論文 Corrosion of Steel Bars in 15-year Old Pre-cracked Specimens Made with Ordinary Poltland, Slag and Fly Ash Cements

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ABSTRACT: A detailed investigation on the 15 years old precracked concrete specimens made with ordinary portland, slag (Type A, B and C) and fly ash (Type B) cements exposed in the tidal environment was carried out. Based on the results of this investigation, the chloride ingress as well as the degree of corrosion of steel bars in concrete is sequenced as OPC>FACB>SCA>SCB>SCC for narrow cracks (≦0.5 mm). Narrow cracks heal irrespective of the cement types. Wide cracks are not healed and caused the formation of bottle-neck due to the severe corrosion around the perimeter of the bar. The presence of voids at the steel-concrete interface causes the formation of corrosion pits at the uncracked regions as well.
KEYWORDS: chloride ingress, corrosion, precracked concrete, fly ash cement, crack healing, ordinary portland cement, slag cement, tidal environment.

1. INTRODUCTION

Utilization of blended cements in concrete is realized for making more durable concrete structures, reducing the disposal problem of the by-product of steel making industries and thermal power plants, and also indirectly reducing carbon dioxide emission to the global atmosphere. A lot of studies were performed in accelerated laboratory environments and also in natural environments in order to verify the performance of concrete made with blended cements. However, studies on the long-term performance of concrete made with blended cements are still necessary and will be very useful to the concrete professionals.

With this background, chloride ingress, crack healing and corrosion of steel bars in precracked concrete made with ordinary portland cement, slag cement (Type A, B and C) and fly ash cement (Type B) were investigated utilizing precracked concrete prism specimens of size $10 \times 10 \times 60$ cm which were exposed in a tidal pool for 15 years. Fifteen years old uncracked cylinder specimens made with the cements of this study were also investigated to check the change in compressive strength, chloride ingress and corrosion of steel bars in concretes made with the cements investigated here. The results were reported elsewhere [1].

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2. SCOPE

Precracked prism specimens of size 10×10×60 cm were investigated. The specimens were made with different types of cement, such as ordinary portland cement (denoted as OPC), slag cement of Type A, B and C (denoted as SCA, SCB and SCC) and fly ash cement of Type B (denoted as FACB). Water-to-cement ratio was 0.45. Using these variables, reinforced concrete specimens of the five cases were investigated. The specimens were exposed continuously in the tidal zone of a tidal pool after 28 days of curing for a period of 15 years.

3. MATERIALS AND MIXTURE PROPORTIONS

Ordinary portland cement (OPC), slag cement of Type A, B and C (SCA, SCB and SCC) and fly ash cement of Type B (FACB) were used in this investigation. The definitions of the blended cements and their specified physical and chemical compositions can be obtained from JIS R5211-1992 and JIS R5213-1992. Crushed river gravels and sand were used as coarse and fine aggregates respectively. Specific gravity, absorption and fineness modulus of coarse aggregate were 2.76, 1.10% and 6.66 respectively, and 2.64, 1.02% and 2.89 for the fine aggregate. Japanese Industrial Standard (JIS) steel bar (JIS SR 24) of diameter 9 mm was used. The yield strength of the steel bar was 230 MPa.

Mixture proportions of concrete are listed in **Table 1**. Water-to-cement ratio was 0.45. The slump of the fresh concrete was fixed at 8±1 cm and air content at 4±1 %. Both air entraining and air entraining water reducing admixtures were used based on the cement weight. Mixing water was tap water.

Table 1 Mixture Proportions of Concrete

	G max mm	Slump cm	Air %	W/C %	s/a %	W kg/m^3	C kg/m^3	S kg/m^3	G kg/m^3	AEWRA kg/m^3	AEA mL/m^3
OPC	20	8±1	4±1	45	41	162	360	738	1110	3.60	360
SCA	20	8±1	4±1	45	42	160	356	756	1091	3.56	356
SCB	20	8±1	4±1	45	41	160	355	736	1108	3.55	355
SCC	20	8±1	4±1	45	41	162	360	714	1120	3.60	360
FACB	20	8±1	4±1	45	41	160	356	733	1103	3.56	356

W = Water, C = Cement, S = Sand, G = Gravel, s/a = sand to aggregate ratio, AEWRA = Air Entraining Water Reducing Admixture, AEA = Air Entraining Admixture.

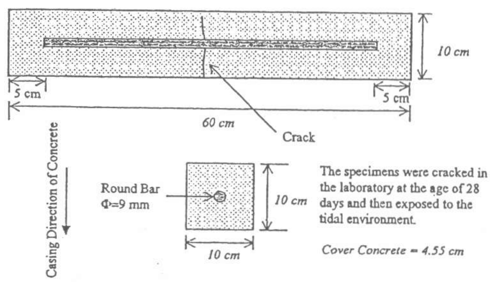


Fig. 1 Details of the Specimen

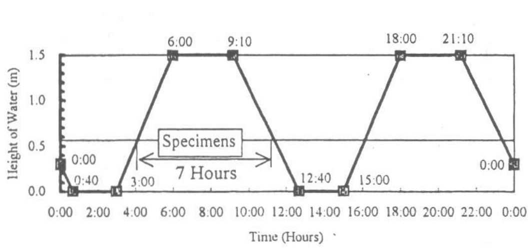


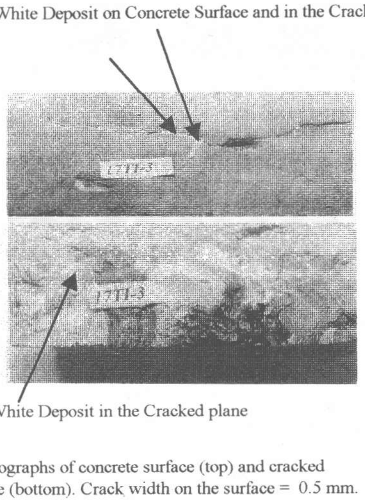
Fig. 2 Variation of the Water Level in the Tidal Pool with Time

4. SPECIMENS AND TESTING METHODS

The details of the specimens are shown in **Fig. 1**. The size of the specimens was 10×10×60 cm. In each specimen, a round steel bar of diameter 9 mm and length 50 cm was embedded at a cover depth of 4.55 cm, i.e., at the center of the specimen. After 28 days of standard curing, the specimens were cracked with a specified crack width in the laboratory by bending. Then the specimens were exposed in the tidal zone of a tidal pool as shown in **Fig. 2**. Seawater was automatically pumped into and drained out. The specimens were subjected to a cycle of 7 hours wetting and 5 hours air drying. The pH of the seawater was 7.7.

Carbonation depth of the specimens was evaluated after spraying 1% phenolphthalein solution on freshly cut surfaces. Water soluble chloride concentrations were measured around the steel bars at cracked and uncracked regions. To measure chloride concentration at cracked region, a strip of 5-cm was cut across the specimen keeping the crack at the middle of the strip. After that it was cut again to remove the portions of concrete 5 mm from the steel bar. Concrete samples surrounding the steel bar were collected and broken in pieces by a hammer to remove the parts of the coarse aggregates. The mortar samples were milled and the water soluble chloride concentrations were measured as per JCI SC4. After cutting, the steel-concrete interfaces were also checked with an optical microscope. Similarly, samples were also taken far from the crack to measure the chloride concentrations around the steel bars at the uncracked regions (in between 10~15 cm from the end of the specimen). All segments of the specimen were broken open and the steel bar was removed. Steel bars were immersed in 10% diammonium hydrogen citrate solution for 24 hours and then cleaned by a steel wire brush. Pit depths were measured with a needle marked with different depths. The depths of the pit less than 0.5 mm were not counted. During this investigation, it was found that narrow cracks were healed. Therefore, EPMA (Electron Probe Micro Analyzer) analysis was carried out to detect the possible chemical composition of the deposit in the crack. SEM (Scanning Electron Microscope) micrographs were also taken to see the surface morphology of the deposit. Electrochemical evaluations (polarization resistance, concrete resistance, half-cell potential and polarization curves) of corrosion of steel bars in concrete were also carried out. Moreover, the distribution of corroded area over the steel bars were measured. These data were not reported here due to the limited space.

White Deposit on Concrete Surface and in the Crack



White Deposit in the Cracked plane

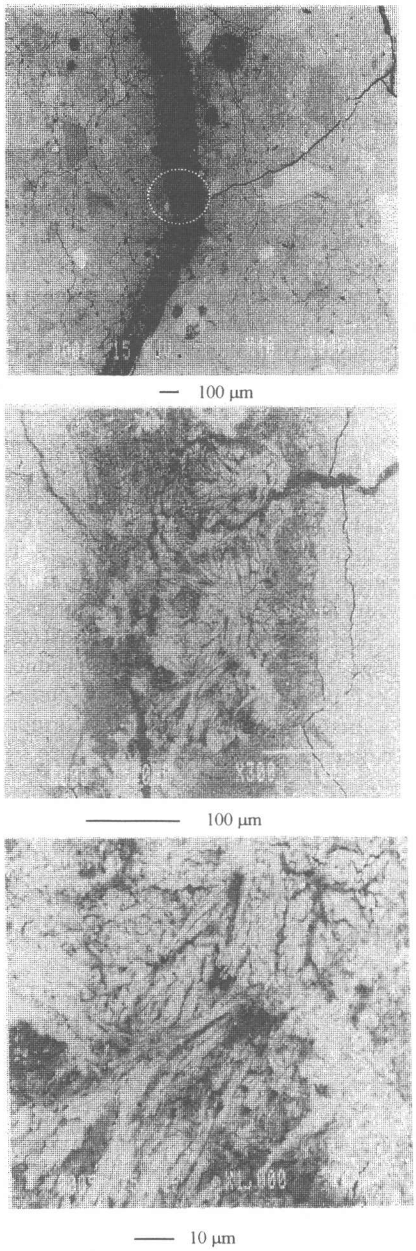
Photographs of concrete surface (top) and cracked plane (bottom). Crack width on the surface = 0.5 mm.

Fig. 3 Photographs of Healed Crack (FACB)

Table 2 Water Soluble Chloride Concentrations in Concrete

Specimen	Crack Widths (mm) and Water Soluble Chloride Concentrations (wt. % of C) *		
	1	2	3
OPC	0.2 (1.28) ((1.27))	0.1 (1.14) ((0.64))	0.1 (1.38) ((1.41))
SCA	0.1 (0.33) ((0.17))	0.3 (0.78) ((0.23))	0.2 (0.49) ((0.43))
SCB	0.3 (0.45) ((0.31))	0.1 (0.41) ((0.28))	5 (3.2) ((0.16))
SCC	1.5 (1.67) ((0.19))	0.1 (0.37) ((0.23))	2 (1.84) ((0.69))
FACB	0.1 (0.9) ((0.67))	0.3 (0.82) ((0.29))	0.5 (1.42) ((0.27))

*The figures in (.) and ((.)) indicate chloride ion concentrations at cracked and uncracked regions respectively. The figures without bracket indicate crack widths in mm.



Crack width on the surface = 0.1 mm. Sliced plane is located at 1.3 cm from the surface

Fig. 4 SEM Micrographs of Concrete Surface Cutting Across the Crack (SCB)

Table 3 Crack Widths, Pit Depths and Number of Pits

Specimen	Crack Widths (mm) and Maximum Pit Depths at Cracked and Uncracked Regions (mm) *		
	1	2	3
OPC	0.2 (0.5) ((1.0))<7>	0.1 (0) ((0.5)) <5>	0.1 (0.5) ((1.5)) <8>
SCA	0.1 (0) ((0)) <0>	0.3 (0.5) ((1.0)) <7>	0.2 (0) ((0)) <7>
SCB	0.3 (0.5) ((0)) <2>	0.1 (0) ((0)) <0>	5 (3.5**) ((0)) <3>
SCC	1.5 (1**) ((0)) <1>	0.1 (0) ((0)) <0>	2 (0.5**) ((0)) <1>
FACB	0.1 (0.5) ((0.5)) <4>	0.3 (1.0) ((0.5)) <4>	0.5 (1.5) ((0.5)) <4>

*The figures in (.), ((.)) and <.> indicate pit depths at cracked and uncracked regions and total pit numbers respectively. Pit depths <0.5 mm were only counted. The figures without bracket indicate crack widths. **Bottle-neck formed due to the corrosion around the perimeter of the bar.

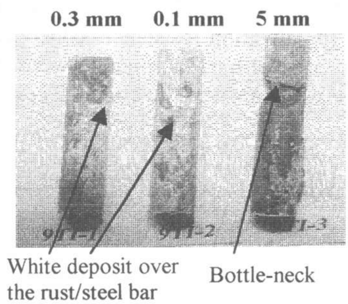


Fig. 5 Steel Segments at the Cracked Regions (SCB)

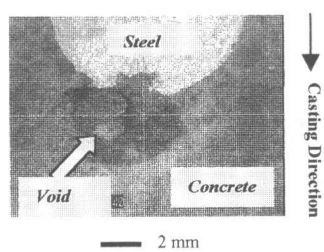


Fig. 6 Corrosion Pit due to the Void at the Steel-Concrete Interface (OPC)

5. EXPERIMENTAL RESULTS AND DISCUSSION

5.1 CHLORIDE CONCENTRATIONS AND CARBONATION DEPTHS

Water soluble chloride concentrations at the cracked and uncracked regions are listed in **Table 2**. Relatively less chloride concentration is observed at the uncracked region. In the case of wide cracks (>0.5 mm), significant amount of chloride concentration is observed at the cracked region. For narrow cracks (≦0.5 mm), slag cements, especially SCC shows the best performance against the chloride ingress in concrete. Based on these results, chloride ingress in concretes is sequenced as OPC>FACB>SCA>SCB>SCC. Same conclusion was also drawn in another study on 15 years old uncracked cylinder specimens made with OPC, SCA, SCB, SCC and FACB [1]. Carbonation depths of the specimens were almost nil irrespective of the cement types, therefore it could not be compared with the variation of cement types investigated here.

5.2 HEALING OF THE CRACK

Narrow cracks (≦0.5 mm) were healed by autogeneous healing. **Figure 3** shows a case of crack healing. White deposit is clearly observed in the crack plane and also it extended to the surface of concrete. In a detail study of crack healing, it was concluded that the deposition of calcite ($CaCO_3$) is the sole reason of crack healing due to the reaction of calcium ion of concrete with the carbonate and bicarbonate ions of seawater depending on the pH value of seawater as below [2]:

$$Ca^{++} + CO_3^{--} \Leftrightarrow CaCO3 \text{ (pH of water >8)}$$

$$Ca^{++} + HCO_3^{-} \Leftrightarrow CaCO3 + H^{+} \text{ (7.5<pH of water<8)}$$

EPMA analysis of concrete samples at the cracked regions was carried out to determine the chemical composition of the deposit. It was confirmed that the deposit composed of calcite, brucite and ettringite. SEM micrographs across the cracked region are shown in **Fig. 4**. The needle-shaped ettringite ($3CaO.Al_2O_3.3CaSO_4.32H_2O$) is mixed with other deposits, which are expected to be calcite and brucite. The progress of healing with the variation of the cement types cannot be judged from this investigation. However, in Reference 2, based on the detail investigation on crack healing process, it was concluded that the type of cements has no influence on the progress of autogenous healing [2]. In this study, it was also found that the narrow cracks were healed irrespective of the cement types. Therefore, for the same crack widths, the progress of healing is assumed to be the same irrespective of the cement types, such as OPC, SCA, SCB, SCC and FACB.

5.3 CORROSION OF STEEL BARS –PHYSICAL EVALUATIONS

Crack widths, maximum pit depths and number of pits are listed in **Table 3**. For narrow cracks, maximum corroded depth was not necessarily observed at the cracked regions. Narrow cracks were healed during the exposure period as explained in the previous section. In **Fig. 5**, deposit is also observed over the debonded area of the steel bars near the crack. Therefore, corrosion process is assumed to stop or reduce significantly after a certain period of exposure. At the uncracked regions deeper pits were formed due to the presence of voids at the steel-concrete interface, especially for OPC and FACB. A typical case is shown in **Fig. 6**. Shallow pits (<0.5 mm) were also observed for slag cements but not noted in **Table 3**. This was observed even in the specimens with the chloride concentration (water-soluble) less than the chloride threshold value defined as 0.4% of cement mass [3]. The same kind of observation was also reported in other studies [4,5]. Pit numbers in the case of slag cements, especially SCC was the lowest. For narrow cracks, the degree of corrosion of steel bars in concrete is sequenced as OPC>FACB>SCA>SCB>SCC as in chloride ingress in concrete.

For wide cracks, significant amount of corrosion around the perimeter caused the formation of bottle-neck (**Table 3 and Fig. 5**). Unfortunately, due to the limited number of the specimens with wide cracks, the performance of the cements investigated here cannot be compared. Further investigations are still necessary on this matter. Deep localized corrosion is suspected for blended cements. It is clearly understood that to enhance durability of concrete structures in the marine environment, crack widths should be narrow to allow possible healing.

6. CONCLUSIONS

The following conclusions are drawn based on the scope of this investigation:

1. For narrow cracks (crack widths ≦ 0.5 mm), corrosion of steel bars as well as chloride ingress in concrete is sequenced as OPC>FACB>SCA>SCB>SCC.
2. Narrow cracks heal irrespective of the cement types.
3. Wide cracks are not healed and significant corrosion of steel bars around its perimeter causes the formation of bottle-neck.
4. The presence of voids at the steel-concrete interface causes the formation of corrosion pits at the uncracked regions as well.

ACKNOWLEDGEMENT

The authors wish to express their gratitude and sincere appreciation to the authority of *Port and Airport Research Institute, Independent Administrative Institution, Japan* for giving support to perform this study. Sincere thanks and appreciations are also due to the previous members of the *Materials Laboratory, Port and Airport Research Institute* for planning this precious experimental plan before 15 years.

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