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Corrosion of Steel Fiber and Its Effect on Tension-Softening Behavior of Ultra High Strength Fiber Reinforced Concrete

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ABSTRACT

Ultra high strength fiber reinforced concrete (UFC) has high ductility, strength and durability compared to general concrete. When steel fiber is corroded, however, those high performance may be lost. The objectives of this study are to experimentally investigate the tensile performance of UFC after crack occurrence. As the results, corrosion of steel fiber and chloride ion penetration in UFC without an initial crack are not observed. On the other hand, more corrosion products on steel fiber are observed near the surface of seawater when UFC has a wider initial crack. Additionally, a crack due to external loading is propagated widely and chloride ion is distributed along the cracks in UFC with an initial crack of 0.5 mm or wider. It was also made clear that corrosion of steel fiber increases tensile stress carried by the UFC regardless of the initial crack width.

Keywords. Ultra high strength fiber reinforced concrete, Chloride penetration, Bending test, Tension softening curve.

INTRODUCTION

Ultra high strength fiber reinforced concrete (UFC) has excellent mechanical properties, which can afford enough tensile stress even after cracking due to the fact that the steel fiber can bear the tensile force after cracking mainly by a bonding effect between cement matrix and fiber (Fukuura and Mioke, 2005). However, it is specified that the tensile stress on UFC should not exceed the crack initiation stress according to the Design Guidelines (JSCE, 2004). In other words, UFC does not allow occurrence of cracks during its service life. Meanwhile, when it is considered UFC can be applied to the condition where cracks due to shrinkage, etc. it is necessary to investigate an allowance for cracks initiation on UFC. In particular, under corrosive environments, there is a possibility of degradation on the expected tensile performance by corrosion of steel fiber. Accordingly, in this study, initially cracked UFC is immersed in artificial seawater for 3 months to investigate the characteristics of tension-softening properties with corrosion of steel fiber experimentally.

Table 1. Mix design of UFC

Mass of unit volume (kg/m^3)					
W	LC	SF	S	F	SP
180	1146	214	927	157	24

Mixture formulation (vol.%)		
W/(LC+SF)	SF/(LC+SF)	F
40	20	2.0

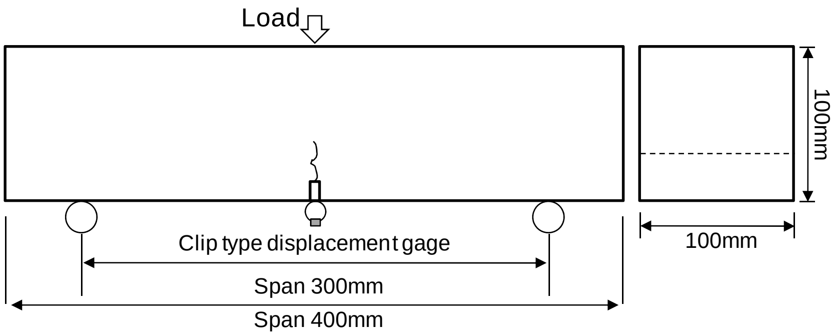


Figure 1. Geometry of specimen and test setup

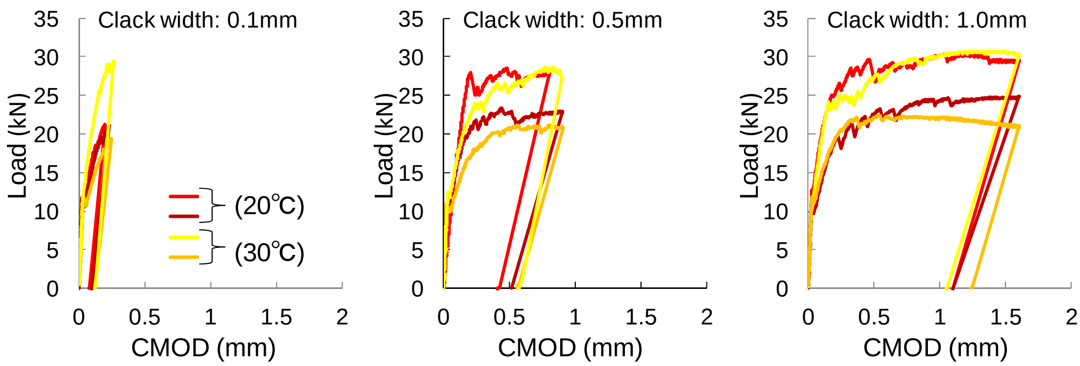


Figure 2. Initial crack formation

EXPERIMENTAL PROGRAM

Materials. Mix design and mixture formulations of UFC are presented in Table 1. As for the materials, low-heat Portland cement (LC; density: 3.22g/cm^3), silica fume (SF; BET specific surface area: 10m^2/g and density: 2.40 g/cm^3), silica sand (S; density: 2.61 g/cm^3), steel fiber (F; diameter: 15mm, length: 0.2mm, and density: 7.84 g/cm^3) and superplasticizer (SP) are used. Figure1 shows the geometry of the specimen and test setup.

Test specimens. The test specimens were prepared based on JCI-S-001-2003 (JCI, 2003). The specimen was a beam of 400 mm long having a square cross section of 100 mm by 100 mm. The specimen was notched at the midspan, in which the notch measured 5 mm wide and 30 mm deep. The specimens were demolded after 24 hours from casting and allowed to be placed for 24 hours in a constant temperature and humidity chamber of 20 °C and 95% RH. In the steam curing chamber, they were heated at 90 °C for 48 hours. The heating and cooling rates were ±15 °C /hour.

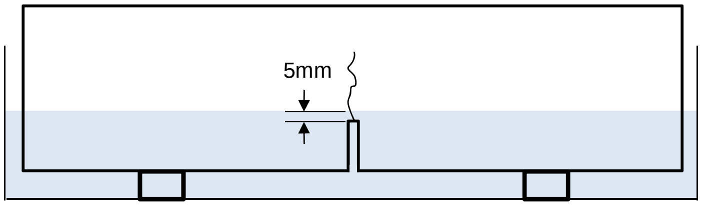


Figure 3. Exposure setup

Initial crack. An initial crack was induced at the tip of the notch by bending load application, in which the residual crack width was controlled to be 0.1, 0.5 or 1.0 mm. Figure 2 shows the load-CMOD (crack mouth opening displacement) curves during this process. As shown in the figure, each initial crack was successfully induced having a respective target residual width.

Exposure. Figure 3 shows the overview of the exposure procedure to artificial seawater. The test specimens were exposed in the artificial seawater for 3 months up to a height of 5 mm from the tip of the notch. During the exposure, the temperature was kept constant at 20 or 30 °C. The relative humidity was set at 95% for both the exposure temperatures.

Bending test. Using a universal testing machine, the specimens after 3 months exposure were subjected to a three-point bending test with 300 mm loading-span and 0.05 mm/min loading speed. By performing this test, the CMOD is measured with attaching a knife-edge to the shoulder of the notch and a clip gauge. Displacement at the loading point was also measured and recorded. Using obtained load-CMOD curves, a tension-softening curve[3)] was identified.

Observation of corroded steel fiber by microscope analysis. Some steel fibers were taken from the specimens after loading tests to confirm the corrosion tendency by using microscope, which was investigated at different heights from the tip of notch.

Chemical composition analysis by EPMA. Samples were taken out from the center of the specimen after the test to analyse chloride ion ingress by EPMA (electron probe micro analyzer). A color map regarding chloride ion concentration in a cross-section was obtained according to JSCE-G 574-2010 (JSCE, 2010).

EXPERIMENTAL RESULTS

Observation of corroded steel fiber. Figure 4 shows the steel fibers taken from the specimens with initial crack widths of 0.1 mm, 0.5 mm and 1.0 mm, all of which were exposed to the 20 °C environment. The fibers were taken at the area far from the water level (upper), at 0-5mm deep from the water level (lower) and at 0-5mm deep from the tip of the notch where the fibers were submerged in the artificial sea water (submerged). In the case with an initial crack of 0.1 mm wide, corrosion of fiber did not occur from the upper and the lower areas of the cross section, while fibers corroded in the submerged condition. On the other hand, in the case of the initial clack of 0.5 mm or wider, corrosion of fiber occurred from the upper and the lower areas in the upper and the lower cases.

Chemical composition analysis by EPMA. Figure 5 shows the color map of chloride ion concentration drawn by using EPMA. The upper side of the figure is the exposure surface. As for the result with the 0.1 mm wide crack specimen, chloride ion was concentrated near the surface of the crack, which means chloride ion is not diffused beyond the surface area of an initially induced crack. Conversely, as for the results with the initial crack of 0.5 mm and 1.0 mm wide, chloride ion is diffused deeply and widely. In other words, the wider the initial crack, the more widely and deeply the chloride ion penetration due to propagation of micro cracks, where the threshold value of initial crack width for the chloride ion diffusion is 0.5 mm.

Load-CMOD curve. Figure 6 shows load-CMOD curves obtained by the bending test. The results with an initial crack width of 0.1 mm showed a slight increase-decrease repetition while maintaining the maximum load, where the behavior showed excellent bonding capacity between cement matrix and steel fiber after the seawater exposure. On the other hand, in the result with an initial crack width of 0.5 mm and 1.0 mm, the load was slowly reduced to be almost constant. That difference in the load-CMOD curves was caused by the corrosion of steel fiber; that is, much chloride ion was transported through the crack when its width was 0.5 mm or more. Therefore, it was made clear that corrosion of the steel fiber influences on bonding capacity.

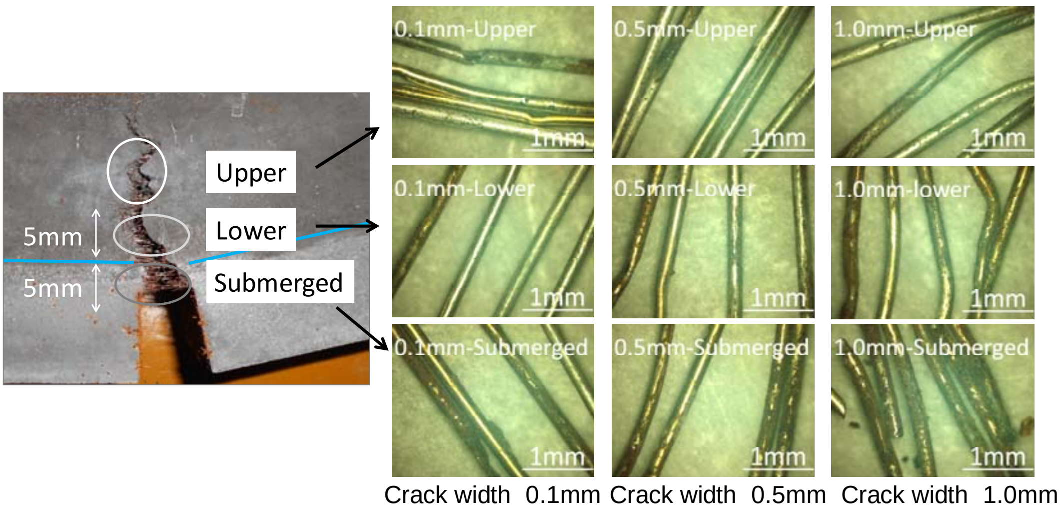


Figure 4. **Corrosion of steel fiber (20 °C)**

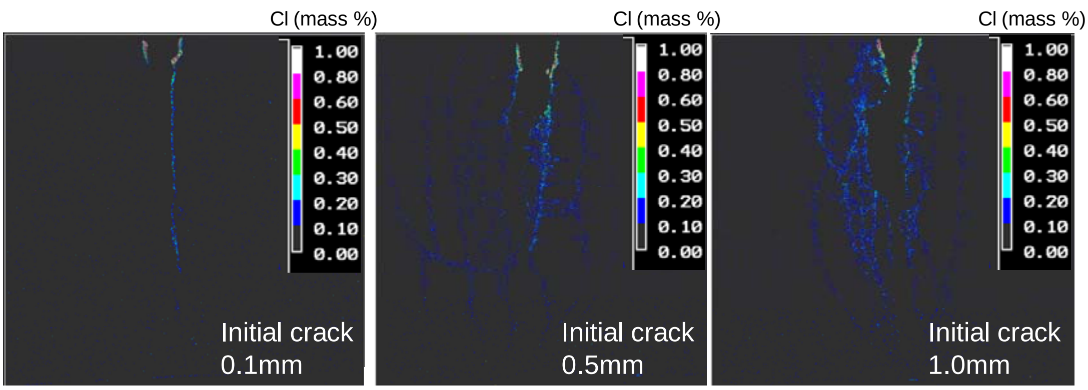


Figure 5. **Chloride ion penetration (20 °C)**

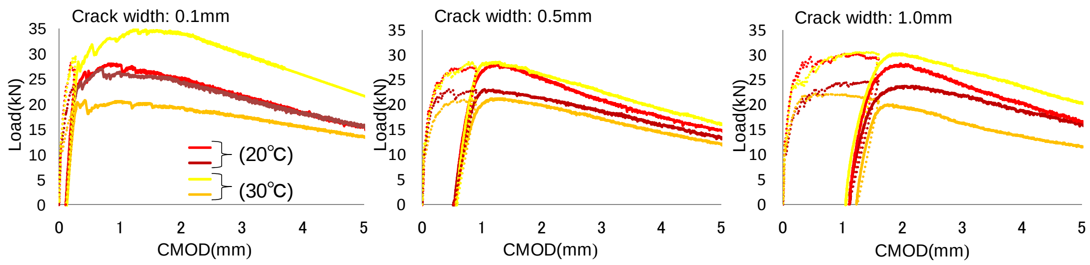


Figure 6. Load-CMOD curve

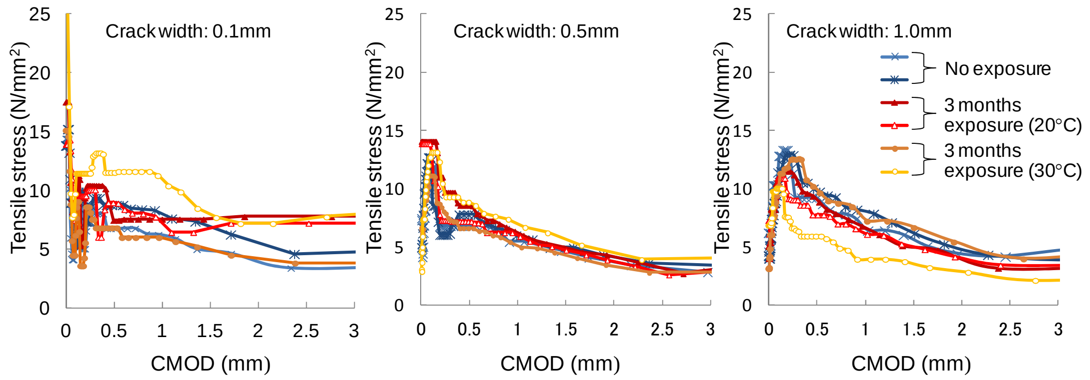
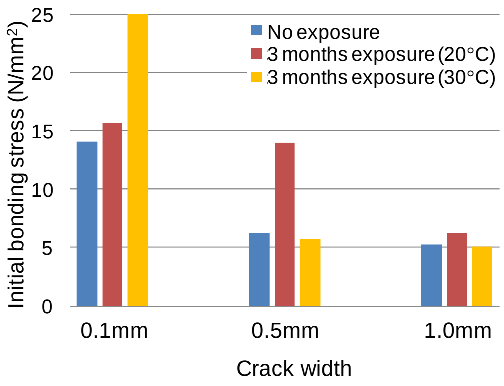


Figure 7. Tension-softening curve

Tension-softening curve. Using the load-CMOD curves shown in Figure 6, tension softening curves, which are shown in Figure 7, were identified as per JCI-S-001-2003 (JCI, 2003). In the result of an initial crack of 0.1 mm wide, tensile stress decreased rapidly from the initial bonding stress, which is shown as the intercept of *y*-axis, with the repetition of stress increase and decrease. On the other hand, in the results with the initial crack of 0.5 mm or wider, tensile stress was increased from the initial bonding stress though the initial bonding stress was lower than that of the 0.1 mm wide crack case. The initial bonding stress with an initial crack width of 0.1 mm showed higher than that of the specimens without an initial crack and exposure to the seawater. In the case of an initial crack is 0.5 mm or 1.0 mm, there was no particular increase in the initial bonding stress after the exposure. From the above results, these two phenomena are considerably different. It can be said that more than 0.5 mm initial crack width influenced on corrosion behaviour of steel fiber and the initial bonding stress shown in tensile softening characteristics.

Influence of temperature on the initial bonding stress. Figure 8 shows the influence of temperature on the initial bonding stress. It was confirmed that the initial bonding stress with an initial crack width of 0.1 mm with the 30 °C exposure was larger than that with the 20 °C exposure. It seems that high temperature exposure accelerates steel fiber corrosion which increases bonding stress. On the other hand, in the case with an initial crack of 0.5 mm, the initial bonding stress was larger in 20 °C than that in 30 °C. This means that the influence of corrosion on the bonding stress depends on the environmental temperature. Therefore, it is indicated that allowance of crack propagation on UFC should be defined based on the width of a crack and environmental temperature.



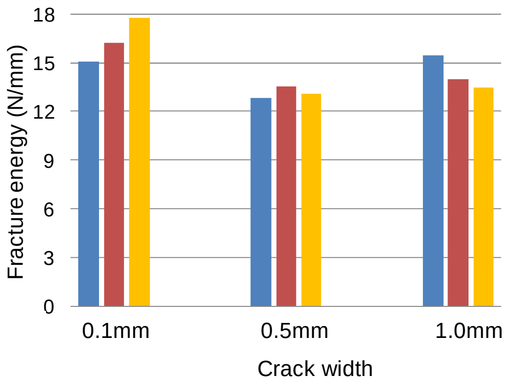


Figure 8. Initial bonding stress **Figure 9. Fracture energy**

Fracture energy. According to JCI-S-001-2003 (JCI, 2003), fracture energy G_f was calculated with Equation (1), the results of which are shown in Figure 9. Regardless of the initial crack width and environmental temperature, fracture energy showed almost the same on all the experimental condition. The fracture energy, even when it is obtained in the case with the increase in the initial bond stress, was not changed from the value from the specimen without initial crack and exposure.

$$G_f = \frac{(0.75W_0 + W_l)}{A_{lig}} \tag{1}$$

where W_0 is the area under a load-CMOD curve, W_l is the work of the weight of specimen and loading jig, and A_{lig} is the area of the ligament

CONCLUSIONS

The following conclusions were drawn in this paper:

1) Corrosion of the steel fiber by immersion of seawater has an effect on bonding capacity, which resulted in subsequent change in tensile-softening behavior of UFC. When the crack is 0.5 mm or wider, that effect becomes significant.

2) It may be possible to allow crack formation in UFC if the crack width and environmental temperature are specified during the service life of UFC.

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