TENSION-SOFTENING BEHAVIOR AND CHLORIDE ION DIFFUSIVITY OF CRACKED ULTRA HIGH STRENGTH FIBER REINFORCED CONCRETE

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Abstract

Ultra high strength fibre reinforced concrete has high ductility, strength and durability compared to normal concrete. When steel fibre is corroded, however, the high performance may be degraded. This study aims to experimentally investigate the tensile performance of UFC after crack occurrence under corrosive environment. As the results, corrosion of steel fibre and chloride ion penetration in UFC without an initial crack did not occur significantly. On the other hand, more corrosion products on steel fibre are detected near the surface of seawater when UFC has a wider initial crack. Additionally, cracks due to external loading propagated more widely and chloride ions distributed along the cracks in UFC with a wider initial crack. Also, corrosion initiation of steel fibre increased tensile stress carried by UFC regardless of the initial crack width, and it was made clear how variations in corrosion of steel fiber affected degradation of tensile characteristics of UFC.

Résumé

Les BFUP sont caractérisés par de beaucoup plus grandes performances en termes de ductilité, résistance et durabilité que les bétons courants. Néanmoins, quand les fibres métalliques sont corrodées les grandes performances peuvent en pâtir. Cette étude s'intéresse à l'évolution de la résistance en traction de BFUP pré-fissurés et conservés dans des environnements de corrosion tels que les environnements marins. Les études menées sur BFUP non fissurés initialement montrent une très faible pénétration des chlorures et pas ou très peu de points de corrosion des fibres. Par contre, lorsqu'il y a pré-fissuration des échantillons, des produits de corrosion sont détectés près de la surface en contact avec l'eau de mer. De plus, les fissures se propagent et s'ouvrent plus largement lorsqu'un chargement extérieur est appliqué, entrainant une pénétration accrue des ions chlore le long de la fissure. Ainsi, la corrosion des fibres modifie la résistance en traction des BFUP.

1. INTRODUCTION

Ultra high strength fibre reinforced concrete (UFC) has excellent mechanical properties, which can carry enough tensile stress even after cracking due to the fact that the steel fibre can bear the tensile force after cracking mainly by bridging effect between cement matrix and fibre [1]. However, it is specified that the tensile stress on UFC should not exceed the crack initiation stress according to the Design Guidelines [2, 3]. In other words, UFC does not allow occurrence of cracks during its service life. Meanwhile, when it is considered UFC can be applied to a condition with cracks due to shrinkage, etc, it is necessary to investigate an allowance for cracks initiation on UFC. In previous studies, mechanical and tensile properties of high performance fiber reinforced cement composites [4 - 6]. Moreover, chloride diffusion in steel fibre reinforced marine concrete has been investigated [7]. In particular, under corrosive environments, there is a possibility of degradation on the expected tensile performance by corrosion of steel fibre. 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 fibre experimentally.

2. EXPERIMENTAL PROGRAM

2.1 Mix proportion of specimens

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

Table 1: Mix proportions of UFC

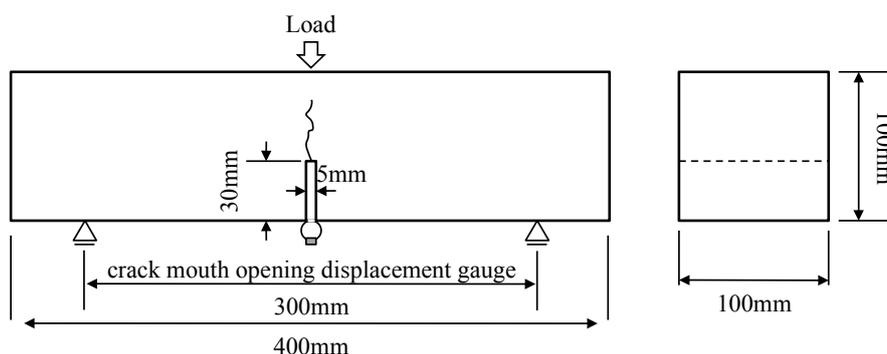| Mass of unit volume (kg/m^3)						Mixture formulation (vol. %)		
W	LC	SF	S	F	SP	W/(LC+SF)	SF/(LC+SF)	F
180	1146	214	927	157	24	40	20	2.0

Figure1: Geometry of specimen

2.2 Fabrication of test specimens

The test specimens were prepared based on JCI-S-001-2003 (Japan Concrete Institute, 2003). The specimen was a beam of 400 mm long having a square across 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 demoulded 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. Then the specimens were steam cured at 90°C for 48 hours. The heating and cooling rates were +/-15°C/hour.

2.3   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 figures, each initial crack was successfully induced having a respective target residual width.
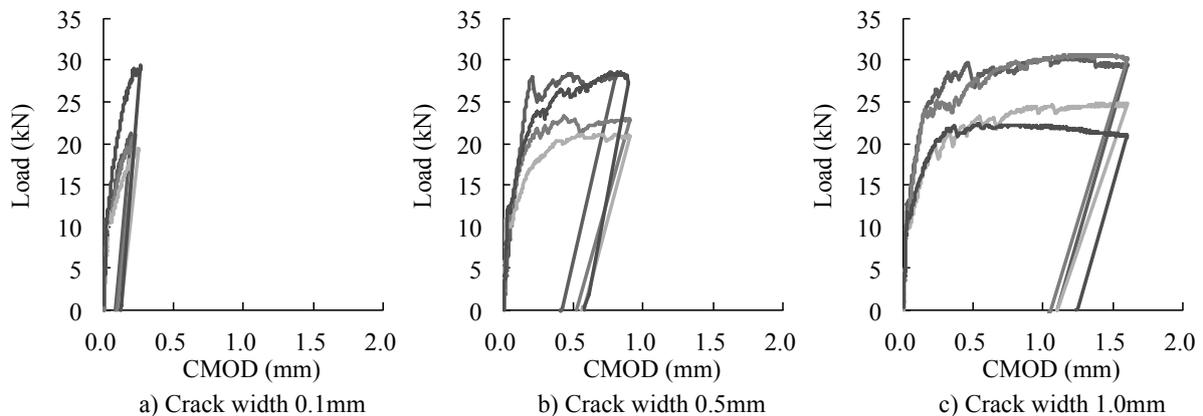

Figure 2: Induction of initial crack

2.4   Exposure process

The test specimens were immersed in artificial seawater (Cl⁻: 3.4 wt %) for 3 or 6 months up to a height of 5 mm from the top 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.

2.5   Bending test

Using a universal testing machine, the specimens after 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 was measured with attaching a knife-edge to the shoulder of the notch and a clip gauge. Displacement at the loading point (LPD) was also measured. Using obtained load-CMOD curves, tension softening curves were identified [8].

2.6   Corrosion extent of steel fibres

The steel fibres were taken from the specimens after loading tests to confirm the corrosion extent and degree by using microscope, which was investigated at different heights from the tip of notch.

2.7   EPMA analysis on chloride ion ingress

Samples were taken out from the cracked section of the specimen after the test to analyse chloride ion ingress by EPMA. Accordingly, a colour map regarding chloride ion concentration in the cross-sectional was obtained.

3.   EXPERIMENTAL RESULTS

3.1   Influence of crack width on corrosion of steel fibres

Figure 3 shows the steel fibres taken from the specimens with initial crack widths of 0.0, 0.1, 0.5 and 1.0 mm, all of which were exposed to 20°C environment for 3 months. The fibres existed at 40 to 70 mm above the water level (upper), at 0 to 5 mm above the water level (lower) and at 0 to 5 mm below the water level, where fibres were fully submerged in artificial seawater (submerged). In the case with an initial crack of 0.1 mm, corrosion of fibre did not occur in upper and lower area, while fibres corroded in the submerged area. On the other hand, in the case of the initial crack of 0.5 mm and 1.0 mm, corrosion of fibre considerably occurred in all the three areas. Corrosion of steel fibres has been observed visually in this study and it showed if the corrosion did occur or not as above mentioned.
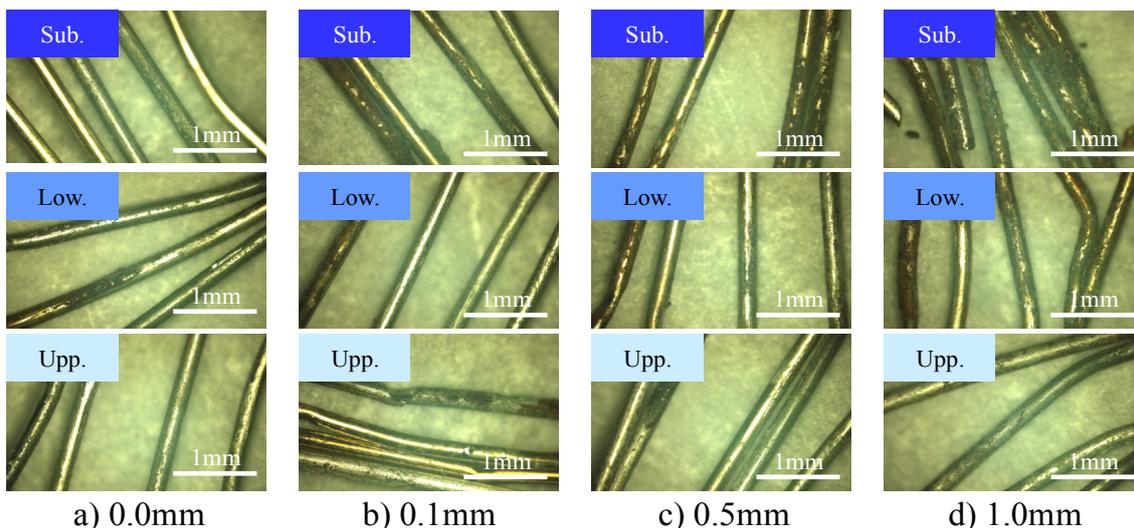

| a) 0.0mm | b) 0.1mm | c) 0.5mm | d) 1.0mm |

Figure 3: SEM observation on corrosion of steel fibers

3.2   Chloride ion ingress

Figure 4 shows the colour map of chloride ion concentration of samples, which were immersed in 20°C seawater for 3 months, drawn by using EPMA. Chloride ion was transported from the top of the figure. As for the result with initial crack of 0.1mm, chloride ion concentrated near the crack surfaces, which means chloride ion was 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, chloride ion was diffused deeply and widely. In other words, the wider the initial crack, the more widely and deeply the chloride ion penetrated due to propagation of micro cracks with induction of initial crack. In other words, it was confirmed that chloride ions are diffused widely and deeply into a specimen with crack of 0.5 mm or wider.

3.3   Loading capacity

Figure 5 shows load-CMOD curves obtained by the bending test. The curves with an initial crack width of 0.1 mm showed a slight increase-decrease repetition on the pre- and post-peak states, which was indicating that steel fibres were maintaining the maximum load and this behaviour showed excellent bonding capacity between cement matrix and steel fibre after seawater exposure for 6 months. On the other hand, in the result with an initial crack width of 0.5 mm and 1.0 mm, the load did not show the increase-decrease repetition but was slightly increased before and decreased after the peak. That difference in the load-CMOD curves was caused by the corrosion of steel fibre; that is, much chloride ion was transported through the crack when its width was 0.5 mm or more. It was made clear that corrosion of the steel fibre influences on bonding capacity.
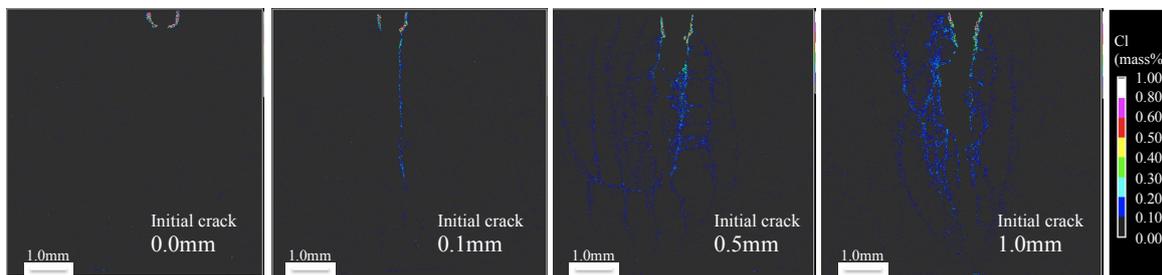

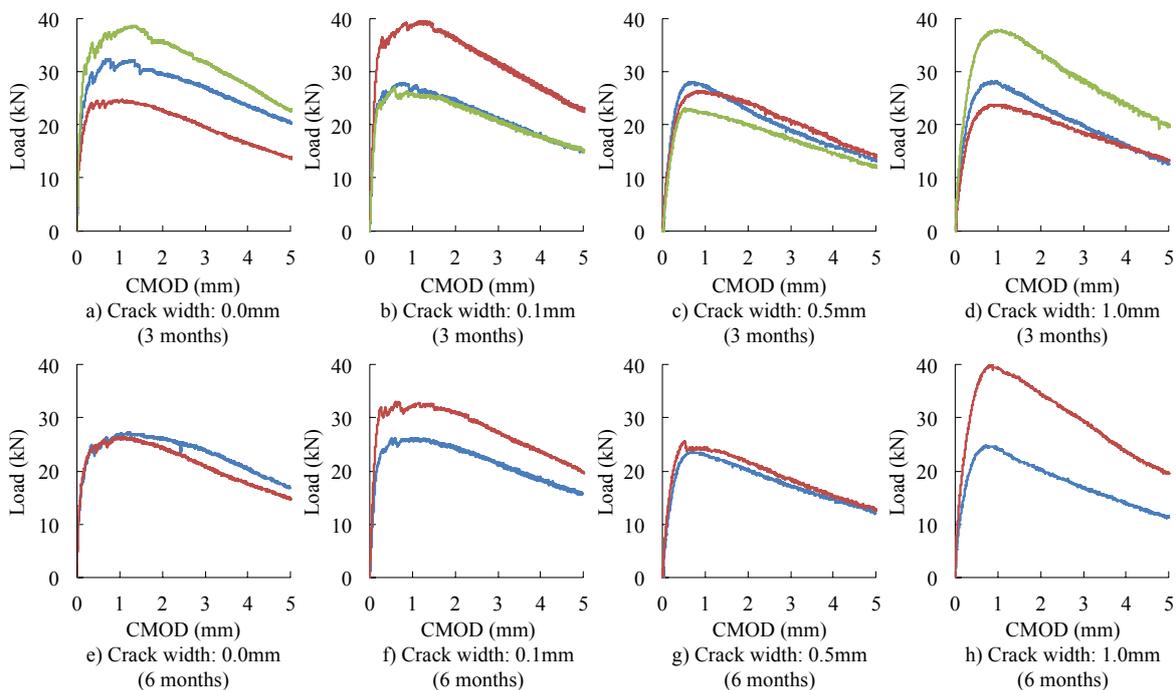Figure 4: Chloride ion ingress for 3 months in 20°C (EPMA)

Figure 5: Load-CMOD curves (20°C)

3.4   Tension softening behavior

Using the load-CMOD curves shown in Figure 5, tension softening curves, which are shown in Figure 6, were identified according to JCI-S-001-2003 (Japan Concrete Institute,

2003). In the result of an initial crack of 0.1 mm, 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 and 1.0 mm, tensile stress was increased from the initial bonding stress though the initial bonding stress was lower than that with the initial crack of 0.1 mm. The initial bonding stress with an initial crack width of 0.1 mm showed higher than that of the specimens without induction of initial crack and exposure to 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 seawater 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 of steel fibre and the initial bonding stress shown in tension softening characteristics.
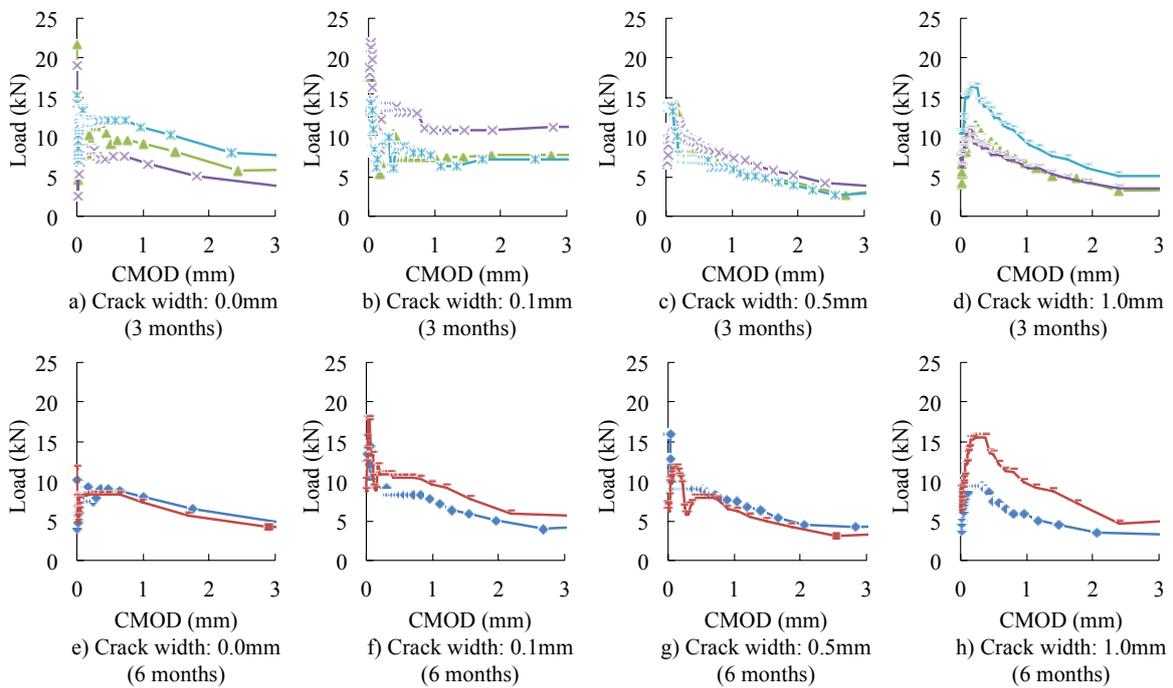

Figure 6: Tension softening curves (20°C)

3.5   Initial bonding stress and fracture energy

As mentioned above, it was indicated that corrosion of steel fiber affect on tensile softening behavior. In this study, the test specimens were exposed in 20°C or 30°C for 3 months and 30°C for 3 months. The influence of exposure period and temperature on initial bonding stress and fracture energy were evaluated. According to the JCI-S-001-2003 (Japan Cocncrete Institute, 2003), fracture energy G_f was calculated with Equation (1), and the results of which are shown in Figures 7 and 8.

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

where
W_0: Area under load-COMD curve (N•mm),
W_l: Mechanical work by deadweight of specimen and loading fixtures (N•mm), and
A_{lig}: Area of the cross section of the ligament (mm^2).

Figure 7 shows the influence of exposure period on initial bonding stress and fracture energy. It was confirmed that the initial bonding stress with an initial crack of 0.1 mm exposed for 3 months was larger than that for 0 month (initial). Moreover, in the case with an initial crack of 0.5 mm and 1.0 mm, the initial bonding stress was larger in the case of 6 months exposure than that in the case of 3 months exposure. As identified above, phenomena on tensile softening with corrosion of steel fibres in UFC are considerably different as for the crack width propagated, which means that crack width of 0.5 mm or wider influenced on tension softening curve. Initial bonding stress, however, was not reduced due to time elapsed from the initial state. It is indicated that corrosion of steel fiber might improve bonding capacity between cement matrix and steel fiber; therefore, allowance of crack propagation based on the width on UFC should be defined with influence of change in tension softening behavior on structural performance.

As for fracture energy, regardless of the initial crack widths and exposure periods in this study, the experimental condition did not show significant changes in fracture energy.
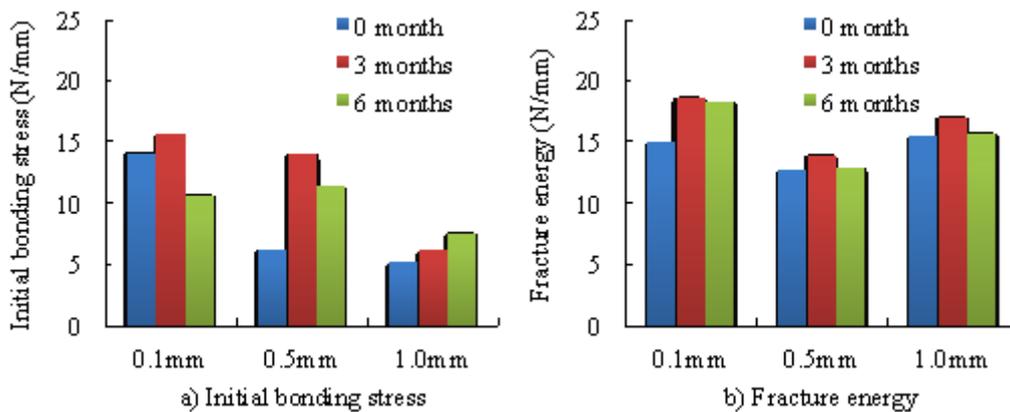

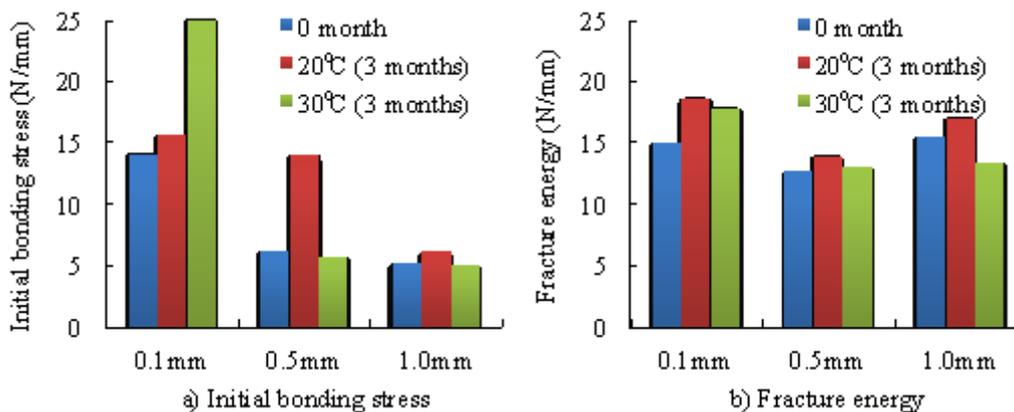Figure 7: Influence of exposure period on tensile characteristics

Figure 8: Influence of exposure temperature on tensile characteristics

Figure 8 shows the influence of temperature on initial bonding stress and fracture energy. It was confirmed that the initial bonding stress with an initial crack of 0.1 mm exposed to 30°C was larger than that exposed to 20°C. 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 the case of 20°C than that in the case of 30°C. This result 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.

As for fracture energy, regardress of the initial crack widths and environmental temperatures, the experimental condition did not cause significant changes in fracture energy.

4. CONCLUSIONS

The following conclusions were drawn in this study:
1. Corrosion of the steel fibre by immersion of seawater has an effect on bonding capacity, which resulted in subsequent change in tensile softening behaviour of UFC. When an initial crack is 0.5 mm or wider on UFC, it significantly influences on tensile softening behaviour.
2. Initial bonding stress was not reduced with wider crack width and higher temperature, which indicated an improvement of bonding capacity between cement matrix and steel fibre, while the experimental condition did not cause significant changes in fracture energy.
3. It may be possible to allow initiation of cracks on UFC if the crack width and environmental temperature are specified during the service life of UFC. The allowance of crack propagation based on the width on UFC should be defined with influence of change in tension softening behavior on structural performance.

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