

Scientific paper

Corrosion of Reinforcing Steel in Fiber Reinforced Cementitious Composites

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Received 22 September 2010, accepted 25 April 2011

Abstract

For the purpose of global sustainability the long life of structures is essential and the durability performance of reinforced concrete structures is one of the key issues to be resolved. This paper reports the results of a series of long term corrosion tests on fiber reinforced cementitious composites containing polyethylene (PE) alone and hybrid steel cord (SC) and PE fibers. The results are also compared with ordinary mortar. The specimens are subjected to accelerated corrosion for one year by applying external potential to the steel bar anode and a cathode made out of a steel wire mesh placed outside the concrete. Durability performances of the specimens are examined through regular monitoring of the time to initiate corrosion, the corrosion area ratio, corrosion depth, and the amount of steel loss. Results show that the hybrid fiber reinforced cementitious composites (HFRCC) containing hybrid SC and PE fibers exhibited excellent performance compared to mortar and fiber reinforced cementitious composites (FRCC) containing PE fiber. The order of the durability performance is HFRCC, FRCC, and Mortar. It is observed that the sacrificial corrosion of some of the SC fibers in the HFRCC specimen played an important role in the significant reduction of steel bar corrosion in the specimen.

1. Introduction

Deterioration of reinforced concrete (RC) structures due to corrosion of reinforcing steel is one of the main durability concerns of RC infrastructures worldwide. The corrosion of reinforcing steel in RC generally occurs through the destruction of passive film that protects the reinforcements in the RC. It is destroyed due to the penetration of aggressive substances through the concrete cover. The presence of cracks in the concrete cover provides easy access to the aggressive substances into concrete. The consequence of corrosion is the reduction of cross-sectional area of the reinforcing steels, volume expansion of corrosion products that cause cracking, spalling and/or delamination of concrete cover, which ultimately reduces the load carrying capacity, ductility and structural safety of the RC. The cracks in the concrete cover occur during their service life. With the use of ordinary concrete and even using high strength concrete, the load and environmentally induced cracks in the RC cannot be prevented due to their poor tensile strength, tensile strain and fracture resistance capacities. To reduce the brittle cracking of concrete, fibers (metallic and/or non-metallic) have been widely used in concrete for quite a long time.

Since early ninety's the utilisation of fibers in the concrete has gained popularity through the development of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) (Reinhardt and Naaman 1991), which were defined as exhibiting strain hardening and multiple cracking behaviour. This development was further extended by considering the micromechanics of fibers bridging using the polymeric fibers such as polyethylene (PE) or polyvinyl alcohol (PVA) leading to strain hardening cementitious composites (SHCC) with significantly larger strain at peak stress (Fischer and Li 2006). Most of the developed SHCCs are limited to a single type of polymeric fibers such as PE and PVA. On the other hand, SHCC containing hybrid fibers have also been developed (Kawamata *et al.* 2003; Otsuka *et al.* 2003; Ahmed *et al.* 2007; Ahmed and Maalej 2009; Ahmed *et al.* 2007, Markovic 2006). Most of the previous studies on the HPFRCC and SHCC have been carried out on their mechanical performances. Research results on their durability performances are still limited.

Due to the strain hardening behaviour, the SHCC exhibits multiple fine cracks under tension and bending. The small width of these multiple finer cracks can be healed through further hydration as experimentally observed by Homma *et al.* (2009) and Yang *et al.* (2005). In a previous study by Homma *et al.* 2009, it is shown that very fine cracks bridged by PE fibers in the strain hardening FRCC healed more by the precipitation of CaCO_3 than that containing steel fibers. It is also shown that permeability of cracked specimens recovered by the self-healing is better in fiber reinforced cementitious composites (FRCC) containing PE fiber than that of hybrid FRCC (HFRCC) containing SC and PE fibers. However, the tensile strength recovery after the self-

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healing was better in the HFRCC than the FRCC. Research also shows that controlling the crack width within a certain value (for example 100 μm) is important for the corrosion durability of reinforcing steel bars in the RC (Li and Li 2008).

Limited durability studies on corrosion and corrosion induced damage resistance of SHCC containing polymeric and hybrid metallic-polymeric fibers are reported (Maalej *et al.* 2003; Miyazato and Hiraishi 2005; Sahmaran *et al.* 2008, Ahmed and Mihashi 2010). While both polymeric and hybrid metallic-polymeric fiber reinforced SHCC exhibited superior corrosion resistance of steel bar and steel fiber (e.g. in Maalej *et al.* 2003, Ahmed and Mihashi 2010), the mechanism of better corrosion resistance of steel bar and steel fibers in hybrid steel-polymeric fibers reinforced SHCC is not well understood. Authors have presented some experimental results in the form of extended summary in a recent RILEM workshop on concrete durability (Kobayakawa *et al.* 2009); this paper describes some insights on the understanding of better corrosion protection of steel bar and SC fibers in hybrid SC-PE fiber reinforced HFRCC material in a long term (one year laboratory exposure)

corrosion study.

Corrosion of reinforcing steels in RC is extremely difficult to avoid but possible to reduce the corrosion rate and extend the time to initiate the corrosion and reduce the corrosion induced damage through the use of different corrosion protection techniques. Recently, the use of strain hardening FRCC to address this issue has received interests in research community. This is due to the small crack width properties, high ductility and high fracture resistance capacities of this material compared to its counterpart regular fiber reinforced concrete. This research attempts to clarify the mechanisms of corrosion of FRCC containing PE fibers and HFRCC containing hybrid PE and SC fibers. A better understanding of the mechanism of corrosion of steel in FRCC and HFRCC will lead better protection of reinforcing steel.

2. Experimental program

Three series of beams were tested in this study. The first series was RC beam made with plain mortar. The second and third series were FRCC containing PE fiber and HFRCC containing hybrid SC and PE fibers, respec-

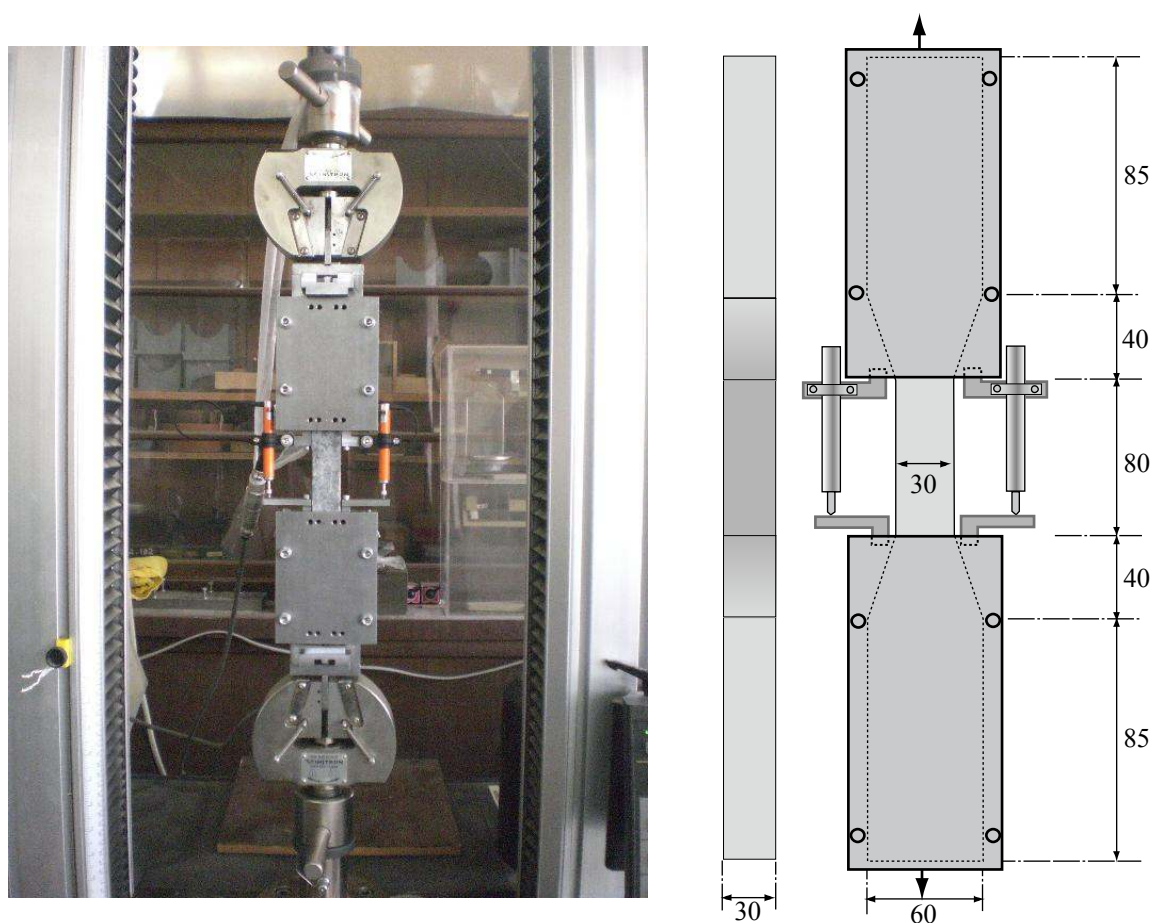


Fig. 1 Uni-axial tension test setup for dumbbell type specimens (All dimensions are in mm).

tively. The FRCC contained PE fiber of 1.5% by volume, while the HFRCC contained 0.75% PE and 0.75% SC fibers by volume. In order to observe the tensile strain hardening behaviour of both materials, six dumbbell type specimens in which size of the central part was 30x30x80 (**Fig. 1**) for each type were cast and cured for approximately 7 days. They were then tested in uni-axial tension using an Instron testing machine under displacement control with a loading rate of 0.2 mm/min. A schematic of the uni-axial tension test setup is shown in **Fig. 1**. In the case of corrosion test one beam measuring 100x100x400 mm was considered (**Fig. 2**). The properties of fibers are shown in **Table 1**. The mix proportions for mortar, FRCC and HFRCC are shown in **Table 2**. The cement used in this study was ordinary Portland cement with a fineness of 4450 cm²/gm, while the sand was silica sand with average size of about 0.5 mm.

3. Specimens, curing, and exposure condition

In all the beams a polished plain reinforcing steel bar of 13 mm diameter and 360 mm length was placed with a clear cover of 20 mm from bottom face of the beams. After casting, all specimens were wet cured for 7 days and then subjected to an accelerated corrosion regime for one year. Accelerated corrosion was achieved by

exposing the specimens to cyclic wetting (20°C, 100% RH for 3.5 days) and drying (20°C, 60% RH for 3.5 days) using water containing 3% (by weight) sodium chloride. In addition, a very low electrical potential of only 3-Volt was applied across an internal anode (the steel bar) and an external cathode built with wire mesh placed near the bottom face of the beams (**Fig. 3**). Three sides (two sides and top) of the specimens were coated with epoxy resin, and only the bottom surface was exposed to the salty environment. During the wet cycle, only the clear cover of each beam was submerged in the sodium chloride water.

Although the accelerated corrosion technique used in this study is far from the natural corrosion, it provided relative comparison of the durability performances of two different types of FRCCs and mortar. Similar kind of accelerated corrosion test setup was also used by other researchers to shorten the test period (Maalej *et al.* 2003; Hon and Chung 1997; Sahmaran *et al.* 2008).

4. Measurement of corrosion

The corrosion of the steel bar in the beams was evaluated from the measured current in the beams. In this study, the applied potential and resulting current values were automatically recorded using a data acquisition system and a personal computer throughout the corrosion test. The measured current was used to estimate the

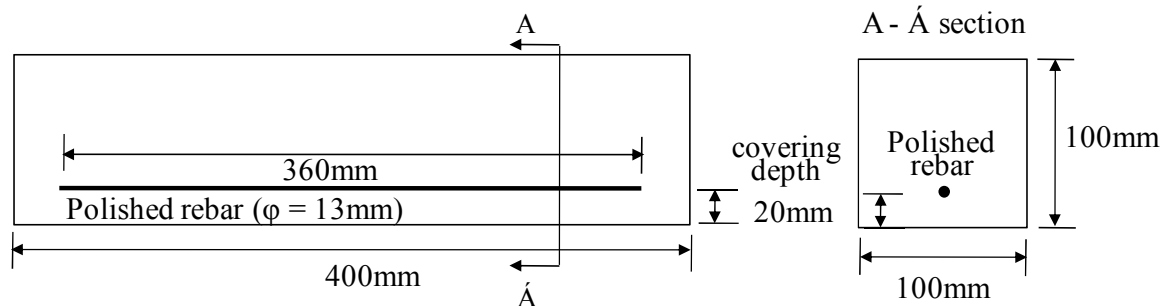


Fig. 2 Outline of test specimens.

Table 1 Properties of fibres.

Types of fiber	Symbol	Density (g/cc)	Length (mm)	Diameter (μm)	Tensile strength (MPa)	Young's modulus (GPa)
Steel cord	SC	7.84	32	400	2850	200
Polyethylene	PE	0.97	6	12	2580	73

Table 2 Test series and mix proportion.

Types of Mix	No of specimens	Water/Binder	Sand/Binder	Silica fume/Binder	SP/Binder	PE fiber (Vol. %)	Steel fiber (Vol. %)
Plain mortar	1	0.45	0.45	0.15	0.009	-	-
FRCC containing PE fiber	1					1.50	-
HFRCC containing hybrid ST-PE fiber	1					0.75	0.75

Note: Binder = Cement + Silica fume

SP = Superplasticizer (Polycarboxylate)

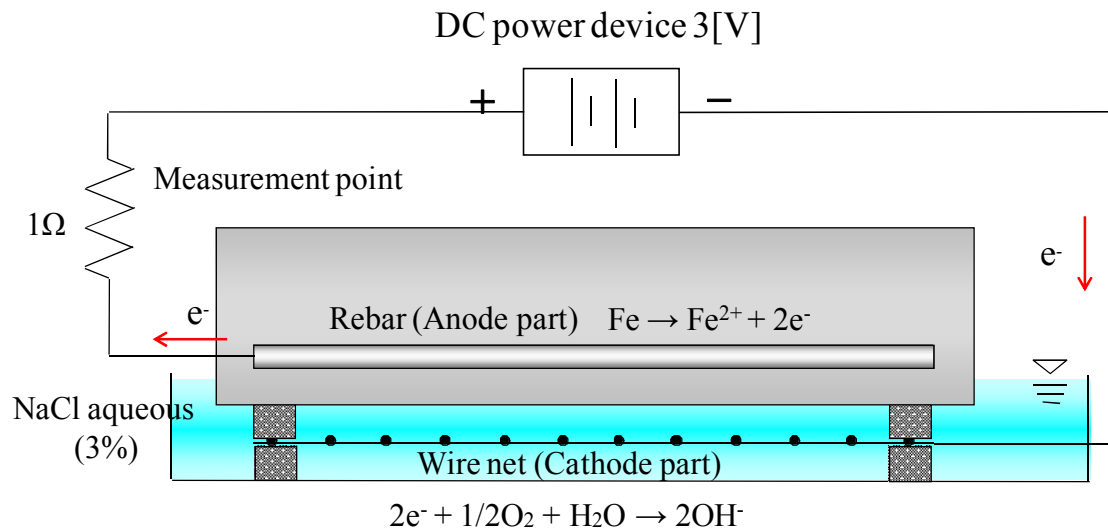


Fig. 3 Accelerated corrosion setup.

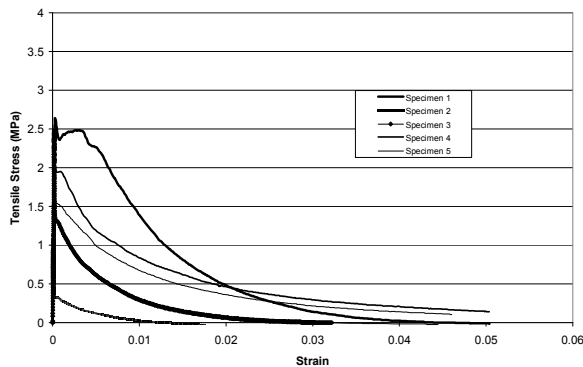


Fig. 4a Tensile strain hardening behaviour of FRCC material containing 1.5% polyethylene fibers.

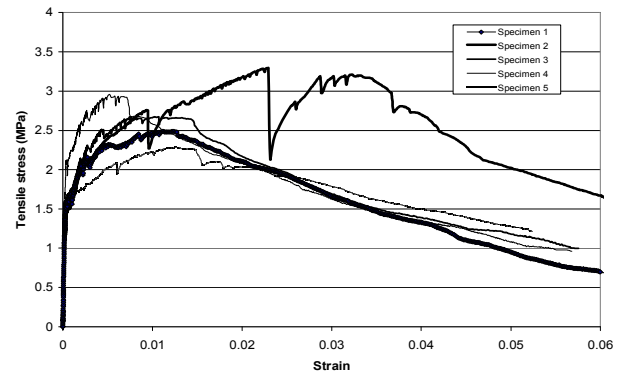


Fig. 4b Tensile strain hardening behaviour of HFRCC material containing 0.75% polyethylene and 0.75% steel fibers.

amount of steel loss using Faraday's law (Maalej *et al.* 2003 and Auyoung *et al.* 2000):

$$\Delta w = \frac{MI t}{ZF} \quad (1)$$

where, Δw = mass of steel loss (grams), I = corrosion current (amperes), t = time (seconds), F = Faraday's constant (96,500 amperes seconds), Z = valency of Fe (2), and M = atomic mass of Fe (56 grams/mole).

After one year, the experiment was stopped and the reinforcing steel bar was taken out from each beam. The corrosion area ratio, the corrosion depth, and the amount of corrosion of the reinforcing steel bar were measured. The corrosion area ratio is defined as the ratio of corroded surface area to the total surface area of the steel bar. The corroded surface area was measured as the corroded part traced on the transparent sheet. After the measurement of corroded surface area the rust in the corroded bars was removed according to JCI standard (JCI 2004; Karasawa *et al.* 2004) and the corrosion depth was measured by vernier callipers. The bars were then weighed to determine the extent of corrosion.

5. Results

5.1 Tensile strain hardening behaviour and fracture energy of mortar, FRCC and HFRCC

Figure 4 shows the tensile stress-strain curves of both FRCC and HFRCC materials. Clear strain hardening behaviour with a strain capacity of around 1% is observed in HFRCC (Fig. 4(b)), where as the FRCC exhibited strain hardening behaviour with very low strain capacity of about 0.4%. Better tensile strain hardening behaviour with higher ultimate tensile strength in HFRCC could be attributed to the long length and high modulus of SC fibers in that composite. Due to the longer length of SC fibers compared to PE fibers, the cracks are bridged by the SC fibers and promoted the strain hardening behaviour in HFRCC composite. In Fig. 5 the comparison of fracture energy of all three materials is shown. In case of mortar, the three point bending test of notch beams were conducted (Fig. 6) and the tension softening curves were generated by adopting the 1/4 model according to JCI standard. As expected the HFRCC exhibited the highest fracture energy that those of mortar and FRCC.

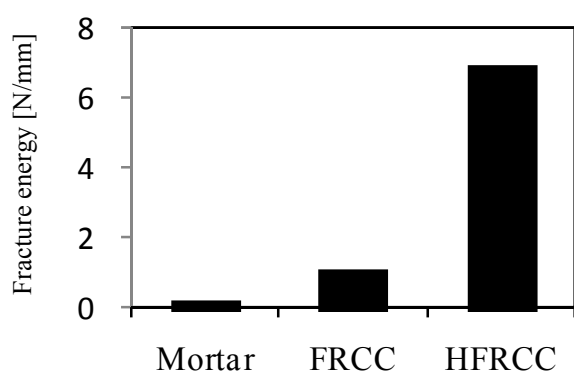


Fig. 5 Fracture energy of each series.

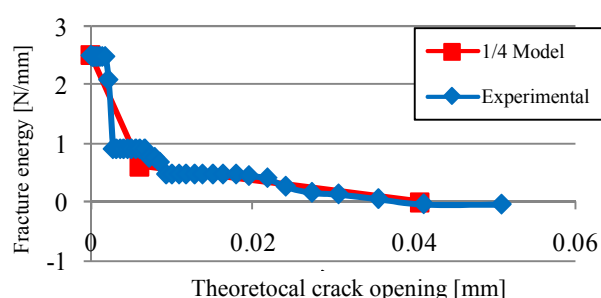


Fig. 6 Tension softening curve of mortar obtained from three point bend test of notch beam and the 1/4 model according to the JCI standard.

5.2 Time-dependent change of specimens and the amount of corrosion

One of the objectives in this study was to monitor the corrosion induced cracking. As three sides were epoxy coated only the bottom surface in each specimen was examined weekly to observe any sign of corrosion and corrosion induced cracks. At about the 27th week corrosion product and a small crack parallel to the rebar was observed in the mortar specimen. Corrosion product and an expansion crack was also observed in the FRCC specimen after about the 36th week. However, no such expansion crack was observed in the HFRCC specimen instead some corrosion spots on the bottom surface were noticed and careful observation showed those rust as localized corrosion of the SC fibers at the bottom surface of the specimen.

Figure 7 shows the appearance of corrosion induced damage on the bottom surface of the specimens at 30th, 40th, and 52nd week due to the accelerated corrosion. This figure shows that in the case of mortar specimen the crack which was formed at 27th week localized and the crack width continued to increase. Therefore, the corrosion of steel bar is accelerated as can be seen at 52nd week where the leaching of corrosion products through the crack can be observed. Similar situation was also observed in the FRCC specimen. However, in the case of HFRCC, even after one year, the expansion

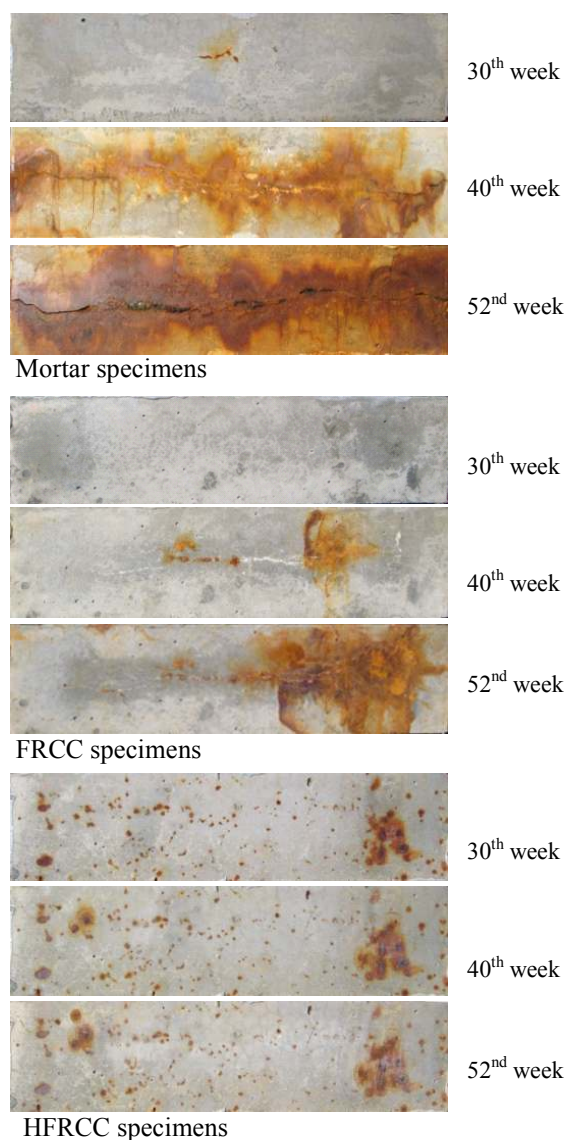


Fig. 7 Time-dependent change of corrosion status in the specimens.

crack was not observed. The formation of corrosion induced cracks in mortar and FRCC specimens is due to the low fracture energy of mortar and FRCC as measured in this study (**Fig. 5**), whereas the absence of corrosion induced cracks in the HFRCC specimen is due to its highest fracture energy.

The corrosion of reinforcing steel bar was monitored by measuring the corrosion current and the amount of steel loss was estimated using the Faraday's law; this is illustrated in **Fig. 8** for all three specimens. It can be seen in the figure that in the mortar specimen the time when the amount of steel loss increased rapidly was almost the same as the time when the corrosion induced expansion crack along the reinforcing steel bar was confirmed on the bottom surface of the specimen. This confirmed that the occurrence of such expansion crack accelerated the corrosion of the steel bar. Similar situation happened

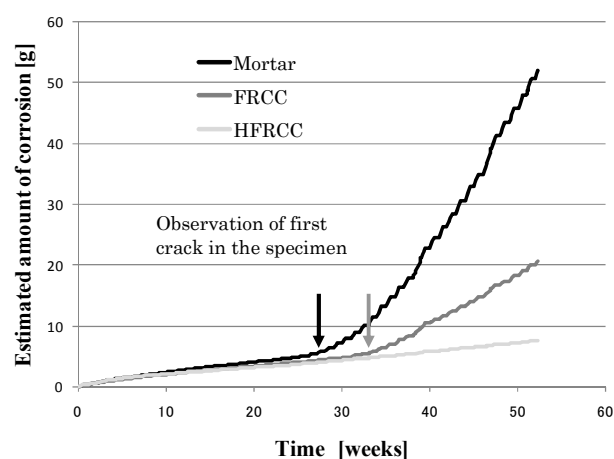


Fig. 8 Amount of corrosion estimated by Faraday's law.

in the FRCC specimen; it can be also seen in the same figure that although the steel loss in the FRCC specimen increased rapidly after about the 36th week when an expansion crack was formed in the specimen, the rate of increase of steel loss was lower than that in the mortar specimen. The reason for this lower rate of steel loss is discussed in the following section. The scenario was quite different in the HFRCC specimen. The rate of steel loss in this specimen was very similar to those of mortar and FRCC during the first few weeks. However, after that time no sudden increase in steel loss was observed in this specimen, which coincided with the periodic visual observation during the test where no sign of corrosion induced expansion cracks were observed and instead rust spots were noticed on the bottom surface of the specimen. And these rusts were confirmed to be associated with the corrosion of SC fibers. Better corrosion resistance of HFRCC specimen could be attributed to the sacrificial corrosion of SC fibers on the bottom surface of the specimen. This is also being discussed in the following section.

5.3 Corrosion of reinforcing steel bar

Figure 9 shows the development of corroded parts of the reinforcing steel bar in three specimens. The A-A' sides in the figure show the reinforcing steel bar in the upper part of the specimens and the B-B' sides in the figure show the reinforcing steel bar in the bottom part of the specimens. Table 3 shows the percentage of corrosion area estimated from the development of corroded surface area and the measured maximum corrosion depth. Both the corrosion area and the corrosion depth were also large and in the following order: Mortar, FRCC, and HFRCC. Table 4 shows the comparison between the actual amounts of corrosion of reinforcing steel bar and estimated ones using the Faraday's law. The actual amount of steel loss is also large and decreasing in the following order: Mortar, FRCC, and HFRCC. Therefore, the order of high durability to the corrosion of reinforcing steel bar judged from the direct corrosion measurement was HFRCC, FRCC, and Mortar.

6. Discussion of the results

According to Table 4, in the mortar specimen, the estimated value of steel loss was smaller than the actual amount of steel loss. It could be attributed to the continuation of corrosion activities in the specimen during the dry cycle. When the crack width is large enough, it could happen that the anode part and the cathode part are created in the reinforcing bar, and the corrosion progressed even during the drying process. Thus in the mortar specimen the corrosion progressed even during the dry cycle.

In the FRCC specimen, the actual amount of corrosion and the estimated value were almost same (Table 4). It can also be seen in Fig. 8 that during the first 30 weeks the rate of steel loss was very similar to that of mortar specimen. After that period, the rate of steel loss

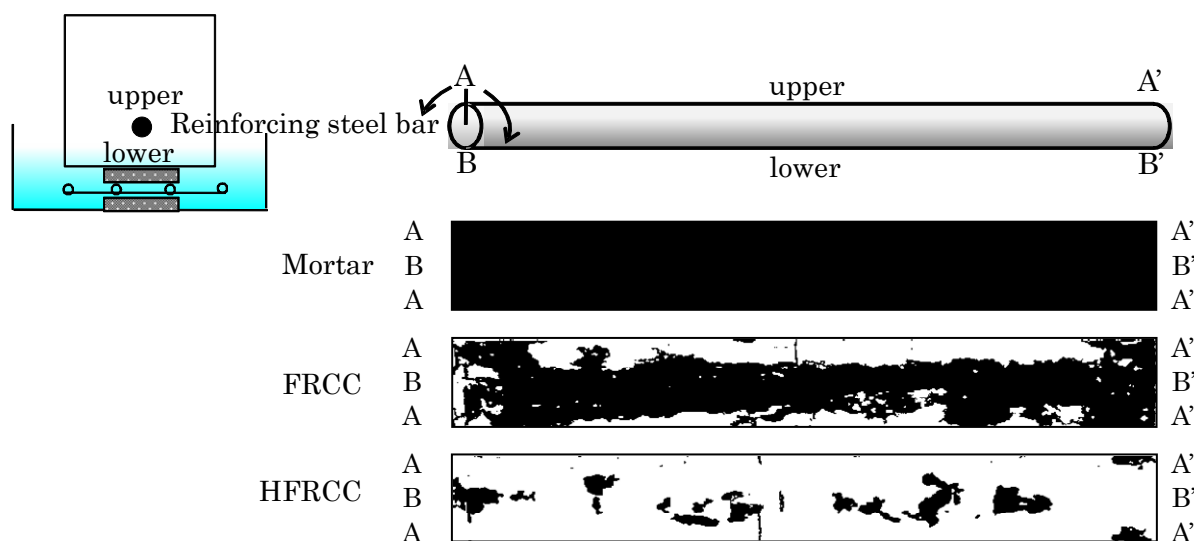


Fig. 9 Development of corrosion area in the reinforcing steel bar.

Table 3 Corrosion area ratio and depth after one year exposure.

	Mortar	FRCC	HFRCC
Corrosion area* [%]	100.0	65.4	11.8
Corrosion depth [mm]	3.1	1.2	0.0

*corroded surface area / total surface area of the reinforcing steel bar

Table 4 Comparison between the actual amount of corrosion and the calculated by measuring the current.

	Mortar	FRCC	HFRCC
Actual amount of corrosion [g]	69.9	20.0	1.0
Estimated amount of corrosion [g]	52.1	20.6	7.7
Difference [g]	-17.8	0.4	6.7
Error of estimation [%]	25.4	2.2	671.5

increased rapidly due to the formation of corrosion induced longitudinal crack. However, this increase of rate of steel loss was much lower than that of mortar specimen. This is believed to be due to two reasons. Firstly, the cracks which were formed were not as wide as that formed in the mortar specimen due to the bridging of cracks by the PE fibers and the higher fracture resistance of FRCC than that of mortar. Thus the cracks that were formed were narrow enough to partly obstruct the access of chloride ions, hydroxyl ions, etc. in the specimen. Secondly, the self healing of cracks in this specimen also contributed in the reduction of steel loss. During routine observation the formation of self healing products in some of the cracks in the FRCC specimen was noticed. Moreover, in a separate study by the authors the self healing was also confirmed in the cracks in FRCC specimen containing PE fibers (Homma *et al.* 2009). The mix proportion of FRCC was identical in both studies. The above two phenomenon is believed to be contributed to the limited corrosion of steel bar in the FRCC specimen, and at the end of the test the final steel loss in the specimen was about 60% lower than that of mortar specimen.

On the other hand in the HFRCC specimen, the estimated value was much larger than the actual amount of steel loss. It could be attributed to the formation of "sacrificial anodic zones" by the SC fibers on the bottom surface of the beam (Someh and Saeki 1997). Generally, when corrosion of steel bar occurs in the RC an anodic region and a cathodic region are formed in the steel bar. The iron (Fe) in the anodic region breaks and releases electrons (e^-) which then combine with oxygen and moisture in the cathodic region and form hydroxyl ions (OH^-). These hydroxyl ions later combines with free irons (Fe^{++}) in the anodic region and form corrosion products such as ferrous hydroxide ($Fe(OH)_2$), ferric oxide (Fe_2O_3), etc. These corrosion products, which are expansive in nature, cause cracking in the concrete cover and provide easy access to aggressive substances into the concrete and further accelerate the corrosion process. In the case of accelerated corrosion in this study, however, the reinforcing bar is connected with a

positive terminal and the external cathode i.e. the wire mesh is connected with a negative terminal of a DC supply (Fig. 3). In this case, the electron is forced to go to the wire mesh. The electrons in the wire mesh then combined with water and oxygen available near the beam's bottom surface and generated the hydroxyl ions (OH^-) and chloride ions (Cl^-). These ions are then attracted by the Fe^{++} ions in the anode and cause the corrosion reaction. In the case of HFRCC, the SC fibers are distributed randomly and due to their random distribution it might be possible that few SC fibers are interconnected in the cover zone and touched the steel bar. Fig. 10 shows the schematic of the likely random distribution of SC fibers in the cover zone of the HFRCC specimen and their connectivity with the steel bar. Because of their connectivity with the steel bar the anodic region is extended to the SC fibers on the bottom surface of the specimen. Hence, the SC fibers on the bottom surface of the specimen formed the "sacrificial anodic zone" and the corrosion continued with the availability of hydroxyl ions in the cathodic region (i.e. the wire mesh near the bottom surface of the specimen). Therefore, although the external potential is supplied to the anode (the steel bar), the actual corrosion first started in some of the SC fibers due to their close proximity to the cathodic region. This may explain the big difference between the actual steel loss and the estimated steel loss by the Faraday's law in this study. This also explains why the HFRCC specimen performed better in terms of steel loss compared to its counterpart FRCC and mortar specimen. On the other hand, the rest of the SC fibers in the concrete which were not connected to the steel bar were protected by the alkalinity of the concrete and did not provide mechanism for the corrosion propagation actively (Mangat and Gurusamy 1988). Better corrosion resistance of HFRCC specimen in this study is also attributed to the small width of the cracks (less than the critical crack width limit for corrosion protection) that might be formed in the specimen due to the high fracture energy of HFRCC (see Fig. 5). This is also due to the fact that the high modulus steel fibers contributed to the superior crack resistance capac-

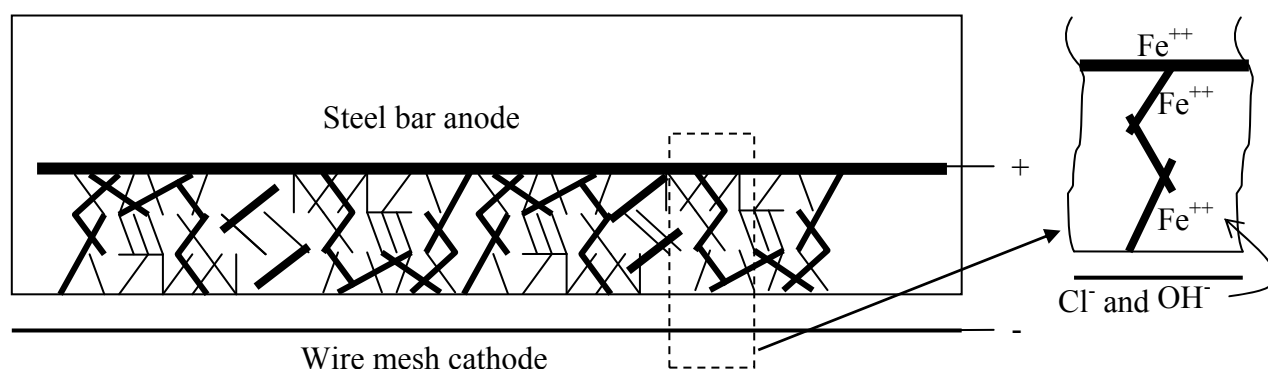


Fig. 10 Schematic of distribution of SC fibers (—) and PE fibers (—) in the specimen and the formation of sacrificial corrosion of SC fibers.

ity which reduced the crack widths compared to its counter part low modulus PE fiber in the study.

However, in the case of natural corrosion the phenomenon will be rather different. It is argued that in the case of natural corrosion where the steel bar is embedded in the HFRCC containing SC fiber, the passivity of the steel fibers at the concrete's surface would be broken down first due to the presence of aggressive ions and oxygen. As the SC fibers are randomly distributed in the beam, some fibers might be interconnected while the others might not. Those which are connected to the steel bar will act as anodes, hence, a galvanic couple will be formed and the corrosion of SC fibers will be accelerated and corrosion of steel bar will be reduced or stopped (Someh and Saeki 1997). Moreover, the SC fibers which are not connected, due to discrete nature of SC fibers, the maximum cathodic area available for fibers would be limited. Therefore, even if corrosion initiates in some of the SC fibers it would be possible that the subsequent rate of corrosion would be very small (Mangat, and Gurusamy 1988). The small diameter fibers with their larger surface area to volume ratio would even be more effectively protected by the alkalinity in the concrete. Limited experimental results supporting this hypothesis are available in the literature. However, more thorough research need to be conducted to fully understand the phenomenon of corrosion of reinforcing steel in the HFRCC containing steel fibers.

7. Conclusions

- 1) The time to initiate corrosion of steel bar was shortest for plain mortar, then for PE fiber reinforced FRCC and then for hybrid ST-PE fiber reinforced HFRCC.
- 2) The corrosion rate of the reinforcing steel bar was clearly accelerated after the expansion cracks occurred along the reinforcing steel bar.
- 3) The amount of corrosion, the corrosion area, and the corrosion depth of the reinforcing steel bar were in the following decreasing order: Mortar, FRCC, and

HFRCC.

- 4) The FRCC exhibited better resistance of corrosion of reinforcing steel bar than mortar because of the bridging of cracks by the fibers and the self-healing of some of the cracks.
- 5) Durability performance of HFRCC to the corrosion of reinforcing steel bar was the highest. It might be due to the higher fracture resistance hence the small width of the cracks of HFRCC and the formation of sacrificial anodic zone by the SC fibers.

Acknowledgement

This study was supported by Grant-in-Aid for Scientific Research (A) No.18206058. Authors appreciated Japan Society for the Promotion of Science for the financial support that made it possible to complete this study. Authors gratefully acknowledge to Dr. Kazuyuki Shimozawa for his support and valuable advice in the experimental phase of this study.

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