An Experimental Study on the Mechanical and Durability Properties of UHPFRC for cast-in-place method

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Abstract: In order to repair and reinforce concrete structure, research to develop a method to increase the thickness or replace the surface of concrete members by using UHPFRC has been started. The UHPFRC mix used in the research is characterized by its matrix densified by ettringite (AFt) formation; thus, it is called "AFt-UHPFRC". The AFt-UHPFRC was originally developed for fabrication of precast members with thermal curing. The paper presents results obtained from a construction project and an experimental investigation in both of which cast-in-place UHPFRC is used. The construction project is to replace the 100-year-old suspension bridge with a girder bridge made of UHPFRC. The experimental investigation is carried out to develop an improving method of existing bridge decks. In order to understand the behavior and durability of cast-in-place AFt-UHPFRC, strength evolution, pore diameter distribution, shrinkage behavior and chloride penetration resistance were investigated. It is understood that the AFt-UHPFRC's excellent mechanical properties and durability are achieved even by cast-in-place method if the AFt-UHPFRC is properly cured at early ages.

Keywords: UHPFRC, cast-in-place, curing method, durability, chloride penetration

1. Introduction

UHPFRC is a high-strength and high-ductility material with a compressive strength of 150–250 MPa and a tensile strength of not lower than 8 MPa. It is also characterized by very low water and air permeability, thus attaining high chloride resistance because of the compact matrix.

Recently, through achievements of mass manufacturing of precast members with large sections, applications of UHPFRC to civil engineering structures have been increasing. Among them, application to floor slab at Runway D of the Tokyo International Airport is the largest so far (about 20,000m^3 UHPFRC). In Japan, UHPFRC have been used mainly for precast products manufactured in factories equipped with heat curing facilities in order to utilize its high performance. However, depending on the scale of construction and the conditions, cast-in-place may be more rational.

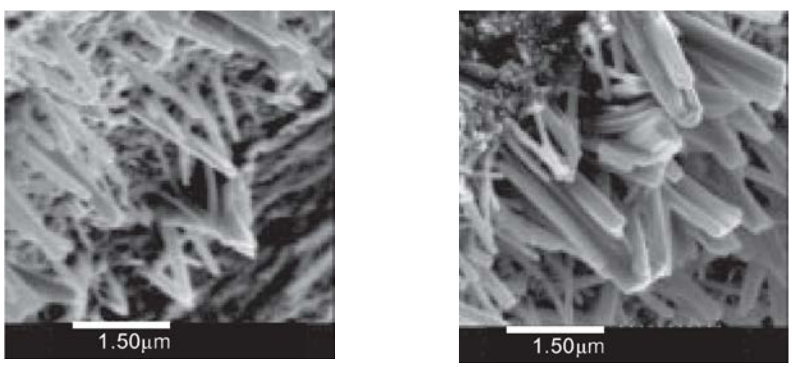
Under such circumstances, recently cast-in-place UHPFRC was successfully applied to the construction of a prestressed girder road bridge without thermal curing [1]. Besides, a research project has been started aiming for improving existing concrete structure by using cast-in-place UHPFRC.

In this paper, to understand the behavior and durability of the UHPFRC as material for improving existing concrete structures by cast-in-place method, strength evolution, pore diameter distribution, shrinkage behavior, and chloride penetration resistance were investigated.

2. AFt-UHPFRC

A commercially available UHPFRC mix called SUQCEM was used. SUQCEM was developed in 2006, characterized by its matrix densified by ettringite (AFt) formation; thus, it is called AFt-UHPFRC. The fine structure of the AFt-UHPFRC matrix is basically formed by decreasing water/binder ratio using spherical pozzolan particles and superplasticiser and packing ultrafine particles optimally. In addition, numerous needle-shaped ettringite crystals of 1–2 μm length fill micropores of hydration structure together with inert and reactive fine fillers.

The standard curing method for fabrication of precast products using AFt-UHPFRC is as follows: the first curing is performed at 20 degrees Celsius for 24 hours. Subsequently, the secondary curing is carried out at 85 degrees Celsius for 20 hours. Unlike in the case of AFt-UHPFRC, the standard UHPFRC (e.g. Ductal) is cured at 90 degrees Celsius for 48 hours by steam curing. Scanning electron microscope (SEM) images of ettringite crystals formed in AFt-UHPFRC during curing are indicated in Figure 1. Significant amount of ettringite crystals has been already formed at the end of the first curing. Therefore, AFt system can make micro structure of cement hydration more dense than non-AFt system and standard UHPFRC at early ages. It becomes more compact and dense during the secondary curing.



After the first curing (20 ℃-24h)　Compressive Strength：73MPa

After the secondary curing (85 ℃-20h)　Compressive Strength：185MPa

Figure 1. Ettringite crystals formed during curing of AFt-UHPFRC

2.1. Materials and mix proportion

The mix proportion of AFt-UHPFRC is shown in Table 1. Portland cement, silica fume (mean diameter 0.2μm), fine particle (mean diameter 3μm) of fly ash is used as binder. In addition to that, ettringite generation additives are used in the AFt-UHPFRC as binder (Table 2). Crushed sand with maximum diameter of 2.5mm is used as an aggregate. The AFt-UHPFRC contains two different lengths of steel fibers with the same diameter of 0.2mm: one fiber length is 15 mm and another is 22 mm. The total steel fiber content is 1.75 vol.%.

Table 1. Mix proportion of AFt-UHPFRC (SUQCEM)

Component	Mass (kg/m^3)	Remarks
Cement	927	
Premixed materials	360	pozzolanic material, materials to form ettringite
Sand	905	manufactured sand (crushed), d_{max}<2.5 mm
Steel fiber**	137.4	1.75 vol.%, d=0.2 mm, l=15 and 22 mm (blended)
Superplasticiser	36	
Shrinkage reducing admixture	12.9	
Defoaming agent	6.4	
Water*	195	W/B=0.152

*contains water in superplasticizer **not included in the unit weight

Table 2. Chemical composition of AFt-UHPFRC binder (mass%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	Na_2O	K_2O
34.0	4.3	2.6	53.2	2.5	0.25	0.27

2.2. Microstructure of AFt-UHPFRC

The compactness of the AFt-UHPFRC was verified by comparing distributions of porosity measured by mercury intrusion porosimetry between the AFt-UHPFRC and standard UHPFRC exemplified in JSCE Recommendations [2] (Figure 2). Although the ratio of the smallest range of pore radius (3–6 nm) of the AFt-UHPFRC is lower than that of the standard UHPFRC, porosity of both UHPFRC is almost the same and approximately half of high strength concrete porosity (about 9 %) whose water to cement ratio is 30 % [2]. Moreover, the air permeability of the AFt-UHPFRC determined with the RILEM-Cembureau method is $4.5\times10^{-20}m^2$ and much lower than that of normal strength concrete which is between 1.0×10^{-16} and 1.0×10^{-15} m^2 [2].

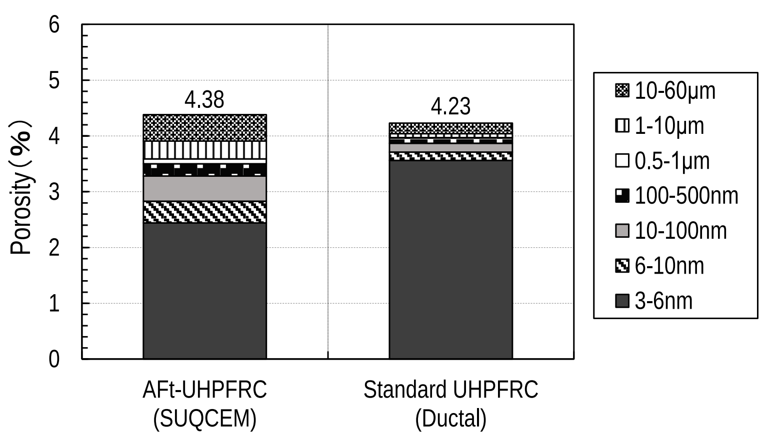


Figure 2. Porosity distribution after standard curing (steam curing)

3. Investigation of cast-in-place AFt-UHPFRC

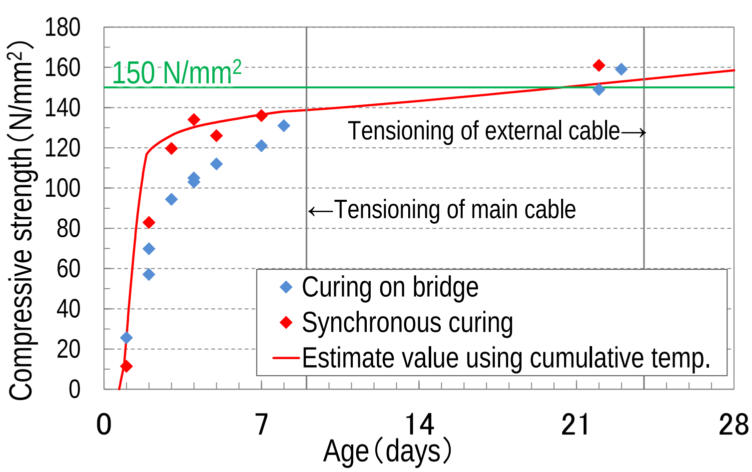
The feature of AFt-UHPFRC is that the initial strength development is promoted by the generation of ettringite. However, when considering the durability of UHPFRC, it is important to grasp how the porosity changes during the atmospheric curing without application of steam. Furthermore, when improving existing structures using UHPFRC, concrete surface and reinforcing bars become constraints against the volume change during hardening process of cement, so it is necessary to consider the possibility of cracking due to shrinkage of UHPFRC.

3.1. Long-term evolution of strength and microstructure

A 100-year-old suspension bridge was replaced with a girder bridge made of UHPFRC in 2014. This is the first project where cast-in-place UHPFRC was successfully applied to the whole structure in Japan (Photo 1) [1]. A survey was conducted about 5 years after completion and the compressive strength of the AFt-UHPFRC was understood to be increased to 215 MPa (Figure 3).

Casting (30m^3/day ×3days) Sheet curing after casting Completed (2014)

Photo 1. Cast-in-place UHPFRC project [1]



Age (day)	Compressive Strength (MPa)
7*	121
23*	159
91**	186
1789** (4.9year)	215

*On the bridge: about10℃ (Outside 0-5℃)
**In the room: 20℃

Figure 3. Evolution of compressive strength of cast-in-place AFt-UHPFRC [1]

In addition to compressive strength test, the porosity of the AFt-UHPFRC was investigated by using mercury intrusion porosimetry for understanding the long-term hardening characteristics. The samples used for the porosity measurement were taken from prism specimens which were placed on the bridge during construction and had been kept in a room at 20 degrees Celsius after completion of the bridge. Figure 4 shows the measurement results of the porosity of the AFt-UHPFRC after about 5 years as well as the ones for each age. The amount of pore diameter of 10–100 nm gradually decreased with time, whereas the pore of 3–10 nm slightly increased.

The number of pores smaller than 10nm (especially about 5nm) which is said to have the greatest influence on chloride penetration resistance decreased during curing as favorable effect by ettringite formation. Furthermore, after 5 years, the porosity of AFt-UHPFRC decreased to one-third (about 9%) of high strength concrete and long-term densification was confirmed.

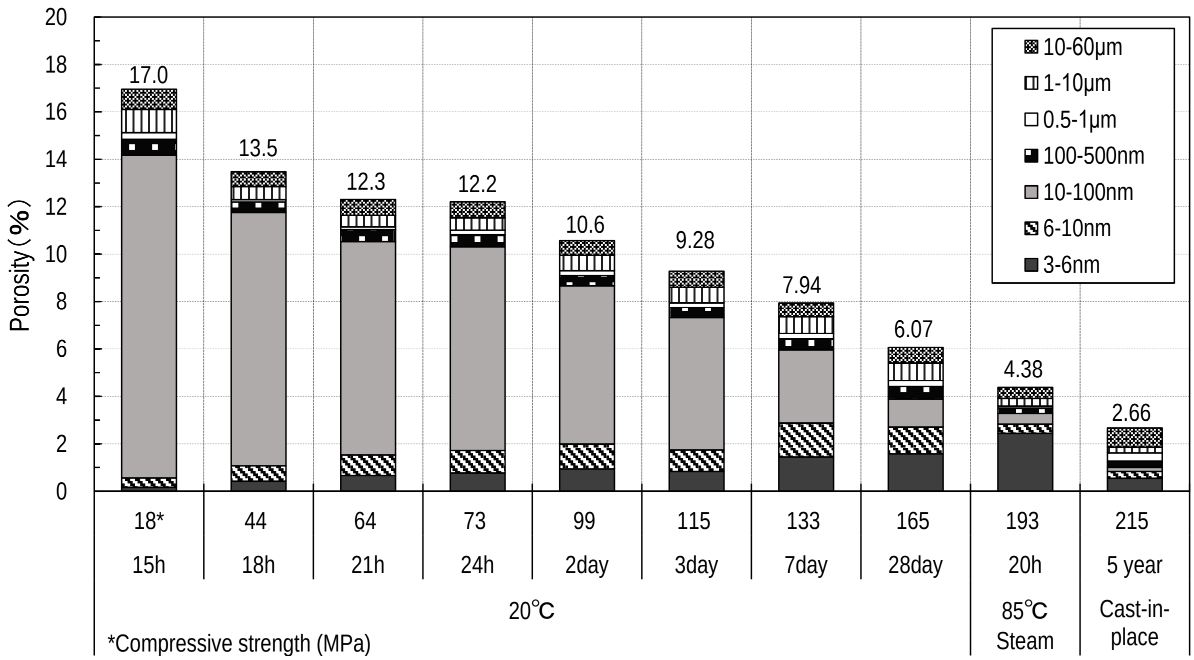


Figure 4. Changes of porosity at material age

3.2. Influence of curing method on durability

Application of UHPFRC on top of concrete bridge decks is an effective method for both increasing load bearing capacity and enhancing durability [3] [4] (Figure 5). However, very high autogenous-shrinkage is observed on UHPFRC due to a large amount of binder, and if a thin layer of UHPFRC is casted on top of concrete bridge decks, shrinkage is restrained by concrete substrates and reinforcing bars (if any) and cracking, warping and interface peeling may occur. In order to investigate this behavior, a small-scale construction experiment using the AFt-UHPFRC was carried out. In the experiment, an RC slab of 4,000 × 2,000mm with thickness of 280 mm was fabricated and the AFt-UHPFRC was cast on top of the slab assuming that the top surface of a bridge deck is replaced with AFt-UHPFRC (Photo. 2). The replaced thickness of UHPFRC was 80-90mm. Reinforcing bars were arranged on top of the slab and top surface of the slab was roughened such that real bridge deck condition is reproduced.

In this paper, shrinkage behavior of and chloride penetration into AFt-UHPFRC focusing on curing at early ages are reported.

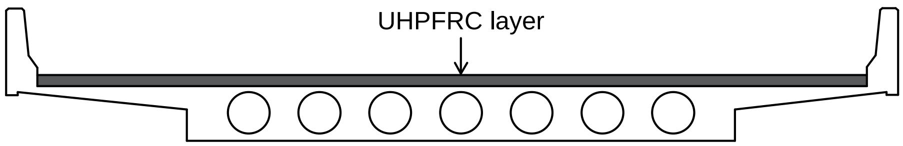
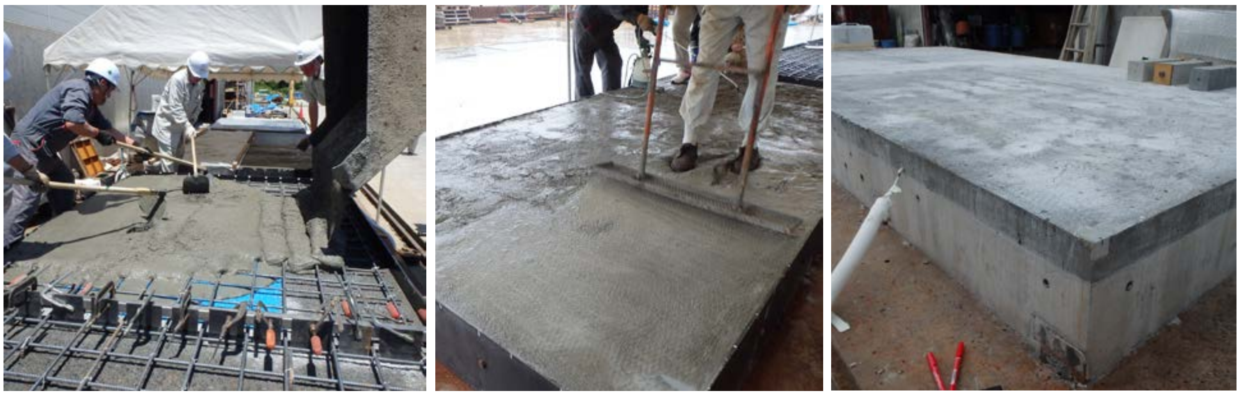


Figure 5. Bridge deck upgraded with UHPFRC [4]



Casting on RC slab | Tamping | Demolding

Photo 2. Small-scale construction experiment using AFt-UHPFRC

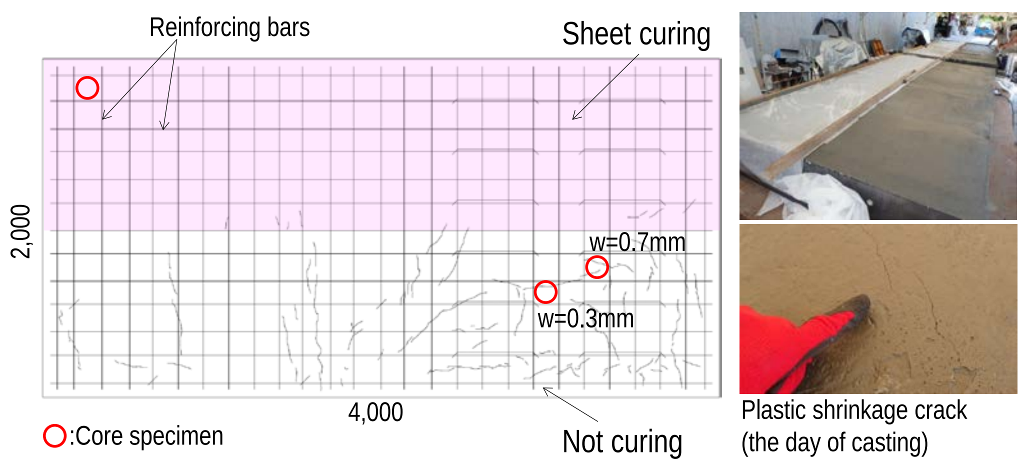


Figure 6. Crack pattern of the top surface of UHPFRC the day after casting

3.2.1. Shrinkage behavior

Figure. 6 shows the crack pattern of the slab specimen observed the day after casting AFt-UHPFRC. There were no visible cracks in the area where plastic sheet curing was applied, whereas in the area without plastic sheet curing, a rather large number of cracks appeared over the whole surface. Since these cracks were plastic shrinkage cracks induced immediately after UHPFRC casting, the amount of cracks didn't increase and no change was observed on the crack length and width one month after casting UHPFRC. This result suggests that moist curing from the early stage of hardening is important for prevention of cracking of UHPFRC.

The measurement results of the shrinkage of AFt-UHPFRC are shown in Figure 7. Shrinkage deformation measured with a prism specimen (100×100×400 mm) free of restraint conditions was about 800 μm. In contrast, shrinkage deformation measured in the slab specimen was about 600 μm, which was smaller than that of the prism specimen. By the way, the deformation of the reinforcing bars in the specimen and the slab were about 230 μm. This is considered to be reduced by tensile creep of UHPFRC where tensile stress was induced by restrained UHPFRC shrinkage due to concrete substrates and reinforcing bars.

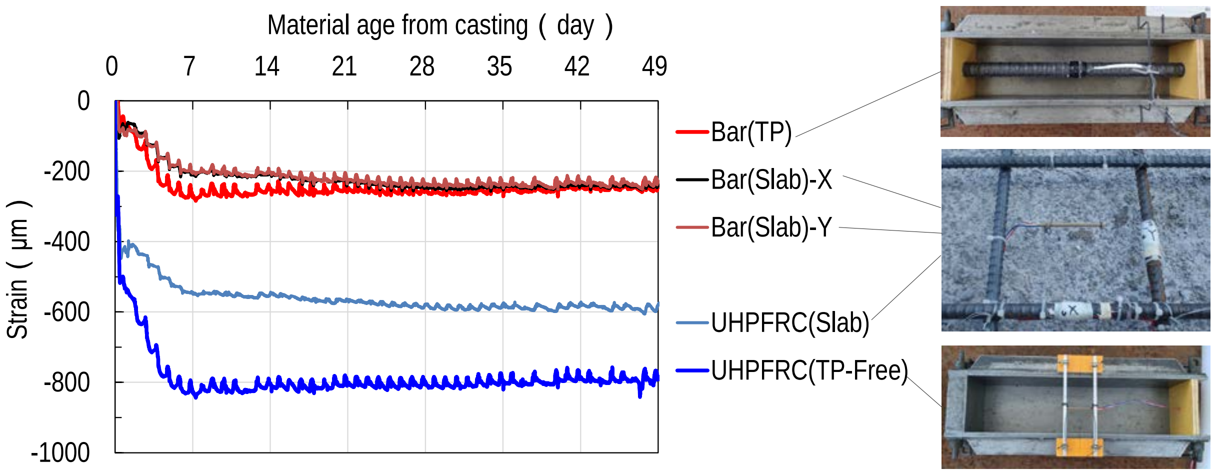


Figure 7. Measurement result of strain of AFt-UHPFRC and reinforcing bars

<u>3.2.2. Chloride penetration</u>

Three core specimens were taken from different parts of the slab specimen (Figure 6) and subjected to cyclic wet and dry test using artificial sea water. Tested core specimens were analyzed by electronic probe micro analyzer (EPMA). Chlorine mappings of the analyzed specimens are shown in Figure 8. In a core specimen without cracks on the UHPFRC top surface, chloride penetration depth was about 2 mm, while in core specimens with a crack on the UHPFRC top surface, chlorides penetrated deep into the UHPFRC along the cracks. Chloride penetration depth was about 85mm in a specimen with a 0.7mm wide crack, almost reaching the concrete substrate. As caused at early ages where crack bridging by fibers was not in effect yet, cracks in the UHPFRC was supposed to grow deep inside the core specimens. From this follows that to keep moisture by sheet curing at early ages after casting is important for cast-in-place AFt-UHPFRC. In addition, it was confirmed that cast-in-place AFt-UHPFRC have an excellent chloride penetration resistance if properly cured.

4. Conclusions

In this paper, strength evolution, pore diameter distribution, shrinkage behavior and chloride penetration resistance of cast-in-place AFt-UHPFRC were investigated. As a result, the following knowledge was obtained.

- It was confirmed that hydration and ettringite formation continue in cast-in-place AFt-UHPFRC in the long term, resulting in increase of compressive strength and decrease of porosity.

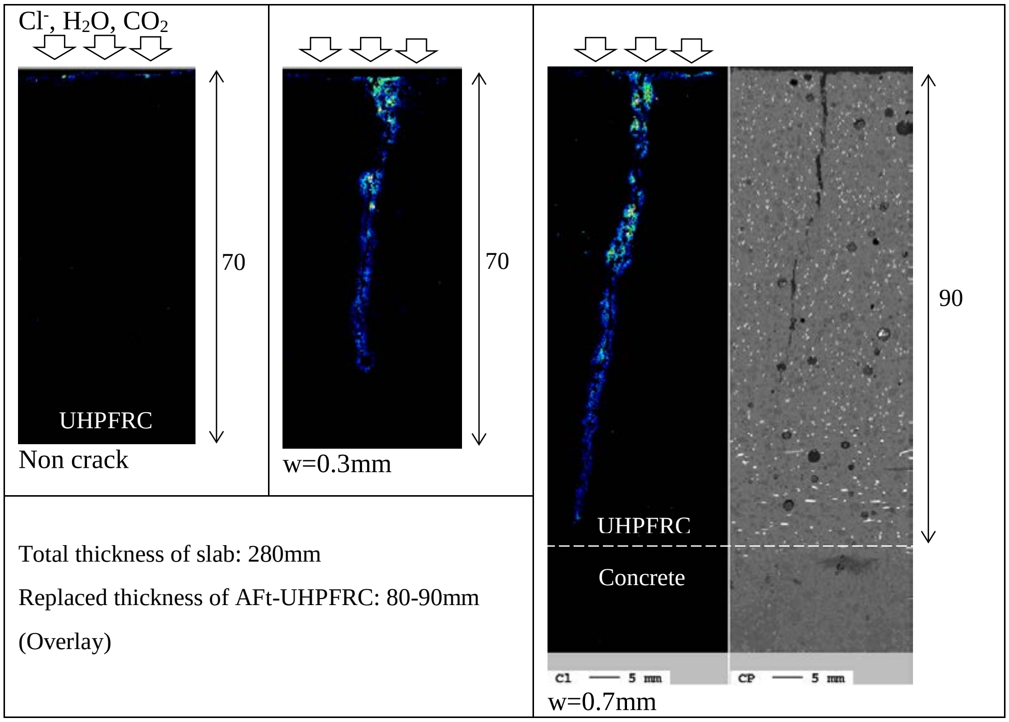


Figure 8. Chlorine mapping of core specimens

- No visible cracks were observed on top surface of cast-in-place UHPFRC covered with plastic sheets, while rather large amount of cracking occurred on UHPFRC under dry conditions. Moreover, cracks caused at early ages grew deep inside UHPFRC elements and chloride penetration resistance was significantly impaired. Curing method is a determinant factor for the quality of cast-in-place UHPFRC.
- Shrinkage of UHPFRC cast on top of the large RC slab specimen was smaller than that of the prism specimen with no restraints. There is a possibility that the tensile stress induced by restraints to UHPFRC mitigates shrinkage deformation.

5. References

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