

《Technical Note》

**Evaluation of Concrete Degradation Under Disposal Environment**

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**Abstract**

The effects of three mechanisms, calcium depletion, sulphate and carbonate penetration, on the concrete degradation have been studied. The shrinking core model (SCM) and the HYDROGEOCHEM (HGC) model have been applied to evaluate how fast the mechanisms proceed. The SCM is an analytical approximation model and the HGC is a numerical mass transport model coupled with chemical reaction. The SCM leads to more conservative results than the HGC, and turns out to be very useful in the viewpoint of simplicity and conservatism. During 300 years, calcium has been depleted within 10 cm from the concrete outer surface, and sulphate has penetrated less than 13.5 cm into the concrete. Carbonate has not penetrated even 7 cm into the concrete in contact with the bentonite, and, furthermore, its penetration into the concrete with the groundwater is negligible. Conclusively, the concrete is expected to maintain its integrity for at least 300 years that are regarded as institutional control period of intermediate- and low-level radioactive waste repository.

**1. Introduction**

Design concept of the cavern for intermediate and low level radwaste is generally that the concrete structure is built in the rock cavern, and the gap between the concrete structure and the cavern wall is filled up with the bentonite-based material. Backfill material restrains the water intrusion and retards the radionuclide release. Concrete prevents repository from being destructed by overload, and it keeps high pH in the repository environment for a long time so that the corrosion of waste package is restricted, and the radionuclide solubility is maintained at minimum. Accordingly, the study on characteristics of the repository components is very important to assure the repository integrity.

Until now, the domestic works have mainly focused on the studies on diffusive properties of bentonite-based material [1-2] and of cement [3]. However, after the repository is saturated with the groundwater, the concrete constituents start to react with the bentonite constituents and the dissolved chemicals of the groundwater. As a result, the original properties of the concrete are changed, and its function as barrier becomes weaker. Therefore, the study on concrete degradation by chemical effects is also needed to predict the long-term integrity of the repository.

The objective of this work is to evaluate the effect of three mechanisms, calcium depletion, sulphate and carbonate penetration, on the concrete degradation

## 2. Degradation Mechanism

Concrete degradation is defined as a loss of concrete durability due to a certain effect. If mechanical and thermal stress from surrounding host rock does not act on the concrete structure, the degradation is mainly caused by chemical effects.

When the concrete is in contact with bentonite, the following degradation mechanisms occur simultaneously or step by step [4].

- 1) Leach out of alkali hydroxides—The alkali hydroxides, NaOH and KOH, diffuse away from concrete into bentonite. The concrete porewater maintains high pH at around 13.5 as long as NaOH and KOH remain in the porewater, however, the value will diminish to about 12.5 after almost all of the hydroxides leach out. This mechanism is completed within initial tens of years.
- 2) Dissolution and leach out of calcium—The portlandite,  $\text{Ca}(\text{OH})_2$ , starts to dissolve in the porewater near pH 12.5, and the dissolved calcium diffuses out to surrounding bentonite by concentration difference.
- 3) Penetration of carbonate— $\text{CO}_3^{2-}$  from bentonite reacts with the dissolved calcium to form the calcite,  $\text{CaCO}_3$ , in the concrete. If the amount of formation does not exceed the solubility,  $\text{CaCO}_3$  will only be in solution phase.
- 4) Penetration of sulphate— $\text{SO}_4^{2-}$  from bentonite reacts with the tri-calcium-aluminate in the concrete to form the ettringite. It also reacts with calcium to form  $\text{CaSO}_4$ .
- 5) Penetration of magnesium—The magnesium from bentonite produces  $\text{Mg}(\text{OH})_2$  in the concrete. However, this process is often neglected because the magnesium concentration in the bentonite is too low to consider its effect.
- 6) Dissolution and leach out of  $\text{SiO}_2$ —One of the main components of concrete skeleton,  $\text{SiO}_2$ , diffuses out very slowly. The process will probably continue for tens of thousands of years

until pH in the concrete reaches the level in the bentonite. Accordingly, the process is unimportant during the initial hundreds of years.

The formation of the ettringite and  $\text{Mg}(\text{OH})_2$  results in volume increase, which leads to disruption and loss of strength of the concrete. The precipitates,  $\text{CaCO}_3(\text{s})$  and  $\text{CaSO}_4(\text{s})$ , deposited in the concrete pore prevent the intrusion of other chemicals, while reduce pH of the solution phase and cause the shrink of the concrete. Of the processes, dissolution and leach out of calcium in concrete, penetration of sulphate and carbonate into concrete make a major contribution to concrete degradation during hundreds of years.

## 3. Evaluation Model

There are a number of models to evaluate concrete degradation [5-8]. In this paper, two models, the Shrinking Core Model (SCM) and the HYDROGEOCHEM (HGC) model [9] have been applied. The SCM is an analytical approximation model and the HGC is a numerical mass transport model coupled with chemical reaction. The former is very simple and gives only the position of concentration front with time, while the latter is rather complex but gives an additional information about concentration profile of all chemicals. The concentration front of the SCM is discontinuous while that of the HGC is continuous and dispersive.

### 3.1. Shrinking Core Model (SCM)

#### 3.1.1. SCM with Film Resistance

This model is to treat the chemicals diffusing away from the concrete to the surrounding groundwater by a concentration difference after dissolution, e.g. dissolution and leach out of calcium. Concept of the model is depicted in Fig. 1.

The diffusion rate of a chemical in the concrete is expressed as

$$\dot{m} = D_p \varepsilon A \frac{(C_s - C_o)}{x} \quad (1)$$

The water flowing along the concrete wall will carry away the chemical diffusing out from the concrete. The washing rate which considers the film resistances near interface can be written as

$$\dot{m} = -Q_{eq}(C_s - C_w) \quad (2)$$

The same amount of the chemical must be dissolved at the front of the undissolved chemical receding with the speed of  $dx/dt$ . The dissolution rate is given by

$$\dot{m} = -q_o A \frac{dx}{dt} \quad (3)$$

From Eqs.(1)~(3), the relationship between  $t$  and  $x$  is derived as the following ;

$$x = -\frac{D_p \varepsilon A}{Q_{eq}} + \left[ \left( \frac{D_p \varepsilon A}{Q_{eq}} \right)^2 + 2 \frac{(C_o - C_w)}{q_o} D_p \varepsilon t \right]^{1/2} \quad (4)$$

where

- $A$  : cross sectional area
- $C_o$  : solubility of chemical in porewater
- $C_s$  : concentration of chemical at concrete/groundwater interface.
- $C_w$  : concentration of chemical in groundwater
- $D_p$  : pore diffusivity of chemical

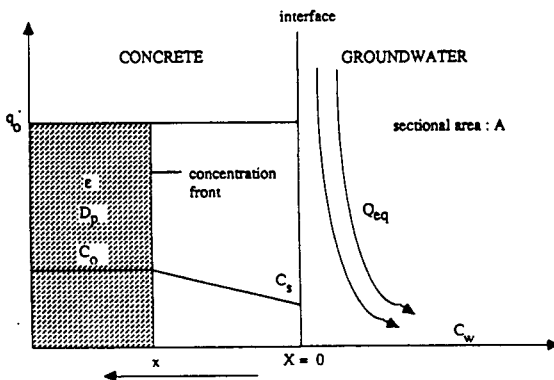


Fig. 1. Conceptual Diagram for Shrinking Core Model with Film Resistance

$q_o$  : concentration of undissolved chemical in concrete

$Q_{eq}$  : flow rate of groundwater

$x$  : position of concentration front

$\varepsilon$  : porosity of concrete

If the diffusion in the concrete is the dominant process, Eq.(5) is used instead of Eq.(4).

$$x = \left[ 2 \frac{(C_o - C_w)}{q_o} D_p \varepsilon t \right]^{1/2} \quad (5)$$

On the other hand, when the transport resistance is mainly due to the limited washing capacity of the water, Eq.(6) is used instead of Eq.(4).

$$x = \frac{(C_o - C_w) Q_{eq} t}{q_o A} \quad (6)$$

### 3.1.2. Two Coupled SCM

This model can simulate the system where a chemical is penetrated into the concrete from the surrounding medium, and thus be used to evaluate the penetration of sulphate and carbonate. In the Fig. 2 the concept is pictured.

It is assumed that the chemical  $SO_4^{2-}$  (A) diffused from the medium 1 reacts irreversibly with the stationary  $X(OH)_2$  (B) in the medium 2 to form precipitate  $XSO_4$ . The diffusion rate in both media can

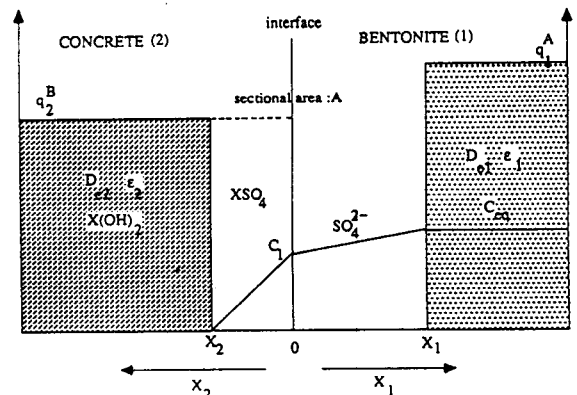


Fig. 2. Conceptual Diagram for Two Coupled Shrinking Core Model

be written as

$$\begin{aligned}\dot{m} &= \varepsilon_1 D_p^1 A \frac{(C_{eq} - C_1)}{x_1} \\ &= \varepsilon_2 D_p^2 A \frac{(C_1 - 0)}{x_2}\end{aligned}\quad (7)$$

The depletion rate by the dissolution of the chemical A in the medium 1 must be equal with the consumption rate of chemical B, which is reacting with the chemical A diffused into the medium 2. These rates are respectively expressed as

$$\dot{m} = q_1^A A \frac{\partial x_1}{\partial t} \quad (8)$$

$$\dot{m} = q_2^B A \frac{\partial x_2}{\partial t} \quad (9)$$

From the equality of Eqs.(7)~(9), the following relationship is obtained.

$$x_2 = \left[ \frac{2(C_{eq} - 0)}{q_2^B} \varepsilon_2 D_{p2}^* t \right]^{1/2} \quad (10)$$

where

$C_{eq}$  : solubility of chemical A in medium 1

$q_2^B$  : concentration of undissolved chemical B in medium 2

$x_2$  : position of concentration front of chemical intruded in medium 2

$\varepsilon_2$  : porosity of medium 2

and

$$D_{p2}^* = \frac{D_{p2}}{1 + \frac{D_{p2}}{D_{e1}} \frac{q_2^B}{q_1^A}} \quad (11)$$

Here,  $D_{p2}^*$  is the weighted pore diffusivity of the chemical A in the medium 2, considering the depletion of the chemical A in the medium 1. If the mass of the medium 1 is much greater than that of the medium 2, that is,  $q_1^A \gg q_2^B$ ,  $D_{p2}^*$  of Eq.(11) becomes  $D_{p2}$

transport of chemical species in saturated-unsaturated porous media. The program iteratively solves the two dimensional transport and geochemical equilibrium equations, and simultaneously handles the mass transfer effects of advection, dispersion, and diffusion, and chemical reactions of precipitation, dissolution, complexation, dissociation, ion exchange, and adsorption. The details of the model are given elsewhere [9].

In this work, the original HGC code has been used after a little modification. The original program has a problem that the calculation continues on the next time step,  $t + \Delta t$ , regardless of the convergence after iterations of given number at time  $t$ . The error is gradually accumulated with the increase of the number of time steps which do not converge, and so ultimately the whole error could become very large. With a large iteration number or very small time increment ( $\Delta t$ ), the problem can be alleviated but requires too much computation time. Accordingly, the algorithm of variable time increment should be adopted to effectively solve the problem. If the calculation at time  $t$  fails in convergence within the given iteration number, the time increment at the time,  $\Delta t$ , is reduced to a half size,  $\Delta t/2$ , and the procedure is repeated until the new solution is within an error tolerance. Once the convergence is obtained, the time increment is increased as twofold factors at the next time step. This algorithm of variable time increment repeats its procedure continuously until the calculation ends. This method reduces the overall calculation time even when a very small time increment is given at the initial time because the time increment will enlarge gradually with time. However, it must be noted that proper values of the initial time increment and the iteration number are important for the efficient calculation.

#### 4. Evaluation of Degradation

The effects of dissolution and leach out of calcium from the concrete, of penetration of sulphate from

#### 3.2. Hydrogeochem(HGC) Model

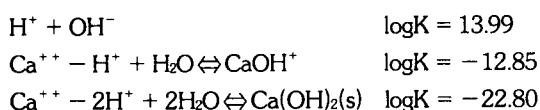
HGC is a computer code which can simulate the

the bentonite, and of penetration of carbonate from the bentonite or the groundwater, on the concrete degradation are individually evaluated.

#### 4.1. Dissolution and Leach out of Calcium

This case assumes that the concrete is in contact with groundwater, and its conceptual diagram is shown in Fig.1. The dissolved calcium in the porewater diffuses out from the concrete to the surrounding groundwater by concentration difference, and, after all, will be completely depleted. As long as there is  $\text{Ca(OH)}_2(\text{s})$  present, the calcium concentration in the porewater will be remained at the level equivalent to the solubility limit.

It is assumed that 1 m<sup>3</sup> concrete contains about 210 kg CaO in its cement phase, and then the maximum calcium concentration in the concrete is possibly to be 3.74 kmole/m<sup>3</sup> concrete [4]. If the porosity of the concrete is 0.2, the concentration based on the porewater becomes 18.7 mole/l. This value is assumed to be the initial undissolved concentration of the calcium. Three calcium species, free  $\text{Ca}^{++}$ , complex  $\text{CaOH}^+$  and precipitate  $\text{Ca(OH)}_2(\text{s})$ , and water dissociation have been considered. The reactions are expressed as follows ;



The initial pH of the concrete porewater is 12.5. This value will be kept up for the time that there exists  $\text{Ca(OH)}_2(\text{s})$ , but start to decrease after the complete dissolving of  $\text{Ca(OH)}_2(\text{s})$ . It is assumed that the concrete is in contact with a large volume of groundwater containing 10<sup>-4</sup> mole/l of calcium at pH 7.5. Subject to the assumption, the groundwater can wash out the species released from the concrete or to supply the concrete with the species present in it without changing its own composition.

The thickness of the concrete structure in the repository is expected to be about 60 cm. However, as

Table 1. Input Data for Calcium Depletion

Items	value
<b>Concrete</b>	
porewater pH	12.5
total amount of Ca, $q_0$ (mole/l concrete)	3.74
solubility of Ca in porewater, $C_0$ (mole/l)	$1.97 \times 10^{-2}$
porosity, $\epsilon$	0.2
pore diffusivity, $D_p$ (m <sup>2</sup> /yr)	$1.58 \times 10^{-2}$
thickness of concrete slab (m)	0.25
<b>Groundwater</b>	
pH	7.5
total amount of Ca, $C_w$ (mole/l)	$1.0 \times 10^{-4}$
<b>Grid</b>	
numbers	15
points (cm)	0, 0.326, 0.729, 1.23, 1.84, 2.59, 3.53, 4.68, 6.09, 7.84, 10.0, 12.7, 16.0, 20.0, 25.0

presumed not to deplete a half or more of the calcium during hundreds of years, only 25 cm from the concrete outer surface is considered to save the calculation time. The boundary condition at the inner side of the concrete remains unchanged to the initial condition. Actually this boundary condition is of no importance because the concentration front will not reach up to the depth. The present work used the same grid spacing and input data that SKB [4] had applied to its study using the CHEMTRN [7], to compare the both results. Input data are summarized in Table 1. The  $C_0$  in the table, the solubility limit of calcium in the porewater, has been calculated at  $t=0$  using the HGC code. The activity coefficient is assumed to be 1 in all runs of the HGC.

The calcium depletion evaluation by the SCM uses Eq.(5). Substituting the related data for Eq.(5), the following equation is obtained.

$$x(\text{cm}) = 0.576 \cdot t^{0.5} \quad (12)$$

Fig. 3 shows the depletion depth of calcium with time. Only the calcium within 10 cm has been depleted during 300 years of typical institutional con-

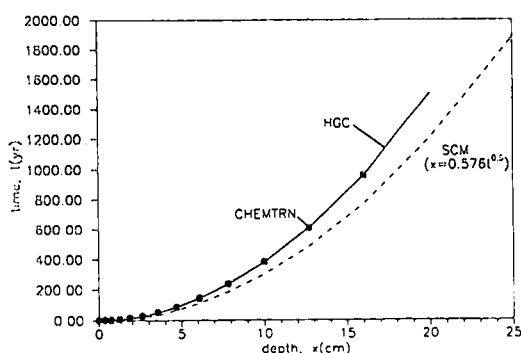


Fig. 3. Calcium Depletion Depth due to Diffusion from the Concrete to the Groundwater

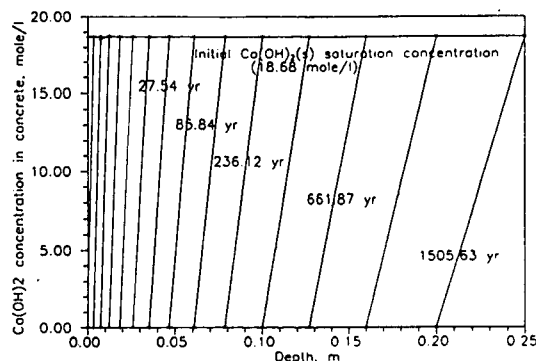
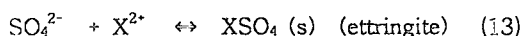


Fig. 4. Concentration Front with Time of  $\text{Ca(OH)}_2(\text{s})$  in the Concrete Evaluated by HGC

tol. No difference is found out between the result by the HGC and by the CHEMTRN. The result verifies that the HGC is well programmed. On the other hand, the SCM leads to more conservative result than the HGC. In the viewpoint of safety and simplicity, the SCM is likely to be more useful than the computer codes. The receding concentration front is shown in Fig. 4. The front becomes more dispersive with time as expected.

#### 4.2. Penetration of Sulphate from Bentonite

Sulphate from bentonite reacts with reactive calcium-aluminate to form ettringite in the concrete, and the transport concept is shown in Fig.2. Let the calcium-aluminate be X, then the ettringite formation reaction is expressed as



If the penetration depth with time is of only interest, for the convenience of calculation, the problem of sulphate migration towards the concrete can be treated as  $\text{XSO}_4$  outward diffusion from the concrete. Comparing with Eq.(5) for the case of calcium depletion, we can hypothetically interpret Eq.(10) as if  $\text{XSO}_4(\text{s})$  is depleted in the concrete system where its undissolved concentration is  $q^{\text{II}}$ , and its solubility in the porewater is  $C_{\text{eq}}$ , and its concentration in the groundwater is 0. In the case, the dissolution reac-

tion of  $\text{XSO}_4(\text{s})$  can be expressed as



if only one basis species,  $\text{XSO}_4(\text{aq})$ , is considered. The dissociation of  $\text{XSO}_4(\text{aq})$  to  $\text{X}^{2+}$  and  $\text{SO}_4^{2-}$  is meaningless because the migration rate of  $\text{XSO}_4(\text{aq})$  is practically equal to the migration rate of  $\text{SO}_4^{2-}$ .

If all the reactive aluminate in the concrete reacts with  $\text{SO}_4^{2-}$  from bentonite to form  $\text{XSO}_4$ , the amount of  $\text{XSO}_4$  produced is 0.135 kmole per 1  $\text{m}^3$  concrete, which corresponds to the capacity of the aluminate in the concrete [4]. This value is transformed to 0.9 mole/l porewater using the porosity of 0.15, and it is used for the initial total concentration. The concentration of the dissolved  $\text{XSO}_4$  in the concrete porewater,  $C_{\text{eq}}$ , should coincide with 0.0104 mole/l, the sulphate solubility in the bentonite porewater which was measured by experiment [10]. It makes outward diffusion of  $\text{XSO}_4(\text{aq})$  quantitatively be in agreement with the inward diffusion of  $\text{SO}_4^{2-}$ . Accordingly, total of 0.9 mole/l exist; 0.8896 mole/l of  $\text{XSO}_4(\text{s})$  and 0.0104 mole/l of  $\text{XSO}_4(\text{aq})$ .

The HGC code demands the value of reaction equilibrium constant rather than  $C_{\text{eq}}$  as one of the input data. It can be calculated by the following equation derived from Eq.(14) according to the mass action's law.

$$1/K = [\text{XSO}_4(\text{aq})][\nu_{\text{SO}_4}] \quad (15)$$

Table 2. Input Data for Sulphate Penetration

Items	value
<b>Concrete</b>	
amount of tri-calcium-aluminate, $q_2^B$ (mole/l concrete)	0.135
porosity, $\varepsilon_2$	0.15
effective diffusivity, $D_{p2}$ (m <sup>2</sup> /yr)	$9.46 \times 10^{-4}$
weighted pore diffusivity, $D_{p2}^*$ (m <sup>2</sup> /yr)	$2.73 \times 10^{-3}$
thickness of concrete slab (m)	0.30
<b>Bentonite</b>	
total amount of $\text{SO}_4^{2-}$ , $q_1^B$ (mole/l bentonite)	$3.10 \times 10^2$
solubility of $\text{SO}_4^{2-}$ in porewater, $C_{eq}$ (mole/l)	$1.04 \times 10^2$
effective diffusivity, of $D_b$ (m <sup>2</sup> /yr)	$3.15 \times 10^{-3}$
porosity, $\varepsilon_1$	0.55
<b>Grid</b>	
numbers	17
points(cm)	0, 0.388, 0.774, 1.23, 1.82, 2.52, 3.37, 4.39, 5.61, 7.08, 8.85, 11.0, 13.5, 16.6, 20.3, 24.7, 30.0

K : equilibrium constant of reaction (14)

$\text{XSO}_4$  : dissolved concentration of  $\text{XSO}_4$

$[v_{\text{SO}_4}]$  : activity coefficient of  $\text{XSO}_4(\text{aq})$

The K value is calculated as 96.16 using Eq.(15) with the activity coefficient of 1, and it corresponds to log K of 1.983.

Neretnieks et. al [10] measured that the weight of 1 m<sup>3</sup> of the dry bentonite was 1050 kg, while that of the wetted bentonite was 1600 kg. As a result, they presumed the porosity of the bentonite to be 0.55. The concrete thickness of 30 cm is considered. The data of the SKB [4] has been chosen for the input data of this work. The data and grid points are summarized in Table 2.

On the other hand, Eq.(10) is used to evaluate the sulphate penetration by the SCM. Substituting the related data for Eq.(10), the following equation is obtained.

$$x(\text{cm}) = 0.795 t^{0.5} \quad (16)$$

Fig. 5 shows the penetration depth of sulphate cal-

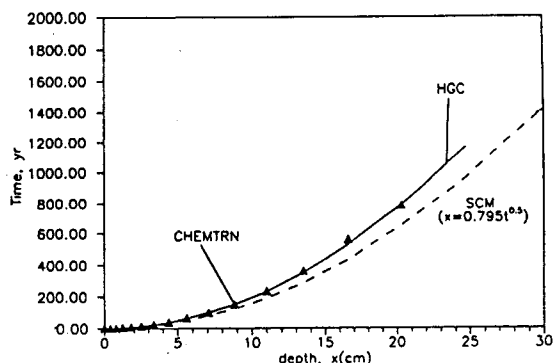


Fig. 5. Sulphate Penetration Depth Due to Diffusion from the Bentonite to the Concrete

culated by the SCM, the HGC, and the CHEMTRN, respectively. The result by the HGC is well agreed with that by the CHEMTRN. Like the case of the calcium depletion, the SCM leads to more conservative result than the HGC. During 300 years, the sulphate penetrates only 13.5 cm or less into concrete.

#### 4.3. Penetration of Carbonate from Bentonite or Groundwater

The carbonate penetration is very similar to the sulphate case except that the penetrated carbonate reacts with calcium to form calcite,  $\text{CaCO}_3(\text{s})$ , in the concrete.

The Na-form bentonite is usually produced from Ca-form bentonite through the following ion-exchange reaction.



It is known that some 2.5 % by weight of  $\text{Na}_2\text{CO}_3$  is added to the dry bentonite for the reaction. The amount of  $\text{Na}_2\text{CO}_3$  required to transform 1 m<sup>3</sup> bentonite is therefore 26.3 kg or 0.248 kmole. If all  $\text{Na}_2\text{CO}_3$  take part in the reaction, the produced amount of  $\text{CaCO}_3$  is 0.248 kmole. Accordingly, the maximum concentration of  $\text{CO}_3^{2-}$  in the bentonite

Table 3. Input Data for Carbonate Penetration

Items	value
<b>Concrete</b>	
total amount of Ca, $q_0^{\text{Ca}}$ (mole/l)	3.74
porosity, $\varepsilon_2$	0.15
pore diffusivity, $q_0^{\text{p}}$ (m <sup>2</sup> /yr)	$4.10 \times 10^{-4}$
thickness of concrete slab (m)	0.30
<b>Bentonite</b>	
amount of carbonate in porewater, $C_{\text{eq}}$ (mole/l)	0.45
porosity, $\varepsilon_1$	0.55
<b>Groundwater</b>	
amount of carbonate, $C_{\text{eq}}$ (mole/l)	$1.44 \times 10^{-2}$

porewater is 0.45 mole/l when the bentonite porosity is 0.55. With a conservatism, this value has been used as  $C_{\text{eq}}$  in the calculation.

The volume of the bentonite or the groundwater is assumed to be a very large, as compared to that of the concrete, so that  $\text{CO}_3^{2-}$  can be migrated into the concrete without changing of its composition in the source medium. This corresponds to the assumption that the concentration is constantly maintained at the concrete outer surface. Input data for the carbonate penetration are summarized in Table 3.

The carbonate penetration has been evaluated with the SCM. When the concrete is in contact with the bentonite, the following estimation equation is obtained.

$$x(\text{cm}) = 0.385 t^{0.5} \quad (18)$$

On the other hand, when the concrete is in contact with the groundwater involving  $\text{HCO}_3^-$  of  $1.44 \times 10^{-3}$  mole/l [4], the following relation is obtained.

$$x(\text{cm}) = 0.022 t^{0.5} \quad (19)$$

The carbonate penetration depth into the concrete is shown in Fig. 6. In the case of the concrete contacting with the bentonite, the penetration depth is about 7 cm during 300 years, while it can be neglected in the occasion of contacting with the groundwater. It is entirely caused by the concentration difference between source media, i.e., the driving force dif-

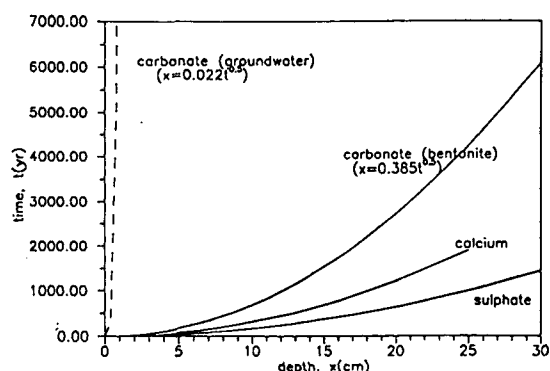


Fig. 7. Comparison of Carbonate Penetration Depth, Sulphate Penetration Depth and Calcium Depletion Depth evaluated by SCM List of Table

ference. The concentration of  $\text{CO}_3^{2-}$  in the groundwater is much lower than that in the bentonite. Fig. 6 also shows relatively how fast the three degradation mechanisms go forward. The dominating mechanisms are in order of the penetration of sulphate, the depletion of calcium, and the penetration of carbonate.

This work has individually evaluated the effect of three mechanisms acting centrally on the concrete degradation. In fact, the mechanisms take place simultaneously, and one of the mechanisms can speed up or disturb the others, and therefore, additional studies which treat all mechanisms comprehensively may be still necessary for the better understanding of concrete degradation.

## 5. Conclusions

The effects of three mechanisms, calcium depletion, sulphate and carbonate penetration, on the concrete degradation have been studied. The shrinking core model (SCM) and the HYDROGEOCHEM (HGC) model have been applied to evaluate how fast the mechanisms proceed. The SCM is an analytical model and the HGC is a numerical mass transport model coupled with chemical reaction. The SCM leads to more conservative results than the



HGC, and turns out very useful in the viewpoint of simplicity and conservatism. During 300 years, calcium has been depleted within 10 cm from the concrete outer surface, and sulphate has penetrated less than 13.5 cm into the concrete. Carbonate has not penetrated even 7 cm into the concrete in contact with the bentonite, and, furthermore, its penetration into the concrete with the groundwater has been negligible. Conclusively, the concrete is expected to maintain its integrity for at least 300 years that are regarded as institutional control period of intermediate- and low-level radioactive waste repository.

This study would not be directly applied to the safety assessment of the domestic repository because its result is based on the Sweden's data due to a lack of the domestic data. However, this study is very significant to establish the evaluation method of the concrete degradation. In the future, more realistic evaluation will be performed using a proper data for domestic repository conditions.

### Acknowledgement

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