Prediction Of Chloride Penetration Into Concrete Exposed To Various Exposure Environments

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Summary: This paper presents the results from a study of prediction model for chloride penetration into concrete exposed to various exposure environments including alternative wet-and-dry environment. A few years ago, a scientific model called ClinConc was developed from our previous work. The model is essentially based on the current knowledge of physical and chemical processes involved in the chloride transport and binding in concrete and has been verified by using the field data from one to five years exposure under seawater. In this study, the model is further developed for the application to alternative wet-and-dry environment, such as splash zone and road environment.

The actual chloride profiles measured from the field exposure stations are used to verify the modified model. The predicted results are in general fairly well in agreement with the field data, especially the shapes of chloride profiles from alternative wet-and-dry environments. The limitations and needs for further improvement of the latest version of the model are discussed.

Keywords. Chlorides, concrete, modelling, prediction.

1 INTRODUCTION

The numerical model ClinConc (Cl in Concrete) for prediction of chloride penetration into concrete was first presented in the middle of 1990’s (Tang & Nilsson 1994; Tang 1995). The model consists of two main procedures:

1. Simulation of free chloride penetration through the pore solution in concrete using a genuine flux equation based on the principle of Fick’s law with the free chloride concentration as the driving potential, and
2. Calculation of the distribution of the total chloride content in concrete using the mass balance equation combined with non-linear chloride binding.

Not like other models, a unique character of the model ClinConc is that the chloride diffusivity, which can be determined by, e.g. the Nordtest method NT BUILD 492 (Nordtest 1999), is considered as a material property. It changes only when concrete is young, like many other material properties, such as porosity and strength. After an age of a half of year, this diffusivity becomes more or less constant according to the experiments (Tang & Nilsson 1992; Tang 1996). Another unique character of the model ClinConc is that the climatic parameters, such as chloride concentration and temperature, are used in both the flux and the mass balance equations. Therefore, the model can well describe the effects of exposure conditions on chloride penetration.

The original version of ClinConc was developed based on the field data up to two years exposure under seawater. Due to the difficulties in combining moisture transport, the application of the original ClinConc was limited to submerged zone only. When five-years field exposure data were available (Andersen et al 1998), it was found that the original ClinConc underestimated the chloride content in the zone closer to the exposure surface, even though it predicted the penetration depth fairly well. In other words, the surface chloride content tends to increase with exposure time even under submerged conditions. This increased chloride content cannot be explained by drying-and-wetting effect, like in the splash zone. Time-dependent chloride binding might be a potential reason, since the chloride binding isotherms used in the original ClinConc were those obtained in the laboratory after about two weeks equilibrium (Tang & Nilsson 1993). The effect of alkalinity on chloride binding was also based on a limited investigation (Sandberg & Larsson 1993). In reality, the pore solution compositions may change due to leaching and penetration of different substances, resulting in different characteristics of chloride binding. Another possible reason is an increased saturation degree of the air voids near the surface. The saturation degree of the air voids will increase after such a long period of immersion, especially in contact with a salt solution. It is difficult, however, to
model the saturation degree of the air voids. Therefore, the time-dependent chloride binding was assumed as a dominant reason for the increased chloride contents in the surface zone (Tang & Nilsson 2000). After this modification, the agreement between modelled and measured chloride profiles becomes better (Tang & Nilsson 2000b).

Very recently, the model ClinConc was modified again in order to make it applicable to various exposure environments including alternative wet-and-dry ones. In fact, nothing except for the exposure conditions has been modified in the latest modification. This paper present this latest modification and the verification of the model using chloride profiles measured from the fields under various exposure environments.

2 MODELLING FOR VARIOUS EXPOSURE ENVIRONMENTS

2.1 Exposure Conditions for Marine Environment under Submerged Zone

Under submerged zone, concrete is constantly in contact with seawater. This might be the easiest case when compared with other exposure environments. However, since both temperature and chloride concentration in seawater change with time, even in this easiest case it is still difficult to use constant boundary conditions for chloride transport in concrete. In the previous versions, both the exposure temperature and chloride concentration were assumed as a sine function. The sine function of annual average temperature has been well verified, but not the chloride concentration in seawater. Therefore, it was suggested in the latest version that average chloride concentration in seawater should be used unless the actual function of chloride concentration is known. An example of the exposure conditions for submerged zone is shown in Fig. 1.

2.2 Exposure Conditions for Marine Environment above Seawater

In the marine environment above seawater, such as splash zone or atmospheric zone, concrete is subjected to alternative wetting-and-drying. The wetting includes both salt water and rain. Owing to the complicated mechanisms involved in both the moisture and chloride transport, it is not an easy task to combine both moisture and chloride transports into a single model, even though some attempts have been done (Nilsson 2000; Francy et al 1996). On the other hand, it could be reasonable to assume that, under such a wet-and-dry environment, the chloride concentration in contact with the concrete surface alters between zero and a specified level. The wick effect due to drying is compensated by the effect of capillary suction due to rewetting. Therefore, the chloride transport could be assumed dominated by diffusion in a saturated pore system, despite of wetting-and-drying processes. In this way, the difficulties in modelling of moisture transport could be skipped and the question becomes how to define the chloride concentration curve. In the latest modification, a statistic normal distribution function was proposed to describe the annual chloride concentration, that is,

\[ c_{\text{obs}} = \bar{c}_0 \exp \left( -\frac{\tau^2}{2\sigma^2} \right) \]  

(1)

where \( c_{\text{obs}} \) is the chloride concentration in contact with the concrete surface, \( \bar{c}_0 \) is the average annual chloride concentration in seawater, \( \sigma \) is the standard deviation that will be explained later, and \( \tau \) is the time difference, which is a periodic function and expressed as

Figure 1. Example of exposure conditions for submerged zone (Swedish west coast).
where $t$ is the actual time, $L$ is the period, $t_m$ is the time when the chloride concentration reaches maximum during the period, and $n$ is the integral of $t/L$.

The standard deviation $\sigma$ is a decisive parameter to the width of a statistic normal distribution curve and can be expressed as

$$\sigma = \frac{L_{Cl}}{\tau \sigma}(3)$$

where $L_{Cl}$ is the chloride duration during the period ($L_{Cl} \leq L$), and $\sigma$ ($= 0.15$) is the standard deviation of $\tau$. It should be noticed that the time difference $\tau$ is a dimensionless parameter, implying that $t$, $L$, $t_m$, and $L_{Cl}$ must have the consistent dimension, which could be hours, days or months. Since the actual repetition of chloride concentration in splash zone is unknown, $L$ was simply assumed to be 12 months, that is, annually repeated in order to simplify the calculation. In this case the sine function of temperature is inapplicable, thus an average annual temperature should be used. Some examples of exposure conditions for the marine environment above seawater are given in Figs. 2 and 3.

<table>
<thead>
<tr>
<th>Chloride Concentration</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual minimum 0 gCl/l</td>
<td>Annual minimum 11 °C</td>
</tr>
<tr>
<td>Annual maximum 14 gCl/l</td>
<td>Annual maximum 11 °C</td>
</tr>
<tr>
<td>Annual Cl period 12 months</td>
<td>Frequency 1 cycles/year</td>
</tr>
<tr>
<td>Max. in the month 10 (number)</td>
<td>First mean at days of year</td>
</tr>
</tbody>
</table>

Figure 2. Example of exposure conditions for splash zone (0–30 cm above seawater in Swedish west coast).

<table>
<thead>
<tr>
<th>Chloride Concentration</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual minimum 0 gCl/l</td>
<td>Annual minimum 11 °C</td>
</tr>
<tr>
<td>Annual maximum 14 gCl/l</td>
<td>Annual maximum 11 °C</td>
</tr>
<tr>
<td>Annual Cl period 6 months</td>
<td>Frequency 1 cycles/year</td>
</tr>
<tr>
<td>Max. in the month 7 (number)</td>
<td>First mean at days of year</td>
</tr>
</tbody>
</table>

Figure 3. Example of exposure conditions for atmospheric zone (30–60 cm above seawater in Swedish west coast).
2.3 Exposure Conditions for Road Environment Using De-Icing Salt

The same principles as described above can be used for the road environment. Thus the chloride concentration in contact with concrete surface is

\[ c_{\text{de}} = c_{\text{max}} \exp \left(-\frac{\tau^2}{2\sigma^2}\right) \]  

(4)

where \( c_{\text{max}} \) is the maximum chloride concentration during the period. The difference from the marine environment is that the chloride period (application of de-icing salt) is a more or less known parameter under the road environment, for instance, from November to March in the winter. Thus the sine function of temperature can be applied as in reality. However, the maximum chloride concentration \( c_{\text{max}} \) in this case becomes unknown. From the field data obtained from the two winters exposure along the highway Rv 40 between Borås and Göteborg it was found that, when assuming a maximum concentration of 50 g Cl per litre, the predicted profiles correspond fairly well with the field data, which will be presented later. An example of exposure conditions for the road environment is shown in Fig. 4.

![Figure 4](https://example.com/figure4.jpg)

Figure 4: Example of exposure conditions for a road environment (Highway Rv 40 between Borås & Göteborg, Sweden)

3 VERIFICATIONS OF THE LATEST MODIFIED MODEL

From two Swedish national projects, many chloride profiles obtained after five years exposure under the marine environment and after two winters exposure under the road environment are available (Andersen et al 1998; Lindvall et al 2000). The chloride profiles from two types of binder and two water-binder ratios, which are commonly used in Sweden for infrastructures, were utilised to verify the latest modified ClinConc. The mixture proportions of concrete and relevant properties are given in Table 1, and the common parameters used in the calculation are listed in Table 2. The exposure conditions are as shown in Figs. 1 to 4. The results are shown in Figs. 5-8. Considering the very complicated mechanisms of chloride transport in concrete, we can conclude that the predicted results are in general fairly well in agreement with the field data, especially the shapes of chloride profiles from alternative wet-and-dry environments. This implies that the assumptions made in the latest modification for various exposure environments are reasonable and close to the reality.

<table>
<thead>
<tr>
<th>Binder type</th>
<th>Water-binder ratio</th>
<th>Cement content kg/m³</th>
<th>Aggregate kg/m³</th>
<th>Air content kg/m³</th>
<th>Diffusivity ( D_{\text{CTH}} ) m²/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRPC 0.40</td>
<td>0.40</td>
<td>420</td>
<td>1692</td>
<td>6.0</td>
<td>8.1×10⁻¹²</td>
</tr>
<tr>
<td>SRPC 0.50</td>
<td>0.50</td>
<td>370</td>
<td>1689</td>
<td>6.4</td>
<td>19.9×10⁻¹²</td>
</tr>
<tr>
<td>95%SRPC + 5%CSF 0.40</td>
<td>0.40</td>
<td>420</td>
<td>1685</td>
<td>5.9</td>
<td>2.7×10⁻¹²</td>
</tr>
<tr>
<td>95%SRPC + 5%CSF 0.50</td>
<td>0.50</td>
<td>370</td>
<td>1683</td>
<td>6.0</td>
<td>13.4×10⁻¹²</td>
</tr>
</tbody>
</table>

* Determined by the CTH method (NT BUILD 492) at an age of about 180 days.
Table 2. Common parameters used in the calculation

<table>
<thead>
<tr>
<th>Chloride Binding</th>
<th>Variable Diffusivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotherm slope ( f_b = 3.57 )</td>
<td>Activation energy ( E_b = 40000 ) J/mol</td>
</tr>
<tr>
<td>Non-linear exponent ( B = 0.38 )</td>
<td>Age dependent ( \beta_t = 0.152 (w/b)^{0.6} )</td>
</tr>
<tr>
<td>Activation energy ( E_b = 40000 ) J/mol</td>
<td>Depth dependent ( t_{D_a} = 180 ) days</td>
</tr>
<tr>
<td>Time-dependent factor ( f_t = 0.36\ln(t_{Cl} + 0.5) + 1 ), ( t_{Cl} ) is the local chloride contamination time in years.</td>
<td>None (steel form)</td>
</tr>
</tbody>
</table>

4 LIMITATIONS AND NEEDS FOR FURTHER IMPROVEMENT

Although the verification results show a good agreement with the field data, there still exist the following limitations:

- **Limited concrete type** In the above verification, the concrete type is limited to two water-binder ratios (0.4 and 0.5) and two types of binder (SRPC and 5% silica fume). Although these two types of concrete are very commonly used in Sweden for infrastructures, more types of concrete, especially HPC with low water-binder ratios and different types of binder, such as fly ash, slag, etc., should be used for verification.

- **Limited exposure time** So far the available data from the field exposure stations are limited to 5 years for marine environment and 2 years for road environment. This exposure time is relatively short when compared with the whole service life of concrete structures. More data from the long term exposure fields, especially with traceable exposure environments, are needed for a better verification.

- **Characterising exposure environment** In the latest modifications of the model, the alternative wet-and-dry environment is described using statistic normal distribution functions. The question is how to determine the key parameters \( L_{Cl} \) – chloride duration for marine environment in equation (3) and \( c_{max} \) – maximum chloride concentration for road environment in equation (4). Some simple methods are needed for characterising different exposure environments.
Figure 5. Example of the predicted chloride profiles. SRPC w/b 0.40.
Figure 6. Example of the predicted chloride profiles. SRPC, w/b 0.50.
Figure 7. Example of the predicted chloride profiles. SRPC + 5% CSF, w/b 0.40.
Figure 8. Example of the predicted chloride profiles. SRPC + 5% CSF, w/b 0.50.
5 CONCLUSIONS

The latest modification has made the model ClinConc applicable to both the marine environment, including submerged, splash and atmospheric zones, and the road environment using de-icing salt in the winter. The verifications up to five-years marine exposure data and two-winters road exposure data show that the predictions of chloride penetration into concrete structures are, in general, fairly well in agreement with the measured chloride profiles.

The exposure environment can be described by the combination of temperature and concentration functions. The former can be expressed as a sine function, while the latter expressed by a statistic normal distribution function. With such a combination, the chloride ingress into concrete under various environments could be approximated by diffusion in a saturated pore system, thus the actual wetting-and-drying processes could be skipped.

There is an urgent need to develop some simple methods for characterising different exposure environments.

6 REFERENCES