Long-Term Performance of Silo Concrete in Low- and Intermediate-Level Waste (LILW) Disposal Facility

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1. Introduction

Concrete has been considered one of the engineered barriers in the geological disposal facility for low- and intermediate-level wastes (LILW). The concrete plays major role as structural support, groundwater infiltration barrier, and transport barrier of radionuclides dissolved from radioactive wastes. It also works as a chemical barrier due to its high pH condition.

However, the performance of the concrete structure decrease over a period of time because of several physical and chemical processes[1]. 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.

An subsurface environment below the frost depth should be favorable for concrete longevity as temperature and moisture variation should be minimal, significantly reducing the potential of cracking due to drying shrinkage and thermal expansion and contraction[2]. Therefore, the concrete structures of LILW disposal facilities below groundwater table are expected to have relatively longer service life than those of near-surface or surface concrete structures.

LILW in Korea is considered to be disposed of in the Wolsong LILW Disposal Center which is under construction in geological formation. 100,000 waste packages are expected to be disposed in the 6 concrete silos below EL -80m in the Wolsong LILW Disposal Center as first stage[3]. The concrete silo has been considered the main engineered barrier which plays a role to inhibit water inflow and the release of radionuclides to the environments.

Although a number of processes are responsible for the degradation of the silo concrete, it is concluded that a reinforcing steel corrosion cause the failure of the silo concrete. Therefore, 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 Wolsong LILW Disposal Center.

2. Design of concrete silo

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

Table 1. Design information of concrete silo 1

Silo diameter	Silo length	Diameter of reinforcing steel	Cover depth of concrete
26.8 m	57 .1m	42 mm	100 mm

3. Degradation processes for subsurface 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[4]. The degradation rate of concrete from sulfate attack is estimated by:

$$R = \frac{EB^2 c_o C_E D_o}{\alpha \gamma (1-\nu)} \qquad (1)$$

where, B is linear strain caused by one mole of sulfate reacted in 1 m^3 (1.8×10^{-6} m^3/mol), c_o is sulfate concentration in water (mol/m^3), C_E is concentration of reacted sulfate as ettringite (mol/m^3), D_o 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), ν is Poisson's ratio (0.3), and the rate of degradation, R, is in (m/yr). The concentration of sulfate (c_o) 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[4] is adopted here. The model assumes the calcium removal from the 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 :

$$X = \left(2 D \tau \phi \frac{C_i - C_{gw}}{C_b} t \right)^{1/2} \qquad (2)$$

where, D is the diffusion coefficient of Ca^{2+} ions in concrete (m^2/s), τ is the tortuosity factor (-), ϕ is the porosity (-), C_i 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

When steels corrode, the corrosion products have a greater volume than the initial metal. The volume expansion can cause the concrete to crack and simultaneously increase the permeability. The concrete pore water tends to passivate the steel surface due to hyper alkaline condition. The passivated condition must be overcome before corrosion starts. The depassivation process is the result of diffusion of chloride ions, through the concrete, to the surface of the reinforcement steel. The diffusion of chloride ion is described by Fick's 2nd law:

$$C(x,t) = C_i + (C_S - C_i) \cdot erf\left(1 - \frac{x}{2\sqrt{D_{Cl}t}}\right) \quad (3)$$

where, $C(x,t)$ is chloride concentration at depth x at time t, C_i is initial chloride concentration (kg/m^3), C_s is surface chloride content (kg/m^3), D_{Cl} is apparent Cl$^-$ diffusion coefficient (m^2/s), and erf is error function. The reinforcing steel starts to corrode after depassivation process of passive film. US DOE assumed that a concrete vault fails completely once 50 volume percent of the reinforcing steel has corroded[5].

Korean Concrete Institute (KCI) reviewed the US DOE approach applying strength design method to calculate the minimal volume 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 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 Wolsong Disposal Center.

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

4. Evaluation of Concrete Degradation

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 the Wolsong LILW Disposal Center.

Groundwater samples were collected from the disposal site to estimate the amounts of sulfate, chloride, dissolved oxygen (DO), dissolved organic carbon (DOC), pH, and other ions. In the sulfate attack process,

the concrete degradation rate was calculated to be 1.313×10^{-2} cm/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 1,000 y, the depth of calcium hydroxide leaching is estimated to be approximately 1.5 cm. Hence, it is concluded that this mechanism is negligible over 40,000 y for the disposal facility.

In the evaluation of Eq. (3), 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 615 y, which is the time it takes for corrosion to penetrate 0.615 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 1,170 y, which gives a concrete silo failure time of 1,725 y after closure of the Wolsong LILW Disposal Center when added to the 615 y corrosion propagation period.

REFERENCES

[1] J. C. Walton, L. E. Plansky, and R. W. Smith, Models for Estimation of Service Life of Concrete Barriers in Low-level Radioactive Waste Disposal, NUREG/CR-5542, 1990.
[2] NCRP Report 152, Report of the National Council on Radiation Protection and Measurements (NCRP), "Performance Assessment of Low-Level Waste Disposal Facilities", 2005.
[3] J. B. Park, H. Jung, E. Y. Lee, C. L. Kim, G. Y. Kim, K. S. Kim, Y. K. Koh, K. W. Park, J. H. Cheong, C. W. Jeong, J. S. Choi, and K. D. Kim, Wolsong LILW Disposal Center: Progress and Challenges, Nuclear Engineering and Technology, Vol.41, p. 477, 2009.
[4] A. Atkinson and J. A. Hearne, Mechanistic models for the durability of concrete barriers exposed to sulfate-bearing groundwaters, Vol. 176, p. 149, 1990.
[5] US DOE, The US DOE Idaho National Laboratory Site DraftSection 3116 Waste Determination For Idaho Nuclear Technology And Engineering Center Tank Farm Facility, 2006.