Quantifying maximum phenomenon in chloride ion profiles and its influence on service-life prediction of concrete structures exposed to seawater tidal zone – A field oriented study

Mehdi Khanzadeh Moradllo a,⇑, Seyedhamed Sadati b, Mohammad Shekarchi c

a School of Civil and Construction Engineering, Oregon State University, Corvallis, OR 97331, USA
b National Concrete Pavement Technology Center, Iowa State University, Ames, IA 50011, USA
c School of Civil Engineering, University of Tehran, Tehran, Iran

HIGHLIGHTS

- The maximum phenomenon is examined in samples exposed to tidal zone for 5 years.
- The results show that the occurrence of maximum phenomenon is time-dependent.
- Both the skin layer thickness and the maximum Cl content are evolving with time.
- The modifications in mixture design affect the formation of the maximum phenomenon.
- Neglecting the maximum phenomenon causes an overestimation in predicted service-life.

ABSTRACT

Only limited work has been completed to characterize and quantify the chloride ion (Cl) maximum phenomenon and its impact on service-life prediction. In addition, there is limited long-term experiment to examine the evolution of the maximum phenomenon. The present study investigates the maximum phenomenon in concrete samples with sixteen varying combinations of water-to-binder ratios (w/b) and silica fume (SF) contents which have been exposed to tidal zone of marine environment for five years. Results show that the presence of maximum phenomenon is time-dependent, and both the maximum phenomenon thickness and the maximum Cl concentration are evolving with time. In addition, concrete matrix plays an important role in occurrence of the maximum phenomenon. Neglecting the maximum phenomenon results in a large discrepancy between the simulated and measured Cl profiles and can cause a significant overestimation in predicted service-life of concrete structures.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

The chloride-induced corrosion of the embedded steel has become the most common cause of loss of integrity and failure in concrete structures placed in the marine environment [1,2], which can impose considerable repair costs every year [1,3,4]. Accordingly, special precautions, including modification of existing service-life prediction models need to be established, under these extreme ambient conditions, in order to enhance the design life and durability of concrete infrastructures in harsh environments.

The mechanisms of chloride ion (Cl) penetration into concrete mainly depend on internal moisture state of the concrete pores and the exposure condition [5–7]. These mechanisms consist of absorption, diffusion, permeation, wicking, and dispersion [8–10]. Absorption due to the capillary action and diffusion under influence of concentration gradient are the main combined transport mechanisms in the splash and tidal zones, where wetting and drying cycles take place [5,11–14]. In addition, carbonation can influence the chloride distribution in these exposure conditions [15]. This complicated penetration mechanism can lead to a non-Fickian Cl distribution profile, resulting in formation of a local peak in Cl concentration profile. In such cases, the maximum Cl concentration occurs in the interior of concrete rather than its surface, resulting in higher risk of corrosion due to elevated Cl concentra-

https://doi.org/10.1016/j.conbuildmat.2018.05.284
0950-0618/© 2018 Elsevier Ltd. All rights reserved.
tions in the vicinity of the reinforcing bars [5,11]. This phenomenon has been referred to as the “maximum phenomenon” in the literature [5,11]. The presence of maximum phenomenon indicates that there are two different layers with different predominant ionic transport mechanism within the concrete surface, the “skin” layer where the Cl concentration increases over the sample depth and the internal or concrete bulk zone where the Cl profile shows a Fickian trend [Fig. 1] [11,16].

The absorption–desorption/evaporation process (convection), skin effect, carbonation, and leaching are the main reasons that have been stated as a cause for the formation of maximum phenomenon in concrete skin layer [5,9,11,12,14,16–21]. However, given the cyclic drying and wetting conditions, the absorption–desorption/evaporation and carbonation processes are the crucial factors in occurrence of maximum phenomenon in tidal zone [5,9,12]. It worth to mention that concrete mixture properties can also influence the presence and extent of maximum phenomenon.

Cl diffusion coefficient (Dc) and surface concentration (Cs) are crucial input parameters in service-life prediction of concrete structures. The most common method to determine Dc and Cs is to conduct a nonlinear regression on Cl profiles obtained from field or laboratory samples using the simplified solution of Fick’s second law of diffusion, i.e. the error function equation [16,22–24]. The presence of maximum phenomenon influences the accuracy of the calculated Dc and Cs based on this simplified procedure, and consequently leads to the unreliable service-life prediction [5,11].

Several methods have been suggested to account for the maximum phenomenon in calculating Dc and Cs and service-life prediction. Andrade et al. [16] demonstrated occurrence of the skin layer in Cl profiles by defining two separate values of diffusion coefficient for diffusivity in the concrete skin layer and concrete bulk zone in the solution of Fick’s second law. RILEM TC 178-TMC [11,25] suggested neglecting the skin layer and using the maximum Cl concentration as an apparent surface concentration (Cmax) and fitting the error function equation into the decreasing concentration profile towards the interior. Recently, Andrade et al. [11] presented a practical procedure to implement RILEM TC 178-TMC method to take the maximum phenomenon into consideration. Liu et al. [12] developed a numerical model to predict the depth of maximum phenomenon with assumption of a linear change of Cl concentration and water influential depth in skin layer.

Although numerous studies [5,8,9,11–14,18,26] have observed the maximum phenomenon in field and laboratory experiments, limited long-term experiment has been completed to quantify the impact of this phenomenon on ionic transport properties and service-life prediction. In addition, there is a need for long-term experimentation to examine the evolution of the maximum phenomenon depth and Cmax, as well as the influence of concrete mixture design parameters on these variables [5,11]. Therefore, the present study explores the maximum phenomenon in concrete samples exposed to tidal zone of a natural marine environment. Data obtained from testing 16 different concrete mixtures with varying combinations of water-to-binder ratios (w/b) and silica fume (SF) contents was investigated. The specimens were monitored for up to 60 months of exposure to a highly saline natural environment. The influence of concrete matrix (w/b and SF content) on maximum phenomenon was examined. Moreover, the evolution of the maximum phenomenon with time was quantified and its influence on service-life prediction was investigated using field data.

2. Service-life prediction with consideration of maximum phenomenon

The Cl penetration rate as a function of depth from the concrete surface and time can be represented by Fick’s second law for diffusion as formulated in Eq. (1) [22].

\[
\frac{\partial C}{\partial t} = D_c \frac{\partial^2 C}{\partial x^2}
\]

where \(x\) is distance from sample surface; \(t\) denotes time; \(D_c\) is diffusion coefficient; \(C_s\) is surface Cl concentration; and \(C(x,t)\) represents Cl concentration at the depth of \(x\) from the surface after time \(t\).

A general solution (error function equation) to the equation is given in Eq. (2) [11,16,22].

\[
C(x,t) = C_s \left(1 - \text{erf} \left( \frac{x}{2\sqrt{D_c t}} \right) \right)
\]

where \(C(x,0) = 0 \times x > 0, \quad C(x,t) \equiv C_s \times t > 0\)

where \(C(x,t)\) represents total Cl concentration at the depth of \(x\) from the surface after time \(t\) and \(C_s\) is the error function and \(D_c\) is the apparent diffusion coefficient.

Eq. (2) assumes that the porous material is fully saturated; the ion concentration at the exposure surface is constant; and there is no impact of co-existing ions. In addition, this equation does not take into account the effect of other ion penetration mechanisms such as capillary absorption. Although these assumptions do not apply to all of the conditions, this equation may still be useful where diffusion plays a significant role in the penetration of outside ions.

Andrade et al. [5,11,25] suggested a modified version of Eq. (2) as shown in Eq. (3) in order to account for the maximum phenomenon.

\[
C_{(x)} = C_{\text{max}} \left(1 - \text{erf} \left( \frac{x - \Delta x}{2\sqrt{D_c t}} \right) \right)
\]

where \(C_{\text{max}}\) is the maximum Cl concentration and \(\Delta x\) is the thickness of maximum phenomenon. The apparent diffusion coefficient \((D_c)\) is determined by fitting the error function equation (Eq. (2)) into the decreasing part of Cl profile.

Eq. (3) assumes that the \(D_c\) and \(C_{\text{max}}\) remain constant with time. However, previous studies [3,8,10,17,23,27,28] have shown that the \(D_c\) and \(C_{\text{max}}\) are time dependent. Therefore, the time dependency of the \(D_c\) and \(C_{\text{max}}\) was expressed mathematically as demonstrated in Eqs. (4) [28] and (5) [23,29], respectively. These equations were drawn based on long-term experimental work in marine environment with varying concrete mixtures and exposure conditions.

\[
D_{c(t)} = D_{c0} \left( \frac{t}{t_{ref}} \right)^{-m}
\]
where \( D_{\text{ref}} \) and \( C_{\text{ref}} \) are the apparent diffusion coefficient and surface Cl concentration at reference time \( t_{\text{ref}} \) (i.e., 3 months), respectively; \( m \) is the diffusion decay coefficient, which depends on mixture proportions; and \( k \) is the regression coefficient.

Therefore, incorporating Eqs. (4) and (5) into the Eq. (3) yields the following relationship to predict the time-dependent Cl profile with consideration of maximum phenomenon.

\[
C_{(x,t)} = \left( C_{\text{ref}} + kt \right) \left( 1 - \text{erf} \left( \frac{x - \Delta x}{2 \sqrt{D_{\text{ref}} (m)^{-m}} t} \right) \right)
\]

### 3. Experimental program

#### 3.1. Materials and mixture proportions

Sixteen concrete mixtures were investigated with w/b of 0.35, 0.40, 0.45, and 0.50 and SF replacement percentages of 5%, 7.5%, 10%, and 12.5% (by mass). This wide range of SF replacement percentage was examined to determine the optimum replacement level of SF in marine environment. More details can be found in other publications [28]. All mixtures were proportioned to have the same total cementitious materials content of 400 kg/m³. The chemical composition of cement and SF (from the mill sheet) is provided in Table 2. The aggregates were crushed limestone and were graded according to ASTM C 33-18. The coarse aggregate had maximum size of 12.5 mm and specific gravity and absorption values of 2.20 and 1.9%, respectively. Polycarboxylate ether polymer superplasticizer was used for the mixtures in order to improve the workability of fresh concrete.

#### 3.2. Casting and curing of concrete samples

The concrete mixtures were prepared following ASTM C 192-16 using a 0.1 m³ countercurrent pan mixer. The fresh concrete was tested for air content according to ASTM C 231-17, slump according to ASTM C 143-15 and unit weight following ASTM C 138-17. Two sample geometries were prepared. Cubic samples of 150 × 150 × 150 mm were cast to determine compressive strength following DIN 1048 and prismatic samples of 150 × 150 × 600 mm were prepared to investigate Cl penetration in the field. Properties of fresh and hardened concrete are summarized in Table 3. The samples were covered with wet burlap for 24 h after casting. The samples were then demolded and cured in saturated limewater at 23 °C until age of 28 days.

#### 3.3. Exposure condition

After the curing period, prismatic samples were sealed on four sides using an epoxy polyurethane coating to ensure one-dimensional ion transport. The specimens were then transported to an investigation site located in Bandar-Abbas coast in south of Iran and subjected to tidal zone exposure condition in Persian Gulf for the entire period of investigations (60 months). The sample storage spot was situated at a distance of 2.2 m from sea level, to ensure a cyclic exposure to sea water (12 h a day) followed by air drying for rest of the day, simulating the tidal zone condition. The chemical composition of the sea water and seasonal temperature and humidity conditions are reported in other publications [23,24,28–30].

#### 3.4. Sampling and testing

Sampling was carried out at the ages of 3, 36, and 60 months of exposure in tidal zone. Each time, 100 mm long slices were cut from the end of the prismatic samples (Fig. 2). The cut surface of the remaining part was coated and exposed to tidal condition for

### Table 2

<table>
<thead>
<tr>
<th>Oxide, % mass</th>
<th>Cement</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>62.25</td>
<td>–</td>
</tr>
<tr>
<td>SiO₂</td>
<td>21.22</td>
<td>93.16</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4.68</td>
<td>1.13</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>3.68</td>
<td>0.72</td>
</tr>
<tr>
<td>MgO</td>
<td>3.63</td>
<td>1.6</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.25</td>
<td>–</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.75</td>
<td>–</td>
</tr>
<tr>
<td>SO₃</td>
<td>1.74</td>
<td>0.05</td>
</tr>
<tr>
<td>LOI</td>
<td>1.37</td>
<td>1.58</td>
</tr>
</tbody>
</table>

### Table 1

Concrete mixture proportions.

<table>
<thead>
<tr>
<th>SF</th>
<th>w/b</th>
<th>Water (kg/m³)</th>
<th>Binder (kg/m³)</th>
<th>Fine aggregates (kg/m³)</th>
<th>Coarse aggregates (kg/m³)</th>
<th>Superplasticizer (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>0.35</td>
<td>140</td>
<td>380 20</td>
<td>931</td>
<td>968</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>160</td>
<td>380 20</td>
<td>833</td>
<td>1018</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>180</td>
<td>380 20</td>
<td>810</td>
<td>990</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>200</td>
<td>380 20</td>
<td>793</td>
<td>991</td>
<td>0.8</td>
</tr>
<tr>
<td>7.5%</td>
<td>0.35</td>
<td>140</td>
<td>370 30</td>
<td>931</td>
<td>968</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>160</td>
<td>370 30</td>
<td>832</td>
<td>1017</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>180</td>
<td>370 30</td>
<td>808</td>
<td>998</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>200</td>
<td>370 30</td>
<td>784</td>
<td>959</td>
<td>1.2</td>
</tr>
<tr>
<td>10%</td>
<td>0.35</td>
<td>140</td>
<td>360 40</td>
<td>906</td>
<td>968</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>160</td>
<td>360 40</td>
<td>830</td>
<td>1014</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>180</td>
<td>360 40</td>
<td>807</td>
<td>985</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>200</td>
<td>360 40</td>
<td>820</td>
<td>1020</td>
<td>1.8</td>
</tr>
<tr>
<td>12.5%</td>
<td>0.35</td>
<td>140</td>
<td>350 50</td>
<td>929</td>
<td>964</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>160</td>
<td>350 50</td>
<td>829</td>
<td>1012</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>180</td>
<td>350 50</td>
<td>806</td>
<td>983</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>200</td>
<td>350 50</td>
<td>782</td>
<td>955</td>
<td>2</td>
</tr>
</tbody>
</table>
future testing. The slices were shipped back to the laboratory and tested to determine the CI concentration profiles.

In the laboratory, a nominal 45 mm diameter core was taken from each slice to provide CI concentration profiles. Powdered samples were obtained from each core in 8 incremental depths from the finished surface to an estimated depth of CI penetration following NordTest NT Build 443. At each depth, a sample of approximately 10 g was selected to determine the acid-soluble CI content by the potentiometric titration of CI with silver nitrate according to ASTM C 1152-12, and ASTM C 114-15, part 19. The cross-sectional area of a 45 mm diameter core was large enough to represent the concrete and limit the sample to sample variations due to varying aggregate contents. More details can be found in other publications [23,24].

4. Results and discussion

4.1. Evolution of maximum phenomenon

Time-dependent CI profiles for the samples with varying w/b and SF contents are presented in Fig. 3. These CI profiles were obtained after 3, 36, and 60 months of exposure in tidal zone of marine environment. Based on Fig. 3, the maximum phenomenon appears in all samples after 60 months of exposure, while this phenomenon occurs in about half and none of the samples after 36 and 3 months, respectively. This reveals the fact that the presence of maximum phenomenon or non-Fickian trend is time-dependent. This data presents that CI concentration was almost constant in the skin layer or the region of maximum phenomenon. As mentioned earlier, the absorption–desorption/evaporation process can be the crucial factor in occurrence of this phenomenon in tidal zone under cyclic drying and wetting condition.

In addition, Fig. 3 shows that both the skin layer thickness (Δx) and the maximum CI concentration (Cmax) are evolving with time. Based on CI profiles, Cmax moves inward and its value increases over the exposure time. This finding answers the previous uncertainties regarding the Cmax and Δx trend with time. Fig. 4 exhibits the time-dependent box and whisker plot of Cmax and Δx. It is worth to mention that Δx is an approximate interval that covers the area around the measured peak concentration (Fig. 1). Based on Fig. 4, the median and mean Cmax exhibit an approximate increase of 35% between 36 and 60-month exposure times. The average surface CI build-up rate was about 0.014% of the mass of concrete per month. This is consistent with the results from previous studies in the Persian Gulf region [23]. Moreover, the median Δx in 60-month samples is 6 times higher than the 36-month samples. For the 36-month observations, the Δx was limited to 8.5 mm. However, this thickness increases to 13 mm after 60 months.

4.2. Influence of concrete matrix on maximum phenomenon

Fig. 5 presents the CI concentration profiles of concrete mixtures with varying w/b and SF contents after 60 months of exposure to tidal zone. In addition, the calculated Δx of 60-month samples versus w/b and SF content is shown in Fig. 6. Based on the presented results, it was concluded that the Δx mainly increases with an increase of w/b and a decrease of SF percentage. This reveals the fact that in addition to the environmental conditions, the concrete mixture design parameters can play an important role in occurrence of maximum phenomenon. On average a 50% decrease in thickness of maximum phenomenon was observed for the mixtures made with w/b of 0.35 when compared to the ones with w/b of 0.50. In addition, the use of 12.5% SF in concrete mixtures resulted in approximate decrease of 30% in the measured Δx while compared to the mixtures with 5% SF. This can be attributed to the higher total porosity of mixtures with high w/b and low SF. Higher porosity promotes deeper penetration of salt solution due to the higher connectivity of the pore system, which leads to the greater Δx [5]. In addition, Song et al. [21] observed that the concrete samples with higher w/b are most prone to form a thicker porous cement paste layer on the concrete surface due to wall effect during concrete casting. Therefore, this can also cause a larger Δx in the surface of concrete.

4.3. Impact of maximum phenomenon on service-life prediction

Eq. (6) was applied to explore the presence of the maximum phenomenon in simulating the long-term CI concentration profiles and consequently in service-life prediction based on early age field results. In this study, early age CI transport profiles (3–36 months)
were used to determine the unknown variables of Eq. (6). Then, the 60-month Cl profiles were predicted for different mixtures with and without considering the maximum phenomenon. Finally, the predicted profiles were compared to the measured results from the field.

The 3-month CI diffusion coefficients and surface CI concentrations were considered as $D_{ref}$ and $C_{ref}$ in Eq. (6), respectively. This information is tabulated in Table 4 for different mixtures. The diffusion decay coefficient was also calculated by fitting the early age diffusion coefficients into the Eq. (4), and the $m$ values were
Fig. 5. Cl concentration profiles of concrete mixtures with varying w/b and SF contents after 60 months of exposure in tidal zone.

Fig. 6. The influence of (a) w/b ($R^2 = 0.53$) and (b) SF content ($R^2 = 0.36$) on maximum phenomenon thickness after 60 months of exposure.

Table 4
Input parameters for the simulation and the calculated MAE.

<table>
<thead>
<tr>
<th>SF</th>
<th>w/b</th>
<th>m</th>
<th>$C_{wloi}$ %</th>
<th>$D_{ref} \times 10^{-12}$, m$^2$/s</th>
<th>MAE, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>0.35</td>
<td>0.422</td>
<td>0.11</td>
<td>1.02</td>
<td>0.039</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>0.240</td>
<td>0.35</td>
<td>0.99</td>
<td>0.072</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>0.239</td>
<td>0.23</td>
<td>2.04</td>
<td>0.112</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>0.508</td>
<td>0.64</td>
<td>4.92</td>
<td>0.061</td>
</tr>
<tr>
<td>7.5%</td>
<td>0.35</td>
<td>0.250</td>
<td>0.08</td>
<td>0.49</td>
<td>0.087</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>0.256</td>
<td>0.31</td>
<td>1.67</td>
<td>0.085</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>0.241</td>
<td>0.25</td>
<td>1.26</td>
<td>0.039</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>0.569</td>
<td>0.38</td>
<td>3.41</td>
<td>0.009</td>
</tr>
<tr>
<td>10%</td>
<td>0.35</td>
<td>0.287</td>
<td>0.36</td>
<td>0.53</td>
<td>0.054</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>0.256</td>
<td>0.26</td>
<td>1.22</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>0.241</td>
<td>0.36</td>
<td>1.07</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>0.534</td>
<td>0.77</td>
<td>4.08</td>
<td>0.065</td>
</tr>
<tr>
<td>12.5%</td>
<td>0.35</td>
<td>0.280</td>
<td>0.17</td>
<td>0.33</td>
<td>0.043</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>0.211</td>
<td>0.41</td>
<td>1.52</td>
<td>0.101</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>0.240</td>
<td>0.42</td>
<td>1.64</td>
<td>0.069</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>0.224</td>
<td>0.44</td>
<td>1.86</td>
<td>0.096</td>
</tr>
</tbody>
</table>
summarized in Table 4. More details can be found in other publications [28]. In addition, the k coefficient of 0.008% mass/month was used in service-life prediction according to previous study by Khanzadeh Moradllo et al. [23]. The calculated $D_x$ values were used to consider the impact of the maximum phenomenon.

The predicted Cl profiles of different mixtures with and without considering the maximum phenomenon and the comparison with the measured results are presented in Fig. 7. The predicted Cl profiles with consideration of maximum phenomenon exhibited good agreement with measured field data. It was observed that neglecting the maximum phenomenon occurrence results a large discrepancy between the estimated and measured Cl profiles. This uncertainty can cause a significant overestimation in predicted service-life of concrete structures.

The mean absolute error (MAE) for the predicted values with consideration of the maximum phenomenon for different mixtures was calculated using Eq. (7) [27]. Results were summarized in Table 4.

$$MAE = \frac{\sum |\hat{y} - y|}{n}$$

where $\hat{y}$ is the simulated Cl concentration; $y$ is the measured Cl concentration; and $n$ is the number of data points used in the analysis.

Based on the data presented in Table 4, an average MAE of 0.06% is another evidence for the good agreement between the measured and simulated Cl profiles while taking into account the maximum phenomenon. This observation again confirms the importance of considering the maximum phenomenon in service-life prediction of concrete structures.

5. Conclusions

The study summarized in this paper characterizes and quantifies the “maximum phenomenon” (non-Fickian Cl penetration) in concrete samples with sixteen different combinations of w/b and SF contents. The investigated concrete mixtures were exposed to tidal zone of marine environment for five years. Additionally, this work quantifies the evolution of the maximum phenomenon with time and the influence on service-life prediction of concrete structures by using field data. Based on the obtained data, the following conclusions can be drawn:
1. The results show that the presence of maximum phenomenon is time-dependent. The maximum phenomenon appears in all of sixteen mixtures after 60 months of exposure in tidal zone, while this phenomenon only occurs in half of the samples after 36 months.

2. Both the maximum phenomenon thickness (Δx) and the maximum Cl concentration (C_{max}) are evolving with time. A median C_{max} and Δx show about 35% and 102% increase between 36 and 60 month exposure times.

3. The Δx was limited to 8.5 mm of concrete surface after 36 months of exposure. However, this layer thickness increased to 13 mm after 60 months.

4. It was observed that the modifications in concrete mixture design can affect the formation of the maximum phenomenon. Samples with w/b of 0.35 showed in average a 50% decrease in thickness of maximum phenomenon compared to the samples with w/b of 0.50. This can be attributed to the higher total porosity of mixtures with high w/b.

5. An average MAE of 0.06% was observed for the simulated values with consideration of maximum phenomenon. This shows good correspondence between the measured and simulated Cl profiles with consideration of maximum phenomenon, while neglecting the maximum phenomenon occurrence leads to a large discrepancy between the estimated and measured Cl profiles. This will cause a significant overestimation in predicted service-life of concrete structures.

These long-term field experiments allowed critical insights into the evolution of maximum phenomenon in varying concrete mixtures exposed to tidal zone of marine environment. This work shows the importance of considering the maximum phenomenon in service-life prediction of concrete structures, and it highlights the need to establish service-life prediction models and concrete durability specifications which take the maximum phenomenon presence into consideration.

Conflicts of interest statement

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Acknowledgment

The authors gratefully acknowledge the financial support from the Construction Materials Institute (CMI) at University of Tehran.

References


