

DURABILITY STUDY OF THE FIRST PC BRIDGE CONSTRUCTED WITH ULTRA HIGH STRENGTH FIBER REINFORCED CONCRETE IN JAPAN

Katsuya Kono (1), Hiroyuki Musha (2), Tetsuo Kawaguchi (1), Akira Eriguchi (1), Satoshi Tanaka (1), Tadashi Kobayashi (3) and Masayuki Ikeda (3)

(1) Research & Development Center, Taiheiyo Cement Corporation, Japan

(2) Technology Center, Taisei Corporation, Japan

(3) Maeta Concrete Industry Ltd., Japan

Abstract

In Japan, the use of ultra high strength fiber reinforced concrete (UFC) has been increasing since the publication of recommendations on the design and construction of UFC structures by the Japan Society of Civil Engineers in September 2004. UFC is a unique cementitious composite with high tensile strength which enables concrete structure designs without reinforcing bars. Its durability is also very high compared to conventional concrete. UFC has been mainly applied to bridges, taking advantage of its high strength. Sakata-Mirai Footbridge was the first bridge constructed with UFC in Japan in October 2002. In this paper, the durability and strength performance of this UFC footbridge has been periodically studied. It was found that ten year old UFC footbridges can maintain good condition and mechanical properties even against severe environments, and thus the sustainability of UFC structures is verified in terms of the 10 year investigation.

Résumé

Au Japon, l'utilisation de BFUP a augmenté depuis la publication des recommandations sur la conception et la construction de structures en BFUP éditées par la "Japan Society of Civil Engineers" en septembre 2004. Les BFUP sont des matériaux cimentaires uniques possédant une grande résistance en traction, ce qui autorise la conception d'ouvrages en béton sans armatures. Leur durabilité est elle aussi très supérieure à celle des bétons courants. Les BFUP sont très utilisés dans les ouvrages d'art en raison de leur grande résistance. La passerelle piétonne Sakata-Mirai a été le premier pont construit en BFUP au Japon en octobre 2002. La durabilité et la résistance de cet ouvrage ont été régulièrement contrôlées. Ces inspections réalisées durant 10 ans sur l'ouvrage lui-même et sur des éprouvettes de contrôle stockées dans le même environnement agressif montrent le maintien des propriétés de résistance et de durabilité du matériau et la robustesse des structures en BFUP.

1. INTRODUCTION

The development of concrete and cementitious composites with fibre reinforcement to improve tensile load-deformation behaviour has resulted in three distinct classes of materials. These include conventional Fibre Reinforced Concrete (FRC) with tension softening response, High Performance Fibre Reinforced Cement Composites (HPRC) with strain hardening and multiple cracking behaviour, and Ultra High Strength Fibre Reinforced Concrete (UFC) with increased tensile strength.

In Japan, the use of UFC has been increasing since the publication of recommendations on the design and construction of UFC structures by the Japan Society of Civil Engineers (JSCE) in September 2004 [1]. UFC is a unique cementitious composite with high tensile strength which enables concrete structure designs without reinforcing bars. Its durability is also very high compared to conventional concrete.

Sakata-Mirai Footbridge, shown Photograph 1, was the first bridge constructed with UFC in Japan in October 2002 [2]. The structure has a single span length of 49.35 m, a section height of 1.65 m and width of 2.4 m at mid-span with external prestressing tendons. This structure was built to span the Niita River that flows through the urban area of Sakata City, Yamagata Prefecture. Since the location is about 3.4 km from the Japan Sea coastal line, this footbridge is exposed to severe corrosive environments in winter.



Photograph 1: Sakata-Mirai Footbridge

In this paper, the durability and strength performance of this structural concrete have been periodically investigated over 10 years, using samples obtained by core drilling from the web of the bridge, as well as samples prepared and contained in similar conditions to those of the bridge.

2. PROPERTIES OF UFC (DUCTAL®)

2.1 Material, mix proportion and consistency

Table 1 shows the materials used for UFC, and Table 2 shows the standard mix proportion of UFC. UFC is a material produced by mixing a pre-mix powder of cement, silica fume, silica fine powder, and silica sand in the optimum proportion with water, high performance polycarboxylic superplasticizer, and dispersed short fibres. Steel short fibre (0.2 mm dia. x 15 mm length) of 2vol.% mixture (FM) is standard. Flow value obtained from mortar flow test with no drop shows about 260-270 mm where the fresh concrete is self-compactable.

Table 1: Materials of UFC

Material	Property
Premix (PM)	UFC premix powder
Admixture (Ad)	Polycarboxylic superplasticizer
Steel fibre (FM)	dia. 0.2 x 15 mm
Water (W)	Tap water

Table 2: Mix proportion of UFC

Unit content (kg/m ³)			
W (incl. Ad)	PM	FM	Ad
180	2254	157 (2vol. %)	24 (Average)

2.2 Pore structure

In producing UFC, after the mixed material has hardened at the age of 24 hours, it undergoes steam curing at 90 degrees centigrade for 48 hours. Due to steam curing, a dense structure will be formed when setting, and it will improve durability. Figure 1 shows the distribution of pore volume measured by mercury penetration method for steam cured UFC without fibres, water cured UFC without fibres, and high strength concrete with water-cement ratio of 30% [1]. The porosity of UFC is about 4% irrespective of curing conditions, and is very small compared to high strength concrete. It also shows that more than 80% of pores are 3 to 6 micrometers when steam curing is applied.

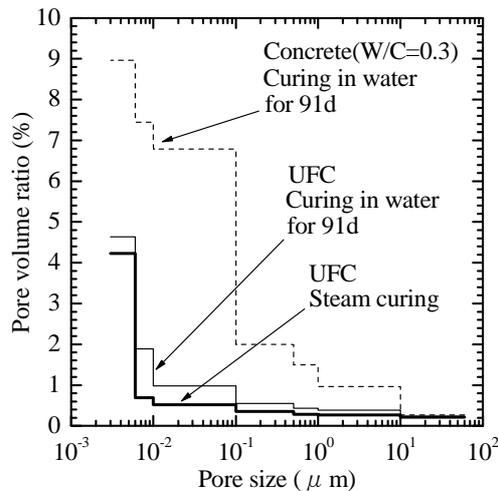


Figure 1 Pore size distribution of UFC

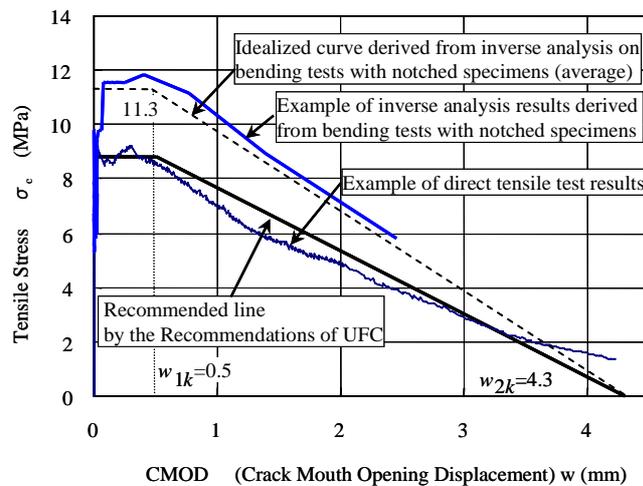


Figure 2 Tension softening diagram of UFC

2.3 Strength

Table 3 shows compressive strength, bending strength and modulus of elasticity in compression. Compressive strength of 200 MPa or more and flexural strength of 40 MPa or more (using 40 x 40 x 160 mm specimen) can be achieved [3].

Figure 2 shows the tension softening diagram (hereafter referred to as TSD) of UFC [1]. The proposed TSD was determined based on both the direct tension test results and the inverse analysis of tests using notched beam specimens (100 x 100 x 400 mm). According to the test results, the characteristic tensile strength becomes $f_{tk} = 8.8$ MPa, the crack mouth opening displacement (hereafter referred to as CMOD) for which a certain stress level is retained after the first crack is $w_{1k} = 0.5$ mm, and the CMOD for which the stress comes to zero is $w_{2k} = 4.3$ mm.

Table 3: Compressive, flexural strength and modulus of elasticity

	Compressive strength (MPa)	Flexural strength (MPa)		Modulus of elasticity (GPa)
		Initial crack strength	Maximum flexural strength	
Mean value	238	24.9	46.1	52.2
Standard deviation	8.46	2.36	4.34	0.93
No. of specimens	50	50	50	50

2.4 Chloride ion penetration

Because UFC has a dense structure, resistance to penetration of chloride ions is very high. A cross section of the specimen of UFC (100 x 100 x 400 mm) after immersion in artificial seawater (concentration of chloride ion : 1.9 %, Major component: Sodium chloride, Magnesium sulphate, Magnesium chloride, Calcium chloride, Potassium chloride, etc) shows distribution of chloride ions as indicated in Figure 3 when measured by electron probe micro-analyzer (hereafter referred to as EPMA). As the duration of immersion increases from 0.5 years to 2.5 years, chloride ions may penetrate deeper but the depth is as little as 2 mm. The apparent diffusion coefficient of chloride ions of UFC estimated from the distribution of concentration is shown in Table 4. It is about 0.002 cm²/year, which is a hundredth or thousandth smaller than that of conventional concrete [4].

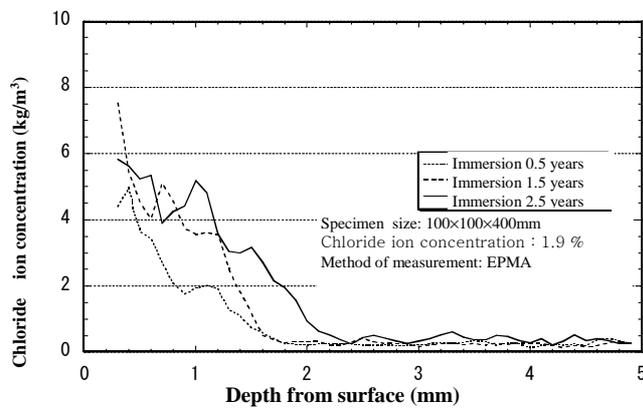


Figure 3 Distribution of chloride ion concentration of UFC after immersion in artificial seawater

Table 4: Apparent diffusion coefficient of UFC

Duration of Immersion (year)	Apparent diffusion Coefficient
0.5	0.0059 (cm ² /year)
	10.48×10^{-14} (m ² /s)
1.5	0.0022 (cm ² /year)
	3.910×10^{-14} (m ² /s)
2.5	0.0019 (cm ² /year)
	3.377×10^{-14} (m ² /s)

2.5 Abrasion resistance

Results of the abrasion resistance test according to ASTM C779 revolving disk method are indicated in Figure 4. The test was conducted in comparison with tests for conventional concrete (compressive strength 70 MPa) and for black granite (compressive strength 260 MPa). After 120 minutes of testing, the UFC specimen showed excellent abrasion resistance with an abrasion depth of 1.1 mm compared to 2.3 mm for conventional concrete and 1.8 mm for black granite [4].

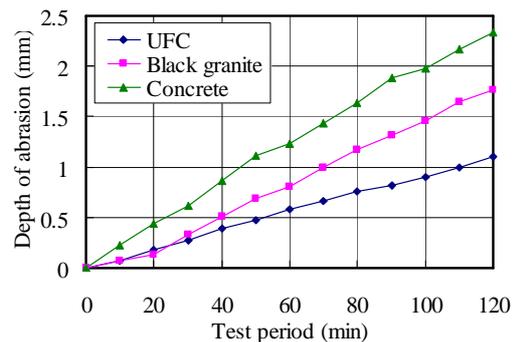


Figure 4 Result of abrasion resistance test according ASTM C779 [4]

2.6 Applications of UFC in JAPAN

UFC has been mainly applied to bridges, taking advantage of its high strength. It is also used in precast panels, and to protect the surface of the concrete structures against environmental effects such as salt attack, abrasion, impact and so on [5].

Photograph 2 shows the UFC forms used in the retrofitting of the bridge pier in the river. In this case, the main function of UFC is not mechanical strengthening but durability improvement, including wearing and abrasion resistance [4]. Photograph 3 shows the repair of the irrigation channel surface by UFC precast panels.



Photograph 2: Retrofitting of bridge pier Photograph 3: Repair of irrigation canal surface

3. DURABILITY PERFORMANCE OF SAKATA-MIRAI FOOTBRIDGE

The durability of UFC is verified by many kinds of laboratory tests using specimens. There is, however, little field data for UFC durability. Since UFC is a relatively new material, such data are necessary in order to attest to its durability in actual structures, which is critical to its further effective utilization. Therefore, continuous investigations are being conducted using Sakata-Mirai Footbridge. The periodic investigation into the bridge has been 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.

3.1 Site location

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

3.2 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 Photograph 4. The compressive strength specimens are ϕ 50 x 100 mm circular cylinders, and the flexural strength specimens are 40 x 40 x 160 mm regular prisms. The results of compressive strength versus exposure duration time are shown in Figure 5 and those of maximum flexural



Photograph 4: Exposed specimens inside girder

strength and first cracking strength are shown in Figure 6. The compressive strength seems to be gradually increasing. The flexural strength increases almost linearly up to the age of 10 years. In general, the long-term flexural strength gradually decreases with increasing drying shrinkage. This is due to the tensile stresses induced by restrained shrinkage prior to the application of the load, which induces tension at the lower edge of the beam specimen. However, UFC has a small amount of drying shrinkage (about 50×10^{-6}), so that surface shrinkage stress is not generated, and a constant in flexural strength is observed.

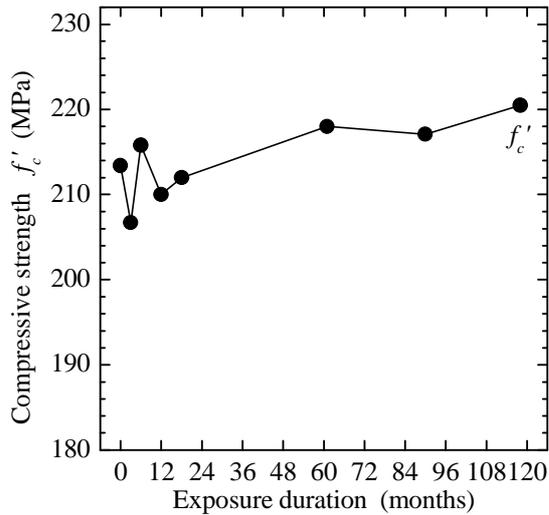


Figure 5: Records of compressive strength

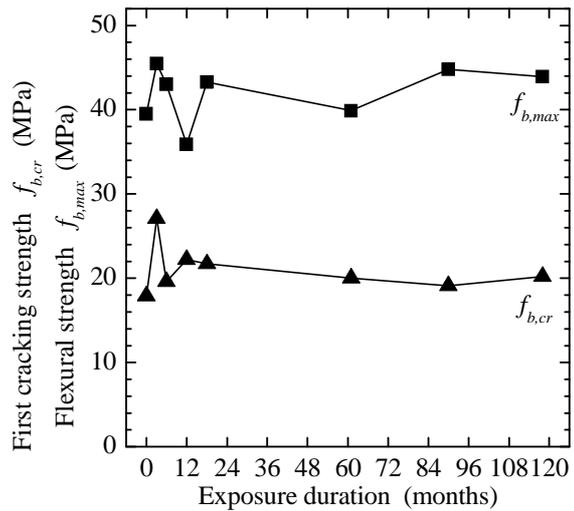


Figure 6: Records of flexural strength

3.3 Chloride ions concentration profiles

The 40 x 40 x 160 mm rectangular prisms exposed for 120 months (about 10 years) inside the box shaped girder were cut to obtain 10 mm thick specimens. The dimensions of the test surface were taken to be 20 mm in width and 5 mm in depth from the surface and this piece was grinded to apply EPMA. Figure 7 indicates the chloride distribution obtained by EPMA, and the chloride ions concentration profile and regression curve are illustrated in Figure 8. It should be noted that compared to the test specimen that was immersed in a NaCl solution (shown in Figure 3), 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 5: left side of exposed specimen), which is very small compared to the immersed case (Table 4). The chloride ion concentration on the surface was calculated to be 9.9 kg/m^3 . It is apparent that the chloride ions penetrated into just the surface of the specimen (1 to 2 mm) and the level of permeation of the chloride ions is equivalent to that of the immersed case (Figure 3).

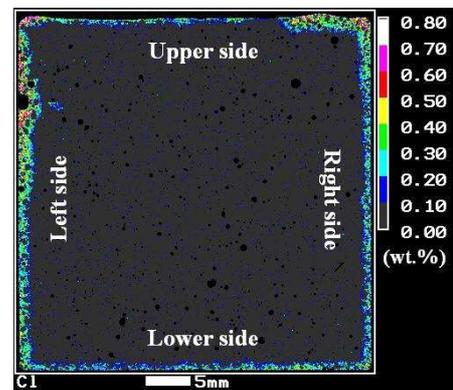


Figure 7: Image mapping of Cl

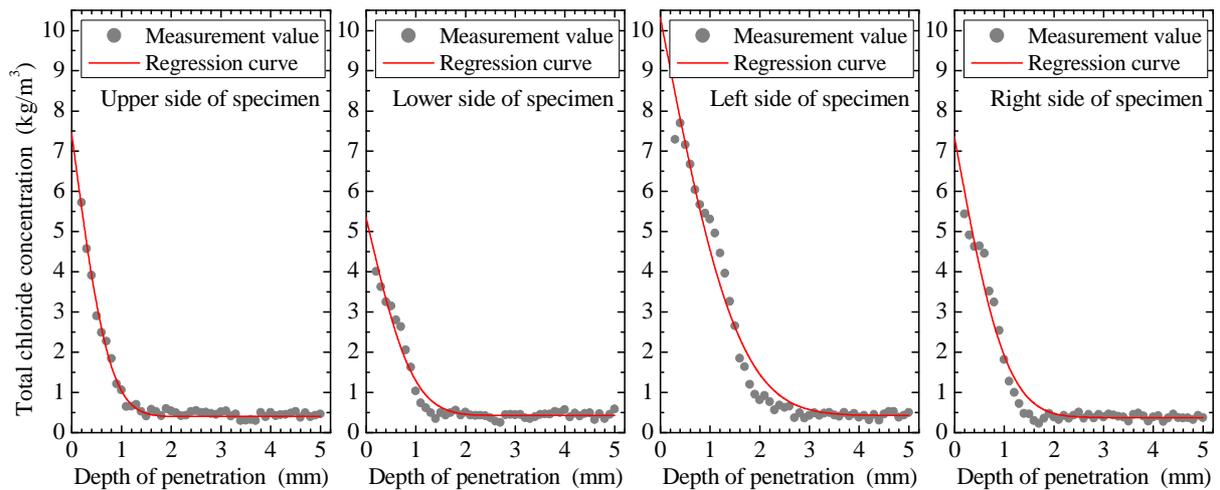


Figure 8: Chloride ions profile of exposed specimen

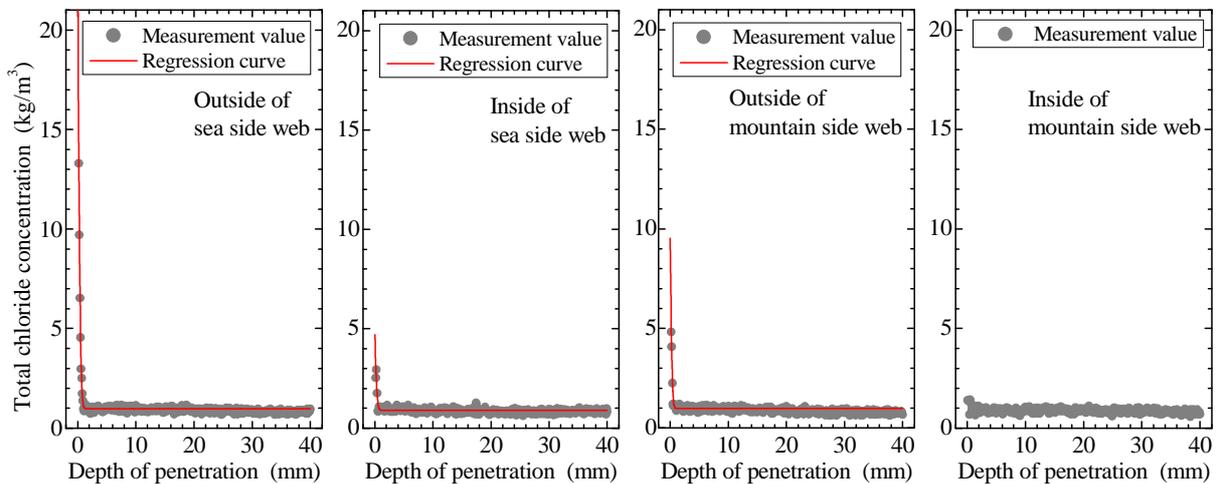


Figure 9: Chloride ions profile of core test piece

While these valuable durability data were obtained from the specimen exposed in the girder, it is still necessary to verify that they reflect the state of the actual bridge. To that end, test pieces (ϕ 25 x 80 mm circular cylinder) were obtained by core drilling from the both sides of the web (Photograph 5), and similar analysis was executed. The chloride ion concentration profile and the regression curve are illustrated in Figure 9. The chloride diffusion coefficients and the surface chloride ion concentration are shown in Table 5. 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 coefficient is the same level as other sides (i.e. the mountain facing side web).



Photograph 5 Core drilling in web

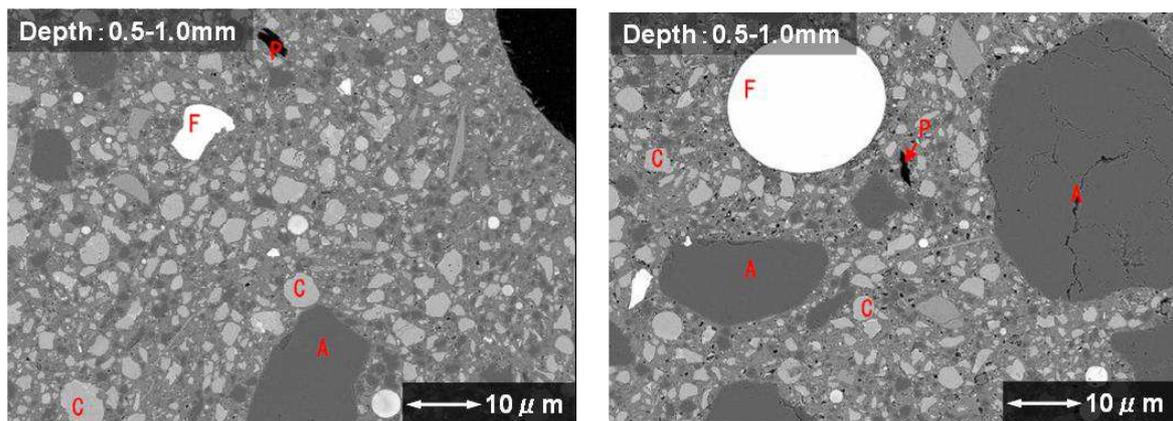
The chloride diffusion coefficients determined from the test pieces obtained by core drilling are same or less than those of the specimens placed inside of the girder. Since the chloride diffusion coefficients obtained from the specimens kept inside of the girder are larger than those of the actual bridge,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

Table 5: Apparent chloride ion diffusion coefficient (field data)

	Face	Apparent Cl ⁻ diffusion coefficient		Surface Cl ⁻ concentration (kg/m ³)
		(cm ² /year)	(m ² /s)	
Exposed specimen	Upper	0.0001730	3.075 x 10 ⁻¹⁵	7.1
	Lower	0.0002700	4.799 x 10 ⁻¹⁵	4.9
	Left	0.0007530	13.38 x 10 ⁻¹⁵	9.9
	Right	0.0003320	5.901 x 10 ⁻¹⁵	7.0
Core test piece of sea side web	Outside	0.0000667	1.185 x 10 ⁻¹⁵	21.1
	Inside	0.0000503	0.894 x 10 ⁻¹⁵	3.8
Core test piece of mountain side web	Outside	0.0000404	0.718 x 10 ⁻¹⁵	8.6
	Inside	N/A	N/A	0.7

3.4 Backscattered electron image analysis

Figure 10 (a) and (b) are backscattered electron images (BEI) of sections (range from 0.5mm to 1.0mm in depth) of exposed specimen (in the girder) and core test pieces of the sea side web (outside), respectively. Figure 10 shows that the microstructure of UFC consists of two phases: continuous reaction texture (i.e., hydrate), and irregularly-distributed granular texture (i.e., cement, aggregate, steel fibre and air void). Examination of exposed specimens and core test pieces by scanning electron microscopy revealed the presence of many unhydrated cement particles.



(a) Exposed Specimen (b) Core test piece of sea side web (Outside)
 Figure 10: BEI of UFC (C: Unhydrated cement, A: Sand, F: Steel fibre, P: Air void)

Table 6 summarizes the results of BEI analysis, which mainly revealed that the microstructure of UFC contains around 20 % unhydrated cement and around 7% of air void. Rich unhydrated cement grains may be found in the microstructure of hydrated cement pastes

of UFC, even long after hydration by heat curing. As Figure 5 and Figure 10 show, the long-term improvement of compressive strength is considered to be due to the sluggish reaction of internal unhydrated substance.

Table 6 Area ratio of unhydrated cement and air void by BEI analysis

	Areas of analysis (Microscopic field: 10 points)	Area ratio (Volume ratio) (%)	
		Unhydrated cement	Air void
Exposed specimen (Age: 7.5 years, Section: 40 x 40 mm)	Whole area (40 x 40mm)	21.2	7.8
Exposed specimen (Age: 10 years, Section: 40 x 40 mm)	Whole area (40 x 40mm)	19.9	5.7
Core test piece of sea side (Age: 10 years, Section: 25 x 80 mm)	Outside surface area (25 x 20mm)	18.5	7.0
	Central area (25 x 20mm)	22.3	7.0
	Inside surface area (25 x 20mm)	19.2	7.0

4. CONCLUSIONS

The durability and the mechanical properties of the ten year old UFC bridge has been studied by using exposed specimens in the girder and core test pieces of the web. The main results obtained are shown below.

- The compressive strength of the field specimen increases gradually up to the age of 10 years.
- The flexural strength of the field specimen increases almost linearly up to the age of 10 years.
- The Chloride ion diffusion coefficient obtained from the field specimen is much lower than that of the laboratory immersed specimen.
- The Chloride ion diffusion coefficient obtained from the test pieces by core drilling is lower than that of the field specimens exposed in the girder.
- Examination of exposed specimens and core test pieces by scanning electron microscopy revealed the presence of many unhydrated cement particles.
- Ten year old UFC footbridges can maintain good condition and mechanical properties even against severe environments, and thus the sustainability of UFC structures is verified in terms of the 10 year investigation.

REFERENCES

- [1] JSCE, 'Recommendations for Design and Construction of Ultra High-Strength Fiber Reinforced Concrete Structures (Draft)', 2006. (2004, in Japanese)
- [2] Y. Tanaka, H. Musya, A. Ootake, Y. Shimoyama and O. Kaneko, 'Design and Construction of Sakata-Mirai Footbridge using Reactive Powder Concrete', Proc. of 1st fib Congress 2002, 2002.

- [3] M. Uzawa, T. Masuda, K. Shirai, Y. Shimoyama and Y. Tanaka, 'Fresh Mortar Properties and Strength of Reactive Powder Composite Material (Ductal®)', Proceedings of the first fib Congress 2002, session 7, pp.127-132, 2002.
- [4] S. Shirai, K. Matsuda and S. Tanaka, 'DURABILITY OF UFC FORMWORK LEFT IN-PLACE AND ITS APPLICATION', Proceedings of 8th International Symposium on Utilization of High-Strength and High-Performance Concrete, 2008.
- [5] Taiheiyo Cement Corporation (<http://www.taiheiyo-cement.co.jp/ductal/index2.html>)