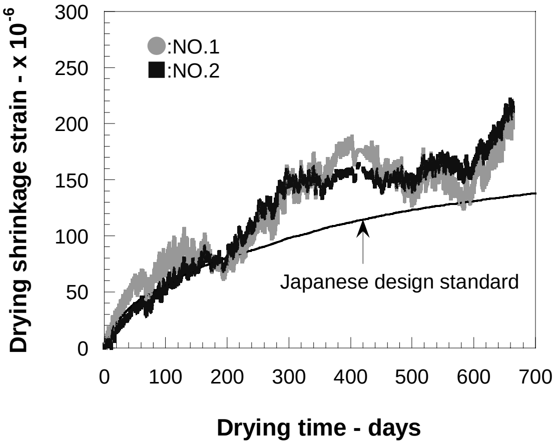

Figure 8. Full-scale test specimen measurements

and the drying shrinkage strain of the concrete was kept under approximately 600×10^{-6}, which prevented damage.

A total of seven large test specimens were built with different concrete compositions and amounts of reinforcing bars for comparison. Two of those were box girder-shaped, of which one used a concrete containing coarse aggregate that causes a larger drying shrinkage strain (composition No. 1) and the other used a concrete containing coarse aggregate that causes a typical drying shrinkage strain (composition No. 2). Figure 6 shows the results of the length change test according to JIS A 1129 for the respective concretes. The shrinkage strain after 26 weeks turned out to be 923×10^{-6} for composition No. 1 and 539×10^{-6} for composition No. 2.

Measurement results. Figure 7 shows types of measuring instruments and their respective locations (the strain gauges on the concrete surface are not installed on the actual bridge). In addition, contact-type strain gauges were used for measuring the strain on the surface of the test specimens. The following describes the results of measurement with the strain gauges embedded in the web of the box girder.

Figure 8 shows the results of measurements in the longitudinal direction of full-scale specimens (perpendicular to the cross sectional plane in Figure 7). The measurement results were subjected to temperature correction by thermocouples. Twenty-two months have passed since the start of drying but not much difference was found between the drying shrinkage strains of the two test specimens at approximately 200×10^{-6}. The graph indicates that there is a time when the change switches from shrinkage to expansion, which coincides with early summer when rainy weather continues and ambient humidity increases in Japan.

To focus on specimen No. 1 with a larger drying shrinkage strain, the strain variation is larger than that of No. 2 not only while expansion continues but also when the change switches from shrinkage to expansion. This suggests that concrete No. 1 has a lower resistance to deformation than No. 2 and, as shown in Table 2, Young's modulus of concrete No. 1 is only about 70% of that of No. 2. In this way, the actual structures undergo repeated shrinkage and expansion because of the external environment and, for concrete with a lower resistance to deformation due to the quality of coarse aggregate, both the expansion strain and the shrinkage strain are large. Accordingly, the average shrinkage strain is not much different from that of the standard concrete and the tendency is assumed to be different from the result of the JIS test, which is an indoor test where only shrinkage continues.

Table 2. Compressive strength and Young's modulus

	test specimens	NO.1	NO.2
compressive strength (N/mm^2)	Full-scale	44.8	43.1
	JIS-test (100×100×400mm)	50.2	46.8
Young's modulus (kN/mm^2)	JIS-test (100×100×400mm)	22.8	32.6

The curves in Figure 8 are change curves with time of drying shrinkage strains calculated based on the Japanese design standard. The average shrinkage strain is apparently slightly larger than the design standard for both No. 1 and No. 2. To focus on the peak value, however, the value for No. 1, for example, reaches 1.7 times the design standard at drying age of around 400 days, which may cause a risk of damage such as cracking depending on the structure. For that reason, to compare the drying shrinkage strain induced in the actual structures with the shrinkage strain for design and JIS test value, attention should be given to the peak value, which appears when drying progresses, rather than the long-term average shrinkage strain.

Figures 9 and 10 show the measurements for the actual PC bridge. The shrinkage strain in the longitudinal direction shown in Figure 9 is about 400×10^{-6} at present, which includes a creep strain resulting from prestressing. The calculated value of the creep strain at drying age of 22 months is around 200×10^{-6} and, with this subtracted, the drying shrinkage strain is estimated to be around 200×10^{-6}, which coincides with the shrinkage strain in the vertical direction shown in Figure 10 (ignoring the effect of prestressing). Accordingly, the drying shrinkage strain in the actual bridge is estimated to be around 200×10^{-6}. This agrees with the measurements with full-scale specimens.

Result of analysis. Figure 11 shows a comparison between measurements of drying shrinkage strain of specimen No. 1, which has a large drying shrinkage strain, and the drying shrinkage strain obtained by analysis with the focus on moisture diffusion in concrete. The relative humidity used for the analysis was 71.6%, the annual average. As shown by this

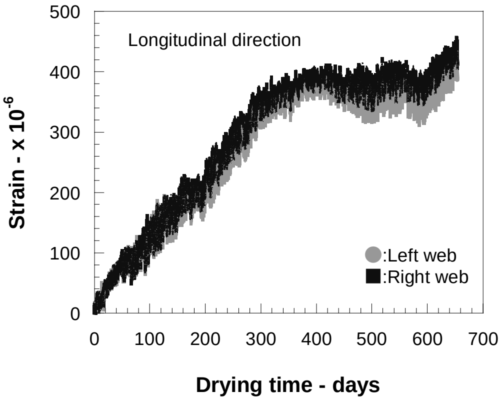

Figure 9. Measurement results of actual bridge (longitudinal)

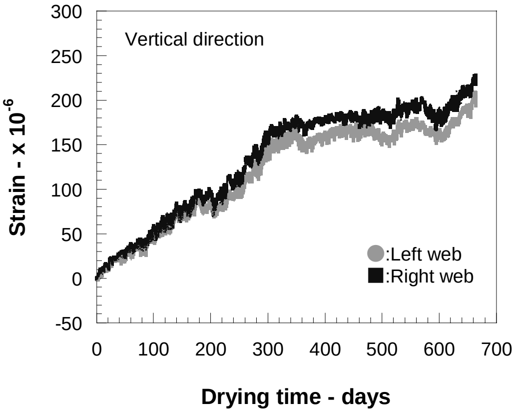

Figure 10. Measurement results of actual bridge (vertical)

graph, the analytical values are slightly larger than the measured values but they are in close agreement with each other. The reason the analytical values are larger than measured values is apparently that the analysis does not take the impact of rainfall or restraint by reinforcing bars into consideration.

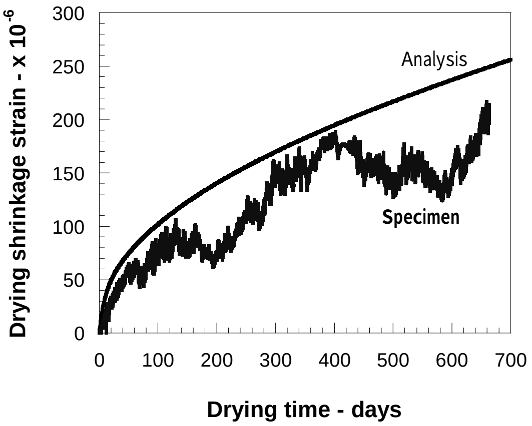

Figure 11. Results of analysis

CONCLUSION

As a result of various tests and analysis based on moisture diffusion in concrete, it is clear that the cause of damages including cracks in PC superstructures in relatively early stages after completion is likely to be closely related to large drying shrinkage strains in concrete.

To determine how the JIS test result can be applied to design for building a actual structure using concrete with a large drying shrinkage strain, the authors created full-scale test specimens simulating an actual PC bridge and measured the drying shrinkage strain over an extended period of time. Based on measurements for about two years, it was found that a shrinkage strain about 1.7 times as large as the design standard may be temporarily induced depending on the type of coarse aggregate but the average drying shrinkage strain during the drying period is only slightly larger than the design standard and is not as much affected by the type of coarse aggregate as the JIS test result is. Another finding is that measurements of full-scale specimens can be closely reproduced by analysis that takes moisture diffusion in concrete into account.

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