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The state of the Primary Degradation Factors and Models of Concrete Cask in Spent Fuel Dry Storage System

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1. Introduction

In South Korea, a total of twenty nuclear reactors are in operation; the cumulative amount of spent fuel is estimated to be 10,490 MTU in 2009. The full capacity of the waste storage is expected to be saturated in around 2016. However, a national strategy for spent fuel management has not yet been set down and high level waste (HLW) such as spent fuel will have to be stored at-reactor (AR) by re-racking. Recently an worldwide interest on the dry storage has increased especially around U.S.

With a perspective of the material of the spent fuel dry storage cask, the system can be divided into two types of metal and concrete casks. The concrete type cask is a very attractive option because of the cost competitiveness of concrete material and its relatively long-term durability. Although the type of metal cask is chosen, the use of cementitious material is inevitable at least for the cask foundation and the facilities for the protection of dry storage structures. Upon being placed, the performance of concrete begins to deteriorate from the intrinsic change of cement and the physical/ chemical environmental conditions. Thus it is necessary to evaluate the durability of a concrete for the increase of reliability and safety of the whole system during the designed life time. Considering the dry storage system of spent fuel is the item which can create a lot of added value, the development of a dry storage cask is usually initiated by private enterprises among developed countries. The detail research results and specific design criteria for the safety assessment of a concrete cask have not been revealed to the public well.

In this paper, the major expected degradation factors and related degradation models of concrete casks were investigated as part of the safety assessment by taking account of the site where Korea industrial nuclear power plants are located.

2. Degradation factors and Models

With the long-term dry storage point of view, the concrete durability is a very important parameter to store storage of spent fuel safely. Concrete is usually considered to maintain its own durability for more than several decades under the ordinary condition. When exposed to the deteriorate environment, the concrete degradation processes become faster dramatically. P.A.M. Basheer et al.[1] listed the main deterioration factors against concrete durability from his literature review(about 400 published documents) as shown in Fig. 1.

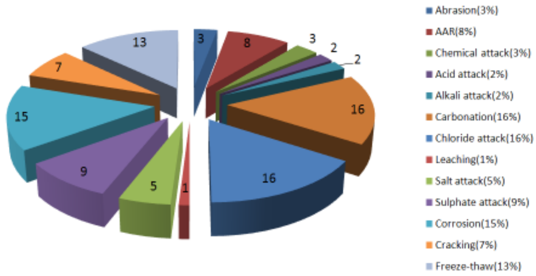

Fig. 1. Deterioration Factors of Concrete Durability

Table I. Average ion concentration in Korea [2].

Ion (ueq/L^3)	Cl^-	NO^{3-}	SO^{4-}	Na^+	NH^{4+}	Mg^{2+}	Ca^{2+}
Anmyeon	74.2	40.4	66.1	65.0	38.5	17.3	22.9
Uljin	77.2	22.9	51.3	64.7	19.7	16.6	19.6
Gosan	85.9	23.1	45.6	75.5	17.9	17.8	13.9
Ulleung	144.6	25.7	58.9	125.7	21.2	26.4	22.4
Korea	102.9	27.4	55.7	89.2	23.5	20.6	20.1

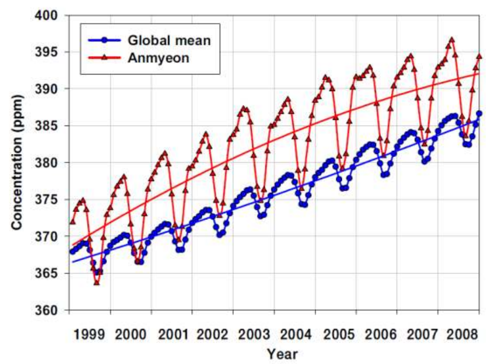

Fig. 2. Variations of CO_2 concentration [2].

Because most of nuclear power plants in Korea are located near the seashore, the concentration of chloride ion is relatively higher than the other area. For the purpose of the main degradation factors of concrete, additionally, the average ion concentration and the changes of carbon dioxide in Korea were surveyed as showing in Table I and Fig. 2. Based on those results, it can be anticipated that the main deterioration factors on concrete durability for long-term storage of spent nuclear fuel are considered as freezing and thawing, chloride attack, carbonation and sulfate attack, which are the similar results of P.A.M. Basheer et al.[1]. The detail descriptions of the aforementioned four main deterioration factors are as follows.

2.1 freezing and thawing

When the concrete pore is filled with water, the freezing of water depends on the ambient temperature, a pore size and a pore location from the surface. The larger the pore size is and the closer to the surface of concrete, the water get easily frozen.

When frozen, the moisture increases 9% in volume and subsequently produces a hydrostatic pressure. If this pressure exceeds the tensile strength of concrete, cracks are generated and can be a cause decreasing the concrete durability. Typical examples of concrete deteriorated from freezing and thawing are scaling, spalling, pop-out, cracking and so on. One of the representative models for describing freezing and thawing in concrete can be shown as following equation (1) [3], [4].

$$\mathrm{RDF} = \left(\frac{\mathrm{DF}}{\mathrm{DF_i}}\right) \times 100 \qquad (1)$$

Here, RDF = Relative durability factor
DF = Durability factor of test concrete
DF_i =Durability factor of reference concrete

2.2 Chloride attack

A.N James et al.[5] insisted the main reason of deterioration on reinforced concrete is associated with chloride attack. When the reinforced concrete is easily exposed to the chloride-free environment, chloride ions continue to attack the concrete and finally the passive layer to protect the corrosion of steel is destroyed. The volume of steel caused by corrosion creates 2~3 times greater than its origin volume. This kind of volume expansion may cause the internal forces on the concrete and result in cracking, spalling, concrete-steel bond strength reduction in the end. To estimate and predict the concrete deterioration against chloride attack, typical deterioration equation (2) based on Fick's laws of diffusion is shown below

$$\frac{\partial C}{\partial t} = D_{\mathrm{eff}} \frac{\partial^2 C}{\partial x^2} \qquad (2)$$

where, D_{eff} = effective diffusion coefficient
x = diffusion distance
t = diffusion time

2.3 Carbonation

The hydrated concrete is generally alkaline and the pH range is approximately 12.6 to 13.5. When concrete is exposed to carbon dioxide in the air, carbon dioxide from the air penetrates into concrete and reacts with calcium hydroxide to form calcium carbonates. Due to this process the pH in the reinforced concrete decrease, which would neutralize the alkaline condition. Eventually the reinforcing steel bars have an inclination to be corroded and finally cracking, spalling, concrete-steel bond strength reduction will also result. The widely used equation (3) for carbonation degradation is shown below and is based on Fick's laws of diffusion.

$$x_c = \sqrt{\frac{2D_c}{a}(C_1 - C_2)t} \qquad (3)$$

where, D_c = CO_2 diffusion coefficient
x = diffusion distance
t = diffusion time
$C_1 - C_2$= CO_2 concentration difference

4. Sulfate attack

Sulfate attack of concrete is occurred when exposed to the environment including the agents such as K_2SO_4, $NaSO_4$ and $MgSO_4$ etc. When concrete is casteed, sulfate source from cement or aggregates reacts with cement hydrate and produces so called ettringite. and this product affects early hydration and concrete durability directly. Typical examples of concrete deteriorated from sulfate attack are dissolution of cement hydration product, cracking, spalling and so on. The equation (4) shown below can be used to predict deterioration of sulfate attack on concrete

$$x_c = 0.55C_a(Mg^{2+} + SO_4^{2-})t \qquad (4)$$

where, x = diffusion distance
C_a = C_3A weight ration in concrete
Mg^{2+}, SO_4^{2-} = ion morality

3. Conclusions

Freezing and thawing, chloride attack, carbonation, sulfate attack can be anticipated as major degradation factors of a spent fuel concrete cask in Korea. Widely used models for those deterioration mechanism were discussed.

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