1 INTRODUCTION

Concrete is a popular material for civil engineers, as it is cheap, easily shaped and easy to be made everywhere. However, more care is required during its making, casting and curing, without which repair is needed after few years of service due to poor design or material, or environmental loads which are not included in the structural design or a combination of these causes. This problem is much more severe in marine environments of hot regions and is one of the challenges for civil engineers in the current decade (Ghoddusi et al. 2000).

In many cases, at the Persian Gulf, even structures which are in compliance with Iranian concrete code advice, were observed to express corrosion problems in early age of their service life. In order to solve this problem, beside changing the code requirements in respect of durability, one should represent methods of durability based design so that to find the most economical solution according to the desired service life for reinforced concrete structures (Ghalibafian et al. 2003, 2004).

During the past decades, many physical and mathematical models have been introduced to calculate the chloride diffusion parameters into concrete and to estimate the time to corrosion initiation and propagation. The first numerical model of this kind was developed by Collepardi, in which he employed the Fick’s second law of diffusion and indicated that diffusion coefficient is one of the most important parameters in service life prediction. Tutti’s model was one of the first attempts to predict the service life of RC structures. As shown in Figure 1, the concept of this model is to divide the service time of the structure into \( T_0 \) (\( t_{\text{init}} \)), as the time to corrosion initiation, and \( T_i \) (\( t_{\text{prop}} \)), as the time of corrosion propagation until failure occurs (Taheri 1998).

Figure 1. Schematic illustration of Tutti’s model for corrosion process of steel in concrete.
2 EXPERIMENTAL PROGRAM

Concerning the fact that there was few data available for concrete durability studies specially regarding the chloride diffusion in Persian Gulf region, a complete set of field experiments were conducted in order to investigate the effect of different parameters on chloride diffusion such as water to cement ratio, silica fume content, curing condition, exposure condition, environment temperature and surface coating. These experiments were a part of a national project on the durability of concrete in Iran (Chini et al. 2004).

In this project, 120 prism specimens measuring 15 x 15 x 60 cm were exposed to marine environment of Bandar Abbas city in Persian Gulf. After 3 and 9 months of exposure, 10 cm part of specimens was cut for preparing the chloride profile and measuring the chloride ion content in different depths from the surface (Fig. 2). Then, by curve fitting of chloride profiles of each specimen to Fick’s second law of diffusion (Crank 1975), data for diffusion coefficient and surface chloride content were calculated, which were used as the input for training DuraPGulf model.

3 NUMERICAL MODELING

DuraPGulf employs advanced mathematical concepts for analyzing input data in order to predict Diffusion Coefficient (Dc) and Surface Chloride Content (Cc) values for new cases. Moving Least Squares method (MLS) was used for data regression. According to this method for each set of new input data in the n-dimensional space of primary data, a regression is conducted so that the nearby primary data have the highest effect on the final output (i.e. diffusion coefficient and surface chloride content). According to the Figure 3, in the Moving Least Squares approach the weighting function \( \phi \) is defined in shape and size, and is translated over the domain so that it takes the maximum value over the point \( k \) identified by the coordinate \( x_k \) where the unknown function \( \hat{u} \) is to be evaluated. The weight factor in this regard, which influences the effect width, can be calibrated after trial and error for new set of experiments (Lancaster & Salkauskas 1981).

After estimating the values of diffusion and surface chloride content, using Finite Element Method, the supposed structural element is meshed and subsequent calculations to solve the differential equations of the diffusion of chloride ion into concrete based on Fick’s second law of diffusion are conducted over time as in Equation 1:

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

where \( D_c \) is the chloride diffusion coefficient and \( C \) is the chloride content at the depth of \( x \) from the surface at the time \( t \) (Crank 1975). Finite Element Method was used in order to be able to enhance the model for various purposes such as taking the effect of surface coatings into account in the next versions simply.

The time, at which chloride content on the reinforcement surface reaches the chloride threshold value, is considered as the corrosion initiation time. In the first version of DuraPGulf, 0.05% of total concrete weight is taken as chloride threshold value. Employing Arrhenius equation (Eq. 2), the effect of temperature is considered on the diffusion coefficient for different months during the year (Page 1981):

\[
\frac{D_T}{D_0} = \exp \left[ \frac{U}{R} \times \left( \frac{1}{T_0} - \frac{1}{T} \right) \right]
\]

where \( T \) and \( T_0 \) are temperature in Kelvin degree, \( R \) is the gas general constant value and \( U \) is the activation energy of the diffusion process. A special value of 2948 for \( U/R \) was suggested in this study for DuraPGulf based on the experiments at the Construction Materials Institute (Chini et al. 2004).
4 PROGRAMMING

For data regression and analysis according to the mathematical methods mentioned earlier, the basic part of DuraPGulf was programmed using FORTRAN. Finite Element Method calculations are also used in this basic part. For the other part, in order to have a user-friendly software, the graphic user interface (GUI) of DuraPGulf was written by Visual Basic, through which all input and output data are transmitted to and from the basic part.

5 EXAMPLE

A typical reinforced concrete structure as a marine wall is supposed to be built in Bandar Abbas city near Persian Gulf. The main concrete mixture proportioning is according to Table 1. Concrete cover of the RC wall, which is in tidal zone, is assumed to be 5 cm. Temperature diagram of Bandar Abbas is also shown in Figure 4. Concrete wall was cured for 3 days after demolding at age of 24 hours.

These parameters were inputted into the program. After running DuraPGulf, the calculated diffusion coefficient and surface chloride content are $9.03 \times 10^{-12}$ m$^2$/s and 0.8% wt, respectively. The corrosion initiation time is also calculated to be 1.4 years, which is very low and shows the severity of this area. Typical GUI of DuraPGulf is shown in Figures 5, 6.

Owner of this structure requires at least 20 years of service without need to repair. So the software is run again changing previous assumptions for the input data to 7 days of curing, reducing W/C to 0.35 and 0.30, using 7.5% of silica fume and 7 and 10 cm of concrete cover as new choices (Table 1). For these changes, DuraPGulf estimates a new value for diffusion coefficient and calculates service life years until corrosion initiation (Table 2). Now, the owner or the consultant engineer can decide on the most economical design for the structure which is designed according to durability concept.

For this case, only the 5th choice meets the service life requirements considering the fact that 10 cm of cover should be applicable from the structural point of view. However, if the corrosion propagation time till the first repair is assumed to be 6 years, 4th choice

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### Table 1. Concrete mixture proportion (Kg/m$^3$)*

<table>
<thead>
<tr>
<th>Main</th>
<th>O1</th>
<th>O2</th>
<th>O3</th>
<th>O4</th>
<th>O5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
</tr>
<tr>
<td>Sand</td>
<td>740</td>
<td>740</td>
<td>740</td>
<td>740</td>
<td>740</td>
</tr>
<tr>
<td>Cement</td>
<td>400</td>
<td>400</td>
<td>370</td>
<td>400</td>
<td>370</td>
</tr>
<tr>
<td>Water</td>
<td>160</td>
<td>120</td>
<td>160</td>
<td>160</td>
<td>140</td>
</tr>
<tr>
<td>Silica fume</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Curing (days)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Cover (cm)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

* In all mixtures, adequate plasticizer should be added in order to achieve the desired workability.
could also be considered as it would result almost in 20 years of service life without need to repair.

6 CONCLUSIONS AND REMARKS

Durability based design of RC structures has received a great concern in the recent decades. In Iran, the need for a model for service life design of concrete structures in Persian Gulf region is highly necessary. In this order, DuraPGulf has been developed based on the local data of this environment which would help engineers to design RC Structures with a better view and understanding of the durability performance.

For the next version of DuraPGulf software, it is planned to study three other important parameters; load-environment combination, chloride threshold value and propagation time. Incidentally, probabilistic approach in the whole procedure would be taken into the account.

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REFERENCES


Table 2. Predicted values for service life.

<table>
<thead>
<tr>
<th></th>
<th>Main</th>
<th>O1</th>
<th>O2</th>
<th>O3</th>
<th>O4</th>
<th>O5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion</td>
<td>9.03</td>
<td>6.21</td>
<td>3.56</td>
<td>9.03</td>
<td>2.61</td>
<td>2.61</td>
</tr>
<tr>
<td>coefficient</td>
<td>(x10^{-12})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrosion</td>
<td>1.4</td>
<td>2.1</td>
<td>4.1</td>
<td>3.0</td>
<td>13.6</td>
<td>33.8</td>
</tr>
<tr>
<td>Initiation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (years)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>