Pergamon

Cement and Concrete Research 31 (2001) 835–838

CEMENT AND CONCRETE RESEARCH

Discussion

A discussion of the paper "Chloride threshold values to depassivate reinforcing bars embedded in a standardized OPC mortar" by C. Alonso, C. Andrade, M. Castellote, and P. Castro☆

T.U. Mohammed*, H. Hamada

Materials Laboratory, Port and Airport Research Institute, Independent Administrative Institution, 3-1-1 Nagase, Yokosuka Shi 239-0826, Japan

Received 7 December 2000

The authors of this paper deserve to be congratulated for their paper on chloride threshold value to depassivate reinforcing bars in mortar specimens. The authors very nicely explained the chloride threshold values in terms of free chloride, total chloride and Cl^-/OH^- ratio. A paper defining chloride threshold values in terms of these terms will be no doubt essential for the concrete professions. However, based on the experiences on corrosion of steel bars in concrete, some observations are noted that are necessary to be considered in the definition of chloride threshold values.

1. Corrosion of steel bars with respect to orientation in concrete

Steel–concrete interfaces are generally varied with respect to the orientation of steel bars against the casting direction of concrete. For the steel bars oriented perpendicular to the casting direction, gaps under the steel bars may form due to the plastic settlement as well as bleeding of water after casting concrete. In such a situation, a very small amount of chloride may cause the initiation of corrosion of steel bars in concrete. With the presence of this situation, the definition of chloride threshold value seems to be contradictory. A detailed study on the corrosion of steel bars in concrete based on their orientation was carried out [1]. It was concluded that the presence of gaps under the steel bars as shown in Fig. 1 led to the formation of an active area that was subjected to significant macrocell and microcell corrosions. In this investigation, 10 kg/m^3 sodium chloride (cement content = 330 kg/m^3 for W/C = 0.5) was added with mixing water. The conditions of the steel bars at the age of 60 days are shown in Fig. 2. The details on the specimens can be obtained from Ref. [1]. From Fig. 2, clear observation of chloride ion-induced corrosion based on the orientation of steel bars can be obtained. Further investigations were also carried out on the specimens exposed to the marine environments for a period of 23 years. The observations of these studies were also reported elsewhere [2]. Significant amount of corrosion under the steel bars oriented perpendicular to the casting direction was found (water-soluble chloride ion concentrations was about 1% of cement). The steel bars oriented along the casting direction (vertical legs of the stirrups) were not corroded even though the water-soluble chloride ion concentrations were about 2% of cement.

The occurrence of corrosion at the locations where the steel–concrete interfaces were damaged by the presence of void or cracking was also reported by another group of researchers recently [3]. In this investigation, it was concluded that steel–concrete interface has a major influence on the prediction of the onset of corrosion in relation to the chloride content. It was also mentioned that the chloride threshold value cannot be considered as a sufficient and single criterion to forecast the corrosion development. The nature of the steel–concrete interface was emphasized with regard to chloride ion-induced corrosion of steel bars in concrete.

Further investigation on the corrosion of steel bars oriented along the casting direction in concrete was also carried out utilizing 10-year-old concrete specimens made with different types of cement as noted later. The detailed result was submitted for publication and will be presented in the 7th CANMET/ACI International Conference on Fly Ash, Silica Fume and Natural Pozzolans in Concrete, Chennai, India, 2001 [4]. It was found that deeply localized corrosion occurred when there was a void at the steel–concrete interface as shown in Figs. 3 and 4. In these cases, the steel bars were oriented along the casting direction of concrete. In addition, it was also observed that for concrete

☆ Cem Concr Res 30 (2000) 1047–1055.

* Corresponding author. Tel.: +81-468-44-5061; fax: +81-468-44-0255.

E-mail address: tarek@cc.phri.go.jp (T.U. Mohammed).

PII: S0008-8846(01)00485-9

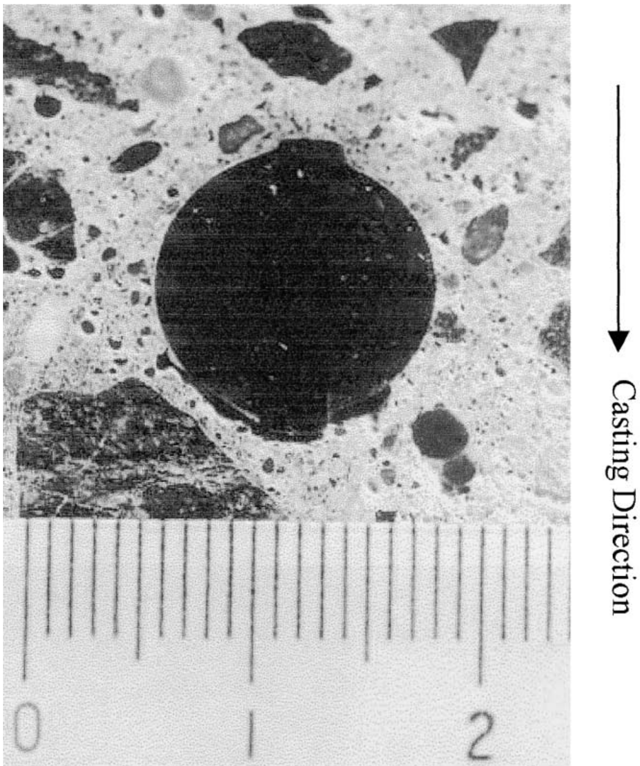

Fig. 1. Gaps under the steel bar.

made with slag cements with high slag contents (60–70%), corroded areas were only concentrated to the voids at the steel–concrete interface. The chloride level and the corroded area of the steel bars are shown in Fig. 5. Here, OPC means ordinary portland cement, SCA means slag cement of type A (slag contents 5–30%), SCB means slag cement of Type B (slag content 30–60%), SCC means slag cement of type C (slag content 60–70%), and FACB means fly ash cement of type B (fly ash content < 10%). These cements are specified in the specifications of JSCE [5]. It was found that for a water–soluble chloride concentration less than 0.5% of cement weight, the corroded area was negligible. Based on these results, it was concluded that a chloride level of 0.4% may be considered as chloride threshold value as with other studies [8]. However, more investigation on chloride threshold limit was suggested considering the above-mentioned points.

The casting direction of the specimens of this paper is not clear based on Fig. 1. The possibilities of the above-mentioned factors were also not considered. The size of the specimens was 8 × 5.5 × 2 cm. For this, the effect of bleeding and differential settlement will be low. However, the presence of voids at the steel–concrete interface could not be completely neglected and seems to be very important to consider in the definition of chloride threshold values. Regarding this matter, the authors also did not mention any comments. From Fig. 1 of this paper, many voids on the surface of the specimens were found. Also the steel bars were located at only 0.5 cm from the surface. Generally, voids are expected to be more near the concrete cover.

2. Corrosion of ribbed and smooth bars

In this paper, it was also reported that mean corrosion current density for the ribbed bar was slightly higher than for the smooth bar. The reason is not clearly mentioned in

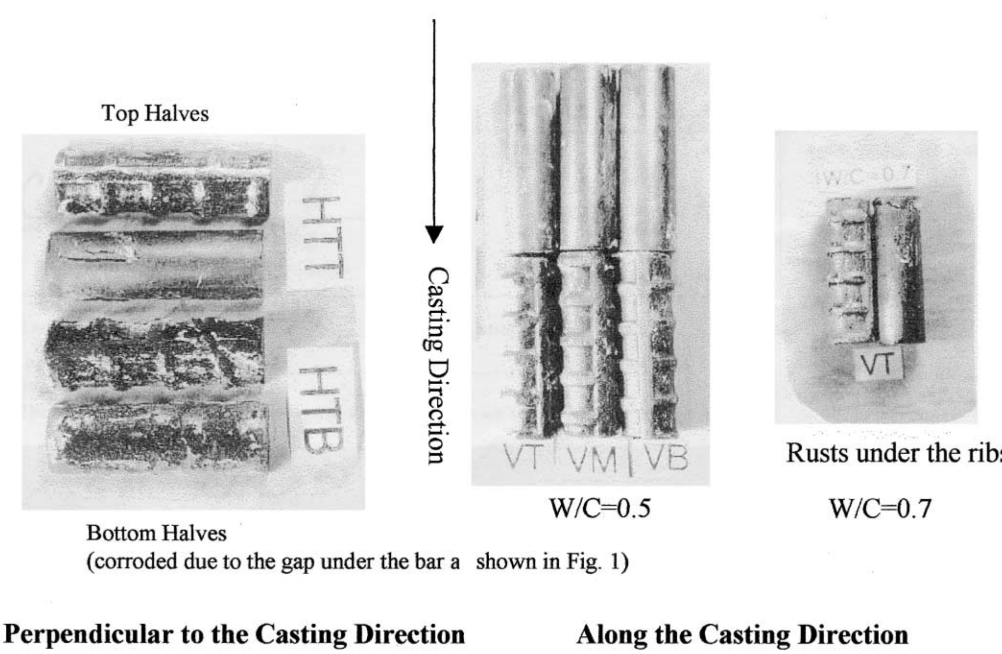

Fig. 2. Rusts on the steel elements.

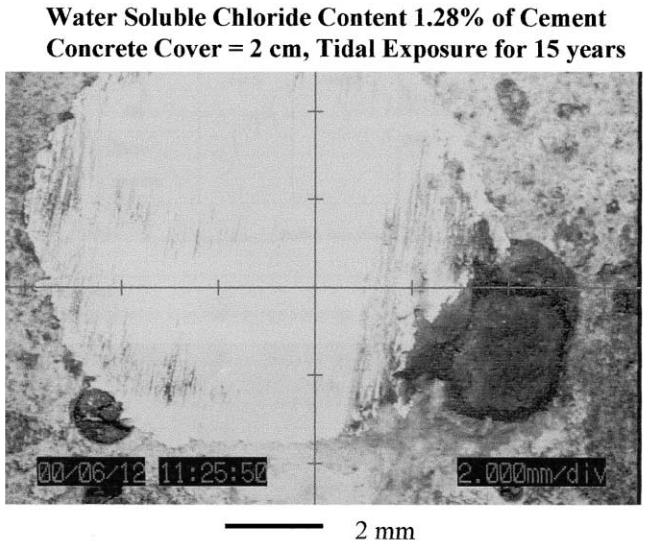

Fig. 3. Rust in voids located at steel–concrete interface.

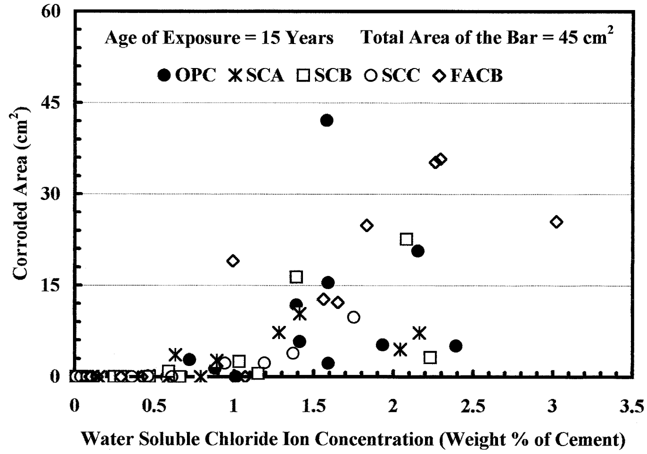

Fig. 5. Corroded area and water soluble chloride ion concentrations.

the paper. It seems to be that for ribbed bar, the possibilities of the formation of gap under the ribs is higher even for casting direction along the steel bar. Observations of rust can be noted under the ribs of the deformed bar for W/C = 0.7 (Fig. 2), even though the casting direction is along the steel bars. It is worth mentioning that corrosion of plain (smooth) and deformed bars (ribbed) in uncracked concrete was also compared and found that deformed bar corroded more than the plain bar [1]. In addition, a study on corrosion of plain and deformed steel bars in cracked concrete was also carried out and concluded that deformed bar is more prone to corrosion than plain bar [6].

3. Consideration of active corrosion current density as 0.1 μA/cm²

The consideration of active corrosion for a corrosion current density of 0.1 μA/cm² seems to be very conservative. With this current density, if the authors exposed the specimens for 1 year, a depth of only about 1/100

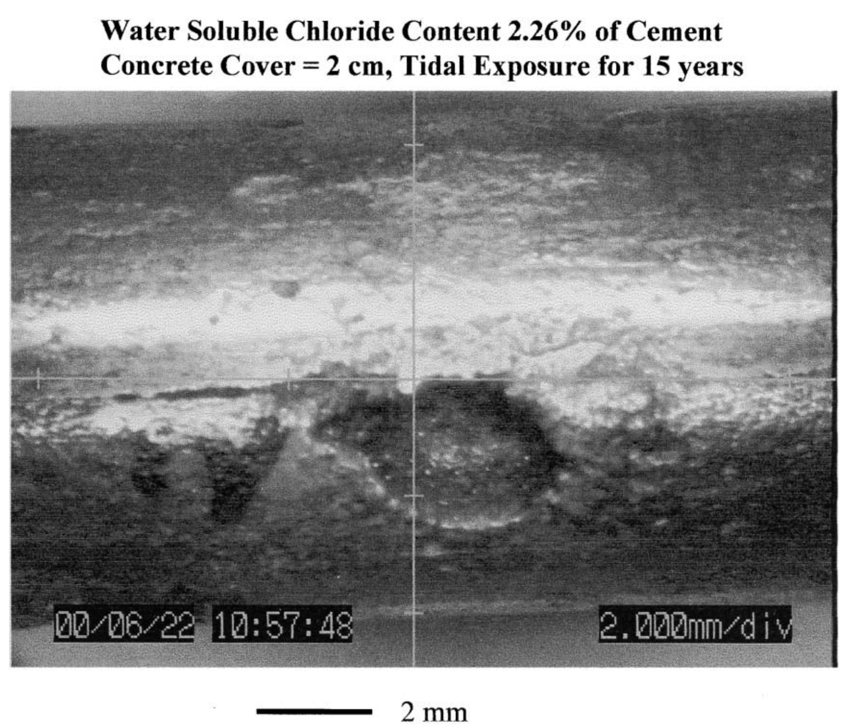

Fig. 4. Deep localized corrosion due to the void at steel–concrete interface.

mm can be expected based on the following equation [7] and considering a pit concentration factor as 8.

$$d = 0.0115 I_{av} t \alpha.$$

Here, d is the depth of corrosion in mm, I_{av} is the average current density in $\mu A/cm^2$, t is the time in year, and α is the pit concentration factor (generally varies from 4 to 8).

4. Consideration of only microcell corrosion to define chloride threshold limit

In this paper, the authors did not consider the macrocell corrosion of steel bars in concrete. As the chloride ion-induced corrosion is very localized, therefore, the consideration of macrocell corrosion together with the microcell corrosion is necessary to evaluate the magnitude of corrosion.

Further studies based on the above-mentioned points are still necessary in order to define the chloride threshold limit. At this stage, it seems that the definition of chloride threshold value will be more meaningful if it is defined as "Chloride threshold value is a level of chloride ion concentration that caused the initiation of active corrosion of steel bars in concrete, provided that there are no voids/damage at the steel–concrete interface." In this case, the decision-maker will be aware about his limitation during the application of chloride threshold limit in the evaluation of the initiation of corrosion or the prediction of service life of the structures. It is necessary to note that the study on the removal of voids at the steel–concrete interface will be very useful in order to ensure the long-term durability of concrete structures in marine environments. Of course, this was beyond of the scope of this paper.

Again, the contribution of the authors of this paper in the field of concrete technology is highly appreciated.

References

[1] T.U. Mohammed, N. Otsuki, M. Hisada, Corrosion of steel bars with respect to orientation in concrete, ACI Mater. J. 96 (2) (1999) 154–159.

[2] T.U. Mohammed, N. Otsuki, M. Hisada, H. Hamada, Marine durability of 23-year old reinforced concrete beams, CANMET/ACI International Conference on Durability of Concrete, Am. Concr. Inst., SP, vol. 192-65, 2000, pp. 1071–1088.

[3] A. Castel, R. Francois, G. Arliguie, Factors other than chloride level influencing corrosion rate of reinforcement, CANMET/ACI Internationals Conference on Durability of Concrete, Am. Concr. Inst., SP, vol. 192-38, 2000, pp. 629–644.

[4] T.U. Mohammed, T. Yamaji, T. Aoyama, H. Hamada, Marine durability of 15-year old concrete specimens made with ordinary portland, slag and fly ash cements, CANMET/ACI International Conference on Fly Ash, Silica Fume and Natural Pozzolans in Concrete, Chennai, India, July 22–27, 2001, (accepted for publication).

[5] Standard Specification for Design and Construction of Concrete Structures, Japan Society of Civil Engineers, Part 2 (Construction) SP-2 First Edition, 1986.

[6] T.U. Mohammed, N. Otsuki, M. Hisada, T. Shibata, Effect of crack width and bar types on corrosion of steel in concrete, ASCE Mater. J., in press.

[7] J.A. Gonzalez, C. Andrade, C. Alonso, S. Feliu, Comparison of rates of general corrosion and maximum pitting penetration on concrete-embedded steel reinforcement, Cem. Concr. Res. 25 (2) (1995) 257–264.

[8] R.D. Brown, Mechanism of corrosion of steel in concrete in relation to design, inspection and repair of offshore and coastal structures, Performance of Concrete in Marine Environment, Am. Concr. Inst., SP, vol. 65, (1980) 169–204.