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Technical report

Study on Performance of PVA Fiber Reinforced Concrete Exposed for 10 Years to Seawater Spray

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Abstract

This paper reports the analytical and the experimental results of changes in the performance of PVA fiber reinforced concrete (FRC) exposed for 10 years to seawater spray. In this study, the specimens were FRC prisms with a corroded rebar and cracks in some areas, after having been maintained in a saline environment. In addition, a push-out test of the rebar in the specimens was conducted to examine changes in push-out load and crack width at surface in FRC. Furthermore, the salinity analysis, the measurement of initial crack widths, and the measurement of the corrosion amount of the rebar were performed.

As a result of the salinity analysis, it was confirmed that the chloride ion density of the concrete increased to around 9-12 kg/m³ by exposure to a seawater spray environment for 10 years. As a result of the chemical analysis of short fibers, the quality of the fibers in this study had not changed after the exposure.

As a result of the rebar push-out test, it was confirmed that fibers mixed into the concrete suppressed the enlarging of cracks immediately below the rebar. By this bridging effect of fiber, there was a tendency for new cracks to develop. The addition of fibers increased the load at the displacement of 2mm based on the rebar push-out test, and the load was proportional to the remaining tensile strength of FRC.

1. Introduction

The corrosion of rebars used in reinforced concrete (RC) structures may be caused by de-passivation of the steel in concrete by salt attack. The expansion will lead to the initiation of cracks at the concrete cover, and the reduction will lead the considerable drop in the load-bearing capabilities of the RC structures. In addition, cracks due to a corroded rebar may lead to the exfoliation of concrete flakes, so it may injure the users of the structure.

In recent years, many researchers have studied the performance of RC structures extensively. It has been found that crack patterns vary with boundary conditions or with depths of the rebar in the concrete. It has also been shown that several expansion coefficients of the corrosion products have been estimated by different experimental methods, including the long-term exposure test and the electrolytic corrosion test (JCI 2013a, 2013b). Many actual tests have shown that rebar corrosion often starts at the surface of any rebar that is covered by only a

shallow layer of concrete. The results of finite element analysis were closer to those of actual empirical tests, when the expansion pressures of corroded rebar were applied to a concrete on the covering side of the rebar that is 1/4 as thick as the diameter of the rebar (Tran *et al.* 2010). Similarly, rebar push-out tests have also been performed to evaluate the resistance of concrete to exfoliation, taking into account the pressure of rebar corrosion expansion applied to the concrete on the covering side of the rebar (Watanabe *et al.* 2014).

Turning to another concrete technology, short-fiber-reinforced concrete (FRC) is often used in the superstructures of viaducts and the tunnel lining to prevent the exfoliation of concrete flakes (JCI 2012). Many researchers have used various tests to evaluate the performance of FRC in the suppression of crack expansion and in the prevention of the exfoliation of concrete debris due to bridging effects (Naaman 2000; Bischoff 2000). Some researchers have also reported that the use of FRC succeeds in suppressing the rebar corrosion by forestalling the occurrence of cracks. However, studies that examine the resistance of FRC against exfoliation by the rebar corrosion had been few. In addition, studies of corrosion in FRC in actual salty conditions have been few.

On the other hand, since about 1990, the studies on mechanical performance of concrete which contained synthetic fiber such as polyolefin or carbon had been performed (Adebar *et al.* 1997; Noghabai 2000). And in about 2000, the studies of PVA (Polyvinyl Alcohol) or PP (Polypropylene) fiber that are used to prevent the exfoliation started (Naaman 2000; Yokota *et al.* 2004). However, the study of the durability of their synthetic fibers has been few (Lhoneux *et al.* 2002).

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Table 1 Test cases and test results.

Concrete prism specimen No.	Preparation condition	Strength test results*1		Loading test specimen No.	Location where collected	Status of specimen after exposure			Push-out test results				
	Volume content of fibers Vf	Compressive strength fc	Young's modulus Ec			Presence of cracks (crack width (mm))			Amount of rebar corrosion	Max. load	Load at a displacement of 2 mm	Displacement at the end of the loading test	Crack pattern
	vol.%	N/mm ²	kN/mm ²			Left	Bottom	Right	mg/cm ²	kN	kN	mm	—
00-1	0.0	35.5	28.6	00-1L	Left	—	—	—	0	6.47	0.00	0.5	A
				00-1R	Right	0.20	—	0.20	246	3.96	0.00	1.1	A
00-2				00-2L	Left	—	—	—	120	5.88	0.00	1.8	A
				00-2R	Right	—	0.25	0.06	216	1.76	0.00	*2	A
05-1	0.5	36.9	28.0	05-1L	Left	0.10	0.25	0.10	168	2.19	0.58	7.6	A
				05-1R	Right	0.30	0.30	0.30	199	0.66	0.44	9.2	A
05-2				05-2L	Left	0.15	1.30	0.06	219	0.92	0.58	7.1	B
				05-2R	Right	0.30	0.25	0.35	326	1.11	0.60	8.0	A
10-1	1.0	37.6	26.9	10-1L	Left	—	—	—	14	6.86	1.07	5.7	C
				10-1R	Right	—	—	—	201	3.67	1.54	*2	C
10-2				10-2L	Left	—	—	—	110	5.28	1.00	8.7	A
				10-2R	Right	0.20	—	0.20	132	3.23	1.73	9.5	A
15-1	1.5	30.5	24.0	15-1L	Left	—	0.15	0.25	243	2.73	2.52	12.4	B
				15-1R	Right	—	—	—	182	2.93	1.39	15.2	A
15-2				15-2L	Left	0.25	0.05	0.35	278	1.75	1.30	*2	D
				15-2R	Right	—	—	—	299	3.81	0.91	8.4	B

*1 Material age of 28 days *2 Missing data

The purposes of this study are to examine changes in short-fiber-reinforced concrete due to long-term exposure to seawater spray, to ascertain if mixing short fibers into concrete improves its resistance to exfoliation, and to determine if FRC has improved resistance to exfoliation due to cracks caused by corroded rebars. In this study, salinity analysis, the measurement of widths of crack induced by exposure, and the measurement of the corrosion amount of the rebar were performed. The specimens were FRC prisms with a corroded rebar and cracks in some areas, after having been maintained in a seawater spray environment for 10 years. In addition, a push-out test of the rebar in the specimens was conducted to examine changes in push-out load and crack width at surface of FRC.

2. Test methods

2.1 Testing procedures

Figure 1 shows the procedures used in this study in the flowchart form. Prism-shaped specimens made from short fiber reinforced concrete were prepared 10 years ago. These had been exposed to a seawater spray environment for 10 years. Then the concrete surfaces of prisms were examined to know the crack situation. Next, the prisms were cut into blocks whose size and type were appropriate to the loading test and the chemical analysis. The crack width of the cut surfaces of the specimens was measured and the distribution of short fibers was ascertained by black light. A loading test was performed using block specimens taken from areas near the longitudinal center of each prism. After the testing, the crack situation of the block specimens was examined and the amount of the corrosion of the rebar taken out of the concrete was measured.

Using the remaining parts of each prism, salinity analysis of the concrete and chemical analysis of the

short fibers were performed. In the text that follows, cracks on the cut surface observed after exposure to the salty environment are called "initial cracks" and those observed after the loading test are called "loading cracks".

2.2 Test cases and description of the prisms

As shown in Table 1, first eight prism-shaped specimens were prepared: two specimens with each of four different levels of short fibers (ranging from 0.0 to 1.5 vol.%). From each of these specimens, two blocks were cut for use as specimens in the push-out test; thus a total of 16-block specimens were created, as shown in Fig. 2. The salinity analysis of the concrete and the chemical analysis of the short fibers were performed using blocks taken out of the remaining parts of each prism. The blocks used for these analyses were selected to have a volume content of short fibers of 0.0% and 1.0%, re-

Fig. 1 Flowchart of the entire procedure.

spectively.

The original uncut prisms measured 100 x 100 x 400 mm, as shown in **Fig. 2**. A deformed bar with a diameter of 13 mm had been bent, then arranged in the concrete before being set. Then the distance between the rebar center and the concrete surface was adjusted so as to be 25 mm and the distance between the rebar surface and the concrete surface was adjusted so as to be 18.5 mm. The direction of casting and the direction of seawater spray were like **Fig. 2**. The loading test specimens (reported on below) were cut from the middle of the length of the prism. The short fibers used were polyvinyl alcohol (PVA) fibers with a diameter of 0.66 mm and a standard length of 30 mm. These fibers had the following physical properties: a density of 1.3 g/cm³, a tensile strength of 880 N/mm², and an elastic coefficient of 29.4 kN/mm². The concrete was mixed under the following conditions: the maximum size of the coarse aggregate Gmax was 20 mm, the water to cement ratio was 53.2%, and the fine aggregate ratio was 47.8%. The base concrete before the addition of the short fibers was set to a target slump of 18 cm and a target air volume of 4.5%. **Table 1** shows the results of a strength test of the material whose age is 28 days. A filling of concrete and the presence of coarse aggregate with a diameter of 10 mm or more were observed on the cut surface. However, since the least distance between the rebar surface and the concrete surface did not satisfy the design value of 27 mm that had been determined on the basis of the Gmax, it seemed that the cracks might be easily to progress (JSCE 2012).

2.3 Exposure to a seawater spray environment

The exposure conditions are shown in **Fig. 3**. The exposure to seawater spray was made on the Yokosuka-city seacoast, in Kanagawa Prefecture, Japan, as follows. The prisms were sprayed with natural seawater for about four hours a day, followed by about eight hours for drying. This cycle was repeated twice a day. The specimens were exposed continuously under these conditions for about 10 years.

2.4 Analysis of short fiber reinforced concrete after exposure

(1) Counting method of the number of short fibers

A photograph of the cut surface of each specimen illuminated with black light was taken. The number of short fibers seen in the photo taken under black light was counted and converted to a volume content.

(2) Chemical analysis method of the short fibers

PVA short fibers were taken out from the specimens. The weight average molecular weight and the number average molecular weight of the PVA were measured by gel permeation chromatography GPC (Tosoh Corporation HLC-8220GPC, Density: 0.1%). Because the fibers might be physically damaged by their removal from the FRC, this method was used instead of a direct tensile strength test. Control PVA short fibers that had been in

the safekeeping at the manufacturing company during about 10 years were compared with the exposure fibers. The properties of control fibers were the same as the exposure fibers.

(3) Salinity analysis method

An area analysis of chloride ions was performed using an electron probe micro-analyzer (EPMA) held against a cut analysis surface that had been made conductive by gold evaporation. As shown in **Fig. 4**, the analysis range was an area of 80 x 80 mm square, including the rebar-covering side and the flanking side. The analysis of chloride ion density was performed according to the constant-current titration technique using a chloride ion pole described in JIS A 1154. There were two analysis positions: the rebar-covering side (direction A) and the flanking side (direction B) as shown in **Fig. 4**. Each specimen was cut as a section, and they were also cut at intervals of 10 mm from the surface to a depth of 50 mm. The measurement was performed twice on the rebar-covering side and once on the flanking side.

Fig. 2 Size of the prisms and locations from which loading test specimens were cut out.

Fig. 3 Salt spray exposure setup.

Fig. 4 Analysis of the cut-out specimens.

(4) Observation of initial cracks

After the exposure, the prisms were visually examined and the width of any cracks was measured using a crack scale with the resolution of 0.05 mm. In addition, as shown in Fig. 5, the cracks on the cut surface of each loading test specimen were examined and the maximum width of any extension from each crack was measured.

(5) Measurement of the amount of rebar corrosion

After the push-out testing was performed, the rebar was removed from the specimens and the amount of corrosion was measured for each. First, all corrosion was

removed by immersing the rebar in a 10% di-ammonium hydrogen citrate solution at 50°C for one or two days. Then, the mass of the rebar was measured to determine the amount of corrosion.

2.5 Rebar push-out test method

A block specimen, 50 mm wide, was cut from each prism specimen and used as a loading test specimen. As shown in Fig. 6 (a), (c), the specimen was cut so that both ends of the rebar protruded about 10 mm each from the two cut surfaces of the specimen. A 20 mm thick steel plate was attached to the top of the specimen with epoxy resin (Fig. 6 (a)). The specimen was fixed to the loading tester by the steel plate as shown in Fig. 6 (b), (c) and a load (forced displacement) was applied vertically on each end of the rebar protruding from the cut surfaces of the specimen. In the test, the load (reaction force of the rebar), the relative displacement between the rebar and the concrete, and the strain of the concrete were measured and the results were recorded on the data logger. The relative displacement was calculated by subtracting the concrete displacement from the rebar displacement that

(a) 00-2R

(b) 15-2L

Fig. 5 Cut surfaces and locations of attached gauges.

(a) Size and direction of force

(b) Whole view

(c) Close view

Fig. 6 Outline of the rebar push-out test.

measured by displacement meters, as shown in **Fig. 6 (c)**. The strain of the concrete was measured by attaching three plastic region strain gauges (with measuring lengths of 20 mm) at three different positions on the cut surface, as shown in **Fig. 5**.

3. Analysis of fiber reinforced concrete after exposure

3.1 Distribution of short fibers

All the prism specimens that have been exposed to the salty environment were checked in order to ascertain the distribution and the number of short fibers specified in each test case. The number of short fibers was counted in order to adapt the case name of specimen's surface to the actual fiber content. **Figure 7** shows a photo of the cut surface of a specimen illuminated with black light. It was confirmed that the greater the volume content, the larger the number of shining fibers that could be seen in the photo. The fibers were found to be oriented randomly. There were some concentrations of fibers when the volume content was 1.5%. It was confirmed that some fibers were present at the rebar-covering on the bottom of the specimen.

Figure 8 shows the relationship between the volume content and the number of short fibers. The straight dotted line also shows the relationship between the volume content and the number of fibers counted by supposing that the cross-section angle of each fiber on the cut sur-

Fig. 7 Photo taken under black light illumination.

Fig. 8 Relationship between the volume content of fibers and the number of fibers.

Table 2 Chemical analysis results of PVA short fibers.

	Mw (Weight average molecular weight)	Mn (Number average molecular weight)
Exposure fibers	198100 (199726 · 196382)	74700 (73717 · 75725)
Control fibers	206200 (204328 · 208144)	74900 (75819 · 73966)

face is 45°. As the volume content increases, the variation also increases. There were fewer fibers than expected by reason of angle supposition. But it was confirmed that the counted number of fibers had a linear correlation with the fiber content.

3.2 Chemical analysis of the short fibers

Table 2 shows the weight average molecular weight Mw and the number average molecular weight Mn of the PVA. When the values of exposure fibers were compared with the values of control fibers for about 10 years, it was confirmed that the difference in Mw was about 0.3% and that the difference in Mn was about 4.0%. It was considered that the dispersion of the quality and the measurement were the causes of these differences. In the fibers used for a slate-covered roof during 12 to 18 years, the molecular weight of the aged fibers was -8.9% to +4.8% against sound fibers, and the fiber strength of the aged fibers was -8.3% to +5.8% against the sound fibers (Lhoneux *et al.* 2002). From this result, it was considered that there were few deterioration of the quality of fiber after exposure.

3.3 Results of the salinity analysis

After the prisms had been exposed to natural seawater spray for 10 years, their penetration of salinity and the effects of mixing fibers were examined. **Figure 9** shows the area distribution of chloride ions. The positions where the chloride ion density (described later) was measured are shown with dotted lines in the figure. The top and left sides of the figure represent the surfaces of the prism-shaped concrete specimen with the left side representing the rebar-covering side. Chloride ions were distributed evenly over the entire specimen although the chloride ion density was lower on the flanking side. The cover side that was exposed directly to seawater spray had a high density of chloride ions. The chloride ion density was high at the position of the rebar in specimens with a fiber content of 0.0% (**Fig. 9 (a)**). And it was high from the concrete surface to the rebar position when the fiber content was 1.0% (**Fig. 9 (b)**).

Figure 10 shows the distribution of chloride ion density in the depth from surface. As shown in the area distribution, the chloride ion density of 40 - 50 mm section sample was higher than that of 0 - 10 mm section sample in direction B. In direction A of the specimen with a fiber content of 0.0%, the chloride ion density of 40 - 50 mm was lower than that of 0 - 10 mm section sample. Average values of the density were from 9.0 kg/m³ to 12.8 kg/m³.

With or without mixture of the fiber, the average values and the ranges were almost same. It did not become clear that the fiber content is effective.

3.4 The development of rebar corrosion and cracks

After the prisms had been exposed in a natural seawater spray environment, some of the prism specimens developed cracks due to rebar corrosion. Here, the relationship between the fibers contents and the progress or width of initial cracks, as well as the amount of the corrosion of the rebar in the concrete, will be discussed. **Table 1** indicates the presence and width of initial cracks. Cracks tended to occur in three directions as shown in **Fig. 5**: bottom, left and right. The presence and width of initial cracks in each direction were recorded.

On the 16 specimens subjected to a loading test, seven had not developed any initial cracks, six had initial cracks that were 0.3 mm or less wide, and three had initial cracks that were more than 0.3 mm wide. As shown in **Fig. 5 (b)**. There was a tendency for multiple cracks to occur in the same direction from the surface to

the interior in fiber mixed concrete specimens.

The relationship between the widths of initial cracks on the surface (surface crack) and widths inside (initial inside crack) is shown in **Fig. 11**. In zone (2) on the graph, there was one case where no initial cracks were found on the surface while an initial crack was found inside with a

Fig. 11 Relationship between surface cracks and initial inside cracks.

Fig. 9 Area distribution of chloride ions.

Fig. 10 Distribution of chloride ion density.

width in the range from 0.20 to 0.35 mm. By contrast, in zones (3) and (4), the widths of initial inside cracks were less than the surface crack width. Especially, in zone (4), the widths of the initial inside cracks were about half the width of the surface cracks. In a test case that the specimen had a 1.5% fiber content, a surface crack with a width of 0.43 mm and an inside crack with a width of 0.0 mm, the said surface crack was the result of a crack that started in another point and ran in the lengthwise direction.

The process of the crack formation that occurred in zones (2) to (4) on the graph is shown in **Fig. 12**. Initial inside cracks in zone (2) occurred due to the expansion pressure of the corroded rebar and the cracks progressed toward the surface of the specimen. Next, as seen in zone (3), cracks from the inside reached the surface of the specimen, so that the surface crack width becomes almost the same as the initial inside crack's width. After that, as zone (4) shows, the surface crack width only enlarges. This examination, measuring crack widths on the cut surfaces, made it possible to make assumptions about the process of crack progress from initial inside cracks due to corroded rebar to surface cracks.

Figure 13 shows the relationship between the amount of the rebar corrosion and the initial inside crack width (maximum width in each direction). The tendency was that the greater the amount of the rebar corrosion, the wider the initial inside crack. Some of the specimens with a fiber content of 1.0% and 1.5% did not have any

initial inside cracks even when there was a relatively large amount of corrosion, such as in the range of 200 to 300 mg/cm^2 . In contrast, some of that had some cracks in the amount of about 300 mg/cm^2 . It was considered that the crack occurrence with expansion energy of rebar was restrained by the fiber. However, it was not clarified that the crack width was restrained by the fiber in this figure.

4. Rebar push-out test

4.1 Occurrence of loading cracks

Figure 14 shows the cracks occurred in FRC during the push-off tests. As shown in **Fig. 14 (a)**, loading cracks occurred in three directions (down, left and right) in test cases without fiber. By contrast, in test cases with fiber, the bridging effect of the fibers suppressed the opening of bending cracks immediately below the rebar. As seen in **Fig. 14 (b)**, the number of loading cracks developing in the lateral directions dominated, and the loading cracks had a different appearance from those in specimens that did not contain fibers. As shown in **Fig. 15**, the cracks could be seen to occur in four different patterns (**Table 1**). Among the 12 test-cases where the concrete contained fibers, three developed in pattern B, two developed in pattern C and one developed in pattern D. Patterns B and D were caused by the effect of the position of the initial inside cracks. Pattern C resulted from specimens that had no initial cracks.

Fig. 12 Types of cracks and their progression.

Fig.13 Relationship between the amount of rebar corrosion and the initial inside crack width.

Fig. 14 Occurrence of loading cracks.

4.2 The relationship between the load and the relative displacement

Figure 16 shows the relationship between the load and the relative displacement of the specimens. The displacement of specimen 00-2L could not be measured due to a failure of the measuring instrument, so only the maximum load was plotted for that case. Likewise, the concrete displacement of 10-1R could not be measured, and the central displacement of the rebar is shown instead. On the graph, after the load reached the maximum, the load dropped and the relative displacement alone increased. In many of the test cases where no initial cracks were found, the maximum load was 4 kN to 7 kN. By contrast, test cases where initial cracks were found could only bear a maximum load of about 4 kN.

Figure 17 shows the relationship between the initial inside crack width and the maximum load for each test case. The tendency was that as the initial crack width increased, the maximum load became small. Initial cracks occur when the concrete around the rebar receives a load corresponding to the tensile strength due to rebar corrosion. For this reason, in test cases with initial cracks, the load-displacement curve follows the hysteresis curve of re-loading as approximating a softening curve after the maximum load, as shown in Fig. 18. This is probably the reason that the maximum load decreases. Among the test cases where no initial cracks were found by observation, three cases had a maximum load range of only 3 kN to 4 kN. To discuss the reason for this phenomenon, the relationship between the amount of rebar corrosion and the

Fig. 15 Types of loading crack patterns.

Fig. 16 Load-displacement relationship.

maximum load is shown in **Fig. 19**. In test cases with no initial cracks, the maximum load was low when there was a large amount of corrosion. The authors guessed that, in three cases of the above, the decreases of the load were caused by the accumulation of tensile stress in the concrete and the existence of undetected fine cracks.

Noting the slope of the graph after the maximum load in **Fig. 16**, it can be seen that test cases without fibers could not sustain the load after the maximum load was reached, so concrete flakes began to drop during the testing. On the other hand, test cases with fibers could sustain the load after the maximum load was reduced, and there was no exfoliation of concrete flakes until the loading was stopped when the displacement reached about 10 mm (**Table 1**). **Figure 20** shows the relationship between the load at which the relative displacement was 2 mm and the remaining tensile strength (stress at the turnoff point) (Ito *et al.* 2014). **Figure 21** shows the remaining tensile strength of tension-softening model for FRC. This figure shows that the tensile strength of FRC is same as that of normal concrete. Also this figure shows the bridging effect of fiber is obtained at fiber bridging zone. In this study, the load at relative displacement of 2 mm was used as an index for the load sustaining performance. A tensile stress can be maintained only by the remaining tensile strength (bridging effect) of the fibers,

after the normal concrete can't sustain the tensile stress due to the occurrence of cracks.

The maximum load of 15-1L was twice as much as that in the other test cases with a fiber content of 1.5%. As seen in **Fig. 16**, the maximum load increases after the relative displacement reaches 0.5 mm, suggesting that its load resistance mechanism was different from the other test cases with the same content of fibers. Except for the case of 15-L, the remaining tensile strength correlated well with the maximum load at relative displacement of 2

Fig. 17 Relationship between initial crack width and maximum load.

Fig. 18 Movement in load-displacement hysteresis curve.

Fig. 19 Relationship between the amount of rebar corrosion and maximum load.

Fig. 20 Relationship between the load at which the displacement is 2 mm and the remaining tensile strength.

mm. As a result, the maximum load in this study was affected by the initial crack width and the amount of the

rebar corrosion. On the other hand, the capability to sustain the load was affected by the remaining tensile strength which could be adjusted by changing the type and content of fibers to be mixed into the concrete.

Fig. 21 Tension softening model for FRC.

Fig. 22 Load-strain relationship (no initial cracks).

Fig. 23 Load-strain relationship (initial cracks present).

4.3 Load-strain relationship

Figure 22 shows an example of the load-strain relationship of a test specimen without the initial cracks. Here, the strain is a measured value obtained using a plastic region strain gauge attached to a position (Fig. 5(b)) 20 mm away from the center of the rebar in the concrete. The value tended to increase as the crack opened. Some strain gauges broke near the maximum load as the crack widened. Therefore, the strain could be no longer measured beyond that point. In many cases without initial cracks, the strain increased first on the bottom of the rebar, followed by an increase on the left side and then on the right. In four test cases without initial cracks of crack pattern A, the strain at the maximum load was 950 to 2500×10^{-6} at the bottom and 50 to 1300×10^{-6} on the right and left sides, and the width of the crack at the bottom was about twice as big as those on the right and left sides. There was not any difference in this regard between the test cases with fibers and those without fibers.

In many of the test cases with initial cracks, the strain on the cut surface increased as the crack opened, as shown in Fig. 23, although there were differences in the progress of the loading cracks, depending upon circumstances.

5. Conclusions

- 1) By the chemical analysis of the short fibers, it was concluded that the quality of the fibers in this study had not changed even though the specimens were exposed in 10 years.
- 2) By exposure to seawater spray environment for 10 years, the chloride ion density of the concrete was increased to around $9\text{--}12 \text{ kg/m}^3$. With or without mixture of the fiber, the average values and the ranges were almost same.
- 3) As the results of measuring the width of the crack on the cut surface, the cracks progressed from the initial inside crack due to the corroded rebar to the surface crack.
- 4) The rebar push-out test confirmed that fibers mixed into the concrete suppressed the enlarging of cracks immediately below the rebar. By this bridging effect of fiber, there was a tendency for new cracks to develop.
- 5) Furthermore, the addition of fibers increased the load at the displacement of 2mm based on the rebar push-out test, and the load was proportional to the remaining tensile strength.
- 6) The rebar push-out test also confirmed that the maximum load was not affected by the fiber content, and in contrast the maximum load was affected by the

width of the initial cracks and the amount of the rebar corrosion.

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