Prediction of Concrete Degradation Due to Sulfate Attack in Nuclear Power Plants Considering Ambient Temperature

Gyeonghee An [a*], Tae-Hyun Kwon [a]
[a]*Structural and Seismic Safety Research Division, Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Korea*
[*]*Corresponding author: akh425@kaeri.re.kr*

Keywords : Concrete Degradation, Sulfate Attack, Atkinson and Hearne Model, Durability, Service Life, Aging Management, UAE Barakah Nuclear Power Plant

1. Introduction

Concrete is a structural material that gradually deteriorates through both physical and chemical processes. Assessing structural safety with respect to such deterioration is essential for the service life management of nuclear power plant (NPP) structures. Reinforcement corrosion caused by chloride ingress is the most widely studied form of chemical deterioration, and extensive research has also been conducted in Korea. However, in regions such as the United Arab Emirates (UAE), where groundwater and seawater contain high sulfate concentrations, sulfate attack on concrete has become a major concern. Sulfate ions penetrating the concrete react with tricalcium aluminate to form ettringite, whose expansive nature induces cracking and subsequently reduces structural performance. These cracks further accelerate chloride ingress, ultimately leading to reinforcement corrosion. In this study, the Barakah NPP(BNPP) in the UAE was considered as a case example. The progression of sulfate attack was evaluated using an existing mechanistic model, and a conservative estimate of service life was performed.

2. UAE Nuclear Power Plant

In this section, the environmental conditions and concrete properties of the Barakah NPP are introduced.

2.1 Environmental Conditions

The Arabian Gulf region is characterized by high temperature and humidity [1]. The average temperature in the UAE is approximately 15~30℃ higher than in Korea. The summer temperature reach nearly 50℃, while winter lows are around 10℃. Relative humidity generally ranges from 40% to 80%, but can rise up to 98% [1].

At the Barakah site, the sulfate ion concentration is 4663 ppm in groundwater and 3440 ppm in seawater [2].

2.2 Concrete Properties

The basic mechanical properties of concrete – compressive strength, elastic modulus and Poisson's ratio - were evaluated at 91 days. Three specimens for each test were cured in water at 20℃. The average compressive strength, elastic modulus, and Poisson's ratio were 57.3 MPa, 38.7 GPa, and 0.13, respectively.

The sulfate ion diffusion coefficient at temperatures from 20 to 50℃ was measured using a natural diffusion cell test [3]. Experimental details are reported in a previous study, and the final results are summarized in Table 1 [3].

Table 1: Sulfate ion diffusion coefficient [3]

Temp. (℃)	D_i(×10^{-12} m^2/s)				COV(%)
	No.1	No.2	No.3	Mean	
20	2.02	1.95	1.87	1.95	3.86
30	3.37	3.45	3.32	3.38	1.94
40	4.72	4.10	4.22	4.35	7.57
50	7.52	5.52	6.85	6.63	15.35

3. Prediction of Concrete Degradation

This section introduces the mechanistic model proposed by Atkinson and Hearne [4], and the service life is conservatively estimated from the model and the basic information summarized in chapter 2.

3.1 Prediction Model

The deterioration rate of concrete due to sulfate ions, R, can be predicted by Eq. (1)[4].

$$R = \frac{EB^2 c_0 D_i x \phi_{Al_2O_3}}{0.10196\alpha\gamma(1-\nu)} \quad (1)$$

Definitions of the variables in Eq. (1) and their input values are summarized in Table 2. Concrete properties such as elastic modulus, diffusion coefficient, and Poisson's ratio were obtained from experiments, while other parameters were adopted from the literature [3,4].

Fig. 1 shows the calculated rate of sulfate attack, R, based on the input data in Table 2. For conservatism, it was assumed that no surface treatment was applied to mitigate sulfate ingress. For the intake/discharge structure, which is exposed to seawater, the external sulfate concentration of 3440 ppm was used. For the basemat of the reactor containment building(RCB) and auxiliary building(AB), exposed to groundwater, 4663 ppm was applied.

Table 2: Input parameters for prediction of the rate of sulfate attack, R

Parameters		Input
E	Elastic modulus	38.7 GPa
B	Stress of 1 mol of sulfate that reacts in 1m^3 of concrete	1.8×10^6 m^3/mol
c_0	External sulfate concentration	4663 ppm (underground water) 3440 ppm (seawater)
D_i	Sulfate diffusion coefficient in concrete	Table 1
x	Cement content of the target structure	113 kg/m^3
$\phi_{Al_2O_3}$	Aluminum oxide content of the target structure	5 %
α	Roughness coefficient of the area where performance deterioration occurs	1.0
γ	Energy required for the concrete surface fracture	10 J/m^2
ν	Poisson's ratio	0.13

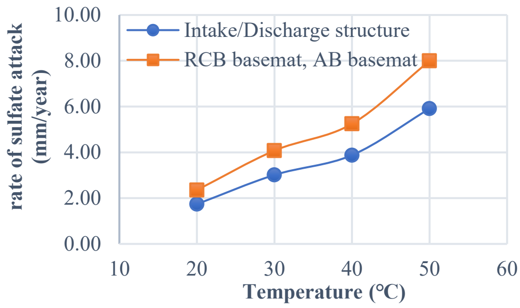

Fig. 1. Rate of sulfate attack for intake/discharge structure and basemat of RCB and AB

3.2 Estimation of Service Life

The covering depth of structural members subject to chemical attack in BNPP was 3 in.(7.6 cm). Based on the deterioration rate shown in Fig. 1, the penetration depth of sulfate ion over time was estimated. Fig. 2 illustrates the sulfate penetration depth for the basemats of the RCB and AB.

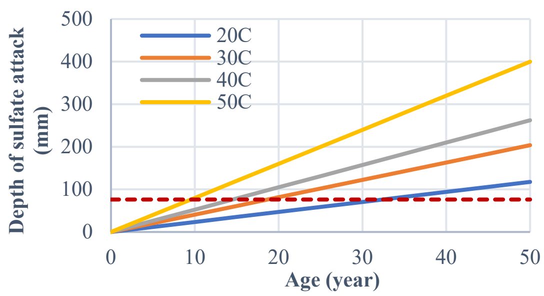

Fig. 2. Depth of sulfate attack over time for basemats of RCB and AB

Assuming the end of service life corresponds to the time when sulfate ions reach the reinforcement, the service life can be determined by comparing the penetration depth with the covering depth. Table 3 presents the estimated service lives of BNPP structures.

Table 3: Service life of BNPP structures

Temp. (℃)	D ($\times10^{-12}$ m^2/s)	Service life (year)	
		Intake/Discharge	Basemat
20	1.95	43.84	32.40
30	3.38	25.29	18.69
40	4.35	19.65	14.52
50	6.63	12.89	9.53

4. Conclusions

In this study, the progression of sulfate attack in BNPP concrete was assessed using a mechanistic model, and the service life was conservatively estimated. The results indicate that service life is strongly influenced by ambient temperature. As the UAE is at least 10℃ hotter than Korea, the predicted service life of BNPP structures is about 10 years shorter than that of similar structures in Korea. These results are based on simplified assumptions and should be refined through further experimental studies and site investigations.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF, No. RS-2022-00144409) and the Korea Institute of Energy Technology Evaluation and Planning (KETEP, 20224B10300010).

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