Study on Long-term Performance of Reinforcing Concrete Structures in Subsurface Environment

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1. Introduction

Concrete is one of the most widely used materials for the construction of structures, and concrete structures have been considered to be durable with large life.

In a LILW disposal facility located in subsurface environment, a silo concrete plays an important role to limit the release of radionuclides from the silo geosphere. However, the performance of the concrete structure decrease over a period of time because of several physical and chemical processes. After a long period of time in the future, the concrete would lose its effectiveness as a barrier against groundwater inflow and the release of radionuclides.

Although a number of process are responsible for the degradation of the silo concrete, it is concluded that a reinforcing steel corrosion cause the failure of the silo concrete. Hence, a concrete silo failure time is calculated based on a corrosion initiation time which takes for chloride ions to penetrate through the concrete cover, and a corrosion propagation time. This paper aims to analyze the concrete failure time in the Wolsung Low- and intermediate-level wastes Disposal Center (WLDC)

2. Design of concrete silo

The detail design information of concrete silo is shown in Table 1.

Table 1. Design information of concrete silo

Silo diameter	Silo length	Diameter of Reinforcing steel	Cover depth Of concrete
26.8 m	57.1 m	43 mm	100 mm

3. Degradation process for concrete

3.1 Sulfate attack

Through a chemical reaction, sulfate ion penetrates into the surface of concrete and weakens the concrete wall. The model for sulfate attack was already proposed by Atkinson and Hearne [1]. The degradation rate of concrete from sulfate attack is estimated by:

$$R = \frac{EB^2 c_0 C_E D_0}{\alpha \gamma (1-v)} \qquad (1)$$

Where, B is linear strain caused by one mole of sulfate reacted in 1 m^3 (1.8E-6 m^3/mol), c_0 is sulfate concentration in water (mol/m^3), C_E is concentration of reacted sulfate as ettringite (mol/m^3), D_0 is intrinsic diffusion coefficient (m^2/s), E is Young's modulus (20 GPa), α is roughness factor for fracture path (assumed to be 1.0), γ is fracture surface energy of concrete (10 J/m^2), v is Poisson's ratio (0.3), and the rate of degradation, R, is in (m/y). The concentration of sulfate (c_0) in groundwater was measured at 119 mg/L. However, in the estimation of sulfate attack, 1,190 mg/L of sulfate concentration was applied for a conservative estimation.

3.2 Calcium hydroxide leaching

A shrinking core model proposed by Atkinson and Hearne [2] is adopted here. The model assumes the calcium removal from concrete exterior is rapid compared to the movement of calcium through the concrete. Thus, the transport of calcium in the concrete is controlled by diffusion. The depth into the concrete affected by Ca removal is then given by:

$$X = \left(2D\tau\emptyset \frac{C_t - C_{gw}}{C_b} \right) \qquad (2)$$

Where, D is the diffusion coefficient of Ca^{2+} ions in concrete (m^2/s), τ is the tortuosity factor (-), $\emptyset$ is the porosity (-), C_t is the concentration of Ca^{2+} ion in the pore space (mmol/kg), C_{gw} is the concentration of Ca^{2+} in groundwater (mmol/kg), and C_b is the bulk concentration of Ca^{2+} ions in solid concrete (mmol/kg).

3.3 Corrosion of reinforcing steel

There are several mathematical models available to predict the chloride diffusion in concrete, based on varying levels of simplifying assumptions. The commonly used ones are presented below:

Fick's second law of diffusion deals with one-dimensional diffusion [3] and given by,

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \qquad (3)$$

For one-dimensional flow into a semi-infinite medium a closed-form solution can be derived for equation (3) as follows,

$$C(x,t) = C_0 \left(1 - erf \frac{x}{2\sqrt{Dt}}\right) \qquad (4)$$

Where, $C(x,t)$ = concentration at depth x (m), at time t (% by mass); t = time of exposure(seconds); C_0 = surface chloride concentration (% by mass); D = constant diffusion coefficient (m^2/s); erf = error function.

The equation (4) can be used only if the diffusion coefficient, D, and surface chloride concentration, C_0 remain constant during the time of diffusion. It has been shown by previous researchers that these conditions do not apply in practical conditions. The equation (1) can be modified to take account of the variation of D with time as shown by Crank:

$$\frac{\partial c}{\partial t} = D(t) \frac{\partial^2 c}{\partial x^2} \qquad (5)$$

The reinforcing steel starts to corrode after depassivation process of passive of passive film. US DOE assumed that a concrete vault fails completely once 50 volume percent of the reinforcing steel has corroded.

Korean Concrete Institute (KCI) reviewed the US DOE approach applying strength design method to calculate the mineral volume of the reinforcing steel for the structure safety of the reinforcing steel for the structure safety of the silo concrete. KCI concluded that the US DOE approach is conservative for the estimation of failure time of the silo concrete.

The US DOE [2] applied a conservative corrosion rate of 10^{-5} m/y to calculate a corrosion propagation time. Under the pore water conditions of the silo concrete, the corrosion rate of the reinforcing steel was reported to be in the range of 10^{-8} to 10^{-9} m/y. However, a corrosion rate of 10^{-5} was applied in the estimation of a corrosion propagation time in the WLDC.

50 volume percent of the reinforcing steel was also used to determine complete failure of the concrete silo in the WLDC based on the KCI review on the US DOE approach.

In this model service life of reinforcing steel is divided into two parts initiation and propagation. Initiation time means time required to initiate the corrosion when chloride concentration of the concrete reaches to its threshold value. The next stage is degradation when delamination, cracking and spalling of the concrete occur [3].

4. Conclusions

The concrete silos were initially assumed to be intact and have low permeability. The effects of sulfate and magnesium attack, calcium hydroxide leaching, and the corrosion of reinforcing steel were analyzed on the degradation of concrete in WLDC.

Groundwater samples were collected from the disposal site to estimate the amounts of sulfate, chloride, dissolved oxygen (DO) and other ions. In the sulfate attack process, the concrete degradation rate was calculated to be 1.313E-2cm/y. For the concrete thickness of 100 cm in the disposal silo, this rate is negligible over 3,800 years, and, therefore, sulfate attack is assumed to be negligible for this analysis.

In the model of calcium hydroxide leaching, the Ca^{2+} concentration in the concrete was calculated to be 15.7 mmol/kg. After 5,000 y, the depth of calcium hydroxide leaching is estimated to be approximately 3 cm.

Hence, it is concluded that this mechanism is negligible over 80,000 y for the disposal facility.

In the evaluation of Eq. (5), it is unveiled that the degradation rate of the concrete silo due to chloride attack is much faster than the rates estimated from sulfate attack and calcium hydroxide leaching.

Based on the DOE approach which estimated that concrete fails completely once 50 volume percent of the reinforcing steel corrodes, a corrosion propagation time was calculated to be 640 y, which is the time it takes for corrosion to penetrate 0.640 cm of the reinforcing steel.

In addition to the corrosion propagation time, a diffusion equation was used to calculate a corrosion initiation period. A corrosion initiation time was calculated to be 1,284 y, after closure of the WLDC when added to the 640 y corrosion propagation period.

REFERENCES

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[3] ACI, 2000, ACI 365R, Service –Life Prediction.