CONCRETE PERFORMANCE IN RELATION TO THE EXPOSURE ZONES IN THE MARINE ENVIRONMENT

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Abstract

An extended condition survey was performed on reinforced concrete columns, which were a part of the marine structure at the Adriatic coast and submerged in the sea for more than 30 years. After the extraction of columns from the sea, numerous testing were performed in order to determine physical, mechanical and chemical properties of the concrete. Based on the visual assessment of the columns’ condition, geometry and chloride determination, they were assigned with five exposure zones: splashing zone, tidal zone, and three submerged zones different in geometrical shape and orientation, in order to determine intensity and influence of the sea action.

Within this paper the results of chloride content determination, chloride profiles and calculation of diffusion coefficients related to the exposure zones are presented. Chloride surface concentrations are discussed further and statistically analysed with the aim to define chlorides as an environmental load to concrete structures.

Splashing and tidal zone, as expected, have the highest chloride concentrations and the highest dissipation of results, while submerged zones unexpectedly have shown a dependence of surface chloride concentration on the structural geometry shape. Correction factors for the chloride surface concentrations in relation to the geometry of the concrete elements are suggested for the first time, which should be included during design stage and calculation of durability properties of concrete elements in submerged zones. Based on this preliminary research results recommendations for the future research work are given.

1. INTRODUCTION

History of reinforced concrete structures gives numerous examples of deteriorated structures, due to different chemical and physical degradation processes such as carbonation, ingress of chlorides, freeze-thaw cycles, alkali-aggregate reactions, etc. The results of
assessing structures around the world have shown that chloride action is one of the most aggressive ones for reinforced concrete structures. [1, 2]

Chlorides are penetrating into the hardened concrete through various mechanisms of transport: absorption, diffusion, permeation of salty water caused by hydrostatic pressure, electro migration, and usually as a combination of several transport mechanism but with one mechanism as the dominant one. Once the process of chloride ions ingress begins, its progress depends on many factors, such as density and quality of the concrete, quantity of water in concrete pores, temperature, presence of cracks and their distribution and size, etc. [3]

Within this paper the results of case study research performed on the concrete columns, which were a part of marine structure at the Adriatic coast are presented. The assessment of concrete has included chloride content determination, chloride profiles and calculation of diffusion coefficients related to the exposure zones. Chloride surface concentrations are discussed further and statistically analysed with the aim to define chlorides as an environmental load to concrete structures, especially for the submerged concrete structures.

2. GENERALLY ON STRUCTURE

About 30 years ago reinforced concrete dock columns were produced and placed into the sea in the Croatian yacht marine near Zadar, at the Adriatic coast, with the average temperatures and precipitation typical for Mediterranean climate, as shown in table 1. The composition of the Adriatic sea is given in table 2. During the year 2003 dock columns were pulled out from the sea during the reconstruction of the marine, while a detailed inspection and evaluation of present condition were performed [4-6]. Concrete quality on compressive strength was designed at 30 MPa (MB30/C25). Columns have variable longitudinal and transversal cross section, with total height of 5.15 meter, as shown in figures 1. Measured thicknesses of concrete cover are between 30 and 60 mm. Figure 1 shows columns after they were extracted from the sea, while.

<table>
<thead>
<tr>
<th>Month</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
<th>X</th>
<th>XI</th>
<th>XII</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of days with precipitation</td>
<td>10</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>8</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>Average temperature (°C)</td>
<td>6.7</td>
<td>7.3</td>
<td>9.4</td>
<td>13.7</td>
<td>18.4</td>
<td>22.3</td>
<td>25</td>
<td>24.4</td>
<td>21.2</td>
<td>16.6</td>
<td>11.1</td>
<td>7.7</td>
<td>15.3</td>
</tr>
<tr>
<td>RH (%)</td>
<td>76</td>
<td>74</td>
<td>75</td>
<td>73</td>
<td>75</td>
<td>72</td>
<td>68</td>
<td>70</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>73.6</td>
</tr>
</tbody>
</table>

Table 1: Exposure conditions for the location of Zadar, Adriatic coast

<table>
<thead>
<tr>
<th>Component</th>
<th>Concentration (g/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₄²⁻</td>
<td>2.97</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>1.42</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>0.46</td>
</tr>
<tr>
<td>Na⁺</td>
<td>21.25</td>
</tr>
<tr>
<td>K⁺</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table 2: Chemical composition of the Adriatic sea

Figure 1: Column pulled out from the sea
3. EXPERIMENTAL RESEARCH

Research on the reinforced concrete dock columns was performed on site and in the laboratory on samples (concrete cores and dust) taken out by drilling from the structures. Visual inspection of columns, extracted directly from the sea, had shown deterioration differences on concrete surface which lead to zoning of the columns, respecting as well the geometry and shape. Columns were divided into five zones: A, B, C, D and E. The aim was to clearly dispense intensity and influence of sea action on columns. Zone A was designated as splashing zone, zone B as tidal zone, and zones C, D, and E as submerged zones. Figure 2 shows scheme of the columns, divided into the five zones A, B, C, D, and E, as well with marked testing and sampling places.

![Figure 2: Scheme of the column No.1 (dimensions in cm)](image)

Determination of the concrete quality was based on testing capillary water absorption (EN 1015-18), gas permeability (EN 993-4:1995), compressive strength (EN 12504-1:2000), determination of chloride ions content (%) in concrete [7, 8], determination of chloride diffusion coefficient $D$ (NT BUILD 443:1995) and determination of corrosion risk by using galvanostatic impulse method [9]. In this paper only part of the performed research results related to the chlorides penetration are presented.

3.1 Chloride profiles

The information about the exposure time, the environment and the measured chloride profile in concrete are giving a picture about the structure and its response to the chloride impact. By simplification of few parameters within this measurement results it is sufficient to determine the shape of the chloride profile from a mathematical point of view. The values of these parameters, their statistical distributions and their development with the time contribute significantly in finding solution for the chloride ingress in the concrete.

As previously mentioned the transport mechanism may vary with material composition, permeability and distribution and cracks widths in the concrete. Here are taken into account the assumptions that diffusion is the predominant mechanism of the chloride ingress and that the concrete is a quasi-homogeneous material. With respect to these assumptions the chloride profiles are calculated for each testing place, applying Fick’s second law of diffusion. [10-12]

All together more than 200 chloride testing were performed, from which 60 chloride profiles were calculated, presented in figures 3 to 5, related to the exposure zone. Average values of all chloride profiles for each zone are graphically shown in figure 6.
Depth of reinforcement location was measured on each testing point where the chloride profile was done. The average concrete cover thickness was 39 mm. From the results shown...
in figure 6 it is obvious that chloride concentration on the level of reinforcement was considerably greater than the threshold value, generally accepted in Croatian practice [13] which implies great probability of corrosion process. Nevertheless, it should be noted that parts of the structure that are totally and permanently submerged in the seawater are less corrosion endangered and therefore there were no significant damages due to the reinforcement corrosion, except in zone A and B.

3.2 Chloride diffusion coefficient

With analysing chloride ions profile data, ulterior calculation procedure gives chloride diffusion coefficient through hardened concrete. Diffusion coefficient can be calculated depending on time during which construction was exposed to severe sea actions, by using following formula, as solution for Fick’s second law of diffusion [10-12]:

\[
C(x,t) = C_s - (C_s - C_i) \cdot \text{erf} \left( \frac{x}{4 \sqrt{D_{app} \cdot t}} \right)
\]

where:

- \(C(x,t)\) - chloride concentration, measured at the depth \(x\) at the exposure time \(t\), mass %
- \(C_s\) - boundary condition at the exposed surface, mass %
- \(C_i\) - initial chloride concentration measured on the concrete slice, mass %
- \(x\) - depth below the exposed surface (to the middle of a layer), m
- \(D_{app}\) - apparent chloride diffusion coefficient, m²/s
- \(t\) - exposure time, s
- \(\text{erf}\) - error function.

The values of \(C_s\) and \(D_{app}\) are determined by fitting the equation (1) to the measured chloride contents by means of a non-linear regression analysis in accordance with the method of least squares fit. [10-12]

The results of the diffusion coefficient calculation (average value for each testing place) from chloride profiles are presented in figure 7. Average values of the chloride diffusion coefficient for each zone are presented in table 1.

Figure 7: Chloride profiles for zones A-E
Table 1: Average values of the chloride diffusion coefficients depending on zones

<table>
<thead>
<tr>
<th>ZONE</th>
<th>Column height [cm]</th>
<th>Chloride diffusion coefficient, $D_{ave}$ [mm²/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A – XS3</td>
<td>470 till 500 (0 do 30 cm above sea level)</td>
<td>4.27E-11</td>
</tr>
<tr>
<td>B – XS3</td>
<td>450 till 470 (0 do –20 cm under the sea)</td>
<td>5.83E-12</td>
</tr>
<tr>
<td>C – XS2</td>
<td>400 till 450 (od -20 do –70 cm under the sea)</td>
<td>1.56E-12</td>
</tr>
<tr>
<td>D – XS2</td>
<td>60 till 450 (od -70 do –460 cm under the sea)</td>
<td>3.07E-12</td>
</tr>
<tr>
<td>E – XS2</td>
<td>0 till 60 (od -460 do –520 cm under the sea)</td>
<td>2.26E-12</td>
</tr>
</tbody>
</table>

3.3 Surface chloride concentration

The measured profiles have been analysed to derive the chloride surface concentration $C_S$, and these computed data have been used as a basis for the further analysis. [14] In Table 2 are given the results of statistical analysis for $C_S$ values, calculated from chloride measurements data. Exposure zones are designated according EN 206-1 [13]. In this calculation design value of chloride surface concentration is defined as:

$$C_{S_d} = C_{S,ave} + 1.3 \sigma_s$$

(2)

where $C_{S,ave}$ is an average value of chloride surface concentrations (load) and $\sigma_s$ is standard deviation. Coefficient 1.3 means that 10% of the population has higher concentrations than $C_{S_d}$. [15, 16]

Table 2. Chloride surface concentration related to the exposure zone

<table>
<thead>
<tr>
<th>ZONE</th>
<th>$C_{S,ave}$ (% by m_con)</th>
<th>$\sigma_s$ (% by m_con)</th>
<th>$C_{S_d}$ (% by m_con)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A – XS3</td>
<td>0.62</td>
<td>0.24</td>
<td>0.93</td>
</tr>
<tr>
<td>B – XS3</td>
<td>0.48</td>
<td>0.10</td>
<td>0.61</td>
</tr>
<tr>
<td>C – XS2</td>
<td>0.39</td>
<td>0.13</td>
<td>0.56</td>
</tr>
<tr>
<td>D – XS2</td>
<td>0.67</td>
<td>0.12</td>
<td>0.83</td>
</tr>
<tr>
<td>E – XS2</td>
<td>0.22</td>
<td>0.04</td>
<td>0.27</td>
</tr>
</tbody>
</table>

The results shown in table 2 confirm previous conclusions about marine exposure conditions. Zones A and B, splashing and tidal zone, have the highest chloride concentrations, concerning that they are partially submerged. In the zone A the results have the highest dissipation, which was caused by splashing and locally different chloride concentrations. Zones C, D, and E are totally submerged zones. These zones show a dependence of surface chloride concentration on the structural geometry shape, as shown in figure 8. Zones C and E have lower chloride surface concentration values, which are slope wise parts of the structure and don’t front directly a seawater flux. Zone D, a vertical part of the column, has very high surface chloride concentration, due to its set up against the seawater flux.

Table 3. Relationship between $C_{S_d}$ and shape of the concrete element

<table>
<thead>
<tr>
<th>Zone</th>
<th>$\theta$ (°)</th>
<th>$\sin \theta$</th>
<th>$C_{S_d}$ (% by mass of concrete)</th>
<th>Corrected value of $C_{S_d}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>90</td>
<td>1</td>
<td>0.83</td>
<td>$0.83 \times \sin 90^\circ = 0.83$</td>
</tr>
<tr>
<td>C</td>
<td>45</td>
<td>0.707</td>
<td>0.56</td>
<td>$0.83 \times \sin 45^\circ = 0.58$</td>
</tr>
<tr>
<td>E</td>
<td>19</td>
<td>0.326</td>
<td>0.27</td>
<td>$0.83 \times \sin 19^\circ = 0.27$</td>
</tr>
</tbody>
</table>
In Table 3, the relationship between chloride surface concentrations and the shape of the concrete element, in this case study columns of the marine structure, is presented. Based on the analyzed results, the following correlation for the chloride surface concentration for the submerged zones (XS 2) is suggested:

\[ C_{sd} = C_{ref} \times \sin \theta \]  

where \( C_{ref} \) is the reference value, accepted or determined experimentally for the vertical part of the element and \( \theta \) is the angle of the slope of the concrete surface on the observed side of the element.

4. CONCLUSION

During the research project on reinforced concrete structures exposed to the marine environment, a detailed condition survey was performed on concrete columns which were part of a marine structure for 30 years. Within experimental assessment, chloride analysis were performed, on the in-situ and laboratory extracted specimens, related to the five zones of exposure.

Chloride concentration on the reinforcement level was considerably greater than the threshold value, which implies a great probability of corrosion process. Nevertheless, parts of the structure that are totally and permanently submerged in the seawater are less corrosion endangered and therefore there were no significant damages due to the reinforcement corrosion, except in splashing and tidal zone.

Splashing and tidal zone had the highest chloride concentrations and the highest dissipation of results, which was caused by splashing and locally different chloride concentrations.

Submerged zones had shown a dependence of surface chloride concentration on the structural geometry shape, which was not expected. Slope wise parts of the structure, which didn’t face directly a seawater flux, had lower chloride surface concentration values. Vertical part of the column had very high surface chloride concentration, due to its set up against the seawater flux. Correction factors for the chloride surface concentrations in relation to the geometry of the concrete elements are suggested, based on this preliminary research results. Further research will be performed in order to evaluate suggested relationship, and to
determine the influence of fluid pressure on chloride rate penetration, when concrete elements are submerged in sea water.

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REFERENCES