- Technical Paper -

MODELING OF ENVIRONMENTAL ACTION FOR PREDICTION OF LONG-TERM WATER CONTENT IN CONCRETE

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ABSTRACT

One of the essential considerations in developing a mathematical model for prediction of long-term water content in concrete is adequate modeling of climatic action. Meteorological data are modeled and imported to the computational program for moisture transport in concrete. Based on the sensitivity analysis, it was found that an environmental model in which temperature, humidity and raining time are averaged month by month is enough practical and assures satisfactory prediction of long-term water content in concrete.

Keywords: climate model, long-term water content

1. INTRODUCTION

Moisture content of concrete is one of the significant variables in predicting the long-term serviceability of concrete structures. The rate of transport process of aggressive agents such as chlorides in concrete depend on the amount of water in concrete pores. Freeze-thaw damage of concrete in cold weather is closely related with degree of saturation. Moisture state in concrete under real weather is affected by time-dependent change of natural climatic events. It is necessary to predict water content in concrete taking into account environmental actions adequately to ensure rational service-life management of concrete structures.

Previous experimental investigations [1] tend to pay attention to short term moisture content in concrete under natural weather with rainfall and sunshine. Studies on long-term moisture transport in concrete under natural and arbitrary climatic situations are very rare. Nilsson studied the ageing effect on moisture diffusion coefficient in high performance concrete under controlled laboratory condition [2]. Andrade investigated the effect of humidity and temperature fluctuations as well as rain fall on the change of moisture state in concrete. She pointed out that abrupt changes in hydrothermal conditions break equilibrium state [3]. This makes accurate prediction of water content in exposed concrete difficult.

While these foregoing studies pay attention to particular effect of climatic events such as rainfall, sunshine, temperature and relative humidity, this work investigates the combined effect of those climatic actions on long-term moisture content in exposed concrete. Climatic models with six levels of roughness are adapted to moisture transport analysis by means of a hybrid model of capillary suction and diffusion [4]. Sensitivity of climatic model on long-term water content in exposed concrete is discussed.

2. MOISTURE TRANSPORT MODEL IN CONCRETE UNDER DRYING AND WETTING CONDITION

2.1 Outline of the hybrid model of diffusion and capillary suction

The mathematical model for water transport in concrete employed considers difference in transport mechanisms between drying and wetting processes [4]. Two different models are alternatively adopted depending on drying and wetting condition of exposed surface: diffusion model for nonsaturated concrete under drying and adsorption process and capillary suction model for partially saturated concrete under wetting condition.

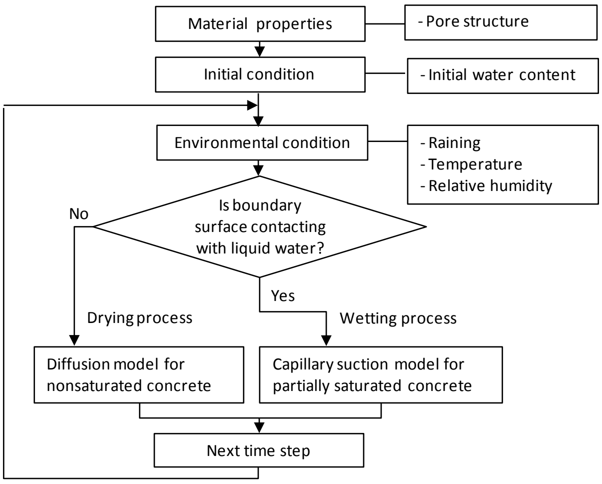

Fig. 1 Outline of computational flow

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The computational flow is shown in Fig.1. When concrete surface is exposed to the air, transport of water at boundary is driven by hydrothermal gradient between the exposed surface and the atmosphere and transport of water within concrete was calculated by diffusion model for nonsaturated concrete [9]. When concrete surface directly contacts with liquid water due to rainfall, capillary suction from the surface becomes dominant. Then, transport of water through the surface and within concrete was calculated by the capillary suction model for partially saturated concrete instead of diffusion model [8].

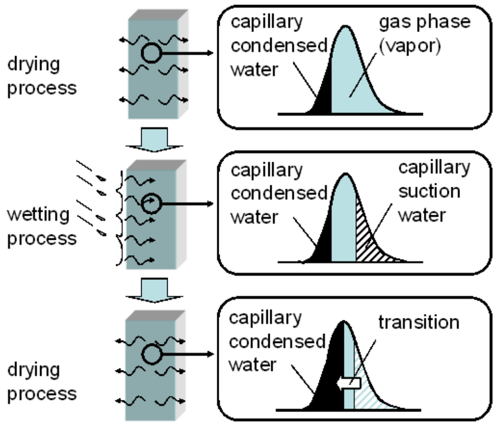

Fig. 2 Modeling of water in concrete under cyclic drying and wetting

The unification of diffusion and capillary suction and description of the state of water in concrete micro pores under these two transport mechanisms are illustrated in Fig. 2 [4].

In the drying process, the diffusion model for nonsaturated concrete by the authors is adopted [9].Capillary condensation of water in micro pores, diffusion of vapor and transport of liquid water within pore structure are taken into account in terms of pore size distribution function. Smaller pores are primarily filled with condensed water in this process.

When concrete surface contacts with water, concrete pores near the surface are immediately saturated and capillary suction from the surface begins. Since capillary suction water is considered to fill greater pores earlier, it is assumed that two kinds of liquid water temporally exist in concrete pores during wetting process: capillary condensed water and capillary suction water. In reality, capillary suction water will locally transit from greater pores to smaller pores and be gradually combined with condensed water. In addition, diffusion also takes places even during wetting process. It is assumed, however, that capillary condensed water does not change and only capillary suction occurs during wetting process because capillary suction is rapider phenomenon and transports greater amount of water compared with diffusion process.

When concrete is subjected to drying condition again, two kinds of liquid water are combined together and accounted as condensed water. Then drying process is calculated again. In reality, the transition from capillary suction water to capillary condensed water gradually takes place as discussed above. Nevertheless, it was verified that the proposed simplified assumption can well approximate change of total water in concrete under drying and wetting cyclic condition [1].

At this stage, change of characteristics of concrete during exposure is not explicitly taken into account. It can be expressed by changing parameters in the model experimentally.

2.2 Experimental Verification of the moisture transport model

The moisture transport model was calibrated and verified with exposed test conducted under four different environmental conditions [1]. Specimens were 100 mm square in cross section and 200 mm in height. The concrete mix whose water-cement ratio is 0.5 and unit water content is 170 kg/m^3 was used. Specimens were cured in water for 28 days. Five surfaces of specimens were sealed with epoxy resin to achieve one-dimensional moisture transfer in concrete. Time-dependent change of total water content of the specimen and profile of pore humidity in the specimen were measured.

Experimental case 1 was carried out under the controlled temperature and humidity (20 ˚C and 60% RH) as a reference case. Specimens in case 2 were placed in normal room and subjected to periodical water shower which simulates rainfall. Specimens in case 3 were placed in the timber shelter built in the field, in which specimens were subjected to the natural atmosphere by ventilation but not directly exposed to rainfall nor sunshine. Specimens in case 4 were exposed to the natural environment including change of temperature and humidity, rainfall and sunshine in the campus of Nagaoka University of Technology.

Based on these experimental cases and their analyses, it was verified that the moisture transport model can simulates weight change of specimens under various conditions when the environmental condition is precisely given [1]. The measurement is still going on. Comparison of analysis and two year's experimental results are shown in this paper.

The experimental and analytical fluctuation of water content in concrete specimen of case 1 and 2 are shown in Fig. 3.

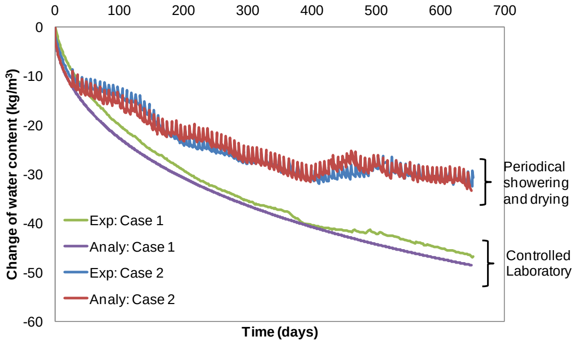

Fig.3 Experimental and analytical results of time-dependent water content in concrete under controlled room (case 1) and cyclic drying-wetting (case 2)

Diffusion due to the humidity gradient depicts the smooth decreasing curve for time-dependent change of total water content in the specimen of case 1. The analytical result follows the experimental one in case 1. The periodical increase of water content every six hours in case 2 is attributable to artificial rainfall. When showering stops, drying process starts, while part of water diffuses toward inside concrete even in this process. As case 2 is tested in a room without air-conditioner, the combined effect of temperature and RH% change can be seen as asymmetric up-down. The experimental and analytical results of case 2 agree with each other, including zigzag-shape by cyclic dry-wet.

Fig. 4 shows the fluctuation of total water content in the sheltered specimen (case 3) and non-sheltered specimen (case 4). The experimental curve for case 3 shows irregular wavy pattern due to natural weather. The experimental and analytical curves coincide twice throughout the experiments.

Although the analytical results fail to follow accurately experimental results of time-dependent change of water in concrete, annually averaged tendency of experimental curve can be approximated by analytical model. The fluctuation of water content in non-sheltered specimen (case 4) can be well simulated by analytical model including seasonal change.

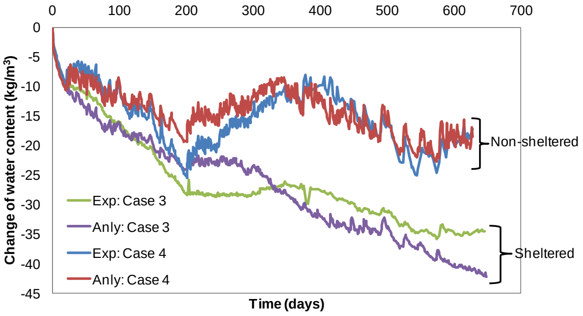

Fig. 4 Experimental and analytical results of time -dependent water content in sheltered concrete specimen (case 3) and exposed one (case 4)

3. MODELING OF ENVIRONMENTAL ACTION FOR NUMERICAL SIMULATION OF LONG-TERM WATER CONTENT IN CONCRETE

3.1 Significance of environmental model

It has been verified that the moisture transport model can simulate drying and wetting behavior of concrete under natural environment when precise environmental data, such as actually measured time-dependent temperature, humidity and raining duration, are available. However, in case of general actual structure, normally there is no such precise environmental data. Moreover, what is practically important is to predict long-term water content in concrete in advance without measured environmental data. Therefore, it is necessary to develop an environmental model that can be used for long-term prediction based on available information such as regional climate data or short term measurement. This study focuses on investigation of suitable environmental model which enables adequate long-term prediction of water content in concrete under natural environment.

3.2 Methodology

The exposure test results shown in chapter 2 are used for verification of environmental model. Rainfall, sunshine, temperature and relative humidity are considered as the significant climatic events for prediction of water content in exposed concrete. In the exposure test, drying and wetting features of environment were not recorded. Therefore, drying and wetting features of environmental actions are estimated from a regional weather data provided by Japan Meteorological Agency (JMA). The available weather information for Nagaoka is temperature, precipitation, wind direction wind speed and sunshine duration. The definition of sunshine duration in meteorology is that the length of time in which the solar radiation falling on a plane perpendicular to the direction of the Sun is greater than or equal to 120 W/m^2 (ECMWF). Therefore, sunshine duration data cannot be adopted directly as the drying duration of concrete surface. Among the available weather information, precipitation can decisively characterize wetting duration of boundary surface of concrete concerning capillary suction. It was reported by Andrade that the amount of rainfall has no significant effect on the change of water content in concrete [7]. Therefore, when precipitation is detected in an interval of hourly weather data in spite of amount of precipitation, this interval is regarded as a raining duration. The imported data series of dry-wet duration is shown as bar graph in Fig 5.

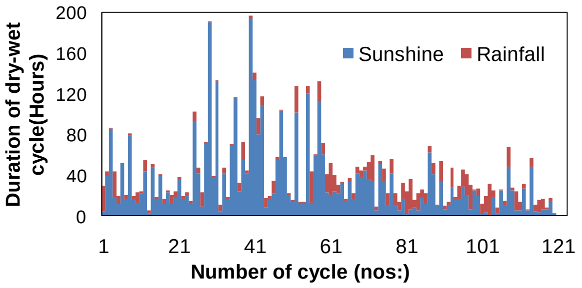

Fig 5. Dry-wet characteristic for Nagaoka regime

In the exposure test, hysteresis of local atmospheric temperature and relative humidity were measured near the corresponding concrete specimens. Therefore, those measured data were directly adapted to the model.

The influence of the level of roughness in environmental model on the analytical results is investigated in this study. Data series of dry-wet characteristic, temperature and humidity are averaged hourly, daily, weekly, monthly, seasonally and annually. In the daily averaged model, temperature and relative humidity are averaged within one day. Daily averaged temperature and relative humidity are calculated by Eq. (1).

$$\overline{f_d} = \frac{1}{24}\sum_{i=1}^{24} f(x) \tag{1}$$

Where $\overline{f_d}$ is daily averaged temperature or relative humidity, $f(x)$ is measured environmental temperature or relative humidity of every hour. Dry-wet duration in the daily model is evaluated by averaging hourly data of dry-wet duration within the day.

The weekly and monthly, seasonal and annual environmental models are made by similar way. Period of averaging temperature and relative humidity is 7 days, 30 days, 3 months and one year in the weekly, monthly seasonal and annual environmental model respectively. The calculation method of dry-wet duration in these models is shown in Table 1.

Table 1 Environmental models

Name of model	T(°C) and RH(%)	Dry-wet duration
Hourly	Measured data of every hour	Recorded dry-wet duration
Daily	$\overline{f_d} = \frac{1}{24}\sum_{i=1}^{24} f(x)$	Average of hourly dry-wet duration within one day
Weekly	$\overline{f_w} = \frac{1}{7}\sum_{i=1}^{7} \overline{f_d}$	Average of daily dry-wet duration within one week
Monthly	$\overline{f_m} = \frac{1}{30}\sum_{i=1}^{30} \overline{f_d}$	Average of weekly dry-wet duration within one month
Seasonal	$\overline{f_s} = \frac{1}{3}\sum_{i=1}^{3} \overline{f_m}$	Average of monthly dry-wet duration within four months
Annual	$\overline{f_a} = \frac{1}{4}\sum_{i=1}^{4} \overline{f_s}$	Average of seasonal dry-wet duration within one year

$\overline{f_d}$, $\overline{f_w}$ $\overline{f_m}$, $\overline{f_s}$, $\overline{f_a}$ indicate the daily, weekly, monthly, seasonally and annually averaged temperature or relative humidity respectively.

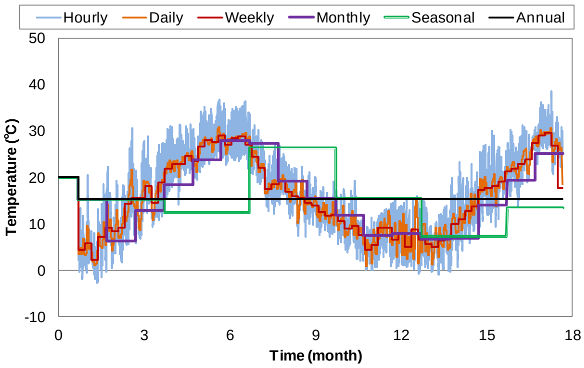

Fig. 6 Temperature models

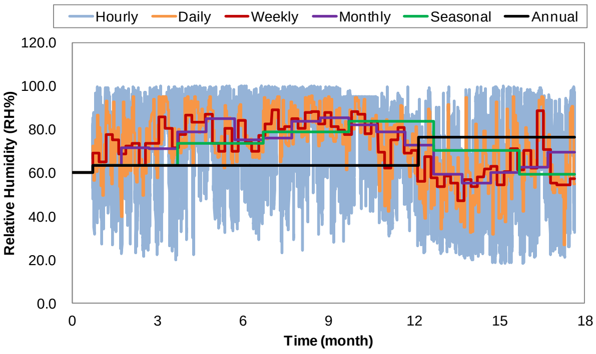

Fig. 7 Relative humidity models

The calculated environmental models for temperature and relative humidity are shown in Fig. 6 and 7 respectively.

3.2 Sensitivity analysis of environmental models

The experimental results of the sheltered specimen (Case 3) and the non-sheltered specimen (case 4) were calculated by using six environmental models. Calculated results of Case 3 by using hourly, daily and weekly averaged environmental model are shown in Fig. 8. Meanwhile, results by using monthly, seasonally and annually averaged environmental model are shown in Fig. 9.

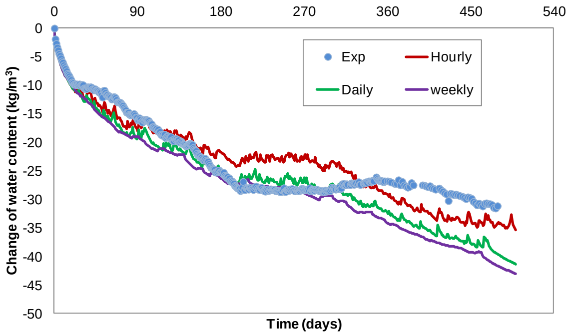

Fig. 8 Simulation of long-term water content in sheltered concrete specimen based on hourly, daily and weekly environmental model

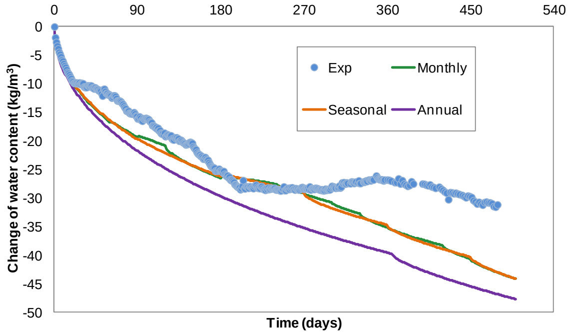

Fig. 9 Simulation of long-term water content in sheltered concrete specimen based on monthly, seasonal and annual environmental model

It is obvious that the difference in roughness of environmental model affects calculated results. The reason of this is considered as following. The difference between actual temperature or humidity and modeled ones each time makes difference between experimental and analytical results of water content. In addition, the influence of temperature or humidity over the averaged value and those below the averaged value on moisture transport phenomena in concrete cannot be compensated equivalently. Consequently, calculated results by rougher environmental models cannot follow experimental curves nor estimate the tendencies in averaged behavior.

Fig. 10 and 11 show experimental and analytical results of water content in the non-sheltered specimen. The number of waves due to cyclic dry-wet in the analytical curve is less and the amplitude is greater in using rougher environmental model. However, different from the case of sheltered specimen in Fig. 8 and 9, averaged value in analytical results are not much affected by the roughness of environmental model. This is attributable to the existence of capillary suction process in non-sheltered specimen. Capillary suction from the surface has greater influences on water content in non-sheltered concrete than diffusion process. It is considered that the effect of capillary suction during certain time can be adequately evaluated even by rough models as much as total wetting time involved is properly accounted.

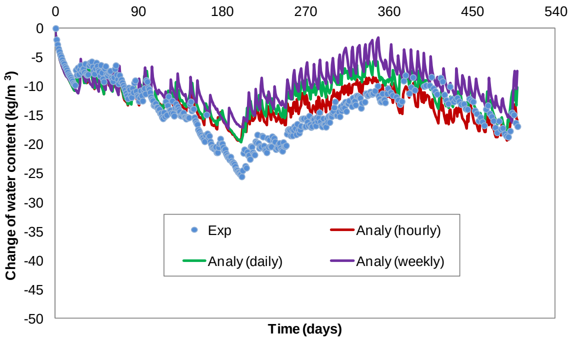

Fig. 10 Simulation of long-term water content in exposed concrete specimen based on hourly, daily and weekly environmental model

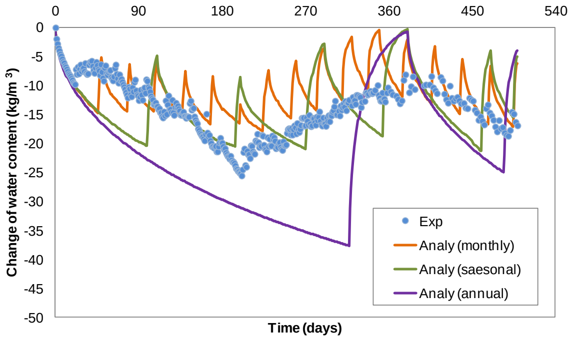

Fig. 11 Simulation of long-term water content in exposed concrete specimen based on monthly, seasonal and annual environmental model

It was confirmed that both dry-wet duration and hydrothermal data affect analytical results. In general, detailed environmental model ensures good analytical results. On the other hand, detailed model is less convenient for long-term prediction because it requires number of climatic data. In consequence, the balance between easiness in data handling and accuracy in prediction results should be of importance in choosing prediction method for long-term behavior of concrete.

The index S, which is calculated by Eq.(2), is introduced in this study to represent the accuracy in numerical simulation. .

$$S = \frac{1}{T}\int_0^T \sqrt{\left(exp(t) - anl(t)\right)^2}\, dt \qquad (2)$$

where, T is duration of experiment (days), $exp(t)$ is experimental result of change in water content in the specimen at time t (kg/m^3) and $anl(t)$ is corresponding analytical result. In numerical calculation, the integral interval in Eq.(2) is set as one day.

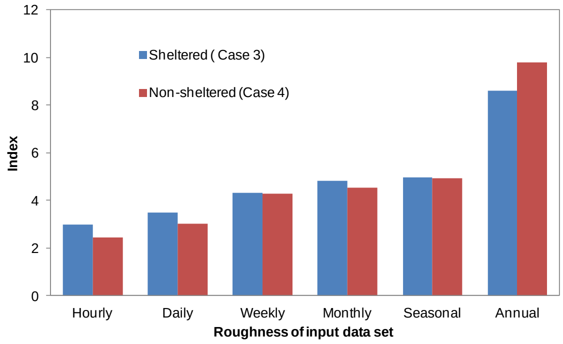

Fig.12 Comparison of accuracy of six environmental models

Fig.12 shows evaluated index S in the calculated results by the six environmental models. The index *S* becomes greater with increasing in roughness of the environmental model. Nevertheless, the index S of weekly, monthly and seasonal model have no significant difference. Considering that monthly averaged climate data can be directly obtained from the JMA weather data base, while preparation for weekly and seasonal model need additional calculation step, monthly environmental model has an advantage in practical use for long-term prediction of water content in actual structures.

4. SIMULATION OF LONG-TERM WATER CONTENT IN CONCRETE STRUCTURE

Proposed method to make environmental model was adapted to actual meteorological data of some regions as trial. Long-term water content in concrete structure under sheltered and non-sheltered conditions in Sapporo, Tokyo and Naha were calculated. Average water content in concrete wall of which thickness is 300mm is predicted. One surface is exposed to the atmosphere and the other surface is sealed.

The monthly averaged temperature and humidity of past 10 years in Sapporo region is plotted in Fig. 13. Average temperature and humidity of each month have no significant difference in past 10 years. It can be deduced that temperature and humidity curve in coming year will be in the same trend with the spectra of past years. Monthly temperature and humidity averaged past 10 years' data were respectively adopted to make annual temperature and humidity curves in the future. Estimated monthly temperature and humidity spectra of Sapporo are also shown in Fig. 13. The hydrothermal conditions spectra of Tokyo and Naha were also prepared in the same way. Dry-wet condition model of Sapporo, Tokyo and Naha were developed in the same way with monthly environmental model in section 3.2.

The simulation results of water content in sheltered and non-sheltered concrete wall in Sapporo, Tokyo and Naha during 60 years are shown in Fig. 14.

Water content in sheltered concrete wall rapidly and continuously decreased in first ten years. Thereafter, decreasing rate gradually became small. After 20 year, water content fluctuates within a stable range and reached equilibrated state. Drying is more promoted in Tokyo than in Sapporo and Naha. This may be because the combination of temperature and humidity in Tokyo ensures the lowest equilibrated water content.

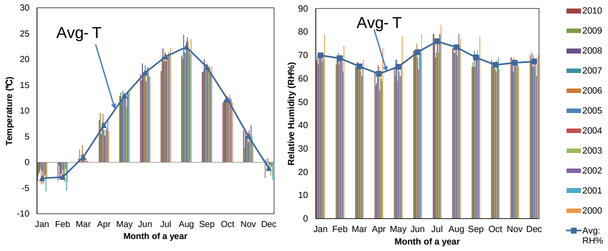

Fig.13 Monthly temperature and humidity hysteresis of Sapporo

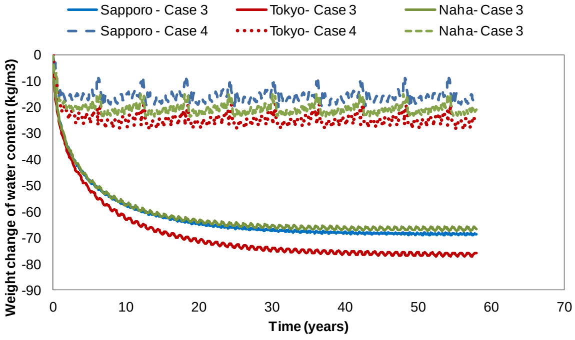

Fig. 14 Predicted long-term water content in concrete wall

Water content in non-sheltered concrete wall is higher than that in sheltered concrete because of capillary suction due to rainfall or snowfall. In addition, concrete walls under non-sheltered condition reached equilibrated state earlier than under sheltered condition. This is also attributable to wetting by rainfall or snowfall.

5. CONCLUSIONS

(1) The moisture transport model in which diffusion in nonsaturated concrete and capillary suction in partially saturated concrete are coupled is verified with the exposure test results for two years.

(2) Environmental models which express cyclic drying-wetting action, temperature and humidity, to predict long-term water content in concrete under natural environment are investigated. It was found that the accuracy of the calculation results depends on roughness of environmental model adopted.

(3) In practical prediction of long-term water content in concrete under natural environment, the environmental model based on monthly averaged dry-wet duration, temperature and relative humidity is recommended because the model can directly utilize meteorological data and its prediction results show satisfactory accuracy.

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