EVALUATION OF THE CORROSION AND STRENGTH OF CONCRETE EXPOSED TO SULFATE SOLUTION

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ABSTRACT

This paper is part of an experimental and theoretical research that leads to evaluate the effect of sulfate solution on mechanical properties of concrete. To study the strength characteristics, the concrete cube samples of 100 mm size with water/cement ratio 0.4 and 0.5 were cast. The concrete cubes were kept in standard curing conditions and 5% sodium sulfate solution for 18 months. Then the cubes were tested for compressive strength. Some expressions were presented to calculate corrosive parameters and the effect of sulfate solution on the strength behavior of concrete. The test results confirmed the validity of the introduced method.

Keywords: sulfate solution, compressive strength, corrosion

1. INTRODUCTION

Reinforced concrete structures in coastal areas like Caspian sea or Persian gulf are under influence of the corrosive and aggressive environments including sulfates. Many examples of corrosion of concrete structures in these regions can be clearly seen. Safety and stability of the reinforced concrete structures is highly important. Although a number of methods and recommendations have been proposed for corrosion prevention and protection of the concrete structures, however in different constructional codes and standards of the world (including Iran) the effect of the concrete corrosion on the loading capacity of members and other important parameters have not been considered.

During the recent years, numerous researchers have discussed the effect of aggressive environments on reinforced concrete structures. Many of them have considered the corrosion

Sulfate environments may have negative effect on the structures such as foundations, retaining walls, basins and storage floors, concrete reservoirs in chemical industries, marine structures, etc.

In previous studies, the concrete samples were exposed under the influence of aggressive environments from one direction. The author has studied the effect of sulfate solutions which exposed from three directions on the reinforced concrete structures as well as the changes in the parameters of physical and mechanical properties of concrete. In that research, the section of the two-span reinforced concrete beam has been exposed to sodium sulfate solution from bottom and lateral sides. The results of this study are not presented here for lack of space but are available elsewhere (Mohebimoghaddam, 2001, 2006).

In present paper the concrete cube samples were elaborated with water/cement ratio 0.4 and 0.5. Eighteen concrete samples kept in standard curing conditions and in a 5% (Na2SO4) solution for 540 days, respectively. Concrete samples were then tested for compressive strength. Also theoretical investigations were performed to introduce equations relating to the influence of the sulfate solution on the compressive strength of concrete. Considering the environment and amount of sulfate ions incoming to the concrete, corrosion parameters were discussed.

2. MATERIAL AND METHODS

Ordinary Portland cement with 8mm maximum coarse aggregate size and fine aggregate (medium-sized natural sand) were used for preparation of concrete mixture. Two different mixtures were prepared with water/cement ratio from 0.4 and 0.5. The mixing water was obtained from the drinking water network. Material quantities for each concrete mixture are shown in table 1.

<table>
<thead>
<tr>
<th>Materials (kg)</th>
<th>water/cement ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Water</td>
<td>200</td>
</tr>
<tr>
<td>Cement</td>
<td>500</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>1300</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>500</td>
</tr>
</tbody>
</table>

Table 1. Proportioning of concrete mixtures (for 1 m3)

Forty two concrete cubes (100x100x100 mm³) were cast for testing the compressive strength. The concrete cubes were cured in the moulds and covered with burlap at 20°C.
for 48 hours. Then they were demolded and kept in a standard curing room for 28 days.

The concrete samples were studied in four separate groups. The variables included the influence environments (standard curing conditions and 5% sodium sulfate solution) and different concrete mixtures. In situ conditions were represented approximately by lower concentrations up to 0.5%. The higher concentrations was chosen to accelerate concrete deterioration process.

The samples were exposed to the influence environments for 540 days. Those samples were immersed in a 5% (Na$_2$SO$_4$) solution, exposed to the solution from three directions (two lateral and bottom sides), so the upper surfaces of the samples were isolated. After 28 days, three concrete cubes from each concrete mixture were tested for compressive strength.

Then the samples were put in mentioned environments for 18 months. Three concrete cube samples from each group were selected after 180, 365 and 540 days and taken to the laboratory, cleaned and tested for compressive strength.

3. ANALYTICAL INVESTIGATION

To evaluate the effect of sulfate solution on the concrete elements, the cross section of the element is divided into a number of layers of equal dimensions in x and y directions. Obviously, the smaller the dimensions of the layers are, the higher the accuracy of the calculations would be. To expose the sodium sulfate solution from three directions (bottom and lateral sides), the upper surfaces of the concrete samples were insulated to prevent from penetration of the sulfate solution in the concrete.

3.1. Compressive strength

To consider the sulfate solution effects on the concrete compressive strength, the following equation is used as (Savitski, 1994):

\[
\sigma_c(t) = \prod \gamma_i(t) \sigma_c
\]

where, \( \prod \gamma_i(t) \) calculates from here:

\[
\prod \gamma_i(t) = \gamma_{cs}(t) \gamma_{ch}(t) \gamma_{cl}(t) \gamma_{ca}(t)
\]

where, \( \gamma_{ca}(t) \) is the performance coefficient of decreasing in the concrete strength due to surface absorption during ponding, which is considered as 0.7.

\( \gamma_{ch}(t) \) is the performance coefficient of the cement paste hydration process during the time (t) which equals to:
\[ \gamma_{ch}(t) = \begin{cases} 1+1.43t & 0 \leq t \leq 1 \\ 1.43 & t > 1 \end{cases} \]

\( \gamma_{cl}(t) \) is the performance coefficient of the effect of loading process on the concrete strength which is considered as equal to unit.

\( \gamma_{cs}(t) \) is the performance coefficient of simultaneous effect of the environment active components and the cement paste during the time (t) which equals to:

\[ \gamma_{cs}(t) = 1 + 0.05Q_{SO3}(t)[1 - 0.14Q_{SO3}(t)] \]

\( Q_{SO3}(t) \) is the sulfate ions volume in each point of the section during the time (t), which with (x_1, x_2, y) coordinates equals to:

\[ Q_{SO3}(x_1, x_2, y, t) = Q_{SO3,0} + Q_{SO3}(y = 0) \left[ 1 - \left( 1 - \frac{x_1}{Y(t)} \right)^2 \right] \left[ 1 - \left( 1 - \frac{x_2}{Y(t)} \right)^2 \right] \left[ 1 - \left( 1 - \frac{y}{Y(t)} \right)^2 \right] \]

### 3.2. Corrosion parameters

The diffusion speed of the sulfate ions in the concrete depends on numerous factors including concentration of the sulfate environments, cement chemical combination, volume and type of the chemical admixtures and water/cement ratio.

To evaluate a reinforced concrete structure under the effect of aggressive environments, the corrosion parameters’ value (Fig.1) should be calculated as (Gouziev, et al, 1990).

The diffusion depth of sulfate ion through time is obtained from the following equation:

\[ Y(t) = k_c \cdot C_s^{0.5} \eta_i(\alpha)^{0.28} \]

where \( \eta_i \) is coefficient for considering the cement chemical combination, type and volume of the chemical admixtures and water/cement ratio.
The depth of totally devastated concrete through time is gained from the following equation:

\[ Y_2(t) = k_z \cdot C_s^0 \cdot \eta \left[ (\alpha t)^{0.28} - (\alpha_0 t)^{0.28} \right] \]

The depth of the weakened layers through time is gained from the following equation:

\[ Y_1(t) = Y(t) \left( 1 - \frac{Q_{SO3,1}}{Q_{SO3,0}} \right) \quad \text{if} \quad Q_{SO3,0} \leq Q_{SO3,u} \]

\[ Y_1(t) = (Y(t) - Y_2(t)) \left( 1 - \frac{Q_{SO3,1}}{Q_{SO3,0}} \right) - Y_2(t) \quad \text{if} \quad Q_{SO3,0} > Q_{SO3,u} \]

In Fig.2 has been shown the concrete corrosion parameters during 25 years.
Fig. 2 Concrete corrosion parameters through the time (t).

Fig. 3 Concrete compressive strength versus time:

- A-samples kept in standard conditions
- S-samples kept in 5% (Na$_2$SO$_4$) solution
- I, II- samples with water/cement ratio of 0.5 and 0.4, respectively
4. RESULTS & DISCUSSION

The compressive strength of the samples kept in standard curing conditions and 5% sodium sulfate solution after 28, 180, 365 and 540 days have been shown in Fig. 3. The tests showed that the compressive strength of the samples (with different concrete mixtures) which were cured in 5% sodium sulfate solution for 365 days increased about 11.7% and 12.5%, respectively; and after 540 days decreased for 3.8% and 0.7%, respectively. The compressive strength of the samples that were kept for 540 days in standard conditions increased to 10.9% and 11.5%, respectively. To describe the results of the tests, it can be said that due to ponding of the concrete samples, compressive strength was first increased and then under the influence of the sulfate ions was decreased. It was observed that the higher water/cement ratio, the higher is the decreasing of concrete compressive strength.

The corrosion parameters through time including the diffusion depth of sulfate ion, the depth of the weakened layers and the depth of totally devastated concrete depend on the following factors: period of exposure, concentration of the sulfate solution, water/cement ratio and diffusion of sulfate ions in the concrete.

5. CONCLUSIONS

Based on the results of this experimental and theoretical study the following conclusions were obtained.

- This paper has highlighted the influence of sodium sulfate on the behavior of concrete from three directions.
- The period of exposure to sodium sulfate governs the change in characteristics of concrete.
- The corrosion parameters under the influence of the sulfate solution from three directions were presented.
- An equation to calculate the concrete compressive strength under the influence of the sodium sulfate from three directions was presented.
- Effects of different concrete mixtures exposed to sulfates were studied.

6. Appendix

The following symbols are used in the paper:

- \( Y(t) \): The diffusion depth of sulfate ion through time
- \( Y_1(t) \): The depth of the weakened layers through time
- \( Y_2(t) \): The depth of totally devastated concrete through time
- \( k_z \): The constant coefficient of the corrosion process, equals to 0.02
Cₜ: The sulfate ions’ concentration value (mg/lit)

α: The correction factor, equals to 0.01(1/year)

\[ t_0 = \frac{Q_{SO_{3,0}} \times 100}{0.05C_s^{0.5} \eta} \]

Q_{SO_{3,0}}: The sulfate ions volume, equals to: \[ Q_{SO_{3,0}} = 0.05C_s^{0.5} \eta (\alpha^{0.5}) \]

Q_{SO_{3,1}}: The sulfate ions volume, which causes weakening the concrete layers

Q_{SO_{3,0}}: The sulfate ions volume by which the concrete totally devastated

REFERENCES