

Corrosion Propagation Behavior of low-Cr steel Rebars in Simulated Concrete Environments

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Corrosion propagation behavior of HRB400 carbon steel and three low-Cr steel rebars in alkaline solution simulating concrete pore solution were studied using potentiostatic /galvanostatic polarization, and wire beam electrode (WBE) measurement. Results show that the radial corrosion process of the steels are controlled by ohm resistance and the propagation time can be calculated by $r = kt^{1/3}$. The corrosion propagation process of the steels are inhibited when the electrode potential is below $-0.6V$ (vs. SCE). The corrosion areas of HRB400 steel is widespread and Cr-modified steels are relatively limited, Cr-modified steels have higher pitting corrosion factors. With the increasing of Cr content, the pitting corrosion factor of the steel increases, and the corresponding localized corrosion anode length decreases. 5Cr steel has the longest corrosion propagation time which is about 16.7 years, 3Cr steel is 10.3 years, 1.5Cr steel is 5.4 years, and HRB400 steel is only 3.6 years. Using Cr-modified steels can prolong the corrosion propagation period of concrete structures, and 5Cr steel shows the best.

Keywords: low-Cr steel; Polarization; WBE; Pitting; Service life

1. INTRODUCTION

Durability design of concrete under harsh conditions such as marine environment and deicing salt has always been a concern for concrete material and structure experts [1–5]. The diffusion of Cl^- is the only theory established so far which links the concrete index with its service life and it is also the foundation to design the durability of concrete structures. In order to quantitatively characterize the

diffusion behavior of Cl^- in concrete and to predict the service life, various mathematical models had been proposed based on the Cl^- diffusion theory [6–9]. The service life is generally divided into two main stages [10,11]: initiation period, which refers to the time required for Cl^- to reach the chloride threshold values; propagation period, which refers to the time for the initiation corrosion of the steel to the cracking of the concrete.

The volume of corrosion products is generally 2–6 times than steel itself [12,13], and the expansion of rust makes the concrete subject to a tensile stress. With the development of corrosion process, the concrete will crack when the stress reaches the tensile strength. After cracking, corrosive media will faster reach to the steel surface, which accelerates the failure process. A series of propagation models have been proposed [14–17], however, those models have their own practicability. The ‘life-365’ concrete durability prediction software has defined the propagation period of carbon steel and stainless steels are all for 6 years [18]. However, Hurley et al. [19] found that 316L stainless steel will be re-passivated in very corrosive neutral solution containing 2M Cl^- , using stainless steel can prolong the propagation period of concrete structures.

In our previous work [20,21], the chloride threshold values of low-Cr steels in simulated concrete pore solution were studied as a function of temperature, and the corrosion initiation period were predicted, using 5Cr steel can significantly prolong the initiation period of concrete structure in harsh marine environment. However, there are few studies on the corrosion propagation behavior of low-Cr steels in harsh environment. In order to supplement our previous work, we aim in this study to investigate the corrosion propagation behavior of HRB400 carbon steel (CS) and Cr-modified steels in simulated concrete pore solution. Potentiostatic/galvanostatic polarization, wire beam electrode (WBE) measurement were employed to quantify the corrosion propagation behavior of low-Cr steels in simulated concrete environments and the propagation period were also predicted. The findings are expected to offer guidance for the development and manufacture of low-Cr steel rebars.

2. EXPERIMENTAL

2.1. Materials and solution

Table 1. Chemical compositions (wt.%) of CS and Cr-modified steels.

Steel	C	Si	Mn	P	S	Cr	Fe
CS	0.196	0.57	1.57	0.024	0.017	0.08	residual
1.5Cr steel	0.171	0.66	1.30	0.014	0.008	1.50	residual
3Cr steel	0.184	0.65	1.23	0.007	0.012	3.02	residual
5Cr steel	0.157	0.45	1.57	0.010	0.004	5.06	residual

HRB400 carbon steel (CS) and three Cr-modified steel rebars were tested [20]. The chemical composition of the steels are shown in Table 1. Saturated $\text{Ca}(\text{OH})_2$ was used to simulate the concrete pore solution, and NaCl were added to simulate the concrete pore solution with Cl^- , the criterion of Cl^-

were close or equal to the chloride threshold values as shown in Table 2, which were based on our previous work [20,21]. All chemicals were of analytical grade and mixed with deionized water.

Table 2. Solution of the tested CS and Cr–modified steels.

Steel	Test environment
CS	Saturated $\text{Ca}(\text{OH})_2$ + 1 wt.% NaCl
1.5Cr steel	Saturated $\text{Ca}(\text{OH})_2$ + 2 wt.% NaCl
3Cr steel	Saturated $\text{Ca}(\text{OH})_2$ + 3 wt.% NaCl
5Cr steel	Saturated $\text{Ca}(\text{OH})_2$ + 5 wt.% NaCl

2.2. Corrosion test

Samples for radial corrosion tests all had dimensions of $\Phi 0.8 \text{ mm} \times 10 \text{ mm}$. Cylindrical specimens with diameter of 0.8 mm. For each test sample, the exposed area was 0.5 mm^2 , which was retained by epoxy resin. Prior to the experiment, the samples were polished with silicon carbide water polishing papers down to 2000 #. Then, the samples were ultrasonically cleaned in acetone and rinsed in distilled water.

The potentiostatic polarization was carried out on the PARSTAT 2273 electrochemical workstation, the electrolytic cell was 1 L glass electrolysis cell. Three electrodes were used in the electrochemical measurement, with the steel as the working electrode, the platinum electrode as the counter electrode, the saturated calomel electrode (SCE) as the reference electrode.

Anodic potentiostatic polarization was used to accelerate the corrosion process. Firstly, the samples were potentiostatic polarized at +0.5 V (vs.SCE) for 3600 s to form an activated corrosion state, then the polarization potential reduced to +0.2 V(vs.SCE), the polarization potential gradually decreased by 50 mV (vs.SCE) until the polarization potential was -0.65V (vs.SCE), and each polarization time was 1800s.

The experimental device for galvanic corrosion of steels with different cathode areas is shown in Fig. 1, it is composed of two completely separate and well-sealed containers connected by a salt bridge and the samples are connected by a copper wire. A zero resistance galvanometer (ZRA) was used to record the galvanic currents of different anode and cathode area samples. The surface area of the anode electrode is 0.5 mm^2 , polarized for 1 h at +0.5 V (vs.SCE), the galvanic current is recorded by changing the area of the cathode samples, and the area ratios of the cathode to anode are 1000:1, 100:1, 50:1 and 10:1, respectively.

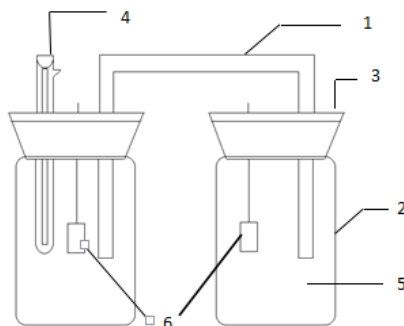


Figure 1. Experimental apparatus for different cathode–anode area ratios (1 is salt bridge, 2 is plexiglass cylinder, 3 is sealant plug, 4 is saturated calomel electrode, 5 is simulated solution steel rebar specimens).

2.3. WBE test

Samples for WBE tests all had dimensions of $\Phi 2.0\text{mm} \times 20.0\text{mm}$, all the samples were welded with copper conductor, inserted into the mould, and the 10×10 matrix were sealed with epoxy resin as shown in Fig. 2. Prior to the experiment, the samples were polished with silicon carbide water polishing papers down to 2000 #. Then, the samples were ultrasonically cleaned in acetone and rinsed in distilled water.

The WBE test was carried out on the CST–520 electrochemical workstation, the electrolytic cell was 3 L glass electrolysis cell, with the WEB specimen as the working electrode, the saturated calomel electrode (SCE) as the reference electrode. All the wire bundles were short connected to each other and connected to the ground, the WBE electrode can be regarded as a complete metal plane when the experiment was not tested; the measured single wire was disconnected from the other electrodes, the coupling current between the single wire and the other 99 wires were measured by a ZRA, the rest 99 wires could be measured by the same way, then the current distribution of the whole electrode can be scanned. The duration of the experiment are 1, 3, 5, 10 days, respectively.

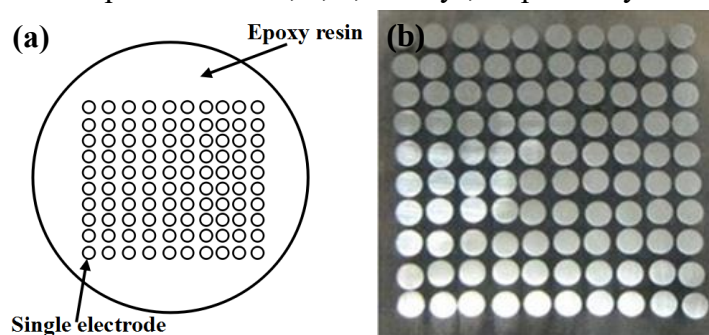


Figure 2. Schematic diagram of WEB CS and 5Cr steel specimen fabrication: (a) schematic diagram, (b) physical map.

2.4. Pitting factor

Galvanostatic accelerated corrosion method was used to evaluate the pitting corrosion resistance

of Cr-modified steels. The size of the sample was $50\text{mm} \times 25\text{mm} \times 3\text{mm}$, the current density of galvanostatic was $1\text{mA}/\text{cm}^2$, the polarization time was 12h, 24h and 48h respectively, and the uniform corrosion rate was calculated by weight loss method. The depth of corrosion pit was evaluated by microscopic method [22].

3. RESULTS AND DISCUSSION

3.1. Radial corrosion

3.1.1. Potentiostatic polarization

The radial corrosion rate of steel rebar can be calculated by Faraday's law, assuming that the volume V of corrosion is hemispherical, V can be calculated by the density of steel [19]:

$$V = \frac{2}{3}\pi r^3 \quad (1)$$

$$\rho = \frac{m}{V} \quad (2)$$

Where V is volume, cm^3 ; R is radius, cm ; ρ is density of steel (g/cm^3) and m is mass. The mass loss during the experiment can be calculated by Faraday's law, Eq. (3). The integral of the current can be calculated by Eq. (4).

$$m = \frac{QE.W.}{F} \quad (3)$$

$$Q = \int I(E_{\text{applied}}, t) dt \quad (4)$$

Where Q is the amount of electricity flowing through the time, t ; ($E.W.$) is the electrochemical equivalent of the steel; F is the Faraday constant (96500 C); $I(E_{\text{applied}}, t)$ is the current intensity (A) of the applied potential; t is the electrified time (s). The quantity of electricity (Q) can be calculated by Eq. (4) and the $I(E_{\text{applied}}, t)$ can be calculated by the relationship between the current $I^*(E_{\text{applied}})$ of each applied potential and the time (t^n) [19].

$$I(E_{\text{applied}}, t) = I^*(E_{\text{applied}})t^n \quad (5)$$

$$Q = \int I(E_{\text{applied}}, t) dt = \frac{I^*(E_{\text{applied}})t^{n+1}}{n+1} \quad (6)$$

The volume of corroded steel can be obtained by combining Eqs. (2), (3) and (6):

$$V = \frac{QE.W.}{(\frac{2}{3}\pi)\rho F} \quad (7)$$

Since the volume of Eq. (1) is equal to that of Eq. (7), the radius r of hemispherical pitting growth can be obtained by Eq. (8).

$$r = \left[\frac{QE.W.}{(\frac{2}{3}\pi)\rho F} \right]^{1/3} = \left[\frac{I^*(E_{\text{applied}})E.W.}{(\frac{2}{3}\pi)\rho F(n+1)} \right]^{1/3} \cdot t^{\frac{n+1}{3}} = kt^{\frac{n+1}{3}} \quad (8)$$

Studies have shown that the growth of single pit of Al alloy and steel are hemispherical [23–25].

The relation between radius r and t can be obtained by Eq. (8). It is assumed that the growth of the active corrosion pit follows the law of power function: $r = kt^{(n+1)/3}$, where r is the pit radius, t is the time, and k is the constant related to the potential. Then k can be calculated by Eq. (8) as long as the relevant parameters of the material are known.

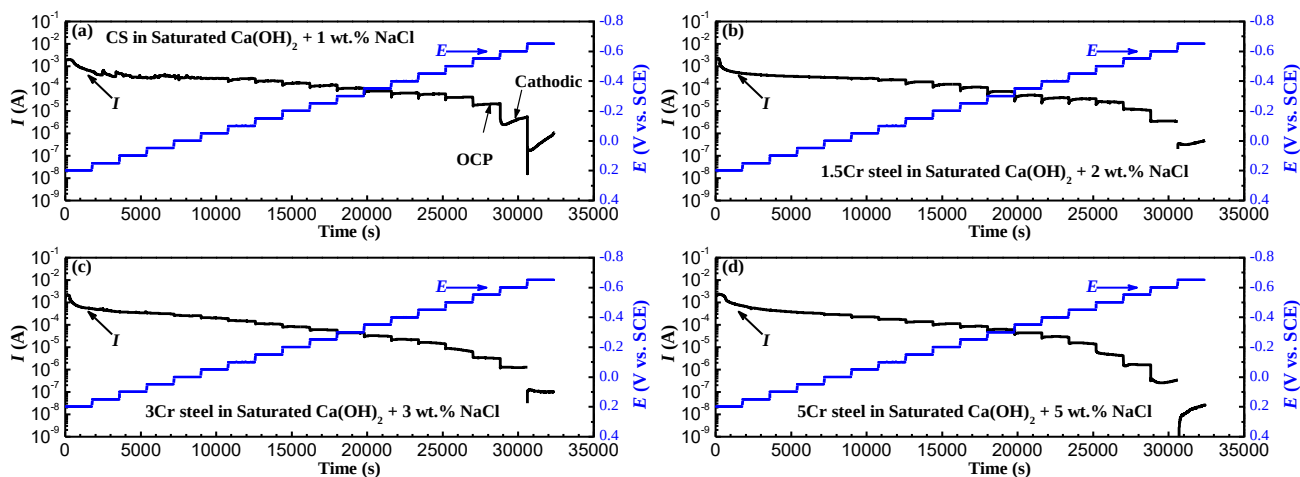


Figure 3. Curves of current (I) and polarization potential (E) versus time (t) of CS and Cr-modified steels: (a) CS in saturated $\text{Ca}(\text{OH})_2$ + 1 wt.% NaCl solution, (b) 1.5Cr steel in saturated $\text{Ca}(\text{OH})_2$ + 2 wt.% NaCl solution, (c) 3Cr steel in saturated $\text{Ca}(\text{OH})_2$ + 3 wt.% NaCl solution, (d) 5Cr steel in saturated $\text{Ca}(\text{OH})_2$ + 5 wt.% NaCl solution.

Fig. 3 shows the curves of current versus time for CS and Cr-modified steel specimens under different potentiostatic polarization. It can be seen that four kinds of steels show active corrosion at all applied potentials, and no re-passivation behaviors could be observed. The potential values of steels reaching open circuit potentials are at about -550 mV (vs.SCE). After reaching more negative potentials, they show cathodic polarization.

Fig. 4 shows the variation of corrosion current with time under different anodic polarization potentials. The corrosion current decreases gradually with the extension of the first applied potential, which indicates that the size of pit changes at the first anodic potential. With the decreasing of applied potential, the current density decreases, but the current is relatively stable during the whole anodic polarization process. Compared by the first anodic potential, the radius of corrosion pit of subsequent potentiostatic polarization is reduced. Therefore, only the steady-state pitting process is considered. After the first potentiostatic polarization, the pitting development is independent with time. The n value of Eq. (5) is 0.

$$I(E_{\text{applied}}, t) = I^*(E_{\text{applied}})t^0 \quad (9)$$

From the above analysis, it can be seen that t has no significant effect on $I(E_{\text{applied}})$, and $I^*(E_{\text{applied}})$ can be calculated by the average current at different anodic potentials. When $n=0$, r in Eq. (8) can be calculated.

$$r = kt^{\frac{1+n}{3}} = kt^{\frac{1}{3}} \quad (10)$$

t has no significant effect on $I(E_{\text{applied}})$, the slope between E_{applied} and $I^*(E_{\text{applied}}, t)$ can be calculated by Ohm's law, which is R_{Ω} [19].

$$E_{\text{applied}} = I^*(E_{\text{applied}}) \times R_{\Omega} \quad (11)$$

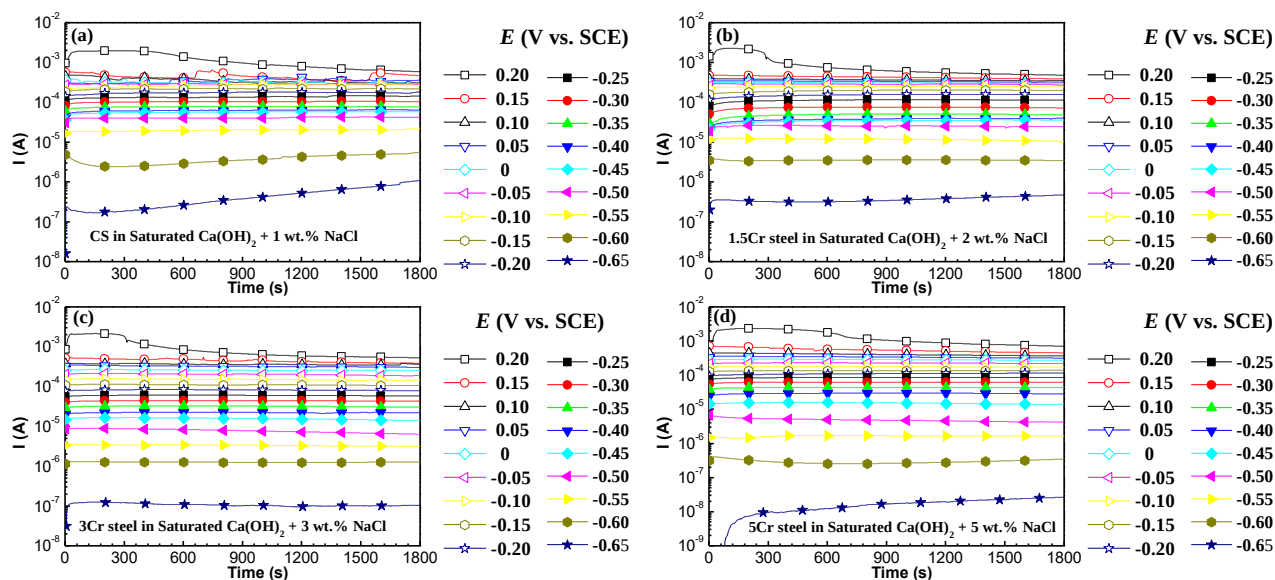


Figure 4. The resultant current at each applied potential on CS and Cr-modified steels, following the first potential step to initiate and propagate corrosion on the anode (exposed anode area $\sim 0.5\text{mm}^2$): (a) CS in saturated $\text{Ca(OH)}_2 + 1$ wt.% NaCl solution, (b) 1.5Cr steel in saturated $\text{Ca(OH)}_2 + 2$ wt.% NaCl solution, (c) 3Cr steel in saturated $\text{Ca(OH)}_2 + 3$ wt.% NaCl solution, (d) 5Cr steel in saturated $\text{Ca(OH)}_2 + 5$ wt.% NaCl solution.

The resistance R_{Ω} of 4 kinds of steels were calculated by linear fitting, as shown in Fig. 5 and Table 3. It can be seen from the fitting results that with the increasing of Cr content, the resistance value R_{Ω} decrease, the R_{Ω} of CS is 4737 Ω , and 5Cr steel has the minimum value, 1081 Ω .

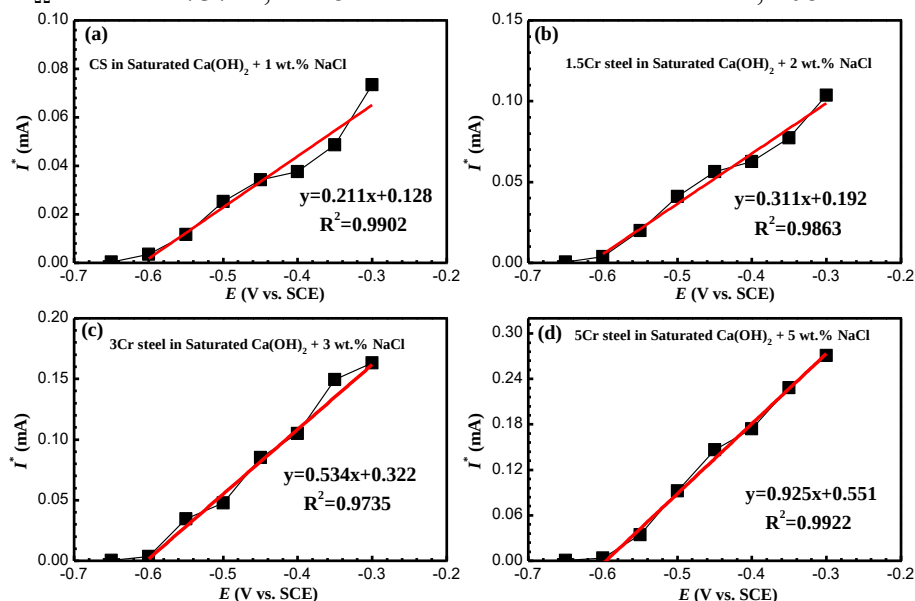
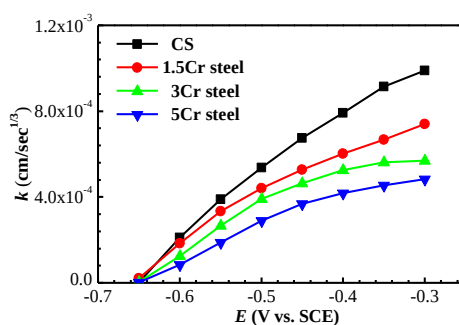


Figure 5. Curves of I^* versus E_{applied} of CS and Cr-modified steels at different polarization potentials: (a) CS in saturated $\text{Ca(OH)}_2 + 1$ wt.% NaCl solution, (b) 1.5Cr steel in saturated $\text{Ca(OH)}_2 + 2$ wt.% NaCl solution, (c) 3Cr steel in saturated $\text{Ca(OH)}_2 + 3$ wt.% NaCl solution, (d) 5Cr steel in saturated $\text{Ca(OH)}_2 + 5$ wt.% NaCl solution.

Table 3. CS and Cr-modified steels R_Ω obtained from the average corrosion current I^* and the polarization potential.

Steel	Test environment	R_Ω (Ω)
CS	Saturated $\text{Ca}(\text{OH})_2$ + 1 wt.% NaCl	4737
1.5Cr steel	Saturated $\text{Ca}(\text{OH})_2$ + 2 wt.% NaCl	3215
3Cr steel	Saturated $\text{Ca}(\text{OH})_2$ + 3 wt.% NaCl	1871
5Cr steel	Saturated $\text{Ca}(\text{OH})_2$ + 5 wt.% NaCl	1081

Studies have confirmed that corrosion pits ultimately developed to be hemispherical shape [26–28]. Assuming that the development of corrosion pit follows the law of $r = kt^{1/3}$, the value of k at the corresponding polarization $I^*(E_{\text{applied}})$ can be calculated by the Eq. (8). Fig. 6 shows the calculated k values of low-Cr steel electrode specimens at variety polarization potentials. With the decreasing of polarization potential, k values decrease, and 5Cr steel has a relative minimum value.

**Figure 6.** The experimentally determined value of $k(E_{\text{applied}})$ plotted versus the potential at which it was determined assuming power law ($r = k(E_{\text{applied}})t^{1/3}$) pit growth behavior from electrochemical radial propagation tests conducted on CS and Cr-modified steels: CS in saturated $\text{Ca}(\text{OH})_2$ + 1 wt.% NaCl solution, 1.5Cr steel in saturated $\text{Ca}(\text{OH})_2$ + 2 wt.% NaCl solution, 3Cr steel in saturated $\text{Ca}(\text{OH})_2$ + 3 wt.% NaCl solution, 5Cr steel in saturated $\text{Ca}(\text{OH})_2$ + 5 wt.% NaCl solution.

3.1.2. Influence of cathode area

The galvanic corrosion result of CS coupling with its different areas as cathode is shown in Fig. 7(a). The galvanic current decreases with the decreasing of the area ratio of cathode to anode and the reaction of anode are affected by the passive cathode area according to Eq. (12) [29]:

$$I_A A_A = I_C A_C \quad (12)$$

Where I_A and I_C are the total anode and cathode current respectively, A_A and A_C are the area of anode and cathode respectively. The cathode area has a great influence on the galvanic current as shown in Eq. (12). It can be seen corrosion rate of anode increases greatly when the area ratio of cathode to anode is 10:1. The galvanic corrosion result of CS coupling with different areas of 5Cr steel as cathode is shown in Fig. 7(b). The results show that the effect of coupling CS to 5Cr steel in different areas ratios are much less than that of coupling with itself, indicating 5Cr steel has no significant effect on accelerating corrosion process of CS.

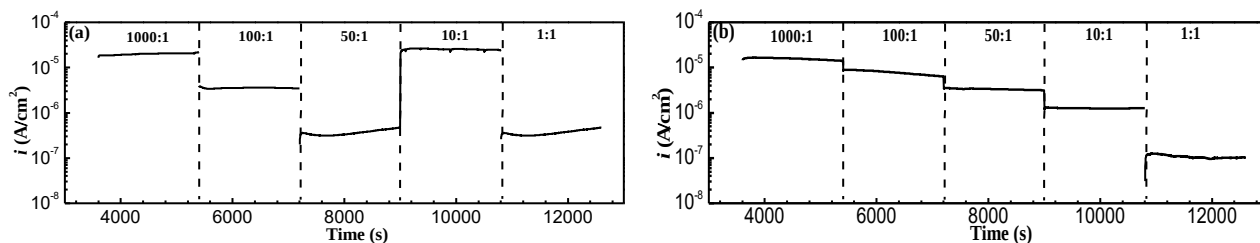


Figure 7. Corrosion current density of CS coupling with CS versus time of different area ratios specimens (a), Corrosion current density of CS coupling with 5Cr steel versus time of different area ratios specimens (b): CS in saturated $\text{Ca}(\text{OH})_2 + 1 \text{ wt.}\% \text{ NaCl}$ solution, 5Cr steel in saturated $\text{Ca}(\text{OH})_2 + 5 \text{ wt.}\% \text{ NaCl}$ solution.

3.1.3. Pitting corrosion development

From the radial corrosion analysis, it can be seen that the Ohm resistance is the main controlling factor affected the development of pitting corrosion. According to Hurley et al. [19], the total impedance value R_Ω can be expressed as follows (Fig. 8):

$$R_\Omega = R_{\text{pit}} + R_{\text{zone}} + R_{\text{bulk}} + R_{\text{cp}} \quad (13)$$

Where R_{pit} is the resistance inside the corrosion pit, R_{bulk} is solution resistance, R_{zone} is the external resistance of corrosion pit, and R_{cp} is the resistance generated by the corrosion product.

Considering the influence of the area on the impedance parameters, and in order to distinguish the influence of each resistance on the total impedance, $\varphi(\Omega \cdot \text{cm})$ and the corresponding shape factor $\lambda(\text{cm}^{-1})$ are defined to distinguish the influence degree of each parameter. The total impedance can be expressed as:

$$R_\Omega = \varphi_{\text{pit}} \cdot \lambda_{\text{pit}} + \varphi_{\text{zone}} \cdot \lambda_{\text{zone}} + \varphi_{\text{bulk}} \cdot \lambda_{\text{bulk}} + \varphi_{\text{cp}} \cdot \lambda_{\text{cp}} \quad (14)$$

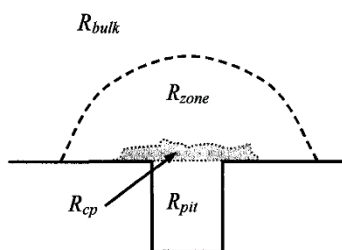


Figure 8. Schematic diagram of ohm resistance of single corrosion pit [19].

In order to simplify the calculation, the following assumptions are made [19,30]: 1) The solution resistance in the pit is stable, about 4.2M metal cations, ($\varphi_{\text{pit}} \sim 1(\Omega \cdot \text{cm})$), $\lambda_{\text{pit}} = L/A$, where L is the external radius of corrosion pit and A is the external area of the corrosion pit. 2) φ_{zone} and φ_{pit} have the same solution composition, φ_{zone} located at the center of the corrosion pit and its radius is 4 times of the φ_{pit} , $\lambda_{\text{zone}} = 1/(4r_{\text{mouth}})$. 3) The solution resistance φ_{bulk} is different, the distance between the working electrode and the reference electrode is $\lambda_{\text{bulk}} = 0.5 \text{ cm}$. 4) There is no diffusion control behavior.

From the above analysis, it can be seen that the whole corrosion process were controlled by the solution resistance R_{bulk} for CS and 1.5Cr steel. For 3Cr and 5Cr steels, the corrosion process exhibited mixed control behavior, meanwhile, R_{bulk} , R_{pit} and R_{zone} were in the same order of magnitude. The ohm impedance has a great relationship with the solution composition.

In general, the development of pitting corrosion controlled by ohm is independent. Each steel has a different R_{Ω} , because the resistivity in the tested environment is different [19]. For example, the CS has the lowest corrosion resistance, the highest resistivity, and the best resistance to radial corrosion. On the contrary, 5Cr steel has highest chloride threshold value, so its resistivity is the lowest and its pitting corrosion resistance is the weakest. Therefore, the $k(E_{\text{applied}})$ in the simulated concrete pore solutions are affected by the Cl^- content.

3.2. WBE

The time-dependent distribution of electrode potential of CS tested by WBE is shown in Fig. 9. It can be seen that the electrode surface potential distribution of CS wire bundle changes, the potential of CS is relatively positive in the initial immersion, with the extension of immersion time, the electrode potential shifts negatively, showing active corrosion, and a large area of uniform corrosion areas are widely distributed.

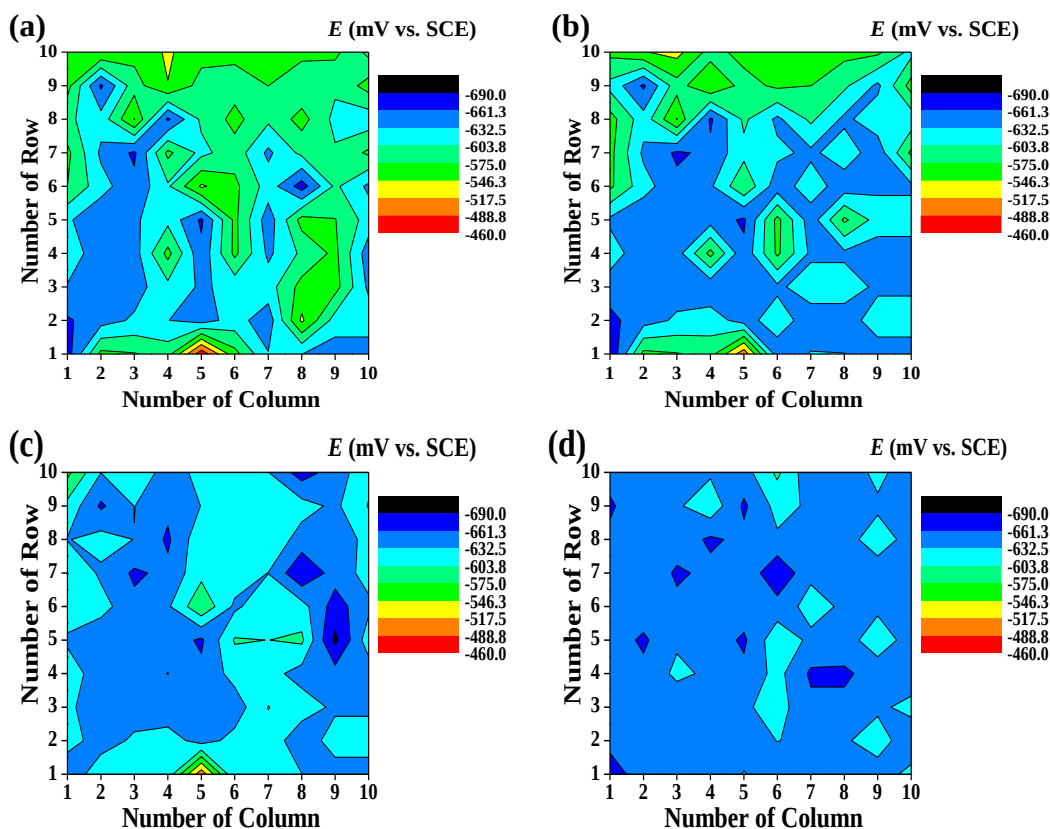


Figure 9. The electrode surface potential distribution diagrams of CS WEB in saturated $\text{Ca}(\text{OH})_2 + 1\text{wt.}\% \text{NaCl}$ solution: (a) 1 day; (b) 3 days; (c) 5 days; (d) 10 days.

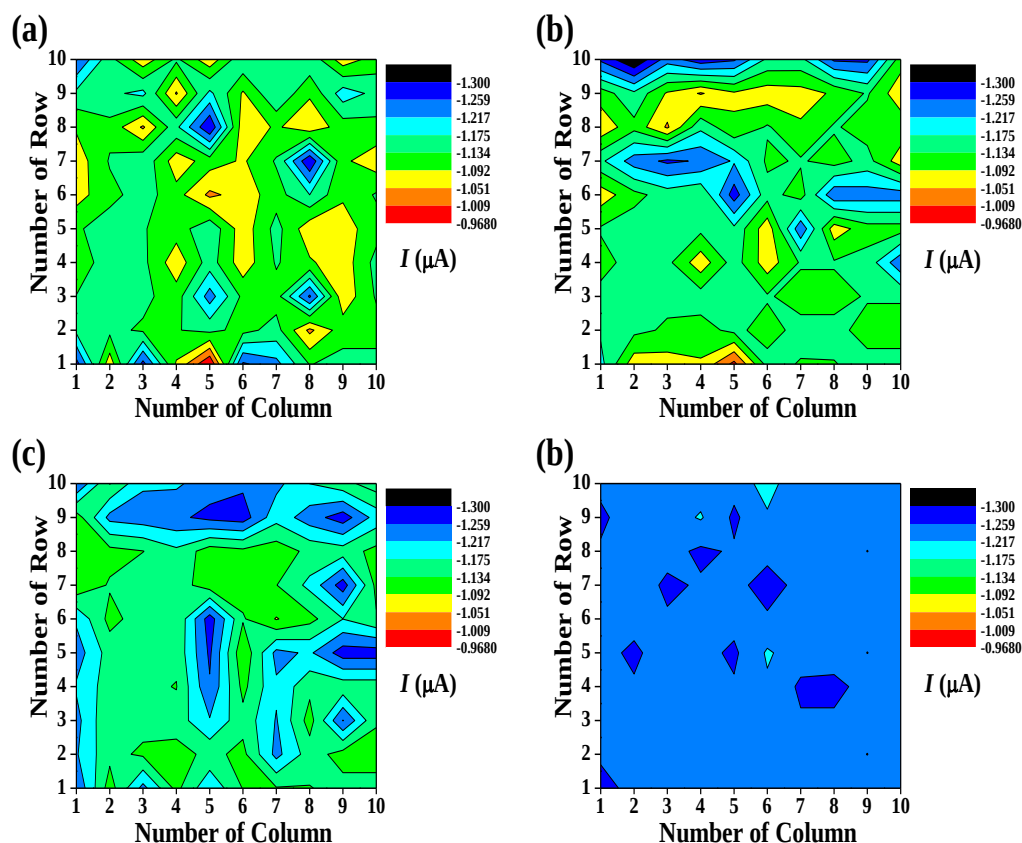
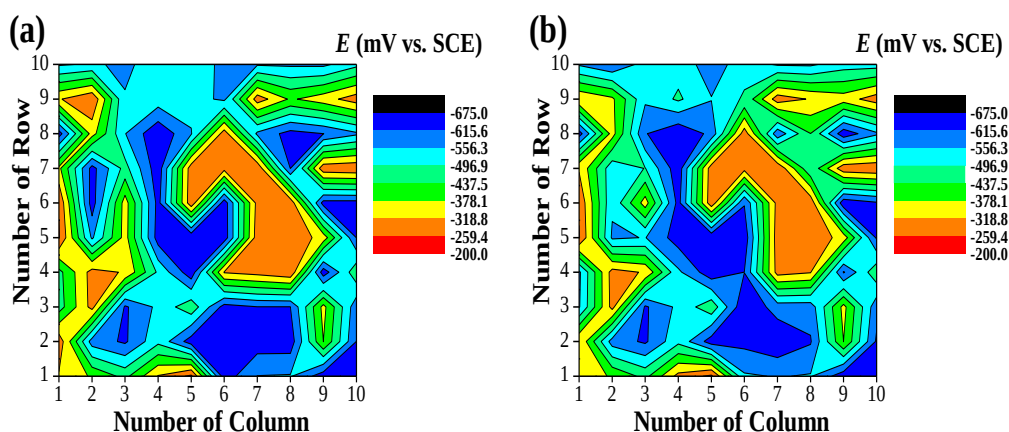


Figure 10. The electrode surface current distribution diagrams of CS WEB in saturated Ca(OH)_2 + 1wt.% NaCl solution: (a) 1 day; (b) 3 days; (c) 5 days; (d) 10 days.

The WBE sample current density distribution of CS is shown in Fig. 10, where the negative current area represents the anode zone, and the positive current area indicates the cathode zone. It can be seen that the current distribution is consistent with the potential distribution, indicating that once the CS is corroded, the corroded area will be more extensively.

Fig.11 shows the time-dependent distribution of WEB specimen potential of 5Cr steel in saturated Ca(OH)_2 + 5 wt.% NaCl solution. It can be seen that the potential of 5Cr steel sample is positive at the initial immersion stage, the potential of localized area is obviously positive than other areas, showing obvious differences.



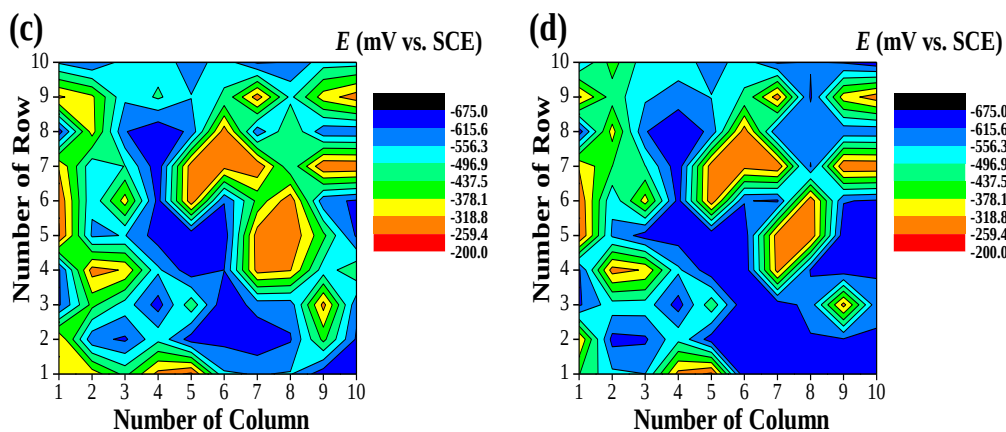


Figure 11. The electrode surface potential distribution diagrams of 5Cr steel WEB in saturated Ca(OH)_2 + 5wt.% NaCl solution: (a) 1 day; (b) 3 days; (c) 5 days; (d) 10 days.

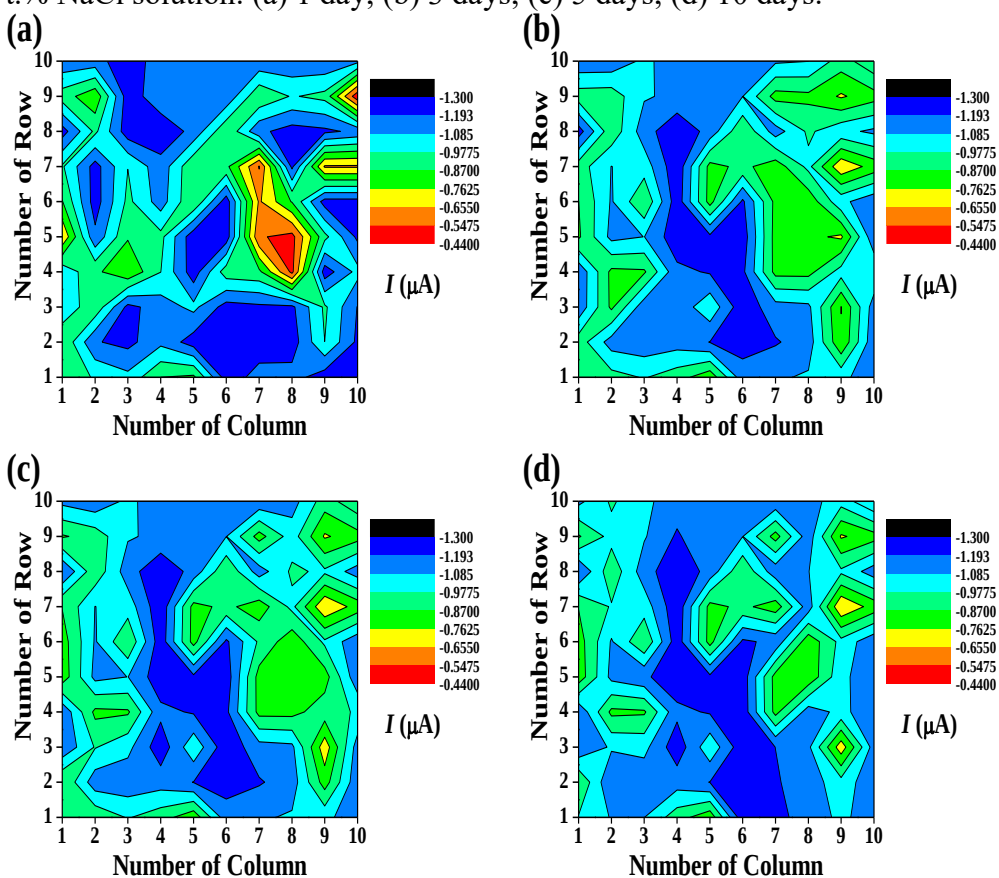


Figure 12. The electrode surface current distribution diagrams of 5Cr steel WEB in saturated Ca(OH)_2 + 5wt.% NaCl solution: (a) 1 day; (b) 3 days; (c) 5 days; (d) 10 days.

With the prolongation of immersion time, the potential of 5Cr steel shifts negatively, and the local high potential regions also shift negatively, but the overall change is small, and the distribution is limited, exhibits non-uniform corrosion.

Fig. 12 shows the current density distribution of WEB specimen of 5Cr steel. It can be seen that the current distribution is extremely consistent with the potential distribution, indicating that 5Cr steel shows mainly inhomogeneous corrosion in the simulated concrete pore solution, which is consistent with our previous research findings [31]: with the increasing of Cr content, the corrosion feature of low-Cr-modified steels are dominated by non-uniform corrosion.

3.3. Pitting factor

Fig. 13 shows the curves of the potential versus time for four kind of steel specimens after 1 h of galvanostatic polarization. It can be seen that when the current density is 1 mA/cm^2 , the potential of HRB400, 1.5Cr, 3Cr, and 5Cr steels are -431 mV (vs.SCE) , -388 mV (vs.SCE) , -368 mV (vs.SCE) , and -320 mV (vs.SCE) , respectively. With the increasing of Cr content, the potential are positive shifted.

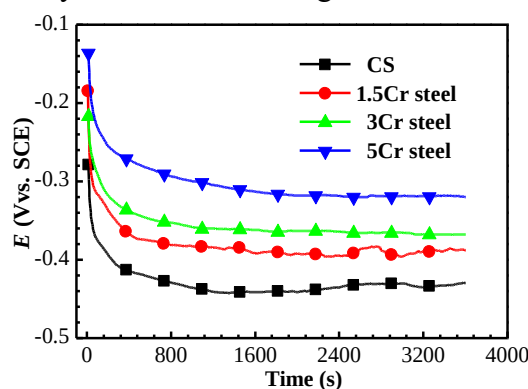


Figure 13. Curves of potential (E) versus testing time of CS and Cr-modified steels at 1 mA/cm^2 galvanostatic polarization: CS in saturated $\text{Ca(OH)}_2 + 1 \text{ wt.}\%$ NaCl solution, 1.5Cr steel in saturated $\text{Ca(OH)}_2 + 2 \text{ wt.}\%$ NaCl solution, 3Cr steel in saturated $\text{Ca(OH)}_2 + 3 \text{ wt.}\%$ NaCl solution, 5Cr steel in saturated $\text{Ca(OH)}_2 + 5 \text{ wt.}\%$ NaCl solution.

Figure 14 shows the pitting factors of four kinds of steels after 1 mA/cm^2 galvanostatic polarized for 12, 24 and 48 hours. With the increasing of Cr content, the pitting factors of steel increases, and 5Cr steel has the largest pitting factor, indicating the corrosion area of 5Cr steel is relatively limited, showing non-uniform corrosion. With the extension of testing time, the pitting factors of steel decrease, and the pitting factor of CS is close to 1 after 48 hours of galvanostatic polarization, almost all the tested areas are corroded, showing uniform corrosion feature, which is also consistent with the previous WEB test results.

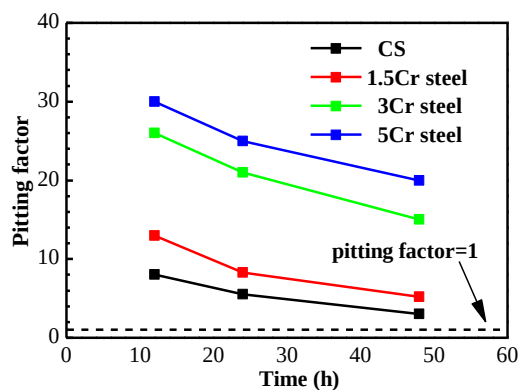


Figure 14. Pitting factors versus time of CS and Cr-modified steels at $1\text{mA}/\text{cm}^2$ galvanostatic polarization: CS in saturated $\text{Ca}(\text{OH})_2 + 1\text{ wt.}\% \text{NaCl}$ solution, 1.5Cr steel in saturated $\text{Ca}(\text{OH})_2 + 2\text{ wt.}\% \text{NaCl}$ solution, 3Cr steel in saturated $\text{Ca}(\text{OH})_2 + 3\text{ wt.}\% \text{NaCl}$ solution, 5Cr steel in saturated $\text{Ca}(\text{OH})_2 + 5\text{ wt.}\% \text{NaCl}$ solution.

3.4. Propagation life prediction

From Fig. 5, it can be seen that there is a linear relationship between I^* and E_{applied} , indicating that pitting corrosion development of steels in saturated $\text{Ca}(\text{OH})_2$ simulated concrete pore solution is controlled by ohm resistance, and the solution resistance is the dominated factor. The R_{Ω} in simulated concrete pore solutions can be converted into R_{Ω} in concrete with the same Cl^- content, and then the I^* in concrete can be obtained. Based on the results of Bentur et al. [32], the R_{Ω} in concrete can be obtained by decomposing R_{Ω} in saturated $\text{Ca}(\text{OH})_2$ solution into a solution resistance and a shape factor. The R_{Ω} of the converted CS, 1.5Cr, 3Cr and 5Cr steels in concrete are approximately 2400, 2000, 1600 and 1200 ($\Omega \cdot \text{cm}$), respectively. The ohm's law can be used to calculate the value of I^* in concrete, then the values of k in concrete can be obtained by I^* , the k in concrete for CS and Cr-modified steels are shown in Fig. 15.

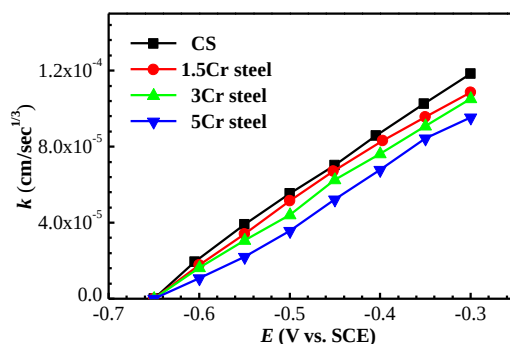


Figure 15. Conversion value of CS and Cr-modified steels corrosion coefficients k in concrete: CS in saturated $\text{Ca}(\text{OH})_2 + 1\text{ wt.}\% \text{NaCl}$ solution, 1.5Cr steel in saturated $\text{Ca}(\text{OH})_2 + 2\text{ wt.}\% \text{NaCl}$ solution, 3Cr steel in saturated $\text{Ca}(\text{OH})_2 + 3\text{ wt.}\% \text{NaCl}$ solution, 5Cr steel in saturated $\text{Ca}(\text{OH})_2 + 5\text{ wt.}\% \text{NaCl}$ solution.

No obvious difference between the density, electrochemical equivalent and other parameters of the CS and Cr-modified steels, k is mainly affected by I^* which is inversely proportional to the ohm resistance, so the value of k is mainly controlled by the ohm resistance. It should be pointed out that the moisture content of concrete has a more significant effect on the resistivity than that of Cl^- and the lower moisture content has more obvious effect [19,33]. In addition, the case of concrete completely immersed in the sea water should be considered, the oxygen diffusion coefficient in concrete will be decreased. Here, we do not consider the reduction of moisture content and oxygen diffusion coefficient in concrete.

The radial corrosion propagation of the CS and Cr-modified steels can be calculated by the equations established previous. Assuming the corrosion development of steel along the diameter direction is hemispherical, and the radial corrosion propagation time t can be inversely deduced from equation (12):

$$t = \left(\frac{r}{k} \right)^3 \quad (15)$$

Andrés et al. [34] have established a empirical formula to calculate the corrosion propagation cracking failure of concrete caused by electrochemical accelerated corrosion test.

$$X_{\text{crit}} = 0.011 \left(\frac{C}{\phi} \right) \left(\frac{C}{L} + 1 \right)^2 \quad (16)$$

Where X_{crit} is the steel corrosion depth when the concrete is cracking, C is the thickness of concrete cover, ϕ is diameter of steel rebar and L is the length of localized corrosion. It can be seen from Eq. (16) that the ratio of the thickness of C to the diameter of steel rebar C/ϕ is an important parameter for corrosion cracking of concrete protective layer caused by local corrosion of steel rebar. When the C is constant, the shorter the corrosion length, the greater amount of corrosion rust is needed for concrete cracking. As for threaded steel rebar, the diameter is usually 16 mm, and the thickness of concrete cover is assumed 50 mm, the relationship between corrosion depth (X_{crit}) and localized anode corrosion length (L) is shown in Fig. 16.

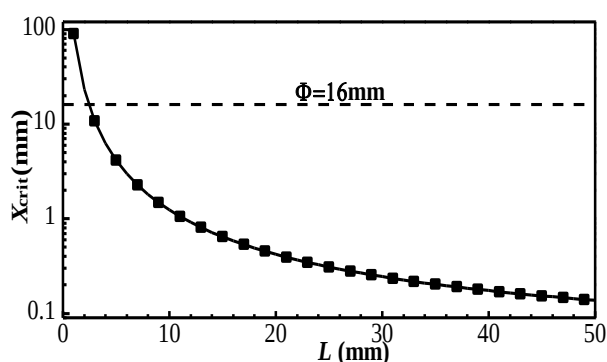


Figure 16. Relationship between corrosion depth (X_{crit}) and local anode corrosion length (L) of steel rebar in concrete.

The concrete cracks when the corrosion depth of steel rebar reaches the critical corrosion depth (X_{crit}) in Cl^- contained environment. According to the experiment results, the corrosion morphology and corrosion propagation rate of low-Cr steels are different. Once the CS is corroded, the uniform corrosion

will occurs, while the Cr-modified steels are mainly showing no-uniform corrosion, and the corrosion areas are relatively limited. The critical corrosion depth (X_{crit}) of CS and Cr-modified steels can be calculated based on Eq. (16) and the local corrosion length (L). According to the radial and WEB experiment results, and combined with the previous studies on stainless steels made by Hurley et al. [19], the following assumptions can be made: HRB400 carbon steel has the lowest pitting corrosion sensitivity, $L/X_{\text{crit}} = 40$, X_{crit} is 0.47 mm; for 1.5Cr steel, $L/X_{\text{crit}} = 30$, X_{crit} is 0.53 mm; for 3Cr steel, $L/X_{\text{crit}} = 25$, X_{crit} is 0.62 mm; for 5Cr steel, $L/X_{\text{crit}} = 20$, X_{crit} is 0.69 mm.

The radial corrosion potential of steel in concrete is assumed to be at -0.35 V (vs.SCE) according Hurley et al. [19], and the corrosion process of CS and Cr-modified steels are ohmic controlled at this potential. The corrosion propagation time can be calculated by $r = kt^{1/3}$, the results are listed in Table 4. It can be seen that the corrosion propagation time of 5Cr steel is about 16.7 years, 3Cr steel is 10.3 years, 1.5Cr steel is 5.4 years, and CS is only 3.6 years. Using low-Cr steels can prolong the corrosion propagation time of concrete structures, and 5Cr steel is the best.

Table 4. Theoretical calculation of corrosion propagation time of CS and Cr-modified steels.

Steel	L/X_{crit}	X_{crit} (mm)	T_2 (year)
CS	40	0.47	3.6
1.5Cr steel	30	0.53	5.4
3Cr steel	25	0.62	10.3
5Cr steel	20	0.69	16.7

4. CONCLUSIONS

(1) Once the localized corrosion occurs, the radial corrosion process is controlled by ohm resistance. The time of radial corrosion can be calculated by $r = kt^{1/3}$, k is related to the material density and electrochemical equivalent and other parameters. The main controlling factor of ohm resistance is Cl^- content in solution or concrete. When the electrode potential is -0.6 V (SCE), the corrosion process of the CS and Cr-modified steel are inhibited.

(2) The corrosion area of CS is widespread and the Cr-modified steels are relatively limited, Cr-modified steels have relatively higher pitting corrosion factors and larger pitting corrosion depths. With the increasing of Cr content, the pitting corrosion factor increases, the resistance to radial corrosion decreases, the lateral corrosion resistance increases, and the corresponding localized corrosion anode length decreases.

(3) Using Cr-modified steels can prolong the corrosion propagation period of concrete structures, and 5Cr steel shows the best.

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