

Sustainable UFC Structures in JAPAN and its Durability Performance

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ABSTRACT

The application of the Ultra-high strength Fiber reinforcement Concrete (UFC) to the many kinds of structure has been increasing in recent years in Japan. UFC application in the PC bridge field is advanced because of taking advantage of thin members and weight reduction achieved by these ultra-high strength and high durability. Sakata Mirai footbridge is the first UFC structure in Japan completed in October 2002. Using UFC, the very thin members as thickness of 8-15 cm and the long simple beam span as 50 m have been achieved in the bridge. Since the bridge is located in severe corrosive environment, a field investigation was conducted to verify its 10 year's durability performance. In this paper, the cases about the UFC bridges where various unique technologies are applied are introduced. Then, the examinations for durability and the mechanical properties of the ten years old UFC bridge are reported.

Keywords. UFC, ultra-high strength, fiber reinforced, bridge, durability

1. INTRODUCTION

UHPFRC is an abbreviation of ultra-high performance fiber reinforced concrete, and there are various kinds of UHPFRC materials in the world. Then, UFC (Ultra-high strength Fiber reinforcement Concrete) is a kind of UHPFRC. This UFC (JSCE, 2004) has extremely high durability because of the fine structure of the matrix. UFC not only has ultra-high strength but also has high toughness by the effect of the steel fiber reinforcement. Since UFC has such toughness, rebars are not usually used in any UFC structures. This remarkable characteristic distinguishes UFC from other UHPFRC materials. UFC, which was developed based on "Reactive Powder Composite Material" (Richard, 1994), is the most applied UHPFRC materials for actual structures all over the world. Especially, UFC applications to

any kinds of structures such as bridges, buildings, tunnel lining, have been increasing, and more than twenty UFC structures were constructed in recent ten years in Japan.

UFC application in the PC bridge field is advanced because of taking advantage of thin members and weight reduction achieved by these ultra-high strength and high durability. The structure, which was not able to be achieved with conventional concrete like a long span simple beam exceeded 50 m and a very thin thickness of 8-15 cm, became possible by the application of UFC to the PC bridge.

Sakata Mirai footbridge (Musha, 2002) shown in Photo 1 has been completed for the first time applying UFC in Japan in October 2002. The location of the bridge is about 3.4 km from the Japan Sea coastal line therefore this bridge is exposed by severe corrosive environment in winter. Authors have been periodically investigating the durability and strength performance of this bridge.

After Sakata Mirai Bridge, more than 20 of UFC bridges have been completed in Japan until today. It also applied to an airport runway slab in a large scale. Various new technologies were developed by using the UFC characteristic, and those technologies have been applied to these UFC structures.

In this paper, the cases about the UFC bridges where various unique technologies are applied are introduced, and those features are described. Then, the examinations for durability and the mechanical properties of the ten years old UFC bridge are reported.



Table 1 Composition of UFC

	mixed ingredient (cement, silica fume, quartz, etc)	water	fiber	super plastcizer	W/C
unit					
kg/m ³	2254	180	157	24	22

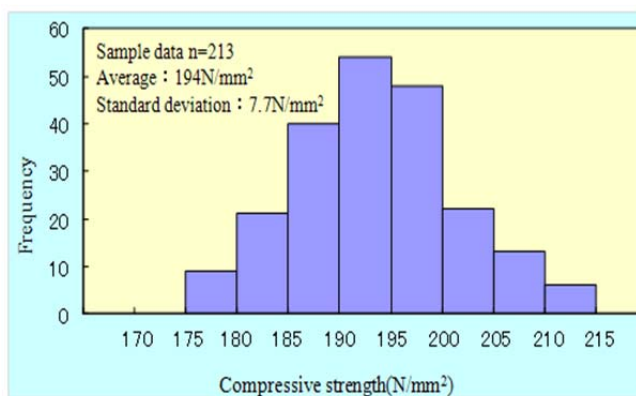


Photo 1 Sakata Mirai foodbridge Fig. 1 Compressive strength frequency (JSCE, 2004)

2. FEATURES OF UFC

2.1 Basic formulation of UFC

The formulation of UFC is shown in Table 1. The major principles are as follows; 1) minimum of defects such as micro-cracks and pore spaces by extremely low water/cement ratio (=22%), 2) enhancement of compacted density by optimization of the granular mixture, 3) enhancement of the microstructure by heat treatment, and 4) enhancement of ductility by

incorporating steel fiber. The self-levelling performance is achieved that a flow value (JIS-R-5202.11) is around 220-280 mm for the material temperature of 20~25°C even for including the steel fiber (0.2 mm in diameter, 15 mm in length) by 157 kg/m³ (2% in vol.) in the matrix. Therefore it is possible to cast it into the very thin shell mold or into the complicated shaped mold. The segregation or sinking of steel fiber from the matrix does not occur because of the viscosity of the paste. However it is noted that the orientation of the steel fiber should be controlled to distribute in all directions when casting.

2.2 Mechanical properties

The mixing plant for the fabrication of pre-cast segments uses an ordinary mixer. For the mechanical quality management of the material, 6 test cylindrical specimens with the size of ϕ 10x20 cm for compressive strength and 3 test specimens with the size of 10x10x40 cm for flexural strength were sampled for each pre-cast segments. All samples with 90°C heat treatment for 48 hours were cured in the same way as the pre-cast segments. Fig. 1 (JSCE, 2004) indicates the frequency distribution of compressive strength showing the mean value is 196 N/mm² and the standard deviation is 7.1 N/mm² for the data number N=48. On the other hand, the results of flexural strength was that the mean value is 36.5 N/mm² and the standard deviation is 4.5 N/mm² for the data number N=24.

The incorporation of small-size steel fibers results in ultra-high energy absorption capabilities. The bending fracture energy is 36,000 N/mm², on the other hand one for the ordinary concrete with compressive strength 30~50 N/mm² is at most a range of 50~200 Nm/m². The high-tensile strength combined with the high ductility makes conventional rebar reinforcement unnecessary.

2.3 Durability

The matrix of UFC forms a dense structure due to the densest packing and microstructures resulting from pozzolanic reaction of silica fume. The pore size distribution of UFC is therefore quite different from the ordinary concrete. Fig. 2 and Fig. 3 (JSCE, 2004) show the comparison of pore size distribution between UFC and the ordinary high strength concrete with W/C=30%. The relationship between the pore volume ratio and the pore diameter was predicted by applying a mercury intrusion porosimetry apparatus. The pore structure is designated depending on the pore size; i.e. it is defined as 'Gel Pore' for the size up to 10 nm on the other hand it is defined as 'Capillary Pore' for the size from 10 nm to 1 μ m. The capillary pore is a continuous pore like ameba and this is related to the water permeability; i.e. the lesser the capillary pore the better durability. It is obvious that UFC is extremely denser structure than the ordinary concrete, as Fig. 2 showing that the pore volume ratio of UFC for either heat curing or curing in water are 4.3-4.5%, hence that for high strength concrete with W/C=30% is 9.0%. In addition, the pore volume ratio of capillary pore of UFC is only 0.5%, hence that for high strength concrete is 5.8%.

Carrying out 1100 freezing and thawing cycles in accordance with JIS A 6204 produces no adverse effect on the specimens; i.e. no relative dynamic elastic modulus reductions for 1100 cycles. The extreme denseness of UFC makes it difficult to determine the diffusion coefficient of chloride ions. For the estimation of chloride diffusion coefficient, the specimen with 10x10x40 cm was immersed in a NaCl solution (1.9% consistency) for couple of years and EPMA (Electron Probe Micro Analyzer) was used to predict the apparent chloride diffusion coefficient through the regression curves to fit the chloride concentration distribution near the specimen surface. Fig. 4 demonstrates the chloride ions concentration profiles after different immersed periods. The pixel size was 0.02 mm and every five-pixel data were averaged in depth direction; i.e. the interval of averaged data in Fig. 5 is 0.1 mm. The chloride concentration distribution measured by EPMA for different immersed periods

is illustrated in Fig. 5. The regression curves to fit the chloride ions concentration designate the apparent chloride diffusion coefficient for those different immersed periods. The chloride diffusion coefficients determined by this method are shown in Table 2. Those results imply the apparent diffusion coefficient ranging from 0.0019 to 0.0059 cm²/year. For comparison, the value for conventional high strength concrete with W/C=30%, which is regarded as having relatively high durability, is 0.14 cm²/year. The durability properties of UFC therefore show a striking difference from those of the conventional normal concrete.

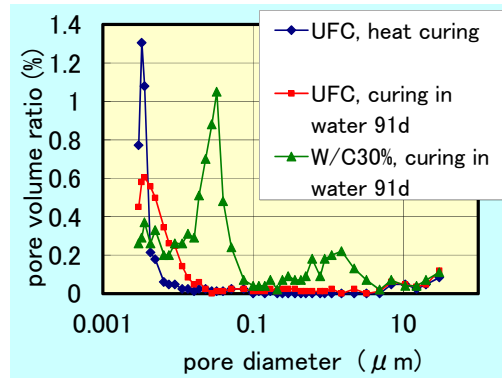
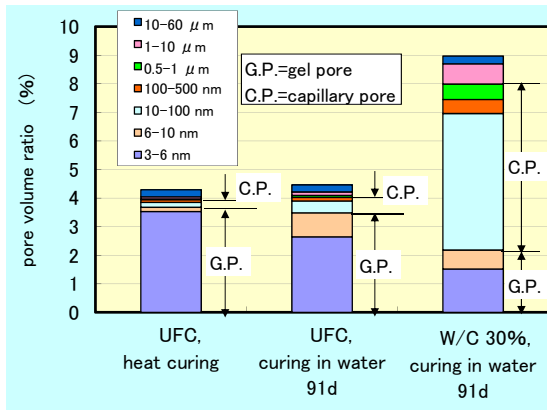


Fig. 2 Comparison of pore volume ratio (JSCE, 2004) **Fig. 3 Pore volume ratio distribution**

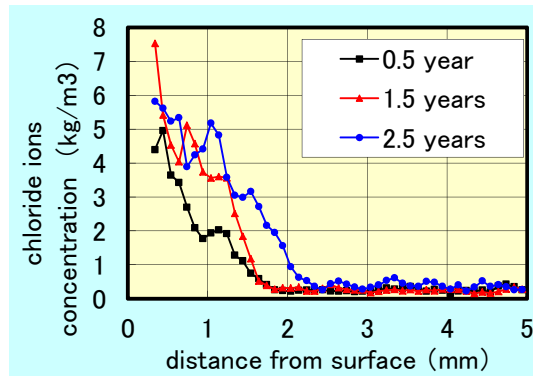


Fig. 4 Chloride profiles after different periods (JSCE, 2004)

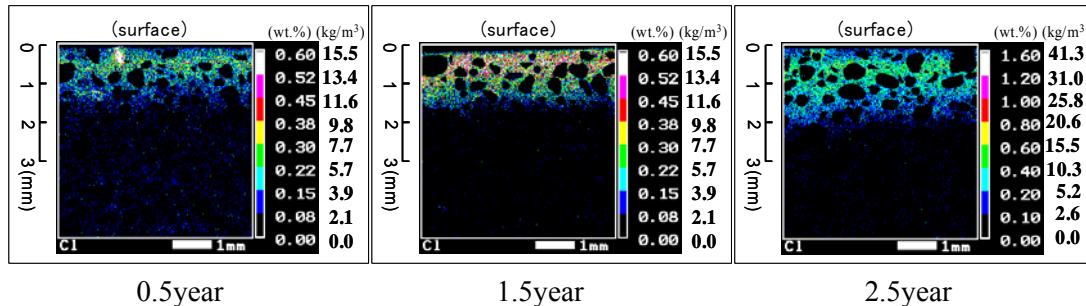


Fig. 5 Chloride ions distribution by EPMA (immersed case)

Table 2 Apparent chloride ion diffusion coeff. (immersed case)

immersed periods (year)	0.5	1.5	2.5
apparent chloride diffusion coeff. (cm ² /year)	0.0059	0.0022	0.0019

3. APPLICATIONS OF UFC TO STRUCTURES

UFC is applied to many kinds of structure in Japan. There are footbridges, road bridges, roofs, sunshades, tunnel linings, slabs and so on. Since UFC makes it possible to reduce the dead weight of the structure drastically and possible to extend a beam's span largely, UFC has been applied to many bridges. There are more than 20 UFC bridges in Japan, now. Three typical UFC bridges are introduced as follows.

3.1 Sakata Mirai Bridge

This footbridge is a single-span PC box girder bridge and has a 49.4 m span shown in Photo 1 (Musha, 2002). It is the first PC bridge in Japan to utilize UFC. The bridge has very thin members. The thickness of the top slab is only 5cm and the web is 8 cm (Photo 2), since there is no rebar inside. The body of the bridge is 53 tons, or about one-fifth the weight of a conventional concrete bridge. The low girder height is only 55 cm at girder ends despite its long span length (50 m). The standard girder height-span ratio is about 1/17 for simply supported box girder bridges having a span of about 50 m, but this bridge has a ratio of 1/90 at the girder ends and a ratio of 1/32 at the center of the girder (1.56 m in height). Utilizing material high performance fully, the distinctive design was realized; i.e. the low girder height and the large circular holes in the webs (Photo 3).

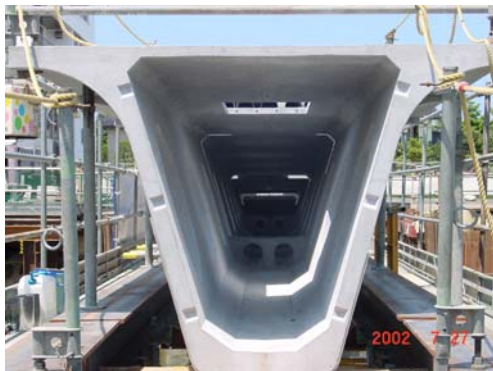


Photo 2 Sakata Mirai Bridge



Photo 3 Erection of precast block

3.2 Mikaneike Bridge

This 81.2 m in length and 3.5 m in width PC bridge is a two-span (2x39.3 m) continuous PC box girder bridge shown in Photo 4 (Musha, 2007).

The girder height is 1.0 m so the ratio of girder height-span is 1/40. The top slab is 7 cm thick, the bottom slab is 8 cm thick and the web varies from 8 to 20 cm thick. The box girder was divided into top slabs and lower U-shaped girders (Photo 5) for pre-cast segment production. The U-shaped pre-cast segments were connected together by wet joints. PBL (Photo 5), which is the abbreviation of the Perfobond Strip shear connector (which German name is Perfobond Leisten), was used to connect the top slab and the U-shaped girder.



Photo 4 Mikaneike Bridge



Photo 5 U-shaped girder and PBL

3.3 Tokyo International Airport (Haneda) GSE Bridge

The bridge structure is a single span pre-tensioned composite girder 48 m long shown in Photo 6 (Musha, 2008). The girder type is determined in 3 box girders because of wide bridge width 16.2 m. This bridge consists of UFC U-shaped girders ($f'_{ck} = 180 \text{ N/mm}^2$) and conventional cast-in-situ concrete slab ($f'_{ck} = 40 \text{ N/mm}^2$). Since UFC does not require any reinforcing bars, the web thickness utilizing its ultra-high strength is only 150 mm, achieving a very slender form compared to the conventional concrete. UFC girders require heat curing and shop fabrication to ensure quality, therefore, those are inevitably precast structure. Taking into account the capacity of the lifting equipment at the shop, it was decided that each segment of the precast girder should weigh less than 25 tons. Therefore the 47.6 m long main girder was divided into seven precast blocks (Photo 7). After the UFC girders were erected on the supports at the erection sites, the joint between the girders was filled with cast-in-situ UFC to create a wet joint, and prestress was introduced to integrate the bridge body. The top slabs and U-shaped girder were jointed together by PBL joints.



Photo 6 GSE Bridge



**Photo 7 UFC precast block
(no rebar inside)**

4. DURABILITY PERFORMANCE OF SAKATA-MIRAI UFC BRIDGE

Durability of UFC is verified by many kinds of laboratory tests using specimens. There are, however, few field data for UFC durability. Since UFC is a relatively new material, the verification of its durability based on actual structure is not enough, and it is essential for further UFC's effective utilization. Therefore, the continuous investigations have been conducting using Sakata Mirai Bridge. The periodic investigation into the bridge has being

conducted at 0.5, 1, 2, 5, 7.5 and 10 years after its completion. This section introduces the durability performance of UFC based on the field investigation.

4.1 Site location

Sakata Mirai footbridge is located in Sakata City, Yamagata prefecture facing to the Japan Sea. The west coastline in Japan usually has severe west or southwest winds and snowy storm in winter. Although the site location is 3.4 km far from the coastline, the seasonal winter storms induce the chloride attack on the footbridge.

4.2 Secular distortion of mechanical properties

In order to investigate the material time history of mechanical properties and durability, UFC specimens were exposed inside of the box girder of the footbridge as shown in Photo 8. The dimension of the specimen for compressive strength is $\phi 5 \times 10$ cm circular cylinder and that for flexural strength is $4 \times 4 \times 16$ cm regular prism. The result of compressive strength versus exposing duration time is shown in Fig. 6 and those of flexural strength and first cracking strength are shown in Fig. 7. The compressive strength seems to be gradually increasing but it can be said that the strength is stable. It is noted that the average compressive strength in Fig. 6 is larger than that in Fig. 1. This is because of the size effect on strength; i.e. the size of specimens in Fig. 6 is small. The time dependent records of the flexural strength are also stable. The strength of ordinary concrete has usually the upward trend in time, however UFC had heat curing in the process of fabrication; therefore the chemical hydration has already completed. This means the strength would not largely increase.



Photo 8 Exposed specimens inside girder

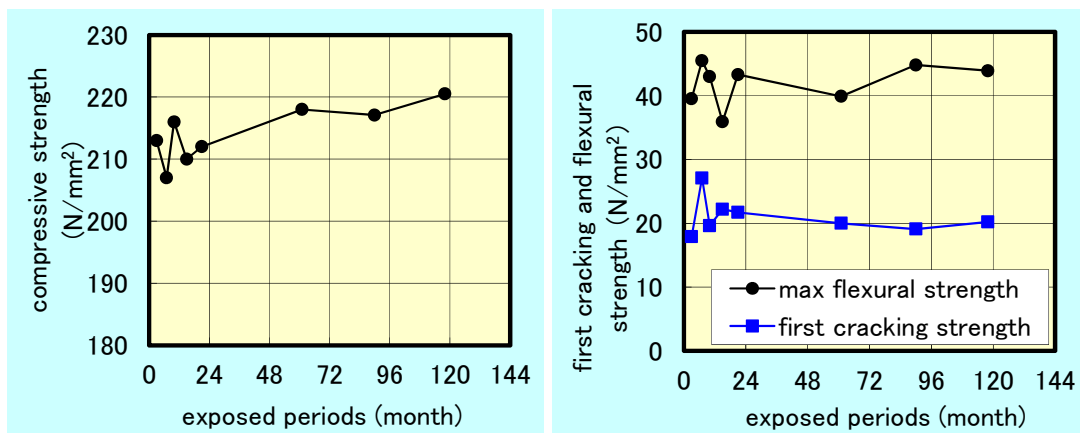


Fig. 6 Records of compressive strength Fig. 7 Records of flexural strength

4.3 Chloride ions concentration profiles

The specimen with 4x4x16 cm regular prism that was exposed for 120 months (about 10 years) inside the box shaped girder (Photo 8), was sliced off 10 mm thickness. The dimension of the test surface was taken to be 10 mm in width and 5 mm in depth from the surface and this piece was grinded to apply EPMA. The chloride ions concentration profile and the regression curve are illustrated in Fig. 8. The pixel size was 0.02 mm and every 5 pixel data were averaged in depth direction. The regression data was taken at deeper points of 0.4 mm. It should be noted that compared to the test specimen that was immersed in a NaCl solution (shown in Fig. 4), this concentration profile of the chloride ions is smooth and fits the regression curve quite well. From the regression function, the apparent chloride ion diffusion coefficient was predicted to be $0.000753 \text{ cm}^2/\text{year}$ (Table 3; left side of exposed specimen) that is very small compared to the immersed case (Table 2) and the chloride ion concentration on the surface was calculated to be 9.9 kg/m^3 . Fig. 9 indicates the chloride distribution obtained by EPMA and the chloride ions concentration profile and the regression curve are illustrated in Fig. 10 in two directions. It is apparent that the chloride ions penetrated into just surface of the specimen such as 1 to 2 mm and the level of permeation of the chloride ions is equivalent with that of immersed case (Fig. 5).

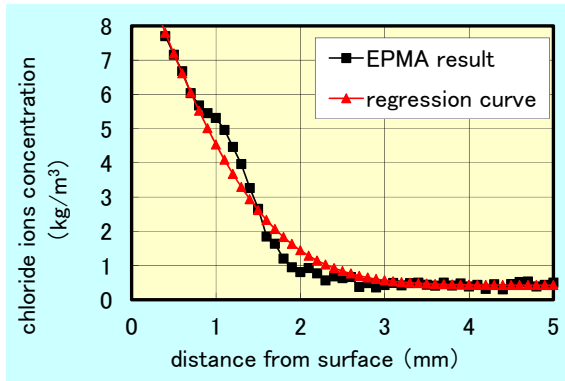
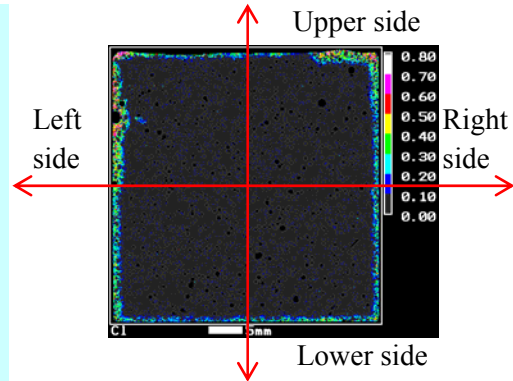


Fig. 8 Chloride ions profile



**Fig. 9 Results of EPMA
(exposed specimen)**

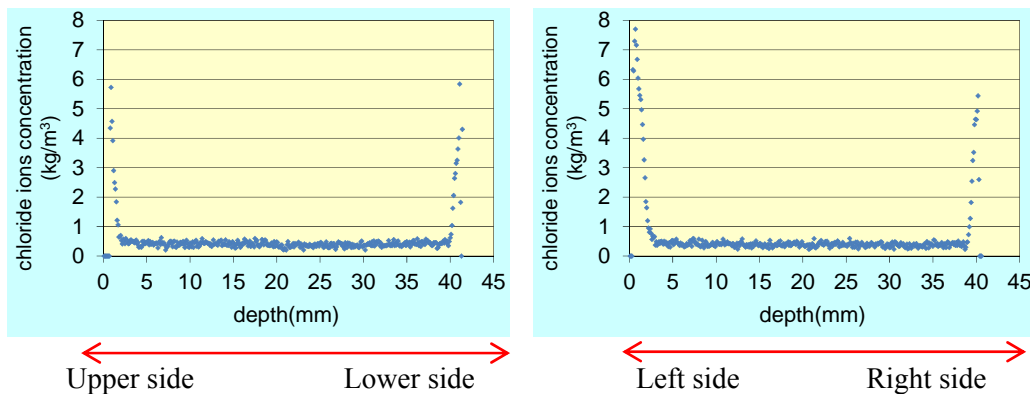


Fig. 10 Chloride ions distribution (exposed specimen)



Photo 9 Test piece from web



Photo 10 Core drilling in web

However these valuable durability data were obtained from the specimen exposed in the girder, it is necessary to verify that these data reflect the state of the actual bridge. Then test pieces (Photo 9; $\phi 2.5 \times 8$ cm circular cylinder) were obtained by core drilling from the both side of the web (Photo 10), and the similar analysis was executed. The chloride ions concentration profile and the regression curve are illustrated in Fig. 11. The chloride diffusion coefficients and the surface chloride ion concentration are shown in Table 3. The strong sea breeze blows the web of the bridge, therefore the surface chloride ion concentration of the outside of the sea side web is relatively big. Even though the surface chloride ion concentration is big, its chloride diffusion coefficients are the same level to other sides (i.e. outside of the mountain side web).

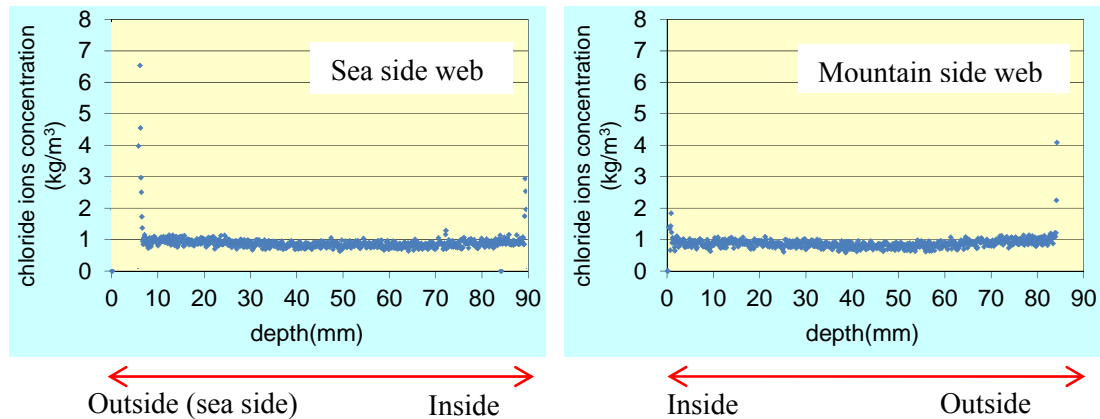


Fig. 11 Chloride ions distribution (core test piece)

Table 3 Apparent chloride ion diffusion coeff. (field data)

	Face	Apparent chloride diffusion coeff. (cm^2/year)	Surface chloride ion concentration (kg/m^3)
Exposed specimen	Upper	0.0001730	7.1
	Lower	0.0002700	4.9
	Left	0.0007530	9.9
	Right	0.0003320	7.0
Core test piece of sea side web	Inside	0.0000503	3.8
	Outside	0.0000667	21.1
Core test piece of mountain side web	Inside	N/A	0.7
	Outside	0.0000404	8.6

The chloride diffusion coefficients determined from the test-pieces obtained by core drill are same or less than those of the specimens (placed inside of the girder). Since the chloride diffusion coefficients obtained from the specimens kept inside of the girder are larger than those of the actual bridge, it is possible to use those specimens to judge the state of the bridge in the safety side.

4.4 Conclusions of durability investigations

- 1) The time dependent records of compressive and flexural strength are stable.
- 2) Chloride ion diffusion coefficient obtained the field specimen is much lower than that in the laboratory immersed specimen.
- 3) Chloride ion diffusion coefficient obtained from the test-pieces by core drill is lower than that the field specimen exposed in the girder.
- 4) Ten years old UFC bridge still keeps good condition with its mechanical property and its durability against the sever circumstances, therefore the sustainability of UFC structure is verified in terms of the 10 years investigation.

5. CONCLUSION

On Sakata Mirai Bridge, which was the first UFC structure in Japan, the superior durability was confirmed by the investigation of ten years after the completion. However, for UFC claimed to have the durability more than 100 years, it is still only ten years. Therefore, it is necessary to continue this investigation in future, and the obtained data will be significant in order to realize sustainable structures.

At a time when the superstructures of general PC bridges are constructed with concrete having a compressive strength of 40-50N/mm², the ability to construct long-span bridges with a material having a compressive strength of 180N/mm² without using rebar has brought a new perspective to the world of concrete. It is hoped that this technology will strongly accelerate the further development of concrete. And it is also hoped that this technology will realize many sustainable structures as gifts to the next generation.

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