DETERMINATION OF CHLORIDE THRESHOLD VALUES FOR REBAR DE-PASSIVATION AND PREDICTION OF DURABILITY LIFE BY SURFACE CHLORIDE ION CONCENTRATION OF REBAR FOR CONCRETE BRIDGE IN MARINE ENVIRONMENT

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Abstract
Chloride threshold values are very important regarding to the durability of concrete bridge in marine environment. In this paper the chloride threshold values were determined at atmosphere zone, splash zone and tidal zone respectively at concrete bridges along Yanwei Offshore Expressway by detecting and analyzing the indexes related to structure durability, such as chloride ion concentration, thickness of concrete cover, half-cell potential of rebar, electrical resistivity of concrete. Prediction method of durability resisting to chloride ingress is proposed based on the chloride threshold and the chloride ion concentration of rebar surface.

1. INTRODUCTION
In marine environment the possibility of rebar corrosion increases with the increase of chloride concentration. Chloride threshold values are usually defined as the maximum concentration values of dissociative chloride ion in the concrete pore solution around the rebar which will not result in the rebar de-passivation. When the chloride ion concentration values of concrete exceed the chloride threshold values, the passivation film of the rebar will be destroyed. Provided with other necessary conditions (mainly supply of water and air required by rebar corrosion), the service life of the concrete structure will be affected. Chloride threshold value is a key index in predicting the durability life of concrete bridge in marine zone.

Chloride threshold value changes with many factors such as concrete components and existing environments. The chloride threshold values are always different between laboratory
and actual conditions because there are many differences in concrete components, casting method, environment humidity, temperature and so on.

Eighty bridges are detected along Yanwei Offshore Expressway and its bypass line. Chloride threshold values are gained with the measuring results of chloride ion concentration, rebar half-cell potential and concrete resistivity. The chloride threshold values are obtained from actual environment, which will be representative and can provide reliable technical supports for the durability design and structure maintenance in the marine environment. Prediction method of durability life is proposed to resist chloride ingress based on above.

2. DETERMINATION OF CHLORIDE THRESHOLD VALUES

Concrete bridges along Yanwei Offshore Expressway have been in service for 12 years. Rebar corrosion has occurred in Jinshan Harbor Bridge and several passages. Durability indexes are measured in Jinshan Harbor Bridge, Yuniaohoe Bridge and Hanhe Bridge which is on the bypass. Field test results are shown in Figs. 1 and 2.

2.1 Chloride threshold value at atmospheric zone

There is no corrosion found in components at atmospheric zone of Jinshan Harbor Bridge where chloride ion concentration values of rebar surface are mainly about 0.01%-0.13%. Whereas the rebar have been in corrosion in beams and slabs at atmospheric zone of Hanhe Bridge nearby and the chloride ion concentration of rebar surface is about 0.24%. The relationship between electric potential and chloride ion concentration is shown in Fig. 1.

![Figure 1: the relationship between electric potential and chloride ion concentration of rebar surface at atmospheric zone](image)

It can be seen that the measured negative electric potential is small when the chloride ion concentration is below 0.13%. The possibility of corrosion is very low. At the same time, the measured results of Hanhe Bridge show the negative electric potential are above -200mV where the chloride ion concentrations are almost larger than 0.13%. Micro-damaged detections are implemented in Hanhe Bridge where electric potentials are -220mV. The chloride ion concentration of rebar surface is more than 0.1312% and the rebar have corroded very slightly.
In the atmospheric zone the rebar corrosion is not obvious, and chloride ion threshold concentration should take the upper limit of measured values which will not result in corrosion. Considering the divergence of concrete quality and rebar corrosion, the upper limit shouldn’t be absolutely treated as the chloride threshold values. Reliability and probability theory are used here to determine the chloride threshold values. The number of measuring values located in uncorroded zone should satisfy the demand of reliability. The determination of chloride threshold values can be expressed as:

\[ P[(C_b < C_{cr}) \cap (V < -200Vmv)] = 1 - p_f \]  

(1)

where, \( p_f \) is the probability of detection values locating in corrosion zone.

Taking 80% as the control possibility, that is \( 1 - p_f = 80\% \). The chloride threshold value should be taken as 0.013% for the atmospheric zone. It should be seen from Fig.1 that 37 points over all the 47 points locate in the uncorroded area which satisfies the requirement.

### 2.2 Chloride threshold values at splash zone and tidal zone

The damaged areas of Jinshan Harbor Bridge located in the tidal zone, and the concrete chloride ion concentrations of rebar surface are all more than 0.18%, which indicates that if the chloride ion concentration exceeds this value severe rebar corrosion would happen. Though parts of the chloride ion concentrations of rebar surface are more than this value, no apparent corrosion evidence appears distinctly, such as the splash zone of 5-1# and 5-2# column, the tidal zone of 5-2# column. But their negative potentials are above - 300mV, some even above - 400mV, which indicates that the very large probability of rebar de-passivation and corrosion has been existed. Rebar corrosion has happened in several components in the Yuniaoh Bridge, one of bridges along Yanwei Offshore Expressway. The relationship between rebar corrosion potential and chloride ion concentration of rebar surface is shown in Fig. 2.

![Figure 2: The corresponding relationship between chloride ion concentration of rebar surface and electrical potential in splash zone and tidal zone.](image)

At splash zone and tidal zone, most of the chloride ion concentration values of rebar surface lie between 0.07% and 0.18%. Only few are beyond this range. For the structures where concrete chloride ion concentration is more than 0.13%, rebar has been corroded and the rust spots are obvious at outside. Half-cell potential will be over –200 mV when the chloride ion concentration is larger than 0.07%, which shows that the rebar has been possible
in corrosion state. Many measuring values are even larger than \(-350\text{mV}\). Also corrosion requirements are easily satisfied with the sufficient supplement of the oxygen and water at splash zone and tidal zone. The probability of rebar de-passivation is very high.

For splash zone and tidal zone, the chloride threshold values should take the lower limit of the measuring values which will result in corrosion. Considering the divergence of concrete quality and rebar corrosion, the lower limit shouldn’t be absolutely treated as the chloride threshold value. The number of detection values located in corrosion zone should satisfy certain demand of reliability. The determination of chloride threshold values can be expressed as Eq. (2).

\[
P_f[(C_b > C_{ct}) \cap (V > -200\text{mv})] = p_f
\] (2)

where, \(p_f\) is the probability of detection values locating in corrosion zone.

Taking 80\% as the control probability, the chloride threshold value should be taken as 0.07\% for the splash zone and tidal zone. It can be seen from Fig. 2 that 29 points of all the 36 points locate in corrosion-possibility zone, which meets the requirements. For the underwater zone, oxygen needed by corrosion is absent, so the rebar is hardly in corrosion. So the chloride threshold values of underwater zone will not be discussed here.

3. PREDICTION OF DURABILITY LIFE

3.1 Prediction method of durability life

The law of chloride ingress in concrete can be modeled by the Fick’s second law, where relationship of chloride threshold values ingress depth, concrete cover thickness, service life and the time of rebar passivation can be expressed as follow:

\[
\frac{t_x}{t_c} = \left(\frac{x}{c}\right)^2
\] (3)

where, \(x\) is the depth of chloride threshold values ingress; \(t_x\) is the time when the chloride concentration reaches threshold values at depth of \(x\); \(c\) is concrete cover thickness; \(t_c\) is the time of rebar de-passivation.

Ratio of chloride ion concentration of rebar surface to chloride threshold values and ratio of chloride threshold ingress depth to concrete cover thickness all reflect the state of concrete suffering chloride ingress and rebar surface passivation. There should exist a corresponding relationship between them if the chloride threshold values determined above are rational. This section develops the relationship between them based on the measuring data, with which, we can not only check out the rationality of the chloride threshold values determined above, but also predict the time of rebar de-passivation.

Ratio of chloride ion concentration of rebar surface to chloride threshold concentration and ratio of chloride threshold ingress depth to concrete cover thickness are shown in Fig.3. Although the measuring values perhaps deviate from the theoretical values due to many factors, most values gather around the point (1, 1), which indicates that the chloride threshold value determined above is rational.
**Figure 3:** Ratio of rebar surface chloride ion concentration to chloride threshold value and ratio of chloride threshold ingress depth to concrete cover thickness

**Table 1: An example for durability life prediction**

<table>
<thead>
<tr>
<th>Component</th>
<th>Threshold values /%</th>
<th>Concentration near steel bar surface /%</th>
<th>Prediction of durability life /year</th>
<th>Remain life /year</th>
<th>Actual durability states</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam, on-sea</td>
<td>0.13</td>
<td>0.0482</td>
<td>17.0</td>
<td>5.0</td>
<td>good</td>
</tr>
<tr>
<td>Beam, off-sea</td>
<td>0.13</td>
<td>0.0099</td>
<td>34.7</td>
<td>22.7</td>
<td>better</td>
</tr>
<tr>
<td>Cope, on-sea</td>
<td>0.13</td>
<td>0.0291</td>
<td>20.7</td>
<td>8.7</td>
<td>better</td>
</tr>
<tr>
<td>Cope, off-sea</td>
<td>0.13</td>
<td>0.0291</td>
<td>20.7</td>
<td>8.7</td>
<td>better</td>
</tr>
<tr>
<td>Column, on-sea, atmosphere</td>
<td>0.13</td>
<td>0.1056</td>
<td>12.8</td>
<td>0.8</td>
<td>Few pitting</td>
</tr>
<tr>
<td>Column, off-sea, atmosphere</td>
<td>0.13</td>
<td>0.1056</td>
<td>12.8</td>
<td>0.8</td>
<td>Few pitting</td>
</tr>
<tr>
<td>Column, on-sea, splash</td>
<td>0.07</td>
<td>0.2396</td>
<td>8.4</td>
<td>0</td>
<td>Obvious rust</td>
</tr>
<tr>
<td>Column, off-sea, splash</td>
<td>0.07</td>
<td>0.2715</td>
<td>8.1</td>
<td>0</td>
<td>Obvious rust</td>
</tr>
<tr>
<td>Column, on-sea, tidal</td>
<td>0.07</td>
<td>0.112</td>
<td>10.4</td>
<td>0</td>
<td>Obvious rust</td>
</tr>
<tr>
<td>Column, off-sea, splash</td>
<td>0.07</td>
<td>0.1822</td>
<td>9.0</td>
<td>0</td>
<td>Obvious rust</td>
</tr>
</tbody>
</table>

The Curve (4) was obtained by data fitting, as shown in Fig. 3 (Dashed line).

\[
\frac{x}{c} = 0.4 \ln \left( \frac{C_b}{C_c} \right) + 0.7767 , \quad R^2 = 0.733
\]  

When the chloride threshold concentration reaches to the concrete cover thickness, the detected rebar surface chloride ion concentration should correspondingly equals to the chloride threshold concentration. The fitting curve should pass the point (1, 1) theoretically. So the dashed line was corrected by continuous line. The relationship between them is expressed as Eq. (5).
\[
\left( \frac{x}{c} \right) = 0.16 \ln\left( \frac{C_b}{C_{cr}} \right) + 1
\] (5)

Eq. (6) is obtained from Eq.(3) and Eq.(5).

\[
\frac{t_e}{t_c} = \left( 0.16 \ln\left( \frac{C_b}{C_{cr}} \right) + 1 \right)^2
\] (6)

With Eq. (6), the durability life can be easily predicted through testing chloride ion concentration of rebar surface and chloride threshold values.

3.2 Example

Jinshan Harbor Bridge has been in service for 12 years. The chloride concentration near rebar surface, threshold values and respective durability states are listed on Table 1. The durability life is correspondingly predicted with Eq. (6). It is shown that predicted results are preferably coincident to actual durability states.

4. CONCLUSIONS

- Chloride threshold values along Yanwei Offshore Expressway are 0.13% at atmosphere zone and 0.07% at splash zone and tidal zone respectively.
- The ratio of chloride ion concentration of rebar surface to chloride threshold value and the ratio of chloride threshold concentration ingress depth to concrete cover thickness are analyzed. The relation curve is corrected and developed.
- The relation between chloride ion concentration of rebar surface, chloride threshold and durability life resistance to chloride ingress of concrete bridge is obtained. The durability life resist to chloride ingress could be predicted with actual data. An example shown the rationality of the prediction method.

REFERENCES