The Mechanism of Chloride Ions Penetration in Various Wetting and Drying Conditions

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1. Introduction

The purpose of this paper is to investigate the mechanism of chlorides transport, especially focusing on the effect of wetting-drying conditions on the penetration. Basically, the movement of chloride ion into concrete is due to two main mechanisms; the diffusive movement caused by concentration differences of chlorides, and advective transport due to bulk suction of pore water. The moisture content or RH inside concrete subjected to an ambient environment, such as complex wetting-drying condition, does not have constant distribution throughout the depth. The surface region at 0-3 cm could have a fluctuation in terms of RH inside pore structure when it is subjected to wetting and drying conditions. This fact affects the penetration of chloride ions from environment. Moreover, a value of an ambient RH also controls the rate of the penetration. Of course, properties of concrete, such as strength, porosity and its distribution, determine how chloride ions behave in concrete. In this paper, the mechanisms of chloride movement under steady-state condition and several types of wetting-drying cycles are discussed. As usual of real environment, each season has a typical environmental condition and all of them have different wetting-drying cycles. At each location in Japan from East to West or from Hokkaido to Okinawa, the difference of environmental condition brings some difficulties to evaluate severity of chloride ions. The important point in this paper is to show some facts of the real mechanism of chloride movement as a basic knowledge to evaluate the effect on the chlorides transport in actual environments.

2. Numerical Simulation and Input Data

A numerical tool simulating concrete properties, such as the microstructure development has been proposed by Maekawa, et al **[1]**. Then the target of this technology has been widened by installing the chloride transport model **[2]**. The combination of these 2 models can simulate the development of microstructure and RH with time and the amount of total chloride ions concentration in each period. The software capable calculating the chloride ions concentration in concrete based on the above model is named as DuCOM program. Following these models, the simulated results on the chlorides transport in several wetting-drying cycles are obtained. The adaptation of this model can be used to realize the quantitative effect of concerned parameters in macro level. Thus, DuCOM is a tool to obtain the result for analysis in this paper. The summarization on the model of chloride ions movement can be shown in the **Eq. 1**,

$$\partial(\phi.S.C_{cl})/\partial t + \mathrm{div}J_{cl} - Q_{cl} = 0 \quad \text{and} \quad Jcl = (-\phi.S.D_{cl}.\nabla C_{cl}/\Omega) + \phi S.u.C_{cl} \qquad (\mathbf{1})$$

ϕ is porosity, S is degree of saturation, C_{cl} is concentration of chloride ion(mol/l), J_{cl} is flux of chloride ion (mol/m^2.s), Q_{cl} is the reduction of free chloride, D_{cl} is chloride ion diffusivity in pore solution phase (m^2/s), Ω is tortuosity of pore = $(\pi/2)^2$

The input data for replicating the mechanism is the concrete with water to cement ratio of 0.55 in 28-days standard curing in water with temperature of 20°c. The chloride ions concentration of environment is set as equal to 0.51 mol/l, which corresponds to 3% of salt concentration in weight. The first environment of input data is steady state, where relative humidity is kept 30% and 99.9%. The second set of input data is the consideration of long-term wetting: 3-days wetting and 10-days drying condition. The third set is short-term wetting: 1-day wetting and 10-days drying. In these 3 sets, the same condition for wetting and drying periods is given, i.e., 30% RH is given for drying, whereas 99.9% RH is set for wetting. Moreover, the fourth set is the short-term wetting condition same as in the third set, nevertheless 60% RH is substituted for drying phase in order to compare the RH effects. The results of all cases from DuCOM are shown in figure 1 to 4 orderly.

3. Results and Discussions

The results are shown in 4 sets of figures in different wetting and drying conditions. The first figure is in steady state condition and the second to fourth figures are 3-days wetting and 10-days drying, 1-day wetting and 10-days drying (RH 30%) and 1-day wetting and 10-days drying (RH 60%), in sequence. All figures show the distributions of chloride ions concentration after having wetting-drying cycles with RH distribution. **Fig. 1** shows 2 results under different ambient RH: 30% and 99.9%. In fact, high RH condition accelerates diffusive movement of chloride ions. Thus, the concentration at surface would be considered as a function of ambient RH. The maximum concentration in concrete is about 2% by weight of cement in case of 30% RH and 4% in case of 99.9% RH. By this result, the steady state of RH condition, the chloride ions concentration has a peak at the surface of concrete. Next, **Fig. 2** is set as long-term wetting of 3-days wetting and 10-days drying. The wetting period is set as 99.9% RH and the drying period is set as 30% RH.

Keywords; wetting and drying, DuCOM, chloride ions penetration, RH distribution

Looking at the RH distribution, the RH increases up to 99.9% during the wetting and decreases to 30% during the drying. In a cycle of wetting and drying, RH is nearly constant throughout the depth after 5 cm because of very low rate of moisture transfer forward and backward. The combination of high fluctuation of RH near surface and a constant RH after 5 cm results in the non-recover of RH at the depth between 3.5-5 cm. That leads us to understand that in this case wetting cannot increase RH all over the depth to be the level of 99.9% at last of wetting time. However, the case of long-term wetting can prevent dropping of RH at later 5 cm depth and keep constant with time. Compared with the case in **Fig. 3** of short-term wetting, that is 1-day wetting and 10-days drying condition, the wetting period is too short in order to prevent the decreasing of RH inside as in the long-term wetting. The large gradient in terms of RH distribution, especially at 3-5 cm, causes large water suction, which accelerates chloride migration into concrete. The analytical results show that the peak of chloride concentration exists at the position of lowest RH. During the wetting period, RH from surface and inside will be transferred to the depth of 3.5 cm and bringing chloride ions to accumulate in this position. In opposite, the peak of chloride ions is decreased by diffusing and moisture movement out of its during drying. Comparing influences in wetting with those in drying, the effect during the wetting has higher impact than that during drying. The parameters influencing on the chloride content at peak position are the wetting period and the ambient RH. This phenomenon is expressed in **Fig. 4** of short-term wetting with 60% RH during drying. Its RH distribution is not dramatically different, as the result the chloride content at peak position is not shown as high as previous case.

Concrete with w/c = 0.55 is specified for all figures

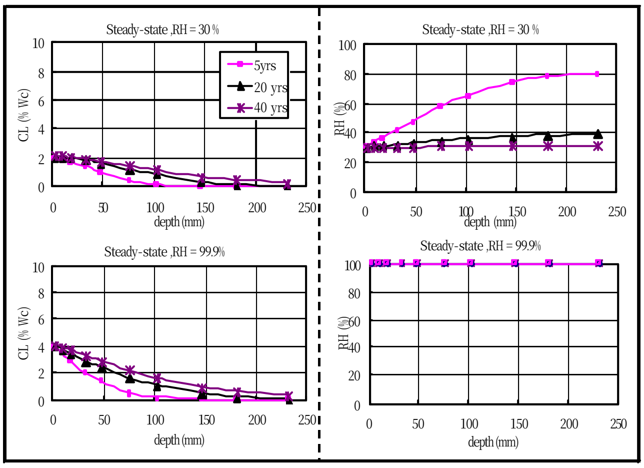

Fig. 1: Steady state of RH = 30% and 99.9%

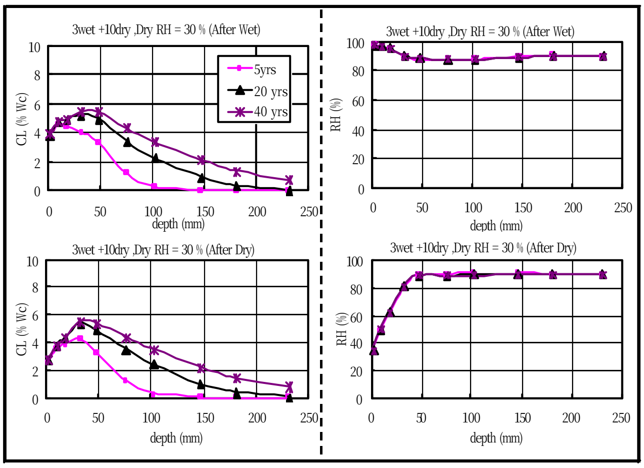

Fig. 2: 3-days wetting and 10-days drying (Drying RH 30%)

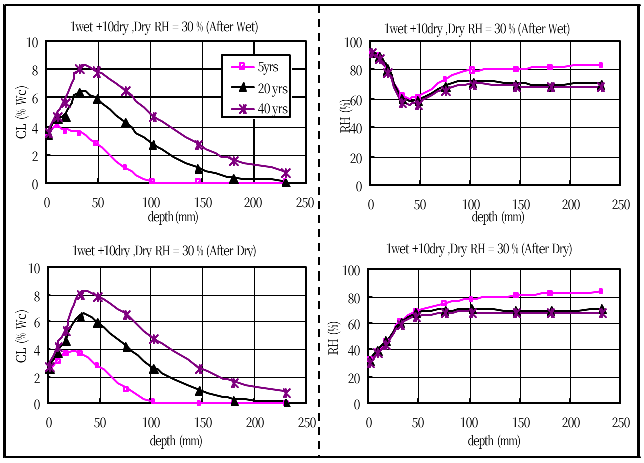

Fig. 3: 1-day wetting and 10-days drying (Drying RH 30%)

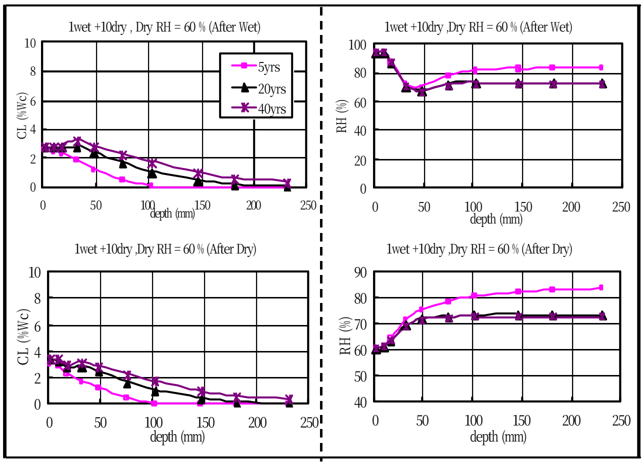

Fig. 4: 1-day wetting and 10-days drying (Drying RH 60%)

4. Conclusions

This paper shows some facts of the mechanisms on chloride ions movement in concrete, which lead us to understand influences of several wetting and drying conditions. After all, in the consideration of the actual environment with combine several conditions annually depending on weather and season seems to be more complex. For achieving the aim of how to simulate the chloride ions movement in an actual environment, the basic mechanism can be helpful. Nowadays, the development of an accurate design procedure used for chloride ions penetration in various environments is necessary to calculate a service life of a structure. However, the design should be based on the accurate mechanisms, which can be gained from this paper.

5. References

1. Maekawa K., Chaube R. and Kishi T., *'Modeling of Concrete Performance'* E&FN SPON, 1999
2. Ishida T., *An Integrated Computational System of Mass/Energy Generation, Transport and Mechanics of Materials and Structures*, The doctoral thesis submitted to University of Tokyo, March 1999 (in Japanese)