# CONCRETE FROST RESISTANCE EVALUATION METHOD CONSIDERING MOISTURE INCREASE BY FREEZE AND THAW

凍結融解による水分増加を考慮したコンクリートの耐凍害性評価方法

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## ABSTRACT

Frost damage to concrete structures in cold regions has been one of the serious problems. In recent years, there are two methods for evaluating the frost resistance of concrete. One widely adopted method in Japan is the accelerated freeze and thaw test based on the JIS A 1148 A (ASTM C 666), and the other is the critical degree of saturation test according to the RILEM CDC 3. In the critical degree of saturation test, cylinder specimens with different water contents are conducted with the freeze and thaw test and the critical degree of saturation $S_{cr}$ where obvious frost deterioration occurs is obtained. Furthermore, the single surface water absorption test at room temperature has also been conducted and the capability that the moisture in the single surface water absorption test reaches $S_{cr}$ is regarded as concrete frost resistance. The more difficult for the water absorption to reach the $S_{cr}$ is, the better frost resistance of the concrete specimens owe. Even though both tests are for the comparison between different concrete frost resistance, the results by the two tests sometimes do not correspond with each other. In particular, the critical degree of saturation test does not take the moisture content increase due to the freeze and thaw in the single surface water absorption test into account, which is one of the important factors for concrete frost deterioration. Therefore, the purpose of this paper is to propose a new method for evaluating the concrete frost resistance using the critical degree of saturation method considering the moisture increase due to freeze and thaw. Furthermore, concrete frost deterioration in the actual environment has been predicted by this method.

Firstly, the single surface water absorption test considering moisture content increase by freeze and thaw has been employed base on the critical degree of saturation test, and the results were compared with the critical degree of saturation $S_{cr}$. However, the moisture content increase by this method was not enough, and the moisture content $S_{cap}$ could not get to the $S_{cr}$. Hence, the accelerated freeze and thaw test was adopted as a freeze and thaw test having a considerable effect on increasing moisture content. In the test, except for the general measurements of the length change, relative dynamic modulus of elasticity change (RDM) and the mass change, the mass moisture content of the specimen has also been calculated. The results were then compared with the critical degree of saturation test. As a result, the moisture content increased due to freeze and thaw, and it has been clarified that the mass moisture contents at the nickpoint where the obvious change appeared in the curve of the length and RDM change were equal to the mass moisture content of the critical degree of saturation $S_{cr}$. The mass moisture content at the nickpoint was defined as the critical mass moisture content $W_{cr}$, and concrete illustrated apparent damage when the critical mass moisture content $W_{cr}$ was exceeded. Moreover, the freeze and thaw cycle at the nickpoint of the accelerated freeze and thaw test was defined as the critical freeze and thaw cycle *Nf*, and *Nf* was proposed as a new concrete frost resistance criterion.

In order to predict concrete frost deterioration in the actual environment, it is necessary to clarify its influential factors. The greatest effect on frost damage is the lowest temperature during freeze and thaw. Hence, the accelerated freeze and thaw test with the lowest temperature -5℃ and -10℃ and the critical degree of saturation test were conducted in this paper. Furthermore, the results were compared with the standard accelerated freeze and thaw test with the lowest temperature -18℃ to figure out the effect of the lowest temperature on concrete frost damage. The results showed that the critical freeze and thaw cycle *Nf* increased as the lowest temperature increased, and the critical mass moisture content $W_{cr}$ was not affected by the different lowest temperatures. In addition, a formula has been proposed to convert the *Nf* calculated by the test with different lowest temperatures to the *Nf* achieved in the standard accelerated freeze and thaw test with the lowest temperature -18℃.

It is reckoned that obvious frost damage occurs when the frost effect of the actual environment surpasses the *Nf* of concrete specimens. Therefore, the concrete specimens were subjected to the outdoor exposure test and the temperature and the relative humidity (RH) of the specimens have been measured. The frost effect of the outdoor exposure with different lowest temperatures has been converted to the freeze and thaw cycle *Nf** by the formula proposed above. Concrete specimens are regarded as damaged when the frost effect *Nf** exceeded *Nf*. Besides, the specimens after the outdoor exposure were conducted with the accelerated freeze and thaw test and it has been confirmed that the *Nf* decreased after the outdoor exposure. These results indicate the possibility of predicting concrete frost damage deterioration by *Nf*. In the future, it is necessary to clarify the influence of other influence factors (drying, outdoor exposure duration, etc.) on concrete frost deterioration.

This dissertation is composed of five chapters. The outline of each chapter is listed as follows.

Chapter 1 is the introduction of the background of concrete frost resistance evaluation methods and the previous achievement on concrete frost deterioration. Besides, the detail of the accelerated freeze and thaw test and the critical degree of saturation test are explained. The problems of the two tests have been proposed and the purpose of this study is exhibited.

In Chapter 2, the single surface water absorption test considering moisture absorption by freeze and thaw has been conducted. Based on this, the accelerated freeze and thaw test and the critical degree of saturation test considering moisture absorption by freeze and thaw were conducted. The mass moisture contents at the nickpoints of the length and RDM were similar to the mass moisture content of $S_{cr}$. The freeze and thaw cycle at the nickpoint of length change was defined as the critical freeze and thaw cycle *Nf* and its mass moisture content was designated as $W_{cr}$. The *Nf* was regarded as a new concrete frost resistance criterion.

Chapter 3 examined the effect of the lowest temperatures on the *Nf*. The *Nf* achieved by the accelerated freeze and thaw test with different lowest temperatures -5℃ and -10℃ were compared with the *Nf* calculated by the standard accelerated freeze and thaw test with the lowest temperature -18℃. As a result, the relationship between the lowest temperature and its corresponding *Nf* was clarified, and the conversion formula was proposed.

In Chapter 4, the frost deterioration in the actual environment has been predicted by *Nf*. It is supposed that concrete specimens are damaged by freeze and thaw as the environmental frost effect reaches *Nf*. The specimens were exposed to the outdoor and its temperature and the relative humidity of the specimens were measured. The frost effect of the outdoor exposure has been converted to *Nf** by the formula proposed in Chapter 3. Moreover, the specimens after the outdoor exposure were conducted with the accelerated freeze and thaw test to verify the deterioration effect of the outdoor exposure.

Chapter 5 summarizes of the results above and presents further research challenges.

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## CHAPTER 1
## INTRODUCTION

### 1.1 BACKGROUND

Cementitious materials are used all over the world for its wide applicability and easy operation performance [1]. The continued prevalence of freeze and thaw related failure in concrete has led to the need to review the current state to help to ensure adequate life-service [2]. According to the previous research, deterioration of the concrete structures in the cold regions is generally manifested in the form of microcracks, scaling and pop-out on the concrete surface [3].

As a kind of concrete deterioration evaluation method where microcracks emerge by frost, two main concrete frost resistance evaluation methods are widely employed in the world. They are the accelerated freeze and thaw method based on the JIS A 1148 A (ASTM C 666) and the critical degree of saturation method according to RILEM CDC 3. Compared to the accelerated freeze and thaw test, the critical degree of saturation test is newly proposed. Therefore, numerous scholars have done research about it. Fargelund proposed the critical degree of saturation test of assessing freeze and thaw resistance of concrete by two types of concrete specimens. The critical degree of saturation $S_{cr}$ was determined by freeze and thaw experiments, while the degree of capillary saturation $S_{cap}$ was achieved by water absorption experiments. The results were used for evaluating concrete frost resistance [4]. Li figured out that the existence a critical degree of saturation when concrete suffered from freeze and thaw and the critical degree of saturation appeared to be independent of the air content. Besides, the materials undergo damage after a few freeze and thaw cycles as the materials with a degree of saturation above the critical degree [5].

Concrete frost resistance evaluation method has been proposed based on the results of the two tests, respectively. However, Hasegawa et. al. found out that the relationship between the concrete frost resistance achieved by the two methods was not clear [6].

### 1.2 CONCRETE FROST RESISTANCE EVALUATION METHODS

#### 1.2.1 The accelerated freeze and thaw test

The accelerated freeze and thaw test based on the JIS A 1148 contains two methods. They are the method A (freeze and thaw test in water) and method B (freeze in air and thaw in water), respectively. The method A is suitable for the concrete specimens with strong frost resistance, while the method B applies for the pervious or lightweight concrete [7]. The accelerated freeze and thaw test in this paper is conducted according to the JIS 1148 method A.

In the accelerated freeze and thaw test, the freeze and thaw function is performed by the apparatus as shown in Fig.1.1. The apparatus has set up with refrigerating and heating equipment to produce reproducible and continuous freeze and thaw cycles. The prismatic specimens are firstly set in the rubber containers and then water is poured into the containers until the liquid level about 3mm above the upper surface of the specimen. One freeze and thaw cycle usually takes no more than 4 hours and the temperature of the central specimen in one cycle should range from -18±2～5±2℃. In one freeze and thaw cycle, the time that the temperature decreasing from 3～-16℃ should be longer than half of the freezing period. While, the thawing period should account for more than 25% of one freeze and thaw cycle. The schematic diagram of temperature change with time is exhibited in Fig.1.2.

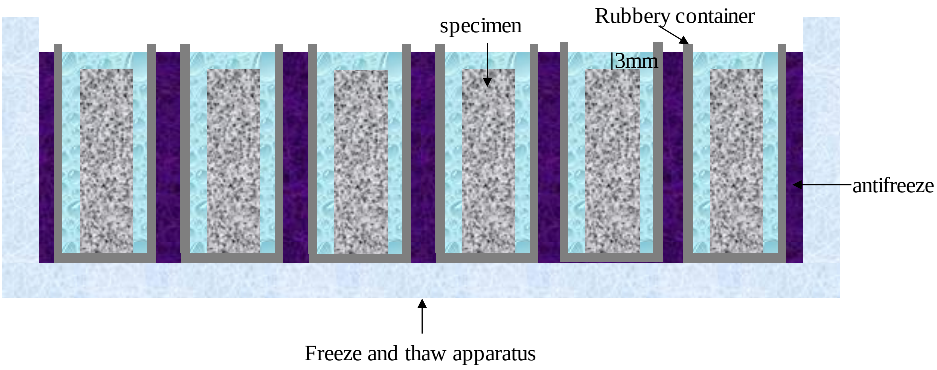


Fig.1.1 The freeze and thaw apparatus

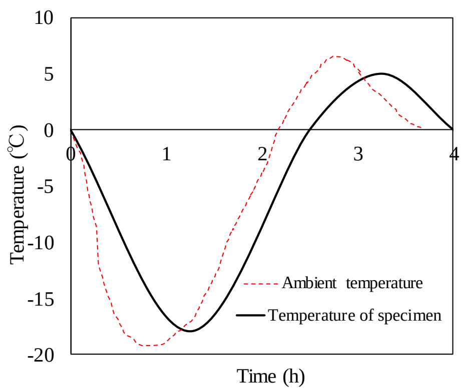


Fig.1.2 The image of the temperature changing with time

The specimens experience cyclic freeze and thaw cycles and then are taken out to measure its length, weight and fundamental transverse frequency in every 4-6 cycles. Concrete frost resistance can be evaluated by the change of these parameters. Here show the results of the calculation of these parameters.

(1) The length change after n freeze and thaw cycles

The length change of the concrete specimen can be calculated by Eq.1.1.

$$L_n = \frac{l_n - l_0}{Y} \tag{1.1}$$

Where, $L_n$ is the length change rate after n freeze and thaw cycles, $l_n$ is the length after n freeze and thaw cycles, $l_0$ is the length at 0 cycle, $Y$ is distance between the two gauges at two ends of specimen.

(2) Weight reduction rate

The weight reduction rate is expressed by Eq.1.2.

$$W_n = \frac{w_n - w_0}{w_0} \tag{1.2}$$

Where, $W_n$ is the weight reduction rate after n freeze and thaw cycles, $w_n$ is the weight after n freeze and thaw cycles, $w_0$ is the weight at 0 cycle.

(3) The durability factor

The relative dynamic modulus of elasticity (RDM) can be calculated by Eq.1.3 and the durability factor (DF) can be acquired by Eq.1.4.

$$P_n = \left( \frac{f_n^{\ 2}}{f_0^{\ 2}} \right) \times 100 \tag{1.3}$$

Where, $P_n$ is the relative dynamic modulus of elasticity after n freeze and thaw cycles, $f_n$ is the fundamental transverse frequency after n freeze and thaw cycles, $f_0$ is the fundamental transverse frequency at 0 cycle.

$$DF = \frac{P \times N}{M} \tag{1.4}$$

Where, *DF* is the durability factor, *P* is the *RDM* at N cycles, *N* is the freeze and thaw cycle numbers where the RDM falls to 60% or 300 cycles, whichever is smaller, *M* is 300 cycles.

### 1.2.2 The critical degree of saturation test

The critical degree of saturation test is conducted based on the RILEM CDC3. The test has been divided into two parts. One part of the test is to figure out the critical degree of saturation $S_{cr}$. In the test, several cylindrical specimens with a dimension of Φ100×200mm are kept in water vacuum saturated condition and then preserved in water for another two days before drying at 50℃ to different moisture saturation degrees. The specimens are then conducted with the freeze and thaw test and the RDM has been measured before and after the freeze and thaw test. As shown in Fig.1.3, the residual RDM of the specimens with different moisture contents after the freeze and thaw cycles are depicted and the moisture degree at the nickpoint is defined as the critical degree of saturation $S_{cr}$. After the critical degree of saturation $S_{cr}$ is achieved, the cylindrical specimens are vacuum saturated again and then dried in an oven at 105℃ to constant weight. The details operation of the critical degree of saturation test are exhibited in Appendix.A.1.

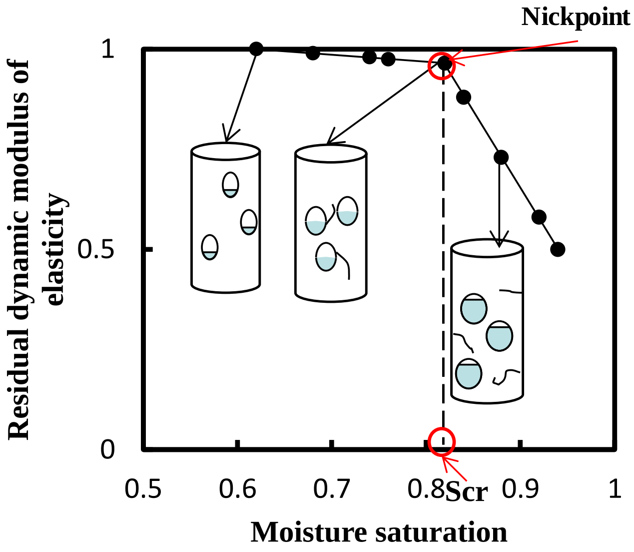


Fig.1.3 The residual RDM of the specimens with different moisture contents

Furthermore, the other part of the critical degree of saturation test is the single surface water absorption test conducted at room temperature. The cylinder specimens are cut into the slices with a size of Φ100×30mm and then the slices are dried at 50℃ for at least 3 days. The slices are set into a stainless tray filled with water as exhibited in Fig.1.4. Besides, the preservative film is covered on the tray to prevent the moisture from evaporating. The slices are taken out and the weights are measured at suitable time intervals. The test yields a sort of potential degree of saturation which can be reached during very moist conditions. It is called the capillary degree of saturation, $S_{cap}$. The moisture content $S_{cap}$ increasing with time is depicted in Fig.1.5. As shown in Fig.1.5, concrete freeze and thaw resistance $T_{pl}$ has been defined by Eq.1.5.

$$T_{pl} = T_{(S_{cap}=S_{cr})} \qquad (1.5)$$

Where, $T_{pl}$ is the concrete freeze and thaw resistance, $T_{(Scap=Scr)}$ is the time that the moisture saturation $S_{cap}$ reaches the critical degree of saturation $S_{cr}$. The concrete frost resistance criterion $T_{pl}$ is proposed by the laboratory of construction building materials in Hokkaido university [8].

Fig.1.4 The set up of the water absorption test

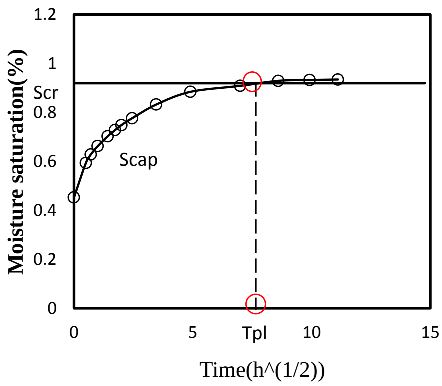


Fig.1.5 The moisture content with time

### 1.2.3 The evaluation criteria for concrete frost resistance

Fig.1.6 shows the schematic graph of the RDM changing with cycles in the accelerated freeze and thaw test. The cyclic freeze-thaw function can cause progressive damage to the concrete materials and this phenomenon is called fatigue. The cyclic loading will cause microcracks and deformations, and finally result in the failure of the materials. Linear elastic fracture mechanics theory has been developed for the inhomogeneous materials and it has proven very useful for these materials. Fracture mechanics theory and its application to plastic materials has been well described in the previous literatures [9]. Stress is defined for S-N testing however, for the fracture mechanics specimens the stress is replaced with the stress intensity factor. Eq.1.6 is defined as follows:

$$K = Y\sigma\sqrt{a} \tag{1.6}$$

Where, K is the stress intensity factor, Y represents the geometry factor, $\sigma$ is the stress and a means the crack length.

Wyzgoski and Novak considered both the initial crack length $a_0$ and final crack length $a_f$, and proposed the relationship between the total number of cycles to fail Nf and the stress range $\Delta\sigma$ [10]. The Eq.1.7 is listed below.

$$Nf = \frac{2}{(m-2)A\gamma^m(\Delta\sigma)^m}\left(\frac{1}{a_0^{\frac{(m-2)}{2}}} - \frac{1}{a_f^{\frac{(m-2)}{2}}}\right) \tag{1.7}$$

Where, Nf is the total number of cycles to fail, m and A are the values obtained from the crack propagation experiment.

On the other hand, Kim and Zhang quantified the fatigue damage at tensile fatigue failure and proposed the relationship between Nf and ultimate tensile strength $\sigma_{uT}$ [11]. The relationship is listed in Eq. 1.8.

$$Nf = \frac{\sigma_{uT}^{-\beta}}{\alpha(\beta-1)}\left[\left(\frac{\sigma_{\max}}{\sigma_{uT}}\right)^{1-\beta} - 1\right] + N_0 \tag{1.8}$$

Where, α, β means the model fitting parameter, $N_0$ is the initial number of cycles.

Fig.1.7 shows the experimental and simulated results of the S-N curve. The simulated S-N curve by Wyzgoski and Novak is achieved according to the Eq.1.7 with t=0.0032m, m=7.41, $A=1.53\times10^{-10}$m/cycle, $\gamma=1.17$, R=0.1 and $a_0$=0.354mm. The other curve was achieved by Eq.1.8 with $\alpha=1.53\times10^{-10}$ and β=15.028. As shown in the figure, the simulated data is in good accordance with the experimental data. Besides, it is found that the tendency of the RDM of specimens changing with cycles is similar with the tendency of the S-N curve. Therefore, the effect of the freeze and thaw cycles can be also regarded as a kind of fatigue function on the concrete specimens.

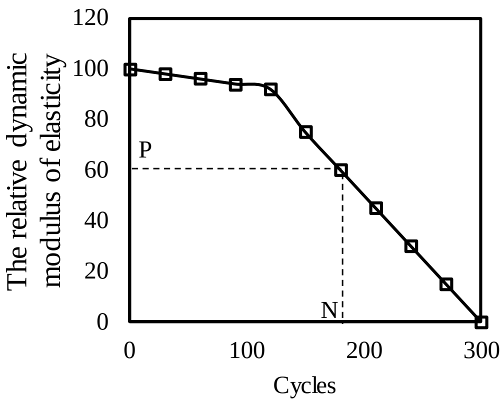


Fig.1.6 The RDM changing with cycles

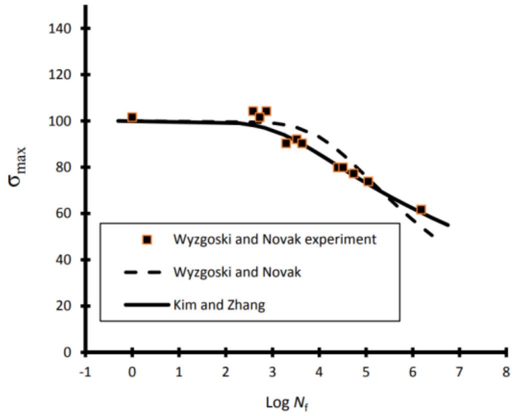


Fig.1.7 The simulated and experimental data of S-N curve

The RDM can be used for evaluating the internal deterioration by freeze and thaw, however, there is no rational method for setting the evaluation criteria. Normally, the RDM with a value of 85%. 80%, and 60% are used as the evaluation criterion, however, these values have no clear meanings. In Japan Society of Civil Engineers' Concrete Standard Specifications (Design 2007), the limit RDM value to satisfy the concrete buildings suffered from freeze and thaw with safe performance has been proposed [12]. Table 1.1 shows the limit value of RDM to satisfy the performance of concrete structures against frost damage according to the actual engineering experience. The limit value of the RDM has not been clearly defined and it is just based on the previous experience and achievements.

Table 1.1 The limit RDM to satisfy concrete performance against frost damage

| Weather condition | Severe weather condition | | Moderate weather condition | |
|---|---|---|---|---|
| Concrete state | Thin state* | Normal state | Thin state* | Normal state |
| High saturation state | 85 | 70 | 85 | 60 |
| Normal saturation state | 70 | 60 | 70 | 60 |

*Section thickness is thinner than 20cm.

Therefore, the influencing factors that decrease the RDM in the accelerated freeze and thaw test have been examined and the proportion of the effect of the actual environment on concrete frost deterioration has been converted to the cycles in the accelerated freeze and thaw test (ASTM C666 (JIS A 1148 A)). According to Matsumura, the effect of the freeze and thaw function of which concrete buildings suffer from the outdoor exposure can be derived from the equivalent ASTM freeze and thaw cycle $C_{yASTM}$ of the standard accelerated freeze and thaw test with the lowest temperature -18℃ [13]. Eq.1.9 expresses the $C_{yASTM}$.

$$C_{yASTM} = C \times F \times \sum (-ts/18)^{\beta} \tag{1.9}$$

Where, *C* is the coefficient of curing condition which includes the effect of summer drying, *F* is the coefficient of freeze and thaw conditions and *F* describes the moisture content of the concrete when freeze and thaw commences, *ts* is the lowest temperature during the freeze and thaw, *β* is the coefficient of the concrete appearing the sign of deterioration (100%≧RDM>90%) or obvious deterioration (90%≧RDM>60%) calculated by the accelerated freeze and thaw test.

Besides, Yamashita proposed a concrete frost evaluation predicting method according to the results of the compressive stress, air void spacing coefficient and frozen water [14]. However, the predicted results by these methods sometimes do not correspond well with the concrete deterioration in the actual environment. Besides, it has been reported that concrete frost resistance changes due to environmental effects such as drying [15]. Hence, it is also needed to figure out these effects on the concrete frost resistance predicting method.

### 1.2.4 The relationship between the two concrete frost resistance evaluation methods

Both the accelerated freeze and thaw test and the critical degree of saturation test can be used to evaluate concrete frost resistance. However, there are some shortcomings to carry out the two tests. For example, the accelerated freeze and thaw test can be quite time and labor consuming. While, on the other hand, the $S_{cap}$ is achieved at room temperature and the effect of additional moisture increase by freeze and thaw has not been considered. Fig.1.8 shows the relationship between DF and $T_{pl}$ [16]. As shown in the figure, concrete frost resistance DF of W/C55% concrete increases obviously as the air content increases from 1% to 5%. While, $T_{pl}$ increases slightly as the air content increases. Moreover, there is no clear relationship between the $T_{pl}$ and DF. It is supposed that since the additional moisture content by freeze and thaw in the critical degree of saturation test has not been considered, the DF and $T_{pl}$ do not correspond well with each other.

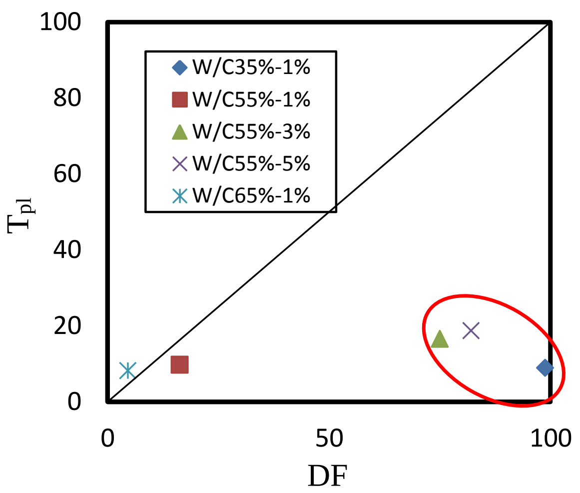


Fig.1.8 The relationship between DF and $T_{pl}$ of several concrete types

## 1.3 THE ADDITIONAL WATER ABSORPTION DURING FREEZE AND THAW

Concrete buildings are deteriorated by the ambient environment factors, such as the freeze and thaw function, carbonation and the chloride ion. The moisture transportation plays a key role in the above environmental factors because it is indispensable in the above reactions. The moisture absorption of concrete buildings can be accelerated by the pumping effect and therefore result in a moisture content higher than the degree of capillary saturation $S_{cap}$, which is calculated at room temperature. The pumping effect causes external water to transport into the concrete specimens beyond the isothermal room temperature conditions. The pumping effect has been associated with a number of mechanisms, such as I. the external pressure, II. the internal suction upon freeze and thaw and III the spontaneous diffusion of water to form ice crystals due to the different chemical potentials. Fig.1.9 briefly explains the moisture absorption during freezing by the pumping effect. It is suggested that negative pressure is generated when the pore water is frozen to ice under high saturation condition [17]. During freezing, the water near the surface freezes first and creates an inward pressure to force the unfrozen water in the surface into the interior zone. Then, the unfrozen water is furtherly forced into the interior as the water in the air voids close to the surface freezes into ice. As a result, the moisture content increases due to the freezing effect.

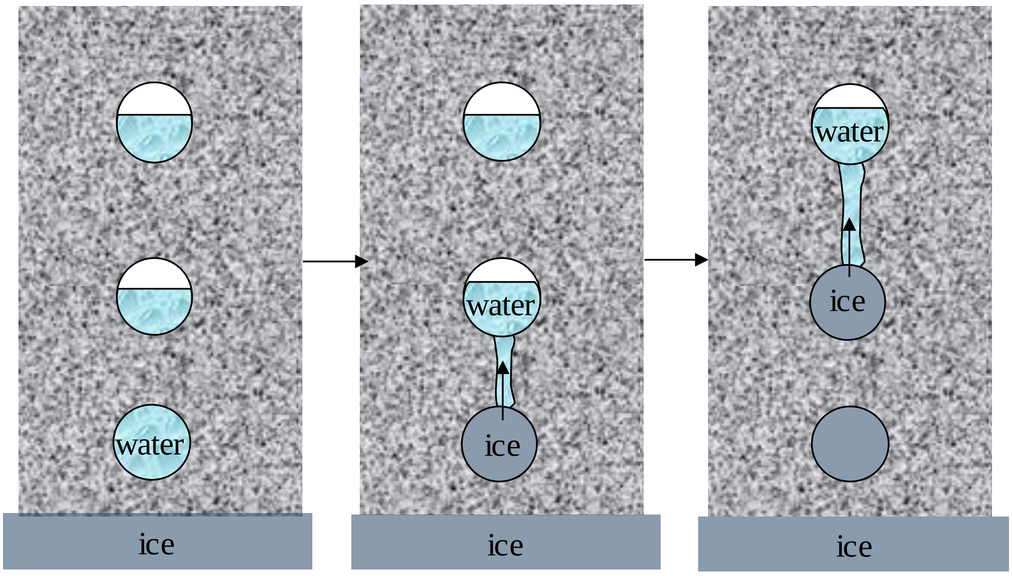


Fig.1.9 The moisture transport by freezing

While, the ice melts into water around the surface, making available liquid water. An extra suction is created when the ice in the interior melts because of the volume decrease caused by the water changing from solidity to liquid. The schematic figure of moisture increase by thawing is shown in Fig.1.10. The pumping effect facilitates the de-gassing of air and furtherly increases moisture saturation of the air voids, which is a common undesirable characteristic in concrete when suffered from freeze and thaw. The moisture transport will furtherly induce the formation of ice and increase the hydraulic pressure. Internal cracks occur once the hydraulic pressure exceeds the tensile strength and therefore the permeability of the specimen increases. As a result, more water invades into the specimen and concrete frost damage is furtherly exacerbated [18].

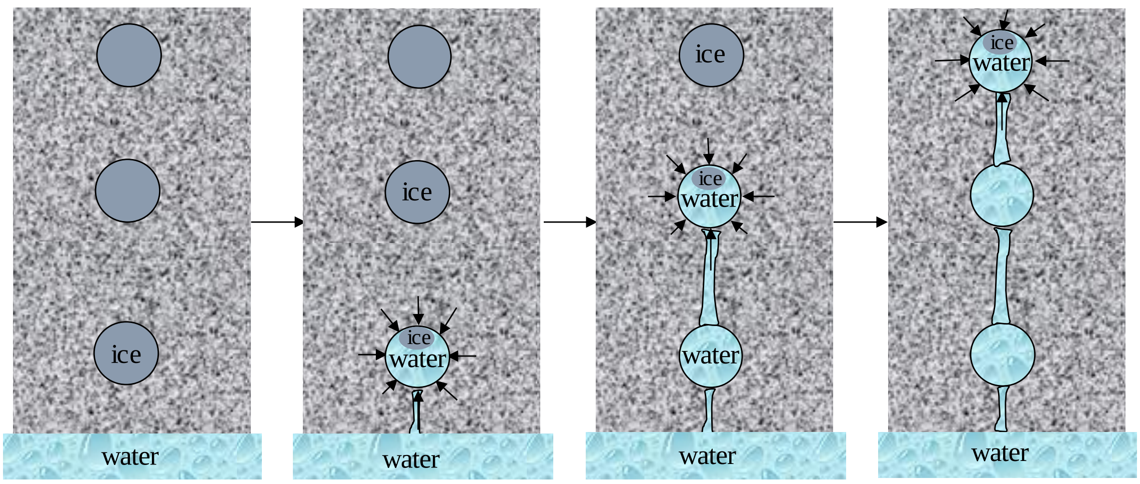


Fig.1.10 The moisture transport by thawing

**1.4 THE PURPOSE OF THIS RESEARCH**

Even though the critical degree of saturation test is widely adopted, the additional water absorption effect by freeze and thaw has not been considered in the test. Therefore, we evaluate concrete frost resistance by considering the additional water absorption effect due to the freeze and thaw in the critical degree of saturation test. Furthermore, the results are compared with the accelerated freeze and thaw test. Based on the results, we have proposed a method for predicting concrete frost deterioration considering the additional moisture absorption by freeze and thaw.

**1.5 THE OUTLINE OF THIS DISSERTATION**

This dissertation compares the accelerated freeze and thaw test and the critical degree of saturation test and therefore proposes a new concrete frost resistance evaluation method. Based on the newly proposed method, concrete frost deterioration in the actual environment has been simulated. The dissertation compromises of five chapters and the configuration is exhibited in Fig.1.11.

Chapter 1 introduces the situation of the concrete frost deterioration and expounds the theoretical mechanism of additional water absorption by freeze and thaw. Furthermore, the details of the accelerated freeze and thaw test and the critical degree of saturation test have also been presented. The problem of the two methods is proposed.

Chapter 2 shows the relationship between the accelerated freeze and thaw test and the critical degree of saturation test. The specimens firstly experienced different drying conditions before conducting the accelerated freeze and thaw test. The length, RDM and mass moisture content change during the whole freeze and thaw cycles have been calculated and the mass moisture contents at the nickpoints were compared with the mass moisture content of the critical degree of saturation $S_{cr}$. Based on this, the mass moisture content at the nickpoint was defined as concrete critical mass moisture content $W_{cr}$ and the cycle *Nf* at the nickpoint was regarded as a new concrete frost resistance criterion.

Chapter 3 presents the effect of the different lowest temperatures -5℃ and -10℃ on the newly defined concrete frost resistance criterion *Nf*. The nickpoints in the curve of length, RDM and mass moisture content in the accelerated freeze and thaw test with different lowest temperatures have been compared with the nickpoint achieved in the standard accelerated freeze and thaw test with the lowest temperature -18℃. The relationship between the lowest temperatures and its corresponding *Nf* is clarified and a linear equation is proposed.

In Chapter 4, concrete specimens were exposed to the outdoor environment for one year before conducting the accelerated freeze and thaw test and the critical degree of saturation test. Besides, the temperature and the relative humidity of the specimens were recorded. The effect of the freeze and thaw function of the outdoor exposure on concrete frost deterioration could be converted to the critical freeze and thaw cycle *Nf** according to the linear equation in Chapter 3. In this paper, a new concrete frost deterioration predicting method has been proposed based on the *Nf*. Concrete was supposed to be damaged by freeze and thaw once the environmental effect *Nf** reached its critical freeze and thaw cycle *Nf*. In addition, the critical freeze and thaw cycle *Nf'* of the specimens after one-year outdoor exposure has been calculated to verify the newly proposed concrete frost deterioration predicting method. We have found that other environmental factors, like drying, couple together with the freeze and thaw to degrade concrete frost resistance.

Chapter 5 leads to the summary and prediction for further study.

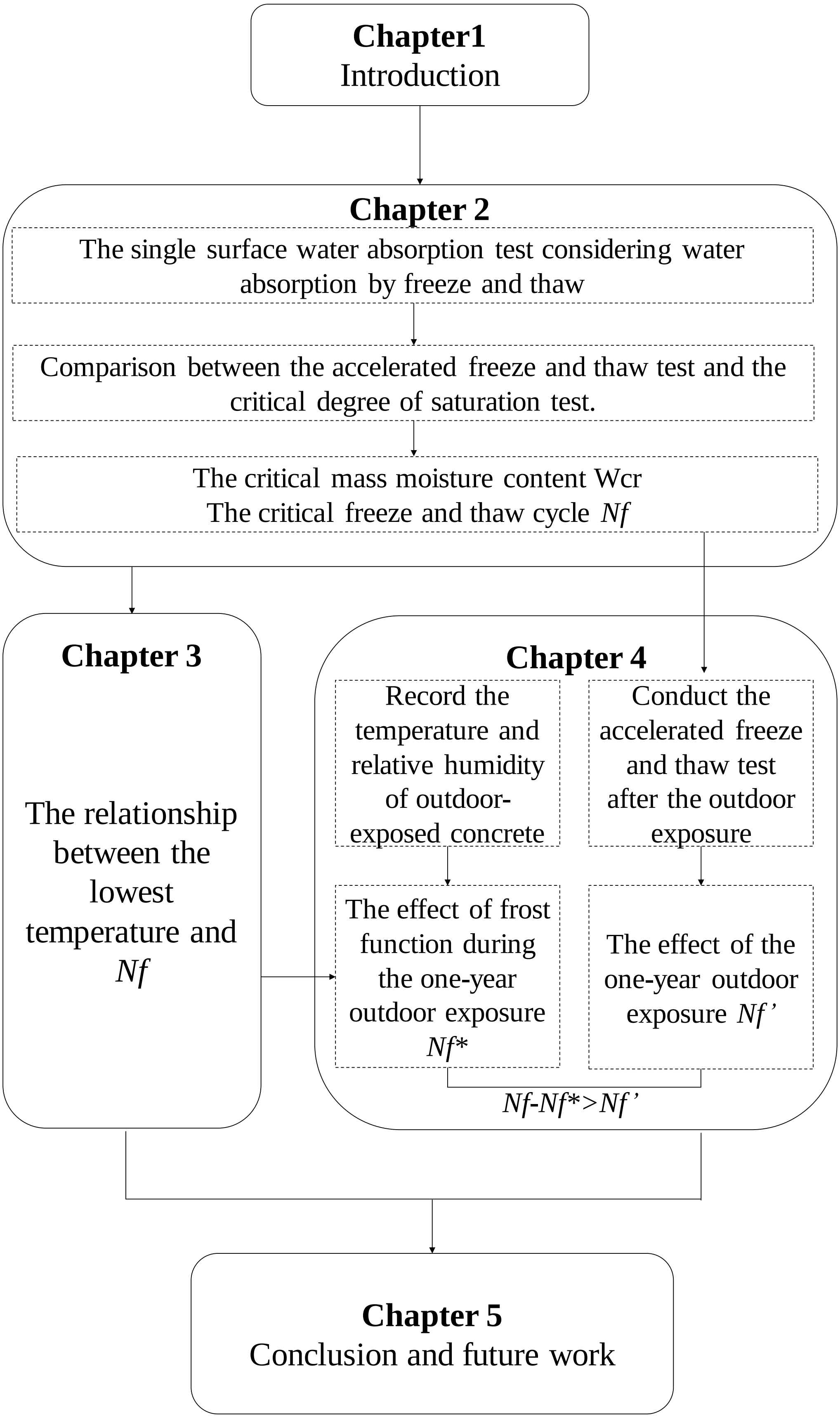


Fig.1.11 The flow of thesis chapter

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# CHAPTER 2

# A NEW CONCRETE FROST RESISTANCE EVALUATION METHOD CONSIDERING THE INCREASE OF THE MOISTURE CONTENT DUE TO FREEZE AND THAW

## 2.1 GENERAL

In this chapter, since the water content of the materials increases due to the freeze and thaw function, a method for evaluating concrete frost damage resistance considering the water absorption upon the freeze and thaw has been examined.

At first, as a kind of water absorption condition upon freeze and thaw, a single surface water absorption test is carried out. It is reported that the moisture content of ceramic siding materials increases in the single surface water absorption test upon freeze and thaw, and the moisture content in which the deterioration occurs is close to the critical degree of saturation $S_{cr}$ [1,2,3]. However, the freezing force under this test condition is sometimes considered not to be strong enough for concrete specimens, and no clear water increase in the moisture content of the dense concrete specimen can be observed.

The freeze and thaw function of specimens fully emerged in water can be considered as a strong freeze and thaw condition. This is the condition of the accelerated freeze and thaw test specified in JIS A 1148 A. Therefore, the moisture content change of the specimen in the accelerated freeze and thaw test has been performed and the results are compared with results by the critical degree of saturation test. In the accelerated freeze and thaw test, the nickpoints in the curve of the length, RDM and mass moisture content are regarded as concrete appearing obvious frost deterioration. It becomes clear that the mass moisture content at the nickpoint in the accelerated freeze and thaw test is close to the mass moisture content of the critical degree of saturation $S_{cr}$ by comparing the results of the two tests. In addition, it can be also revealed that concrete showing severe deterioration from the beginning of the cycles has a moisture content higher than $S_{cr}$. Based on these results, the mass moisture content at the nickpoint is defined as the critical mass moisture content $W_{cr}$ and the cycle at the nickpoint is regarded as the critical freeze and thaw cycle *Nf*, which is a new kind of concrete frost resistance criterion.

## 2.2 SINGLE SURFACE WATER ABSORPTION TEST CONSIDERING ADDITIONAL MOISTURE ABSORPTION BY FREEZE AND THAW

It is known that the freeze and thaw function causes additional water transport into porous materials, such as concrete specimens in contact with water suffer from freeze and thaw. The function is called the pumping effect [4,5,6,7]. Liu figures out that the external pressure and the internal suction upon freeze and thaw are the key factors for the pumping effect, while the spontaneous diffusion is not important [8]. To figure out the effect of the additional moisture absorption by freeze and thaw on concrete frost resistance, both the critical degree of saturation test and the single surface water absorption test upon freeze and thaw test were conducted in this chapter. The change of concrete moisture content due to freeze and thaw has been figured out.

### 2.2.1 The outline of the experiment

The outline of the test is shown in Table 2.1. In this test, two different kinds of coarse aggregates, normal coarse aggregate (SZ) and recycle coarse aggregate (RM) were adopted to achieve concrete specimens with different frost resistance. After curing in water the specimens were dried at 50℃ to different drying degrees by weight. The drying process was used for changing concrete frost resistance. The critical degree of saturation test and the single surface water absorption test upon freeze and thaw were conducted, respectively. The weight of the specimen was calculated at suitable time intervals. The schematic graph of the single surface water absorption test upon freeze and thaw is exhibited in Fig.2.1. The specimens were vacuum saturated and then dried at 105℃ to constant weight after the critical degree of saturation test and the single surface water absorption test upon freeze and thaw. The change of the volume moisture degree U with freeze and thaw cycles and the critical degree of saturation $S_{cr}$ have been compared with each other.

Table 2.1 The outline of the test

| Specimen type | Drying degree | Experimental method |
|---|---|---|
| SZ | 0% | The critical degree of saturation test |
| SZ-A | 2% | ($S_{cr}$, $S_{cap}$, $T_{pl}$) |
| RM | 3% | The single surface water absorption test |
| RM-A | 4% | upon freeze and thaw |

1)SZ: normal coarse aggregate, RM: recycle coarse aggregate

2) SZ-A, RM-A: concrete with AE agent, SZ, RM: concrete without AE agent

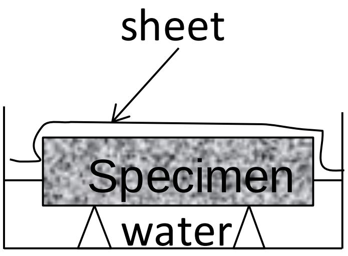


Fig. 2.1 Schematic figure of the single surface water absorption test upon freeze and thaw

### 2.2.2 Experimental method

The experimental flow of the test is shown in Fig.2.2. The concrete specimens were dried to different degrees. Then the critical degree of saturation test and the single surface water absorption test upon freeze and thaw have been conducted.

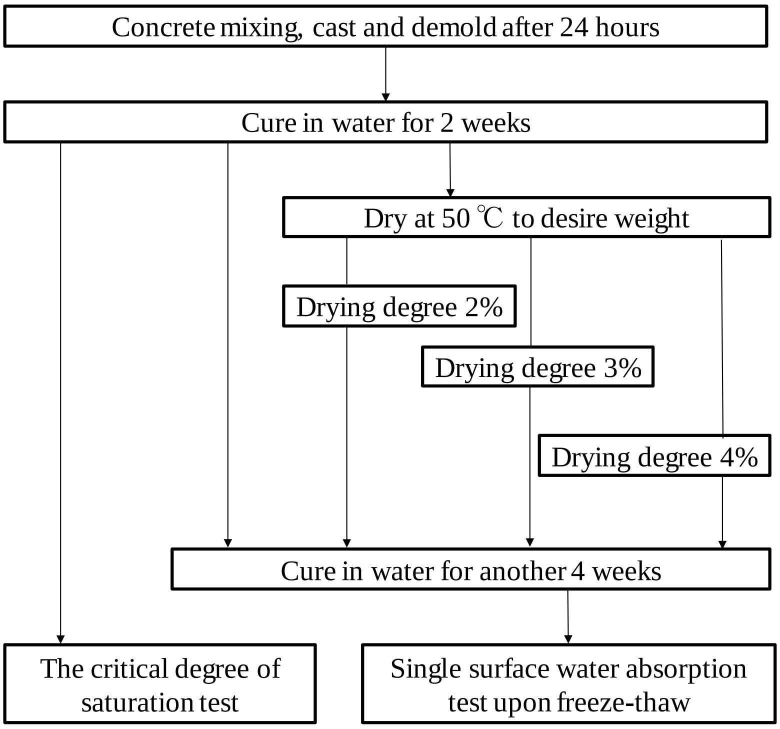


Fig.2.2 The experimental flow

(a) Preparation of specimens

The mix proportion of the concrete specimens and the properties of the fresh concrete are listed in Table 2.2. Table 2.3 shows the basic properties of the normal coarse aggregate SZ and recycle coarse aggregate RM. The water-to-cement (W/C) is 50% and the AE agent has been adopted to achieve air content 2.0% and 4.5%, respectively. The fresh concrete was poured into the mold with a dimension of Φ100×200 mm and the specimens were taken out on the second day. Then the specimens were cured in tap water for two weeks. The specimens after curing were cut into the samples with a size of Φ100×30mm. The cut samples experienced 50℃ drying at first and the drying process was ceased when the moisture weight loss of the samples reached to the weight loss that was 0%, 2%, 3% and 4%, respectively. Then specimens were cured in water for another four weeks before conducting the freeze and thaw test. It is reported by Baba [9] that the drying process by 50℃ altered concrete frost resistance in the accelerated freeze and thaw test.

For the denotation of the specimens (e.g. SZ-A 0%), the first two parameters represent that the concrete is made by the normal coarse aggregate type and added with agent, while the last parameter shows the drying condition.

Table 2.2 The basic properties of coarse aggregate

| Symbol | Type | Surface Dry Density (g/cm$^3$) | Absolute Dry Density (g/cm$^3$) | Water Absorption (%) | Attached Mortar Amount (%) | Simple Freeze-thaw Test Mass Loss (%) | Stability Test Mass Loss (%) |
|---|---|---|---|---|---|---|---|
| SZ | Ordinary aggregate (JIS A 5308) | 2.68 | 2.61 | 2.61 | - | 1.5 | 2.0 |
| RM | Recyled aggregate (JIS A 5022) | 2.55 | 2.47 | 3.13 | 20.4 | 11.9 | 11.8 |

Table 2.3 The mix proportion of concrete specimens

| Specimen type | Target air content (%) | W/C (%) | Fine aggregate ratio (%) | Unite amount ($Kg/m^3$) | | | | AE agent ($g/m^3$) | Maximum size of coarse aggregate (mm) | Actual air content (%) | Slump (cm) | Compressive strength ($N/mm^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | W | C | S | G | | | | | |
| SZ | 2 | 50 | 49.6 | 175 | 351 | 918 | 938 | 0 | 20 | 2.4 | 17.5 | 47.5 |
| SZ-A | 4.5 | | 47.7 | 175 | 351 | 852 | 938 | 0.014 | | 4.3 | 20.5 | 38.4 |
| RM | 2 | | 49.6 | 175 | 351 | 918 | 893 | 0 | 20 | 2.3 | 18.5 | 44.5 |
| RM-A | 4.5 | | 47.7 | 175 | 351 | 852 | 893 | 0.014 | | 4.1 | 20.5 | 41.7 |

(b) The critical degree of saturation test

The test is conducted according to the RILEM CDC 3, which is shown in Chapter 1.2.2. Eight cylindrical specimens experienced freeze and thaw cycles and the critical degree of saturation $S_{cr}$, which manifested by the critical volume saturation $U_{cr}$, was calculated. The single surface water absorption test at room temperature was conducted and the capillary degree of saturation $S_{cap}$, calculated by the volume moisture content $U_{cap}$, was also calculated. Based on the $U_{cr}$ and $U_{cap}$, concrete frost resistance criterion $T_{pl}$ (the time that $U_{cap}$ reaches the $U_{cr}$) could also be achieved. The specimens were then vacuum saturated and dried at 105℃ to constant weight.

(c) Single surface water absorption test upon freeze and thaw

The procedure of the single surface water absorption test upon freeze and thaw is similar to the $S_{cap}$ test. The samples were also set according to Fig.2.1 and then the samples were placed in the freeze and thaw chambers which could alter temperature automatically. The lowest temperature in the freezing process was -25℃ lasting for three hours while the highest temperature was 10℃ lasting for two hours in one freeze and thaw cycle. After suitable freeze and thaw cycles, the samples were taken out into an isothermal environment with the temperature of 20℃ to measure weight in the air and water.

### 2.2.3 Results and discussion

In this paper, the volume moisture saturation U of the specimen has been used to represent the moisture saturation S. The volume moisture saturation can be calculated by Eq.2.1. The volume moisture saturation $U_{cr}$ at the $S_{cr}$ has also been calculated.

$$U_n = \frac{V_n}{V} = \frac{m_{n,air} - m_{105℃}}{m_{n,air} - m_{n,water}} * 100\% \tag{2.1}$$

Where, $U_n$ is the volume moisture saturation at n cycles; $V_n$ is the moisture volume of the specimen at n cycles; $V$ is the volume of the specimen; $m_{n,air}$ is the weight of specimen at n cycles in the air; $m_{n,water}$ is the weight of specimen at n cycles in the water; $m_{105℃}$ represents the oven-dry weight.

The results of the critical degree of saturation test is shown in Table 2.4. The experiment data is listed in Appendix A.2. Based on the results of $T_{pl}$ with drying condition 0%, concrete frost resistance increased according to the order of SZ-A>RM-A>SZ>RM. The specimens with entraining air agent exhibited a better frost resistance. Besides, the normal coarse aggregate concrete (SZ, SZ-A) also showed a better frost resistance than the recycled coarse aggregate concrete (RM, RM-A).

Besides, the effect of drying conditions on the $T_{pl}$ is shown in Fig.2.3. As shown in the figure, no clear relationship can be figured out between the $T_{pl}$ and the drying conditions. It is supposed that the critical degree of saturation test is not able to evaluate the change of concrete frost resistance suffered from 50℃ drying.

Table 2.4 The results of the critical degree of saturation test

| Specimen type | The critical degree of saturation test | | | | |
|---|---|---|---|---|---|
| | $U_{cr}$ (%) | $T_{pl}$ ($h^{1/2}$) | | | |
| | | 0%* | 2%* | 3%* | 4%* |
| SZ | 16.5 | 9.9 | 6.7 | 9.2 | 5.7 |
| SZ-A | 18.6 | 38.4 | 24.5 | 25.8 | 30.6 |
| RM | 15.5 | 6.7 | 6.2 | 2.1 | 6.7 |
| RM-A | 16.6 | 32.3 | 22.6 | 26.8 | 21.7 |

*: the drying degree by weight loss

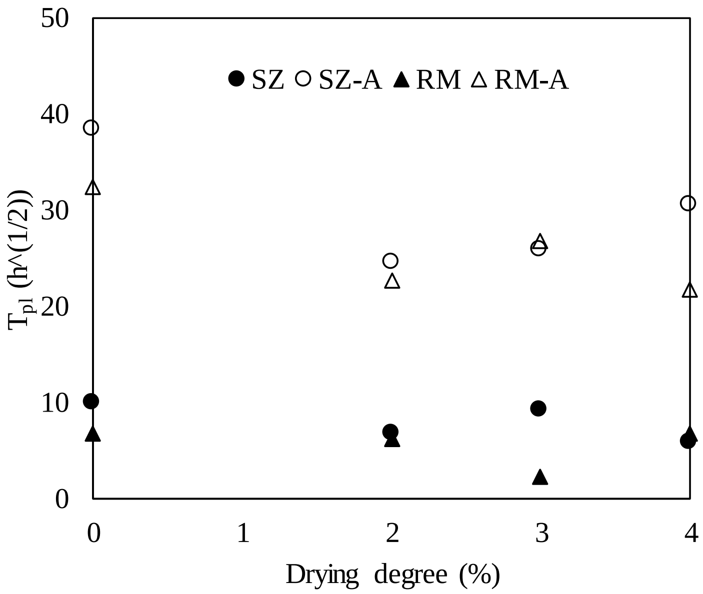


Fig.2.3 The relationship between drying degree and $T_{pl}$

The volume moisture saturation $U_{cr}$ of the single surface water absorption test is exhibited in Fig. 2.4. As shown in the figure, the volume moisture saturation U of the SZ and RM specimens have already been larger than the $U_{cr}$ and showed decreasing tendency. Therefore, the SZ and RM specimens are regarded as damaged right after the start of the freeze and thaw cycles. It is supposed that the SZ and RM specimens are damaged by freeze and thaw and the microcracks will further exacerbate concrete frost deterioration. The decrease of the U is supposed to be the scaling from the surface of concrete specimens.

It is supposed that the external moisture is pushed into the specimens by the pumping effect. However, as shown in the figure, even though the pumping effect works in the SZ-A and RM-A specimens, the volume moisture saturation $U_{SZ\text{-}A}$ and $U_{RM\text{-}A}$ are still smaller than the critical volume moisture saturation $U_{cr}$. Because of the dense surface of the SZ-A and RM-A specimens, the additional moisture increase by the single surface water absorption test upon freeze and thaw is still smaller than the critical degree of saturation $S_{cr}(U_{cr})$ and the freeze and thaw function of the single surface freeze and thaw is therefore considered as not strong enough to lead to the concrete frost deterioration.

Besides, the volume moisture saturation U of SZ and RM have surpassed the critical volume moisture saturation $U_{cr}$ even at the beginning of the freeze and thaw cycles, while the volume moisture content in either SZ-A or RM-A concrete is below its $U_{cr}$. Therefore, the SZ-A and RM-A specimens can be regarded as frost resistant, which also corresponds with the better frost resistance $T_{pl}$ calculated by the critical degree of saturation test. It is supposed that the entrained air may hinder the moisture getting into the specimens, resulting in the moisture content lower than $U_{cr}$. The force of water pushed into the specimen by the single surface water absorption test upon freeze and thaw sometimes is not strong enough to achieve the critical moisture degree. Therefore, a more severe freeze and thaw condition should be adopted to obtain the critical degree of saturation $S_{cr}$.

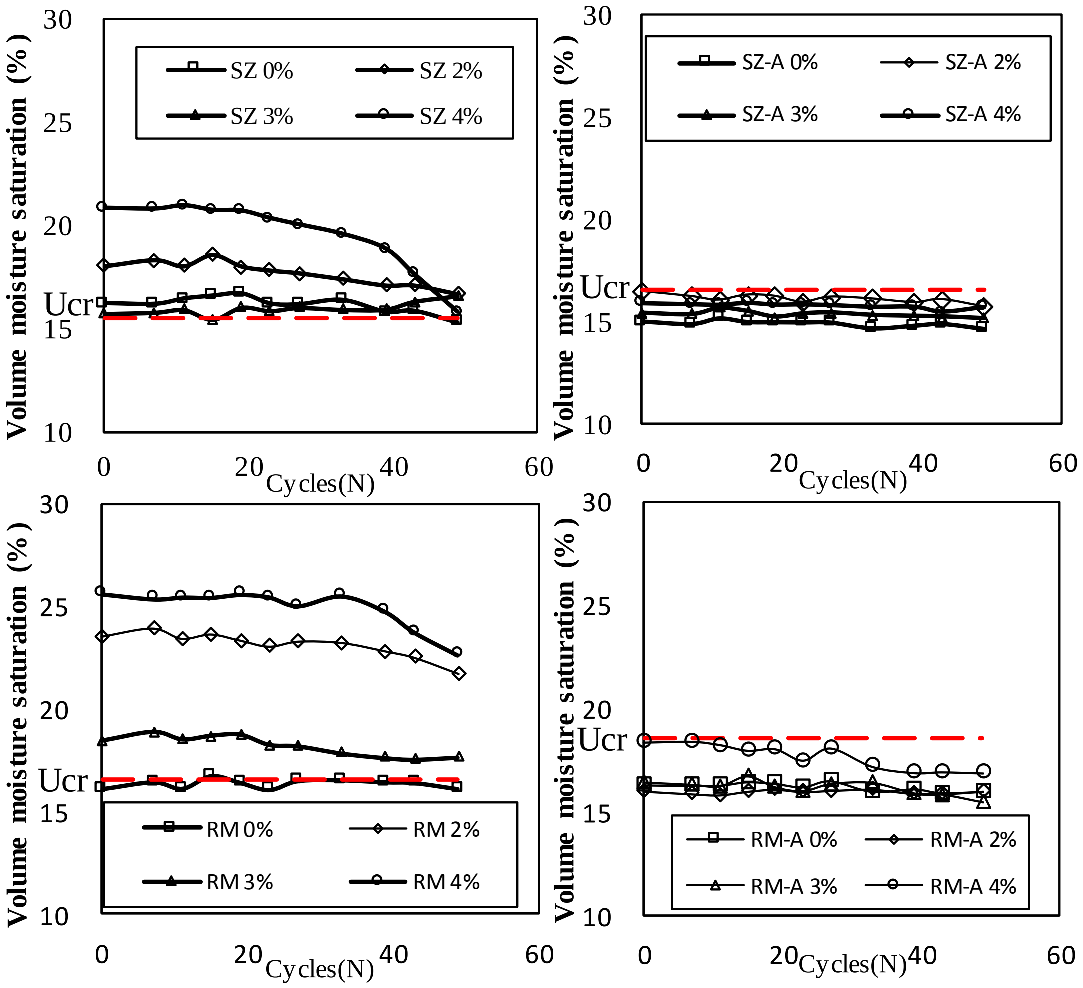


Fig.2.4 The volume moisture saturation of the specimens

### 2.3 THE ACCELERATED FREEZE AND THAW TEST CONSIDERING MOISTURE ABSORPTION BY FREEZE AND THAW

The external moisture absorption caused by the single surface water absorption test upon freeze and thaw sometimes cannot enhance the moisture content of the specimen to the critical degree of saturation $S_{cr}(U_{cr})$. Therefore, a more severe freeze and thaw condition should be considered. In this section, the accelerated freeze and thaw test has been used, and this test is considered to have a strong water absorption condition. In the accelerated freeze and thaw test, the whole specimen is emerged in water during the freeze and thaw cycles. The water absorption increase is manifested by the mass moisture content change of the concrete specimen during the accelerated freeze and thaw test.

#### 2.3.1 The outline of the experiment

The outline of the test is shown in Table 2.5. Three kinds of concrete specimens were used in this test and half of each kind experienced different drying conditions. Then the critical degree of saturation test and the accelerated freeze and thaw test have been conducted, respectively. In the accelerated freeze and thaw test, the moisture increase by freeze and thaw has been considered. The changing moisture content of the specimen in the accelerated freeze and thaw test has been compared with the critical degree of saturation $S_{cr}$ in the critical degree of saturation test.

Table 2.5 The outline of the test

| Specimen type | Drying degree | Experimental method |
|---|---|---|
| W/C35%-1% | No drying<br>Drying at 50℃ for one week | 1.The critical degree of saturation test<br>($S_{cr}$, $S_{cap}$, $T_{pl}$)<br>2.The accelerated freeze and thaw test<br>(Length, weight in water and air, fundamental transverse frequency) |
| W/C55%-1% | No drying<br>Drying at 20℃ for two week | |
| W/C55%-4.5% | | |

#### 2.3.2 Experimental method

(a) Preparation of the specimens

The experimental flow is shown in Fig.2.5. Type 1 Portland cement was used as the cementitious material and fine aggregate was silica sand with the fineness modulus of 2.68. Coarse aggregate was the crushed stone with the maximum dimension of 20mm. Water-to-cement ratio (W/C) 35% and 55% were employed in this experiment. In addition, to set up different frost resistance in the W/C55% specimens, air-entraining agent and defoamer were used to obtain the air contents 1% and 4.5%, respectively. In the specimen of W/C35%, the air content 1% was reached by using the defoamer. Besides, the superplasticizer with a dosage of 0.47g/kg has also been added to guarantee the workability of W/C35%-1% concrete. Concrete mixing of each concrete type has been divided into two batches. The dosage of the admixture has been adjusted to achieve the target air content and slump in each batch. The mix proportion of the concrete specimens is listed in Table 2.6. The specimens were dried to different degrees after two weeks curing in water. Then the accelerated freeze and thaw test and the critical degree of saturation test were conducted, respectively.

The fresh concrete was put into the prismatic mold with a size of 75×75×400mm and the cylindrical mold with a dimension of Φ100×200mm, respectively. Then, covered the surface of the specimen with preservative film and stored the specimens in an isothermal room with the temperature of 20℃ and relative humidity (RH) 60% for one day. The specimens were demolded on the second day and preserved in tap water for two weeks. According to the results by Baba, the different drying conditions may affect concrete frost resistance [9]. Therefore, in this experiment, the specimens after curing were dried according to Baba's experiment to achieve the concrete specimens with different frost resistance even with the same mix proportion. For example, three of the W/C35%-1% prismatic specimens were dried at 50℃ for one week while the other three specimens were immediately conducted with the accelerated freeze and thaw test. Similar to the W/C35%-1% specimens, for both the W/C55%-4.5% and W/C55%-1% specimens, half of the specimens of each concrete type have been dried at 20℃ for two weeks. After the different drying processes, the specimens were cured in water for another three days before conducting the accelerated freeze and thaw test.

For the specimen's denotation (e.g. 35-1-N/D), the first two parameters represent the water-to-cement ratio and the air content. N means that the specimens experienced no drying conditions. While, D represents the specimens suffered from 20℃ or 50℃ drying.

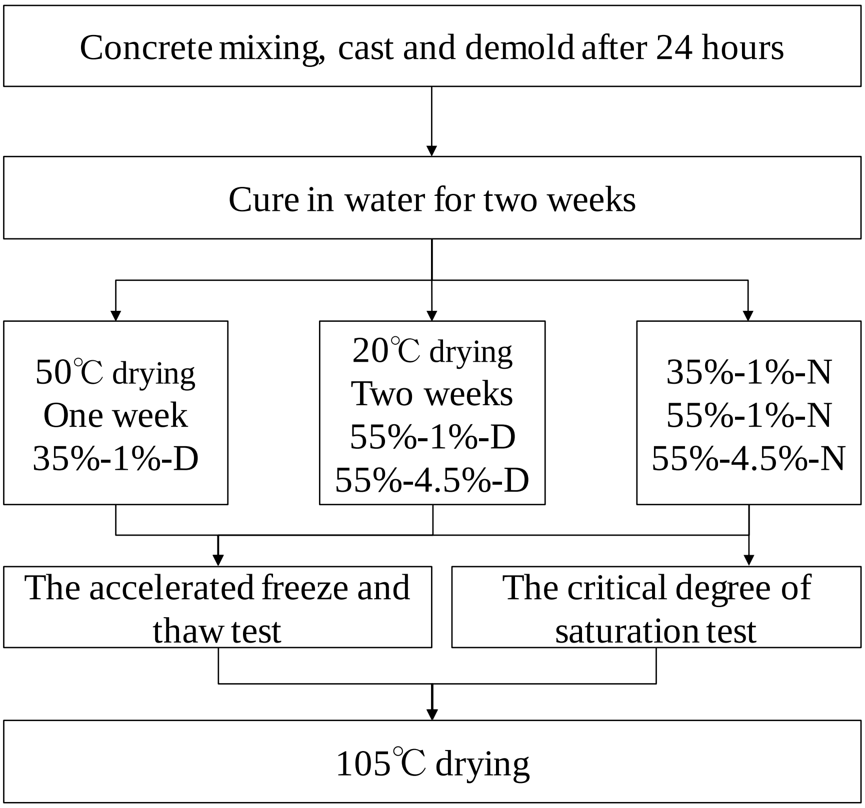


Fig. 2.5 The experimental flow

Table 2.6 The mix proportion of the concrete specimen

| W/C (%) | Target air content (%) | Fine aggregate ratio (%) | Unite amount ($kg/m^3$) | | | | Admixture* (c×%) | | | Actual air content** (%) | Slump (cm)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | W | C | S | G | 303A | 404 | SP8SV×2 | | |
| 35 | 1 | 46 | 165 | 471 | 827 | 978 | | 0.011 | 0.47 | ①1.3<br>②1.9 | ①23.0<br>②22.5 |
| 55 | 1 | 49.9 | 180 | 327 | 936 | 949 | | 0.05 | | ①1.2<br>②1.1 | ①17.5<br>②20.5 |
| | 4.5 | 47.2 | 172 | 313 | 843 | 949 | ①0.014**<br>②0.010** | | | ①4.5<br>②4.9 | ①21.5<br>②22.5 |

* 303A is AE agent, 404 is the defoamer agent, SP8SV×2 is the high-performance water reducer
** Concrete mix has been divided into two batches.

(b) The critical degree of saturation test

The critical degree of saturation test has been conducted according to Chapter 1.2.2. In this test, eight cylindrical specimens of each concrete type were used for the critical degree of saturation test. The critical degree of saturation $S_{cr}$ and concrete frost resistance $T_{pl}$ were calculated. The weights of the specimens in the air and water when the $S_{cr}$ was reached were also measured for calculating the critical mass moisture content $M_{cr}$. The mass moisture content $M_{cr}$ of the specimen at the critical degree of saturation $S_{cr}$ can be calculated by Eq.2.2.

$$M_{cr} = \frac{m_{cr,air} - (m_{cr,air} - m_{cr,water}) \times \rho_{105℃}}{(m_{cr,air} - m_{cr,water}) \times \rho_{105℃}} \times 100\% \quad (2.2)$$

Where, $M_{cr}$ is the mass moisture content at the critical degree of saturation; $m_{cr,air/water}$ is the weight of the specimen in the air or water at the critical degree of saturation $S_{cr}$; $\rho_{105℃}$ is the oven-dry density of the specimen.

(c) The accelerated freeze and thaw test

The prismatic specimens were conducted with the accelerated freeze and thaw test according to JIS A 1148 A. The specimens were taken out to measure the weight in the air and water, the length and the fundamental transverse frequency at every 4 or 6 cycles. Then the oven-dry weight of the specimens in the air and water were measured when the freeze and thaw test was finished. The length change and the RDM after N freeze and thaw cycles can be calculated by Eq.1.1 and 1.3 shown in Chapter 1.

The nickpoints in the curve of the length and the RDM changes were compared with each other. Besides, the mass moisture contents W of the specimen were calculated to figure out its relationship with the mass moisture content at the critical degree of saturation $S_{cr}$ in the critical degree of saturation test. The mass moisture content $W_N$ after N cycles of freeze and thaw is calculated as follows.

$$W_N = \frac{m_{N,air} - (m_{N,air} - m_{N,water}) \times \rho_{105℃}}{(m_{N,air} - m_{N,water}) \times \rho_{105℃}} \times 100\% \quad (2.3)$$

Where, $W_N$ is the mass moisture content at N cycles; $m_{N,air}$ is the weight of the specimen in the air at N cycles; $m_{N,water}$ is the weight of the specimen in the water at N cycles; $\rho_{105℃}$ is the oven dry density.

The oven-dry density $\rho_{105℃}$ of the specimen can be calculated by Eq.2.4.

$$\rho_{105°C} = \frac{m_{105°C,air}}{m_{105°C,air} - m_{105°C,water}} \tag{2.4}$$

Where, $m_{105℃,air}$ is the water saturated weight of the specimen in the air after 105℃ drying; $m_{105℃,water}$ is water saturated weight of the specimen in the water after 105℃ drying.

### 2.3.3 Results and discussion

(a) The critical degree of saturation test

Table 2.7 shows the results of the critical degree of saturation test. The data of the test is listed in Appendix A.3.

Table 2.7 The results of the critical degree of saturation test

| Specimen type | $S_{cr}$ ($M_{cr}$ (wt.%)) | $T_{pl}$ ($h^{1/2}$) |
|---|---|---|
| W/C35%-1%-N | 0.98 (6.10) | 25.72 |
| W/C35%-1%-D | | 28.43 |
| W/C55%-1%-N | 0.86 (7.10) | 2.73 |
| W/C55%-1%-D | | 3.80 |
| W/C55%-4.5%-N | 0.68 (7.08) | 1.91 |
| W/C55%-4.5%-D | | 2.23 |

(b) The accelerated freeze and thaw test

1)The results of W/C35%-1% specimens

Figure 2.6 shows the test results of W/C35%-1% specimens with 50℃ drying condition and no drying condition. The weight in the water has not been recorded until 34 cycles, thus curve of the mass moisture content started from 34 cycles. In the case of no drying specimens (the 35-1-N specimens), the tendency of the mass moisture content before nickpoint also could be figured out. As shown in the figure, the mass moisture content of 35-1-N specimens increased continuously before 54 cycles and it dropped significantly afterward. It is supposed that concrete specimens absorbed water continuously because of the pumping effect and resulted in the increase of the mass moisture content. However, the specimens began to flake dramatically when the 54 cycles were reached, resulting in the decrease of the mass moisture content. It is supposed that the 35-1-N concrete specimens exhibited obvious damage at 54 cycles by freeze and thaw. On the other hand, the mass moisture content of 35-1-D decreased significantly from the beginning of the freeze and thaw cycles and no obvious nickpoint was figured out. As shown in the figure, the 35-1-D specimens was damaged by freeze and thaw right after the start of the freeze and thaw test.

As shown from the length change of 35-1-N specimens, the length almost remained the same before 42 cycles and it increased significantly afterward. Table 2.8 shows the average changing gradient of the two specimens. As can be seen from Table 2.8, the increasing gradient of 35-1-N specimens before nickpoint only accounted for 1/8 of the increasing gradient after the nickpoint. Therefore, the $42^{th}$ cycle was regarded as the nickpoint cycle for the length change. While, on the other hand, for the 35-1-D specimens which were dried at 50℃ for one week, the length change increased dramatically right after the beginning of the freeze and thaw cycles and no obvious nickpoint was figured out. Besides, as shown in Table 2.8, the increasing gradient of 35-1-D specimen was 0.0059 %/cycle which was almost similar to the increasing gradient after the nickpoint in the 35-1-N specimens.

The curve of RDM acted similarly to that of the length change in both 35-1-N and 35-1-D specimens, respectively. The nickpoint of RDM also emerged at 54 cycles in the 35-1-N specimens. Likewise, the RDM of 35-1-D specimens decreased rapidly from the beginning of the freeze and thaw cycles. As exhibited in Table 2.8, the RDM decreasing gradient of 35-1-N before nickpoint was much smaller than that after nickpoint. Besides, the RDM decreasing gradient of the 35-1-N after nickpoint almost equaled to the decreasing rate of 35-1-D.

The length, RDM and the mass moisture content of 35-1-D specimens changed dramatically even from the beginning of the freeze and thaw cycles. Judging from Fig.2.6, the 35-1-D specimens were damaged once the freeze and thaw commenced. It is supposed that more micro-cracks emerged during the 50℃ drying process and resulted in a higher level of the mass moisture content. Therefore, we can draw the conclusion that 50℃ drying for two weeks has a negative effect on the W/C35%-1% concrete frost resistance, which also corresponds with the results by Baba.

The different precisions of the curve of the length, RDM and mass moisture content change resulted in the difference among the nickpoint freeze and thaw cycle. However, as shown in Fig.2.6, the nickpoints of the length, RDM and mass moisture content change almost emerged at the same freeze and thaw cycle. It is supposed that the W/C35%-1% specimen appeared obvious damage by freeze and thaw when the nickpoint was achieved and the obvious frost damage could be detected by all the three kinds of test methods. Hence, the length, RDM and mass moisture content were used for detecting the obvious frost damage. In addition, since the curve of the length change has fewer deviations than that of the RDM, and it was easy to operate, the nickpoint cycle *Nf* in length change has been defined as a new concrete frost resistance evaluation criterion, which reflected that concrete appeared obvious damage by freeze and thaw. The mass moisture content at *Nf* was defined as the critical mass moisture content $W_{cr}$ for concrete specimens.

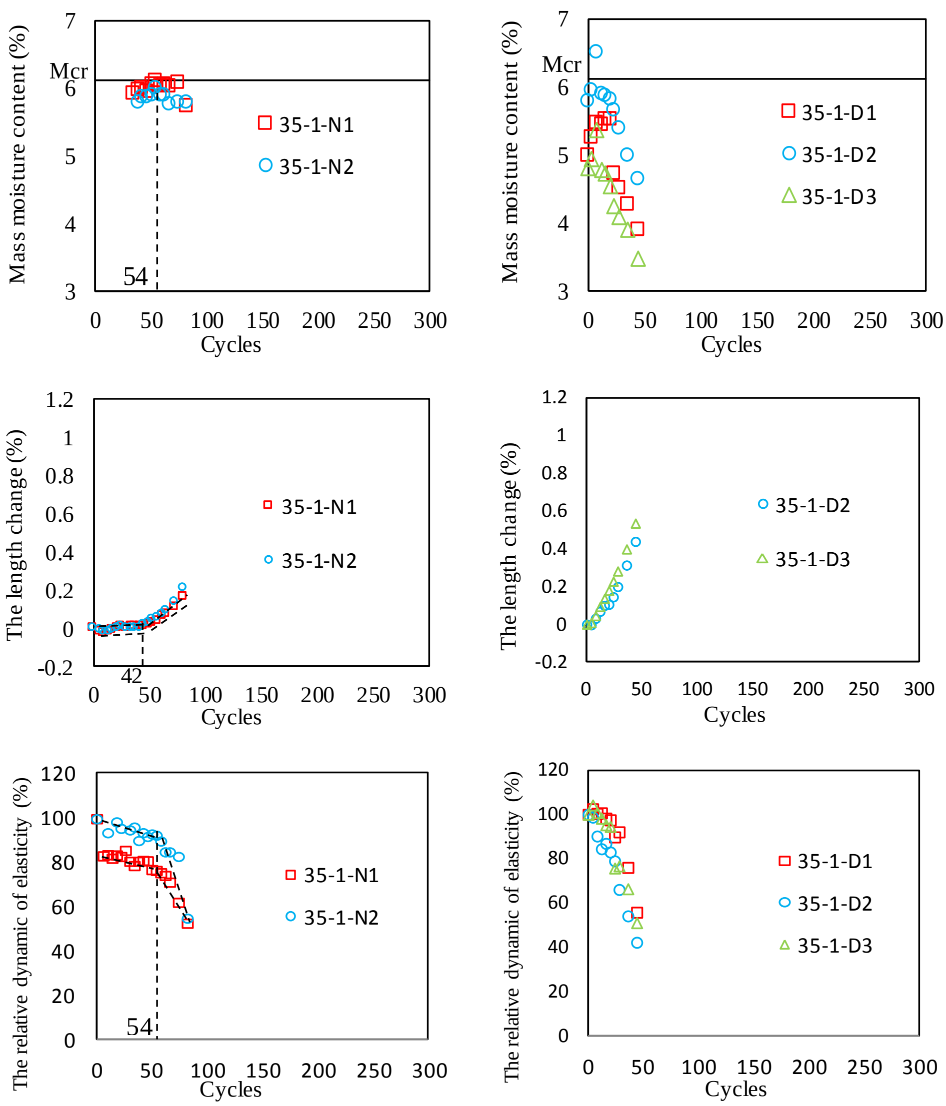


Fig.2.6 The results of W/C35%-1% specimens with different drying conditions

Table 2.8 The average gradient change of W/C35%-1% specimen

| Specimen type | | Average gradient (%/cycle) | |
|---|---|---|---|
| | | Before Nickpoint | After Nickpoint |
| 35-1-N | Length change | 0.0006 | 0.0048 |
| 35-1-D | | - | 0.0059 |
| 35-1-N | RDM change | -0.2872 | -0.8332 |
| 35-1-D | | - | -0.8081 |
| 35-1-N | Mass moisture content change | 0.0058 | -0.0117 |
| 35-1-D | | - | -0.0288 |

The mass moisture content $M_{cr}$ of $S_{cr}$ calculated by Eq.2.2 is compared with the mass moisture content W in the accelerated freeze and thaw test in Table 2.9. For the 35-1-N concrete specimens, the mass moisture content at 34 cycles $W_{34}$ was smaller than the $M_{cr}$. As shown in Fig.2.6, the mass moisture content increased with cycles, reaching to the peak at the $W_{cr}$ before it began to drop. Besides, the $W_{cr}$ was almost equal to the $M_{cr}$ in the critical degree of saturation test. Different from the artificially set $M_{cr}$, the $W_{cr}$ was determined according to a continuously changing mass moisture content. Hence, the $W_{cr}$ was more accurate in representing the apparent concrete frost damage by freeze and thaw. The mass moisture content $W_{cr}$ of *Nf* has been regarded as the critical mass moisture content. Concrete specimens exhibited obvious damage once the $W_{cr}$ was reached, regardless of testing methods.

However, as shown in the figure, the mass moisture content $W_0$ of 35-1-D specimen has already exceeded the $M_{cr}$. The concrete specimens were damaged right after the start of the freeze and thaw cycles, which corresponded with its sharp change of the length and RDM change. The drying process with 50℃ had an adverse effect on W/C35%-1% concrete frost resistance.

Table 2.9 The mass moisture content of the W/C35%-1% specimens

| Type | The mass moisture content W (wt.%) | | | The critical mass moisture content $M_{cr}$ (wt.%) |
|---|---|---|---|---|
| | $0^{th}$ cycle | *Nf* | Final cycle | |
| 35-1-N | 5.87 (34 cycles) | 6.06 | 5.73 | 6.10 |
| 35-1-D | 7.35 | - | 6.48 | |

2) The results of W/C55%-1% specimens

The results of W/C55%-1% specimens with different drying conditions are exhibited in Fig.2.7. As shown in the figure, the mass moisture content of 55-1-N specimens decreased rapidly right after the start of the freeze and thaw cycles and no nickpoint was figured out. Table 2.10 shows the mass moisture content of the W/C55%-1% specimens. Even the mass moisture content at 0 cycle $W_0$ has surpassed its $M_{cr}$. Therefore, the 55-1-N specimens were regarded as not frost resistant concrete. Similar tendency of the mass moisture content was also figured out in the 55-1-D1 and D2 specimens, where the $W_0$ has exceeded the $M_{cr}$. While, for the 55-1-D3 specimens, there emerged an obvious nickpoint. The mass moisture content increased continuously until 16 cycles and the $W_{16}$ was also similar to the $M_{cr}$. Compared with the other two specimens of 55-1-D1 and D2, D3 showed a better frost resistance. It is suggested that the water in the capillary has evaporated because of the 20℃ drying process. These empty capillaries worked as air voids during the freeze and thaw cycles, which improved concrete frost resistance. According to the previous research, the 20℃ drying improved concrete frost resistance. However, the effect was not obvious in W/C55%-1% specimens.

Fig.2.7 also shows the length and RDM change of the W/C55%-1% specimens. The length and RDM of 55-1-N specimens changed dramatically even from the beginning of the freeze and thaw cycles and no obvious nickpoints were figured out. Therefore, the 55-1-N concrete specimens were regarded as not concrete frost resistant and the critical freeze and thaw cycle *Nf* for 55-1-N specimens was regarded as 0 cycle. While, on the other hand, as shown in the figure, 55-1-D1 and 55-1-D2 specimens showed almost similar tendency of the length and RDM change with the 55-1-N specimens. The gradients of 55-1-D1 and D2 also kept a considerable changing rate in length and RDM change. Similar to the result of 55-1-N, the mass moisture contents of 55-1-D1 and D2 decreased from the beginning of the freeze and thaw cycle as well. Therefore, the critical freeze and thaw cycle *Nf* of 55-1-D1 and D2 were 0 cycle. However, 55-1-D3 specimen showed a totally different tendency from the other two specimens of 55-1-D and there appeared nickpoints in the length and RDM change. Hence, the critical freeze-thaw cycle *Nf* of 55-1-D3 specimen was regarded as 16 cycles.

Table 2.10 The mass moisture content of the W/C55%-1% specimens

| Type | The mass moisture content W (wt.%) | | | The critical mass moisture content $M_{cr}$ (wt.%) |
|---|---|---|---|---|
| | $0^{th}$ cycle | *Nf* | Final cycle | |
| 55-1-N | 8.23 | - | 5.73 | |
| 55-1-D1,2 | 10.00 | - | 2.70 | 7.10 |
| 55-1-D3 | 6.68 | 6.81 | 6.21 | |

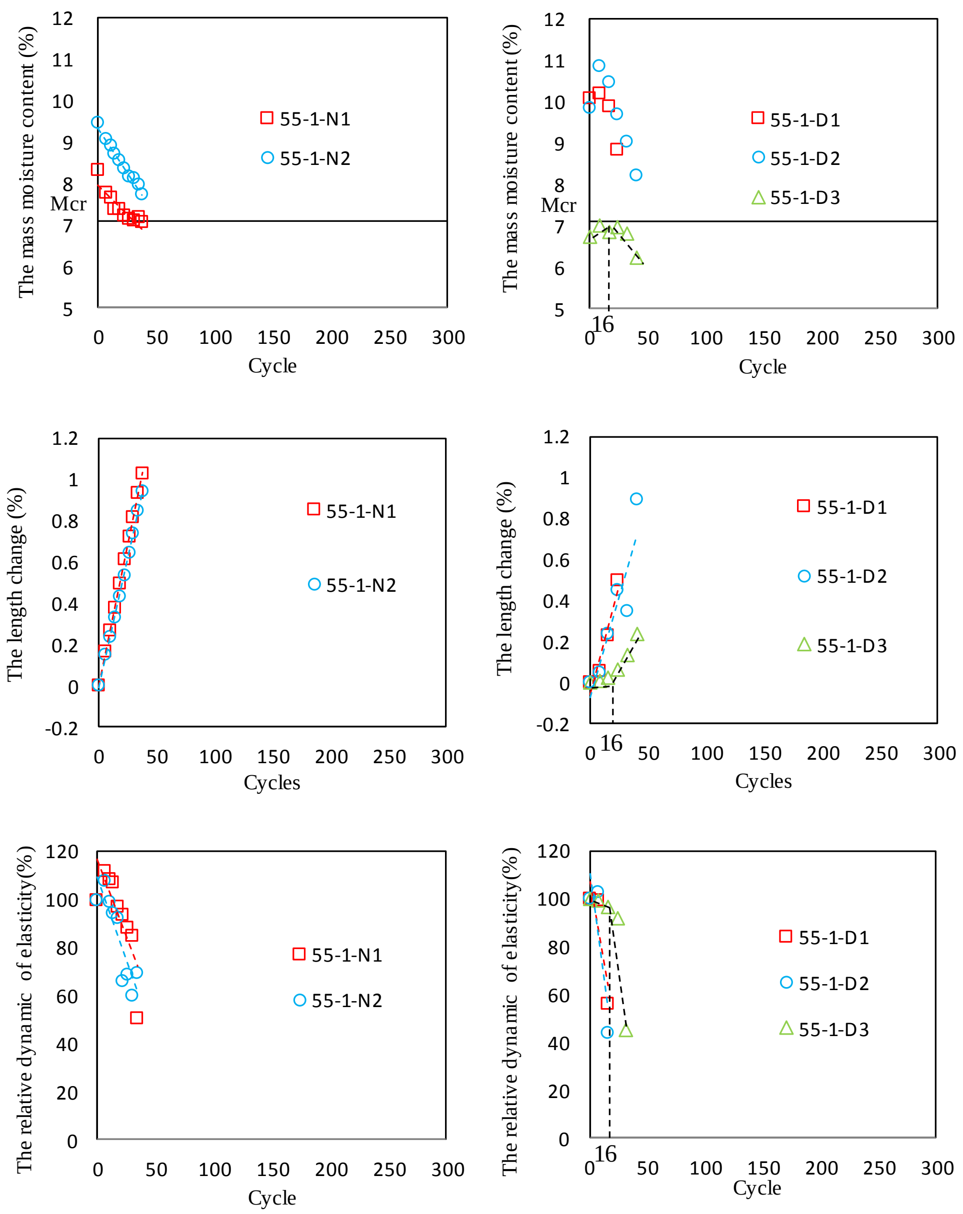


Fig.2.7 The results of W/C55%-1% specimens with different drying conditions

3) The results of W/C55%-4.5% specimens

Fig.2.8 shows the results of W/C55%-4.5% specimens with and without drying condition. Besides, Table 2.11 shows the mass moisture content of the W/C55%-4.5% specimens. For the mass moisture content change, the nickpoint showed up at 178 and 162 cycles for the 55-4.5-N1 and N2 concrete specimen, respectively. The average $W_{cr}$ of 55-4.5-N specimens was 6.80 and it was close to the $M_{cr}$ (7.08). While, for the 55-4.5-D specimens, as shown in Table 2.11, even the mass moisture content at the end of the freeze and thaw cycles was still smaller than its $M_{cr}$. Therefore, it is supposed that the 55-4.5-D concrete specimens was not damaged by freeze and thaw, which could also be figured out in the length and RDM change. It is hypothesized that the critical mass moisture content for the 55-4.5-D specimens is same as that for 55-4.5-N concrete specimens. The curve of the mass moisture content of 55-4.5-D has been linearly extended to the $M_{cr}$ to simulate its critical freeze-thaw cycle *Nf*, which can be seen in Fig.2.9. The average mass moisture content has been adopted and the curve of the average mass moisture content changing with cycles has been linearly simulated. The linear function is shown in Fig.2.9 and the fitness degree $R^2$ illustrates that the linear function is in good accordance with the average mass moisture content curve. Then, the function has been linearly extended to the $M_{cr}$ and the freeze and thaw cycle at the intersection is regarded as the *Nf* of 55-4.5-D specimens.

There appeared nickpoints in the curve of length and RDM change in the 55-4.5-N specimens. The nickpoint of length change occurred at 178 cycles. While, the nickpoint of RDM appeared at 178 and 146 cycles for the 55-4.5-N1 and N2 specimen, respectively. For the mass moisture content change, the nickpoint showed up at 178 and 162 cycles for the N1 and N2 specimen. Except for the length change, deviation of the nickpoints emerged in the curves of the RDM and the mass moisture content. The operational complexity and data calculation may result in these deviations. It could also be seen that the nickpoints among the length, RDM and the mass moisture content changed vary slightly around the 178 cycles. Therefore, the $178^{th}$ cycle was regarded as the critical freeze and thaw cycle *Nf*.

Furthermore, as shown on the right side of the Fig.2.8, the 55-4.5-D specimens showed completely different tendency with the 55-4.5-N concrete specimens. The length of 55-4.5-D specimens almost remained the same during the whole freeze and thaw cycles. Table 2.12 shows the average changing gradient of W/C55%-4.5% specimens. As shown in the table, the average length changing gradient of 55-4.5-D and 55-4.5-N were 0.0001 and -0.0001 %/cycle, both of which could be ignored. Therefore, the 55-4.5-D specimens were regarded as not appearing obvious damage.

The RDM of 55-4.5-D also decreased continuously from the beginning of the freeze and thaw cycles and no apparent nickpoint was figured out. However, different from the sharp decrease illustrated in 55-1-N specimens, the decreasing rate was relatively gentle. As shown in Table 2.12, the average decreasing rate of 55-4.5-D specimens with freeze and thaw cycles is similar to the decreasing rate of 55-4.5-N before its nickpoint. Hence, it is suggested that the 55-4.5-D specimens did not exhibit obvious damage throughout the whole cycles. The 55-4.5-D concrete specimens could be regarded as frost-resistant concrete, which also corresponded with the results by the length change. Besides, the mass moisture content of 55-4.5-D specimens increased constantly until the end of the freeze and thaw cycles. The increasing rate of the mass moisture content of 55-4.5-D specimen was slightly smaller than that of 55-4.5-N. It is suggested that the 55-4.5-D specimen was absorbing water during the whole cycles and the critical mass moisture content had not been reached even at the end of the test. Compared with the results by the W/C55%-1% specimens, the effect of drying manifested itself apparently by the W/C55%-4.5% specimens. The 20℃ drying for two weeks has obviously enhanced the W/C55%-4.5% concrete frost resistance.

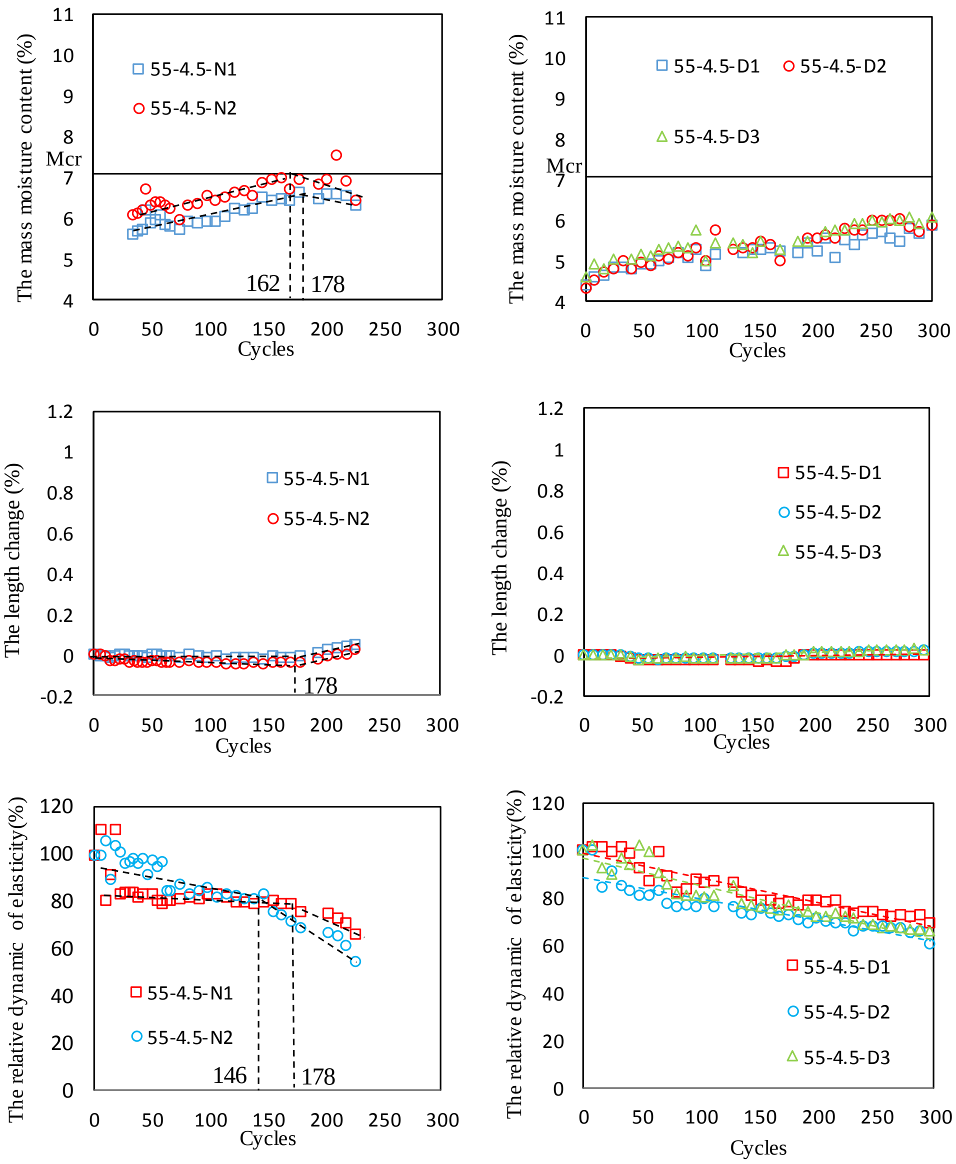


Fig.2.8 The results of W/C55%-4.5% specimens with different drying conditions

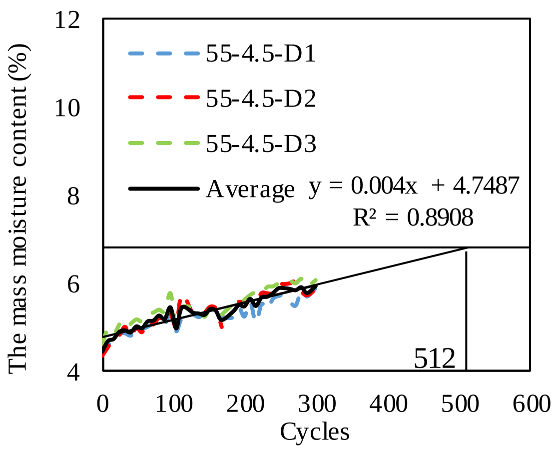


Fig.2.9 The schematic diagram for calculating *Nf* of 55-4.5-D

Table 2.11 The mass moisture content of W/C55%-4.5%

| Type | The mass moisture content W (wt.%) | | | The critical mass moisture content $M_{cr}$ (wt.%) |
|---|---|---|---|---|
| | $0^{th}$ cycle | *Nf* | Final cycle | |
| 55-4.5-N | 5.86 | 6.80 | 6.40 | 7.08 |
| 55-4.5-D | 4.53 | 7.08 (512 cycles) | 6.03 | |

Table 2.12 The average gradient of W/C55%-4.5% specimens

| Specimen type | | Average gradient (%/cycle) | |
|---|---|---|---|
| | | Before Nickpoint | After Nickpoint |
| 55-4.5-N | Length change | -0.0001 | 0.0012 |
| 55-4.5-D | | 0.0001 | - |
| 55-4.5-N | RDM change | -0.1009 | -0.2258 |
| 55-4.5-D | | -0.1034 | - |
| 55-4.5-N | Mass moisture content change | 0.0054 | -0.0040 |
| 55-4.5-D | | 0.0031 | - |

## 2.4 THE PROPOSAL OF A NEW CONCRETE FROST RESISTANCE EVALUATION CRITERION

The critical freeze and thaw cycle *Nf* and its mass moisture content $W_{cr}$, which are determined from the performance of concrete experiencing freeze and thaw in the accelerated freeze and thaw test, can be used to represent concrete appearing obvious frost deterioration. Therefore, *Nf* can be regarded as a new concrete frost resistance evaluation criterion. The critical degree of saturation $S_{cr}$ in the critical degree of saturation test, which also works as a concrete frost resistance criterion, is achieved by the performance when the cylindrical specimens suffered from freeze and thaw. The concrete specimens in the two tests share the same freeze and thaw mechanism, owning similar behavior throughout the freeze and thaw cycles. Hence, the critical freeze and thaw cycle *Nf* and the critical degree of saturation $S_{cr}$ should also share the critical mass moisture content in common. Therefore, the relationship between the *Nf* and $S_{cr}$ is clarified by the mass moisture content and thus a new concrete frost resistance evaluation criterion has been proposed.

Fig.2.10 shows the relationship between the *Nf* and DF/$T_{pl}$. As shown in the figure, there is no clear relationship between *Nf* and $T_{pl}$. While, on the other hand, the *Nf* increases almost linearly with DF. The simulated linear function in the figure has good fitness with the data. Therefore, DF can be used for simulating the *Nf*. In addition, the cycle used for calculating DF is defined as the DF-cycle and the relationship between the DF-cycle and *Nf* has also been clarified by Fig.2.11 below. As shown in the figure, the DF-cycle is larger than the *Nf*. It is suggested that the *Nf* represents the cycle that concrete specimens emerge apparent frost damage, while the DF-cycle is the cycle that concrete is no more frost resistant. Therefore, *Nf* emerges earlier than DF-cycle.

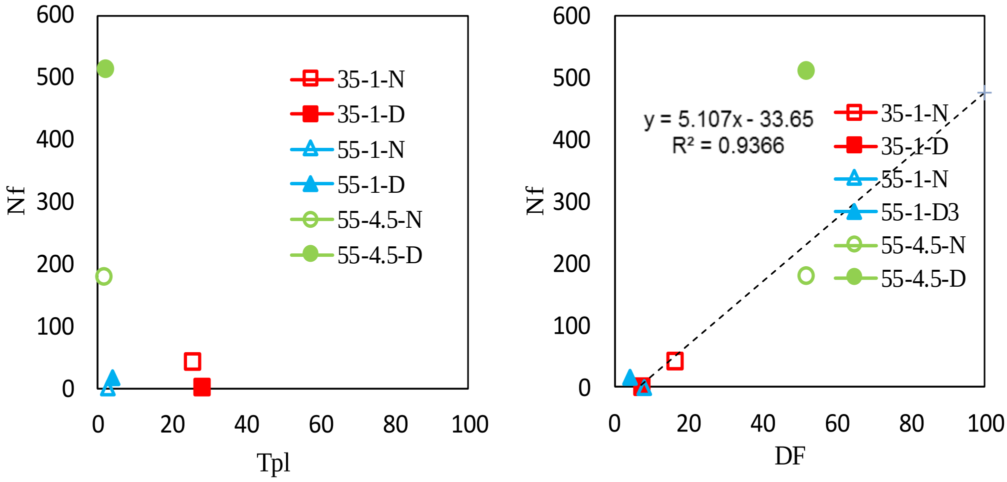


Fig.2.10 The relationship between *Nf* and DF/$T_{pl}$

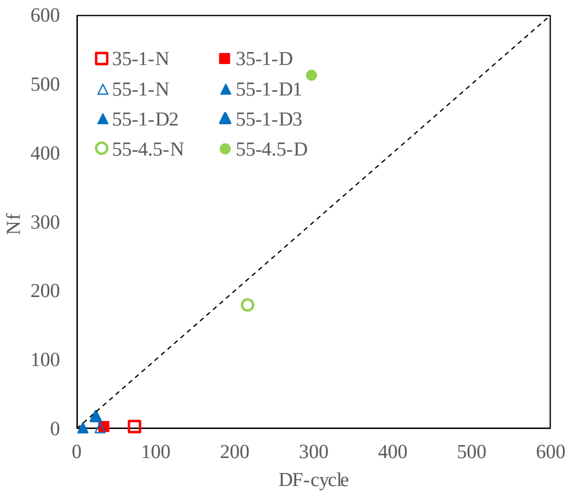


Fig.2.11 The relationship between *Nf* and DF-cycle

## 2.5 CONCLUSION

In this chapter, the single surface water absorption test upon freeze and thaw, the critical degree of saturation test and the accelerated freeze and thaw test considering moisture absorption were conducted, respectively. The relationship between the accelerated freeze and thaw test and the critical degree of saturation test has been clarified by considering the mass moisture content increase by freeze and thaw. The critical freeze and thaw cycle *Nf*, which is regarded as a new concrete frost resistance evaluation criterion, has been proposed.

1) Exterior moisture will be pushed into the concrete specimens due to the pumping effect in the single surface water absorption test upon the freeze and thaw cycles. However, there are occasions that the saturation degree of the specimen under freeze and thaw is smaller than the critical degree of saturation. The specimen will not be damaged by the single surface freeze and thaw. Therefore, a stronger freeze and thaw condition is needed to achieve the critical degree of saturation.

2) Nickpoints of the length, RDM and mass moisture content change almost appear at similar cycle in the accelerated freeze and thaw test. The nickpoint of the length change has been defined as a new concrete frost

resistance criterion *Nf* and the mass moisture content at *Nf* is regarded as the critical mass moisture content $W_{cr}$. $W_{cr}$ in the accelerated freeze and thaw test is in good accordance with the mass moisture content $M_{cr}$ of the $S_{cr}$ in the critical degree of saturation test. $W_{cr}$ is not affected by the different test methods and can be used to evaluate frost deterioration of concrete.

3) There is no clear relationship between the *Nf* and $T_{pl}$, however, there is a linear relationship between DF and *Nf*.

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# CHAPTER 3
# THE INFLUENCE OF THE LOWEST TEMPERATURE ON *NF*

## 3.1 GENERAL

A new concrete frost resistance evaluation criterion *Nf* has been proposed in Chapter 2, and the *Nf* can be used for predicting concrete frost deterioration. The concrete buildings in the actual environment suffer from various environmental influences, like the drying effect and the freeze and thaw function. Therefore, in order to evaluate concrete frost resistance in the actual environment by *Nf*, it is necessary to convert the effect of the actual environmental influences to *Nf*. This chapter aims at figuring out the impact of how the different lowest temperatures affect the *Nf* and proposes a relationship between the lowest temperature and the *Nf*.

## 3.2 THE DISCUSSION OF THE INFLUENCING FACTORS TO CONCRETE FROST DAMAGE

In the actual environment, the different weather conditions, for example, the temperature change, the precipitation, the wind speed and the solar radiation are coupled together to influence the service life of the concrete structures. According to the previous research, the important factors that influences concrete frost resistance have been listed as below.

① The lowest temperature during freezing: The lower temperature causes the more severe frost deterioration [1,2,3].

② Duration of freezing: The duration of freezing has little effect on concrete frost resistance [4].

③ The freezing speed: The effect of freezing speed on concrete deterioration is insignificant when the freezing speed is lower than 10℃/h, while, the freezing speed above 10℃/h will show an obvious effect on the concrete with few air content [5].

④ Wet state: The wet state shows great effect on concrete frost resistance [6,7,8].

⑤ Drying: Drying shows obvious effect on concrete frost resistance. However, there are occasions that concrete frost resistance either enhances [9] or decreases [10] by different drying conditions. The effect of drying process on concrete frost resistance has not been clarified. Besides, according to the previous research, the drying process during the hot summer may not cause the increased moisture content by the freeze and thaw in winter during the outdoor exposure [10]. The effect of different drying conditions on concrete frost resistance has been discussed in Chapter 2.

Here, the effect of various lowest temperatures on concrete frost resistance *Nf* has been discussed in this chapter.

## 3.3 THE EFFECT OF THE LOWEST TEMPERATURES ON CONCRETE FROST RESISTANCE *NF*

### 3.3.1 The outline of the experiment

The outline of the test is listed in Table 3.1. Three kinds of concrete specimens with the mix proportion used in Chapter 2.3 has been adopted. The prismatic specimens with a dimension of 75×75×400mm, suffered from the accelerated freeze and thaw test with the lowest temperature -5℃ and -10℃, respectively. Then, the results were compared with the results calculated by the standard accelerated freeze and thaw test with the lowest temperature -18℃ shown in Chapter 2.3. Moreover, the critical degree of saturation test was conducted as well and the mass moisture content $M_{cr}$ of the critical degree of saturation $S_{cr}$ has been calculated

Table 3.1 The outline of the test

| Specimen type | Experimental method |
|---|---|
| W/C35%-1% | The accelerated freeze and thaw test with the lowest temperature -5℃ and -10℃. ($Nf_{-5℃}$, $Nf_{-10℃}$) The critical degree of saturation test. ($S_{cr}$, $M_{cr}$) |
| W/C55%-1% | |
| W/C55%-4.5% | |

### 3.3.2 Experimental methods

The flow chart of the test is shown in Fig.3.1. Three kinds of fresh concrete with the same mix proportion as shown in Table 2.6 were made. Then, the fresh concrete was also poured into the 75×75×400mm prismatic mold and the cylindrical molds with a dimension of Φ100×200mm for one day before taking them out and curing in water for another two weeks.

The critical degree of saturation test was conducted by the cylindrical specimens. Besides, for the prismatic specimens, the accelerated freeze and thaw tests with the lowest temperature -5℃ and -10℃ were conducted, respectively. In the accelerated freeze and thaw test with the lowest temperature -5℃ and 10℃, the rising and decreasing gradients of the temperature, which affected the ice formation rate, were set same to the rising and decreasing gradients of the standard accelerated freeze and thaw test. The schematic image of the temperature change of the prismatic specimen in the accelerated freeze and thaw test is listed in Fig.3.2. During the accelerated freeze and thaw test, the prismatic specimens were taken out to measure the weight in the air and water, the length and the RDM changes at suitable time intervals. The specimens were dried at 105℃ to constant weight when the test was accomplished. The critical mass moisture content $W_{cr\text{-}5/10℃}$ of the specimens at the critical freeze and thaw cycle $Nf_{-5/10℃}$ were calculated based on the Eq.2.3. While, on the other hand, the critical degree of saturation test of three types of concrete specimens has also been conducted. The critical mass moisture content $M_{cr}$ of all three types were also calculated. The $W_{cr}$ achieved by the accelerated freeze and thaw test with different lowest temperatures were compared with the $M_{cr}$.

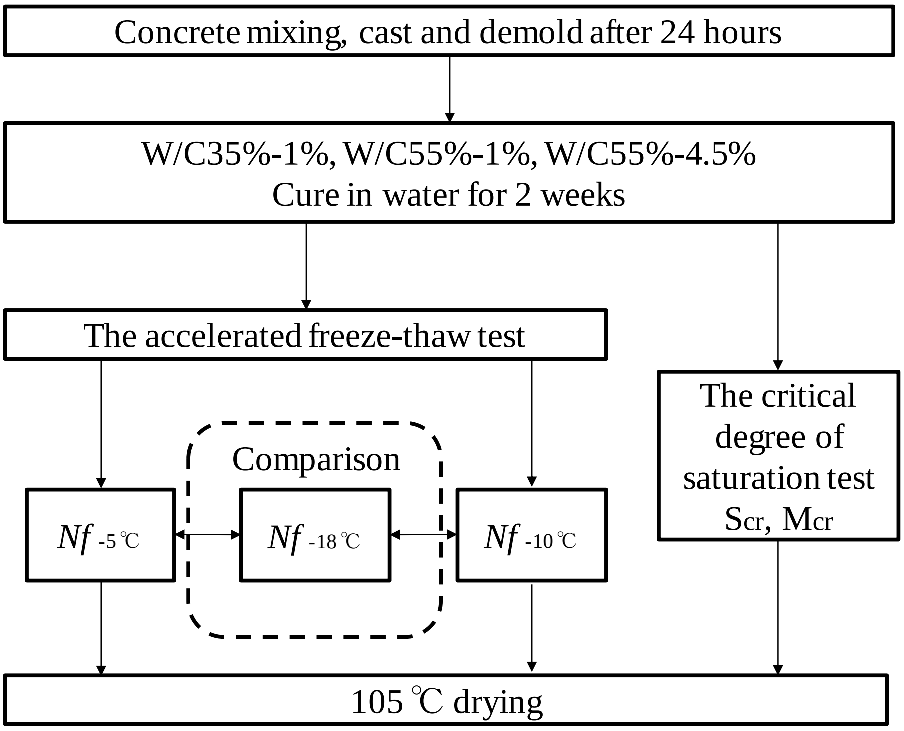



Fig.3.1 The experimental flow of the test

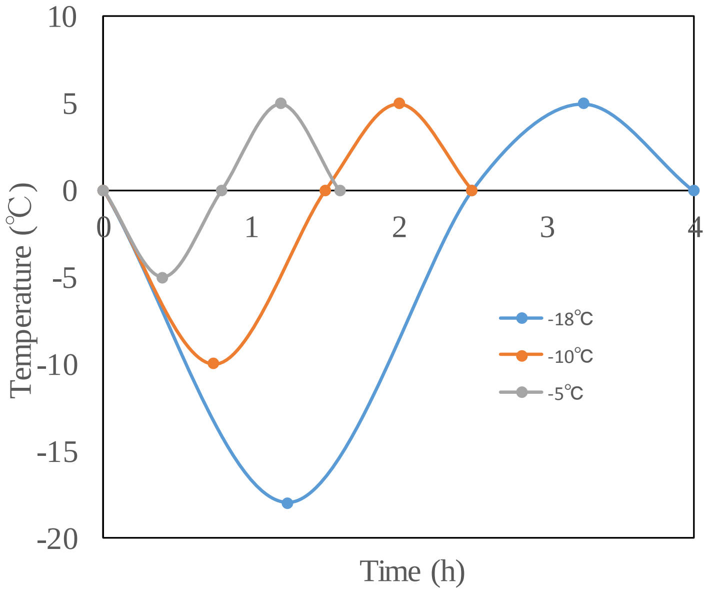



Fig.3.2 The image of the temperature changes of the core concrete specimen

### 3.3.3 Results and discussion

(a) The critical degree of saturation test

Table 3.2 shows the results of the critical degree of saturation test. The detailed data is exhibited in Appendix A.4.

Table 3.2 The results of the critical degree of saturation test

| Specimen type | $S_{cr}$ ($M_{cr}$ (wt.%)) | $T_{pl}$ ($h^{1/2}$) |
|---|---|---|
| W/C35%-1% | 0.94 (6.70) | 10.50 |
| W/C55%-1% | 0.80 (7.72) | 1.96 |
| W/C55%-4.5% | 0.78 (8.39) | 8.83 |

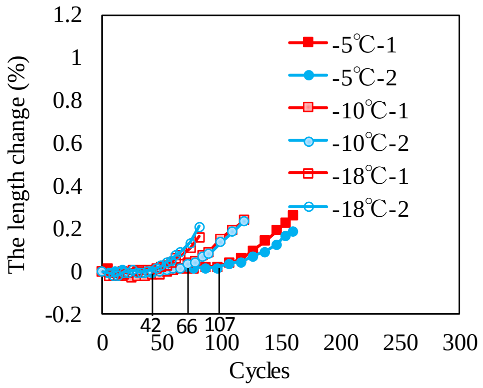
(b) The accelerated freeze and thaw test

1) The results of W/C35%-1% specimens

Fig.3.3 exhibits the length change of W/C35%-1% specimens. As can be seen from the figure, similar to the length change of the standard accelerated freeze and thaw test, the length change also showed nickpoints in the test with the lowest temperature -5℃ and -10℃. The nickpoint cycles were the 107 cycles in the -5℃ test and the 66 cycles in the -10℃ test, respectively. On the other hand, the changes of RDM upon the freeze and thaw with various lowest temperatures are exhibited in Fig.3.4. As shown in the figure, RDM dropped significantly at the 127 and 90 cycles in the accelerated freeze and thaw test with the lowest temperature -5℃ and -10℃. The different sensitivity of the length and RDM change may result in the deviations of the nickpoint. Similar to the *Nf* of the standard accelerated freeze and thaw test, the nickpoint cycle in the length change has been regarded as the critical freeze and thaw cycle *Nf* with the lowest temperatures -5℃ and -10℃.

The mass moisture content change of the specimens is exhibited in Fig.3.5. Similar to the results of the standard accelerated freeze and thaw test with the lowest temperature -18℃, there also appeared nickpoints in the W/C35%-1% specimens with the lowest temperature -5℃ and -10℃. The mass moisture content increased continuously until 117 and 84 cycles for the accelerated freeze and thaw test with the lowest temperature -5℃ and -10℃ before the mass moisture content decreased afterward. Table 3.3 shows the mass moisture content of the W/C35%-1% specimens. As shown in Table 3.3, the mass moisture contents at the nickpoints $W_{cr}$ in the accelerated freeze and thaw test with the lowest temperature -5℃ and -10℃ were similar with each other. It is considered that the $W_{cr}$ was not affected by the various external lowest temperatures. Besides, the mass moisture content $W_{cr}$ was also similar to the $M_{cr}$ calculated by the critical degree of saturation test. According to the results in Chapter 2, the critical mass moisture content $W_{cr}$ was also not affected by the different test methods. Therefore, the critical mass moisture content $W_{cr}$ could be regarded as a characteristic value for concrete experiencing freeze and thaw. Concrete specimens appeared obvious damage once the $W_{cr}$ was achieved regardless of the different lowest temperatures and test methods.

However, the critical mass moisture content $W_{cr}$ in the standard accelerated freeze and thaw test with the lowest temperature -18℃ was different from the $W_{cr}$ calculated by the accelerated freeze and thaw test with the lowest temperature -5℃ or -10℃. It is supposed that the specimens conducted with the standard accelerated freeze and thaw test were not made at the same time with the other specimens. Therefore, the concrete frost resistance properties were different from the others, which leaded to the different critical mass moisture content $W_{cr}$.



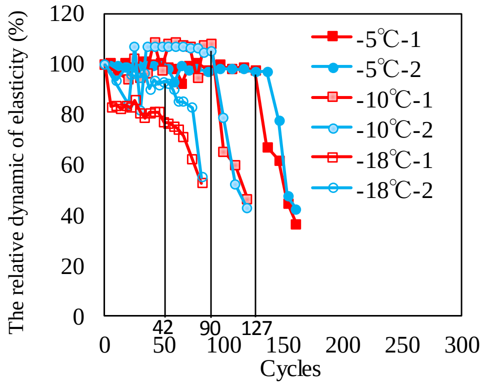




Fig.3.3 The length change of W/C35%-1% Fig.3.4 The RDM change of W/C35%-1%

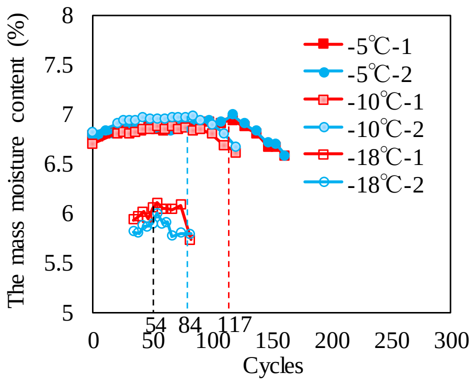



Fig.3.5 The mass moisture content change of W/C35%-1%

Table 3.3 The mass moisture content of W/C35%-1%

| Specimen type | | Mass moisture content (wt.%) | | | |
|---|---|---|---|---|---|
| | | The accelerate freeze and thaw test | | | The critical degree of saturation test |
| | | At 0 cycle | At *Nf* cycle | At Final cycle | $M_{cr}$ |
| 35-1 | -5℃ | 6.86 | 6.95 (107 cycles) | 6.68 | 6.70 |
| | -10℃ | 6.76 | 6.92 (66 cycles) | 6.64 | |
| | -18℃ | 5.87 | 6.06 (42 cycles) | 5.73 | 6.10 |

2) The results of W/C55%-1%

Fig.3.6 shows the length change of W/C55%-1% specimens. As shown in the figure, no obvious differences of the length change were recognized among the specimens with different lowest temperatures. The length change increased significantly right after the start of the freeze and thaw cycles. Therefore, the *Nf* of the W/C55%-1% was regarded as 0 cycle regardless of the lowest temperatures.

The RDM change is shown in Fig.3.7. RDM in the accelerated freeze and thaw test with the lowest temperature -5℃ and -10℃ showed similar tendency with the RDM in the standard accelerated freeze and thaw test. As shown in the figure, RDM decreased dramatically from the beginning of the freeze and thaw cycles.

The change of the mass moisture content is illustrated in Fig.3.8. The mass moisture content also decreased rapidly from the beginning of the cycles despite the different lowest temperatures. Table 3.4 shows the mass moisture content of the W/C55%-1% specimen. Similar with the standard accelerated freeze and thaw test with the lowest temperature -18℃, the mass moisture contents of the accelerated freeze and thaw test with the lowest temperature of both -5℃ and -10℃ have already exceeded the $M_{cr}$. Therefore, the W/C55%-1% specimens were damaged by freeze and thaw immediately regardless of the different lowest temperatures. The W/C55%-1% concrete specimens can be regarded as not frost resistant among all the three kinds of lowest temperatures.

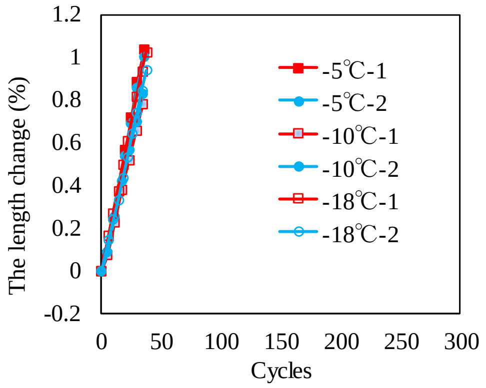



Fig.3.6 The length change of W/C55%-1%

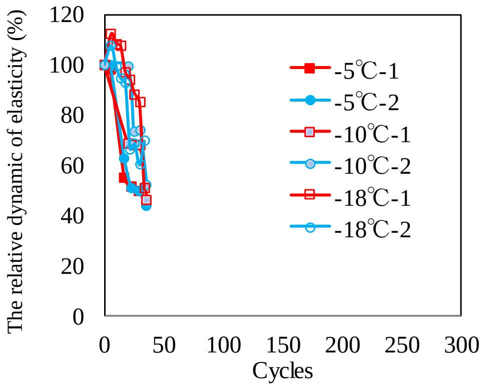



Fig.3.7 The RDM change of W/C55%-1%

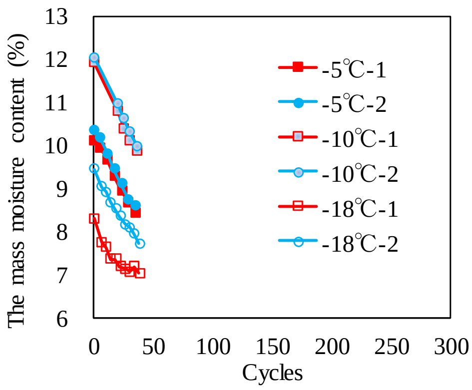



Fig.3.8 The mass moisture content change of W/C55%-1%

Table 3.4 The mass moisture content of W/C55%-1%

| Specimen type | | Mass moisture content (wt.%) | | | |
|---|---|---|---|---|---|
| | | The accelerate freeze and thaw test | | | The critical degree of saturation test |
| | | At 0 cycle | At *Nf* cycle | At Final cycle | $M_{cr}$ |
| 55-1 | -5℃ | 10.25 | — (0 cycle) | 8.53 | 7.24 |
| | -10℃ | 12.00 | — (0 cycle) | 9.93 | |
| | -18℃ | 8.23 | — (0 cycle) | 5.73 | 7.10 |

3) The results of W/C55%-4.5%

The length change of W/C55%-4.5% concrete is shown in Fig.3.9. As shown in the figure, different from the nickpoint appearing at 178 cycles in the length change of the standard accelerated freeze and thaw test with the lowest temperature -18℃, the length change of the specimens with the lowest temperature -5℃ and -10℃ almost kept the same during the whole freeze and thaw cycles and no clear nickpoint was figured out. Therefore, the nickpoint has not appeared even at the end of the freeze and thaw cycles in the accelerated freeze and thaw test with the lowest temperature -5℃ and -10℃.

Fig.3.10 shows the RDM change of the W/C55%-4.5% specimens. The RDM of the specimens with the lowest temperature -5℃ and -10℃ decreased continuously and slowly throughout the whole freeze and thaw cycles and appeared no apparent nickpoints. Similar to the results by the length change, the specimens did not appear obvious frost damage by the RDM change in the accelerated freeze and thaw test with the lowest temperature -5℃ and -10℃.

Fig.3.11 exhibits the mass moisture content of the specimens. The mass moisture content of the specimens with the lowest temperature -5℃ and -10℃ increased continuously throughout the whole cycles, and there also showed no obvious nickpoints even at the end of the freeze and thaw cycles. Besides, Table 3.5 shows the mass moisture content of the specimens. As shown in the table, the mass moisture content at the end of the freeze and thaw cycles was still smaller than $M_{cr}$ calculated by the critical degree of saturation test. It is supposed that for the W/C55%-4.5% specimens, water has been pushed into the specimens during the whole freeze and thaw cycles and the critical mass moisture content $W_{cr}$ has not been reached even at the end of the cycles.

Therefore, we also hypothesized that the $M_{cr}$ calculated by the critical degree of saturation test was equal to the critical mass moisture content $W_{cr}$ for W/C55%-4.5% specimens and the curves of the mass moisture content with various lowest temperatures have been extended linearly to the $M_{cr}$. The freeze and thaw cycle at the intersection has been calculated and exhibited in Fig.3.11. The average freeze and thaw cycle at the intersection, which is listed in Table 3.5, is regarded as the critical freeze and thaw cycle *Nf* for the W/C55%-4.5% concrete specimens conducted with the accelerated freeze and thaw test with the lowest temperature -5℃ and -10℃.

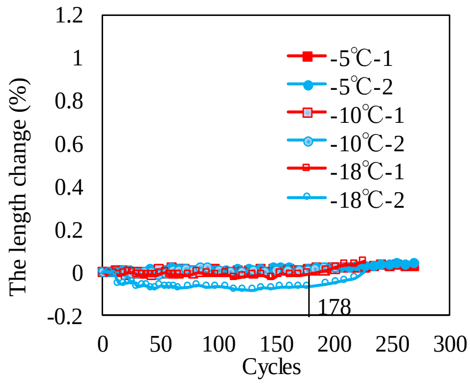



Fig.3.9 The length change of W/C55%-4.5%

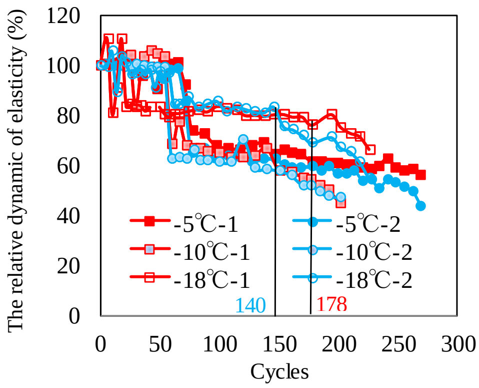



Fig.3.10 The RDM change of W/C55%-4.5%

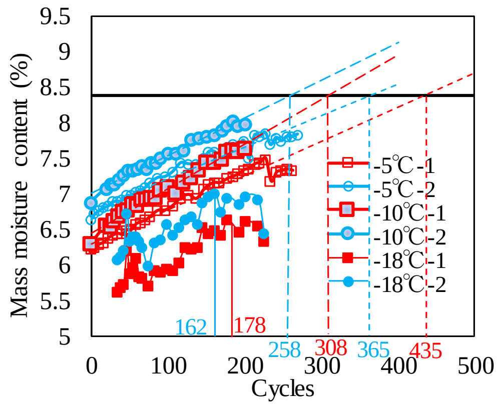



Fig.3.11 The mass moisture content change of W/C55%-4.5%

Table 3.5 The mass moisture content of W/C55%-4.5%

| Specimen type | | Mass moisture content (wt.%) | | | |
|---|---|---|---|---|---|
| | | The accelerate freeze-thaw test | | | The critical degree of saturation test |
| | | At 0 cycle | At *Nf* cycle | At Final cycle | $M_{cr}$ |
| 55-4.5 | -5℃ | 6.57 | 8.39 (400 cycle*) | 7.98 | 8.39 |
| | -10℃ | 6.69 | 8.39 (283 cycle*) | 7.94 | |
| | -18℃ | 6.80 | 6.06 (178 cycle) | 6.40 | 7.08 |

Note)*: The curve of the mass moisture content has been extended to the $M_{cr}$ to get the critical freeze and thaw cycle *Nf*. The average value at the intersection is regarded as the *Nf*.

(c) The relationship between *Nf* and different lowest temperatures

Based on the results above, it is supposed that the different lowest temperatures may not affect the critical mass moisture content $W_{cr}$. However, as the lowest temperature increases, the newly defined concrete frost resistance criterion *Nf* also increases. Therefore, in this paper, the influence of various lowest temperatures on concrete frost resistance has been clarified by the *Nf*. The effect of one accelerated freeze and thaw cycle with the lowest temperature -5℃ or -10℃ on concrete frost deterioration can be expressed by the $1/Nf_{-5℃}$ or $1/Nf_{-10℃}$, respectively. The proportion E of the effect of one accelerated freeze and thaw cycle with the lowest temperature -5℃ or -10℃ to the effect of one standard accelerated freeze and thaw cycle on concrete frost damage can be determined by the corresponding $Nf_{-5℃}$ or $Nf_{-10℃}$. Eq.3.1 shows the relationship between *Nf* and different lowest temperatures.

$$E^{35-1}_{-5℃} = \left( \frac{1}{Nf^{35-1}_{-5℃}} \middle/ \frac{1}{Nf^{35-1}_{-18℃}} \right) = Nf^{35-1}_{-18℃} / Nf^{35-1}_{-5℃} = 0.393$$

$$E^{35-1}_{-10℃} = \left( \frac{1}{Nf^{35-1}_{-10℃}} \middle/ \frac{1}{Nf^{35-1}_{-18℃}} \right) = Nf^{35-1}_{-18℃} / Nf^{35-1}_{-10℃} = 0.636$$

$$E_{-5℃}^{55-4.5} = \left( \frac{1}{Nf_{-5℃}^{55-4.5}} \Big/ \frac{1}{Nf_{-18℃}^{55-4.5}} \right) = Nf_{-18℃}^{55-4.5} / Nf_{-5℃}^{55-4.5} = 0.445$$

$$E_{-10℃}^{55-4.5} = \left( \frac{1}{Nf_{-10℃}^{55-4.5}} \Big/ \frac{1}{Nf_{-18℃}^{55-4.5}} \right) = Nf_{-18℃}^{55-4.5} / Nf_{-10℃}^{55-4.5} = 0.629 \tag{3.1}$$

Where, $E_{-5/-10℃}$ is the proportion of the effect of one freeze and thaw cycle with the lowest temperature -5℃ or -10℃ on concrete frost damage to the effect of one standard accelerated freeze and thaw test with the lowest temperature -18℃.

Therefore, it is considered that the effect of one cycle with the lowest temperature -5℃ and -10℃ on concrete frost damage account for about 0.4 cycle and 0.6 cycle in the standard accelerated freeze and thaw test. In the actual environment, the lowest temperature changes with time and locations. Therefore, it is of great importance to evaluate the effect of different lowest temperatures on concrete frost deterioration. Fig.3.12 exhibits the relationship between the proportion E and various lowest temperatures. As shown in the figure, the proportion E almost increases linearly with the decrease of the lowest temperatures. Therefore, the proportion E with different lowest temperatures can be calculated by Eq.3.2.

$$E_T = -0.0448T + 0.1909 \tag{3.2}$$

Where, $E_T$ is the proportion of the effect of one freeze and thaw cycle with the lowest temperature T to the effect of one standard freeze and thaw cycle with the lowest temperature -18℃. $T$ is the lowest temperature in the accelerated freeze and thaw cycles.

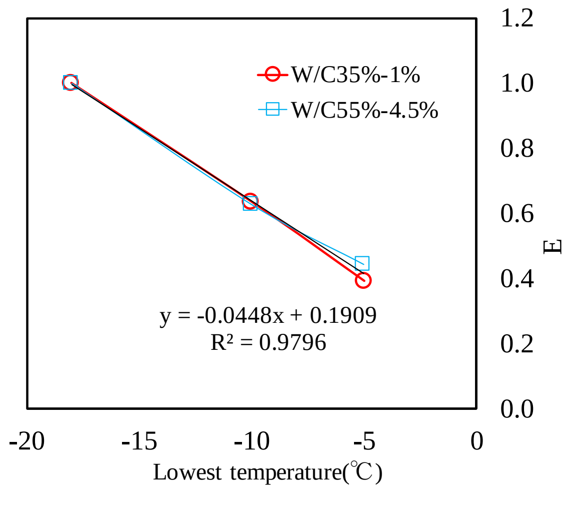



Fig.3.12 The relationship between the proportion E and different lowest temperatures

### 3.4 CONCLUSION

The effect of the different lowest temperatures on concrete frost deterioration has been expounded by the accelerated freeze and thaw test and the critical degree of saturation test. The results of this chapter are listed below.

(1) The critical freeze and thaw cycle *Nf* in the accelerated freeze and thaw test increases with the increase of the lowest temperature. However, the critical mass moisture content $W_{cr}$ is not affected by the different lowest temperatures.

(2) We have figured out the proportion E of the effect of one freeze and thaw cycle at the lowest temperature -5℃ or -10℃ to the effect of one standard accelerated freeze and thaw cycle on concrete frost damage by *Nf*. The proportion E increases almost linearly with the decrease of the lowest temperature and the linear equation between the proportion E and the lowest temperature has been proposed.

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## CHAPTER 4
## PREDICTING CONCRETE FROST DETERIORATION BY *NF* IN THE ACTUAL ENVIRONMENT

### 4.1 GENERAL

In Chapter 2, the moisture increase by freeze and thaw has been considered in the accelerated freeze and thaw test and the freeze and thaw cycle when obvious nickpoint emerges in the curve of the length change, is regarded as a new concrete frost resistance criterion *Nf*. In this chapter, the temperature and the relative humidity of the outdoor exposed concrete specimens have been recorded and the effect on concrete frost deterioration has been converted to the critical freeze and thaw cycle *Nf** by the Eq.3.1 and Eq.3.2 in Chapter 3. Hence, a new concrete frost deterioration predicting method that concrete is damaged by freeze and thaw when the environmental effect *Nf** reaches to its critical freeze and thaw cycle *Nf* has been proposed. In addition, we conducted the accelerated freeze and thaw test with the specimens after the outdoor exposure, and its critical freeze and thaw cycle *Nf'* has also been calculated. The results are used to verify the possibility to predict concrete frost damage by the newly proposed concrete frost deterioration predicting method.

### 4.2 THE PROPOSAL OF CONCRETE FROST DETERIORATION PREDICTING METHOD IN THE ACTUAL ENVIRONMENT

As shown in Chapter 3, the effect of the duration of freezing has been neglected and both the freezing and thawing rate and moisture content of the outdoor exposed specimen have been set to the severest state (same as the standard accelerated freeze and thaw test). Therefore, the predicted concrete frost deterioration is in the safe state. Besides, it has also been discussed in Chapter 3 that the lowest temperature has a significant effect on concrete frost degradation. The effect of the different lowest temperatures on concrete frost deterioration has been converted to the critical freeze and thaw cycle *Nf* by the standard accelerated freeze and thaw test. As shown in Eq.3.2, the proportion E of the effect of one freeze and thaw cycle with various lowest temperatures to the effect of one standard accelerated freeze and thaw cycle with the lowest temperature -18℃ can be clarified by the *Nf*. Thus, the effect of the outdoor exposure on concrete frost deterioration can be quantified to the critical freeze and thaw cycle *Nf* according to the recorded temperature and relative humidity of the outdoor environment.

Therefore, a method for predicting the concrete frost deterioration due to the outdoor exposure has been proposed. The accelerated freeze and thaw test before and after the outdoor exposure have been conducted and the critical freeze and thaw cycle *Nf* and *Nf'* are calculated, respectively. While, on the other hand, the temperature and relative humidity information of the specimens exposed to the outdoor environment have been collected and the effect of the freeze and thaw function during the outdoor exposure has been converted to the critical freeze and thaw cycle *Nf**. In the actual environment, concrete is no more frost resistant when the converted environmental effect *Nf** surpasses the critical freeze and thaw cycle *Nf*.

## 4.3 THE MEASUREMENT OF THE TEMPERATURE AND RELATIVE HUMIDITY OF CONCRETE SPECIMENS EXPSOED TO OUTDOOR AND ITS CONVERSION TO *NF*

### 4.3.1 The outline of the experiment

Table 4.1 shows the outline of the experiment and Figure 4.1 exhibits the outdoor exposure B and C of the concrete specimens. As shown in the figure, the exposure condition B was to place the prismatic and cylindrical specimens directly on the roof of a 2-floor building (about 6 meters in height) in Sapporo from 2017.11.01 to 2018.11.14, while, the exposure condition C was to place the specimens on a platform on the same roof for the same period. In addition, a compact sensor named Hygrocron has been embedded into the three kinds of specimens. The temperature and the relative humidity (RH) of the specimens were measured during the one-year outdoor exposure and the effect of the freeze and thaw during the outdoor exposure was converted to the *Nf** according to Eq.3.2.

For the specimen denotation (e.g, 35-1-B and 35-1-C), the first two parameters indicate the W/C ratio and the air content while the last parameter B and C represents the specimens experienced different exposure conditions.

Table 4.1. The outline of the experiment

| Specimen type | Exposure condition | Experimental method |
|---|---|---|
| W/C35%-1%<br>W/C55%-1%<br>W/C55%-4.5% | Condition B: set on the roof<br>Condition C: set on a platform on the roof | Record the temperature and the relative humidity of the specimen for one year. |


Fig.4.1 The curing condition B and C

### 4.3.2 Testing method

The meteorological condition has a significant effect on the temperature and the moisture content of concrete buildings [1,2,3,4]. Therefore, it is of great importance to monitor the temperature and relative humidity (RH) of the concrete buildings exposed to the outdoor environment. There are more than fifty different types of sensor whose deployment into practical devices facilitates long-term monitoring of structural changes, reinforcement corrosion, concrete chemistry, moisture state and temperature [5,6]. A kind of compact sensor named Hygrocron has been widely used for monitoring the temperature and RH of the concrete specimens [7]. The Hygrocron is exhibited in Fig.4.2. The Hygrocron is an ultra-compact temperature and relative humidity recorder. The temperature measurement of the Hygrocron ranges from -20℃ to 80℃ and the RH measurement varies from 0% to 95%. The temperature and relative humidity have been monitored every 30 minutes in this test. The data was collected at about every month and then the sensor was reset for the next round of monitoring.

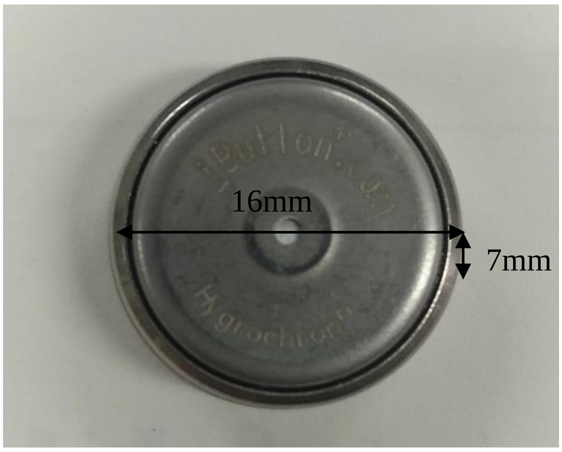



Fig.4.2 The sensor Hygrocron

Fig.4.3 illustrates the setting schematic of the sensor Hygrocron. The plastic foam with a size of 10×10×35mm was inserted into the concrete after the fresh concrete was poured into the mold. The plastic foam was then taken out from the specimen after the specimens cured in water for two weeks. Then the sensor Hygrocron was set into the groove and the plastic foam was inserted into the groove again. The surface of the groove was sealed with the aluminum foil to prevent the rainfall from getting into the groove. Besides, the surface of the specimen with the opening was set on the underside to avoid the rainfall directly getting into the groove. The duration of the outdoor exposure lasted for one year, from 2017.11.01 to 2018.11.14.

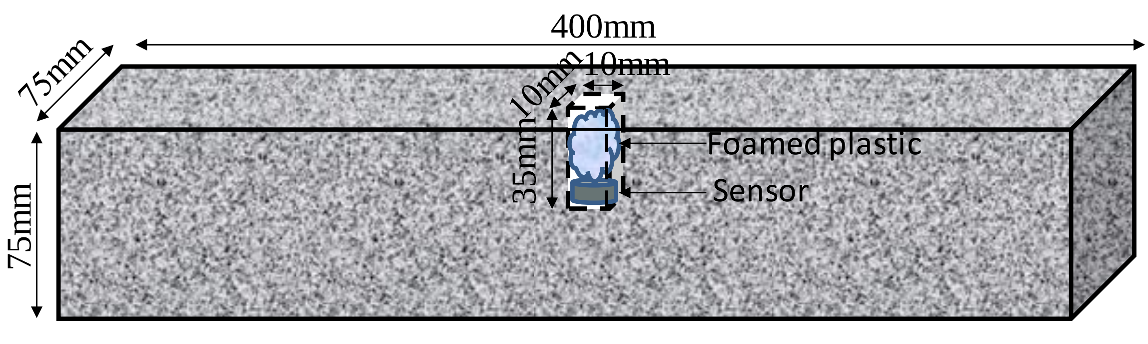
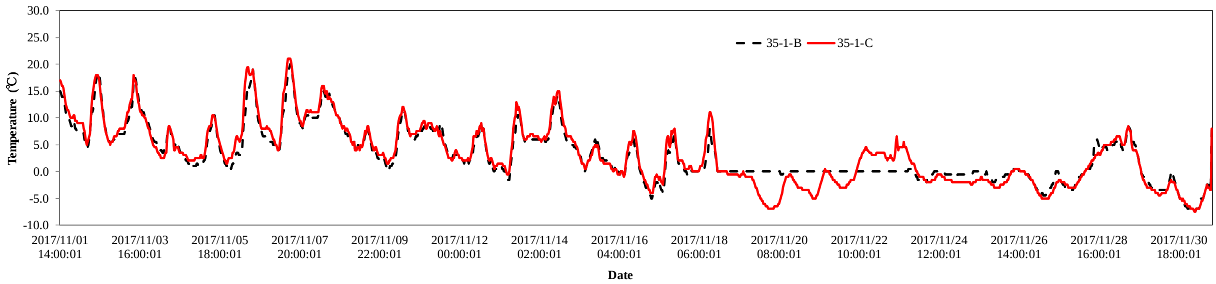
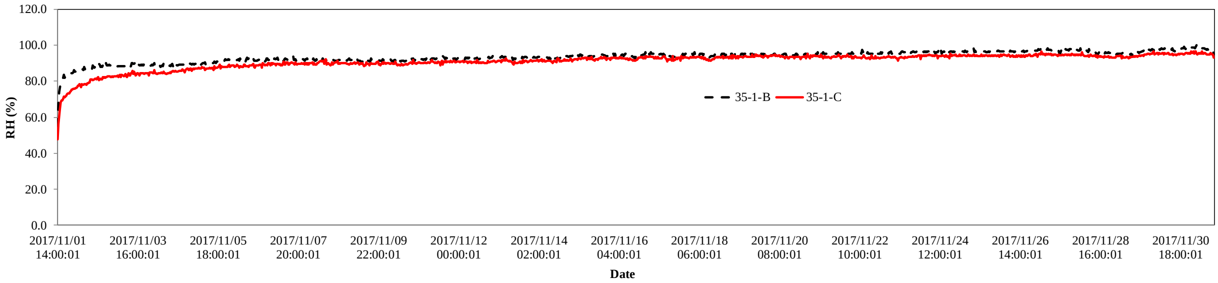



Fig.4.3 The setting schematic diagram of the sensor

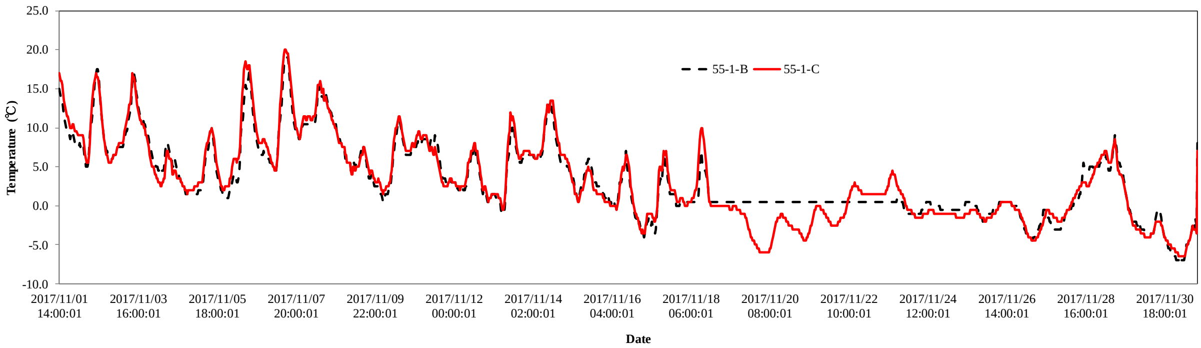
### 4.3.3 Recording environmental information and calculating *Nf**

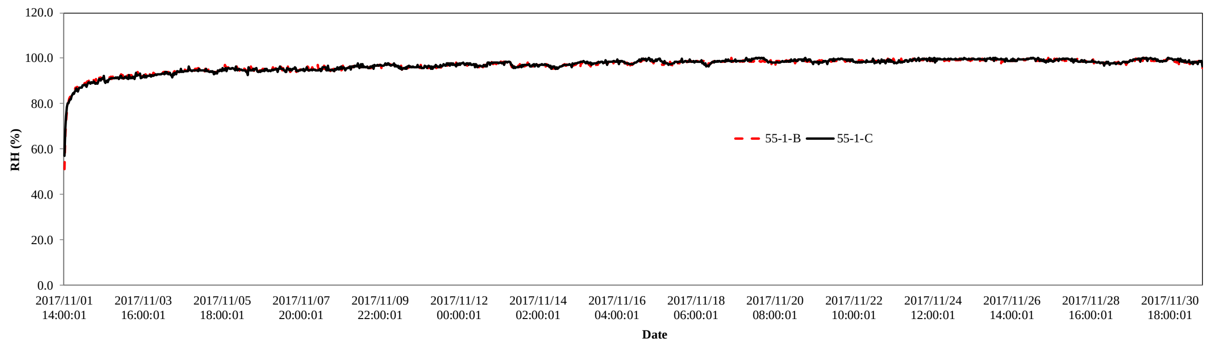
Fig.4.4 shows the temperature and RH data of one month ranging from 2017.11.01 to 2017.12.01. As shown in Fig.4.4, the temperatures of the specimens of condition B and C were almost the same during the whole freeze and thaw cycles. However, there was a period (from 2017.11.19 to 2017.11.23) in which the temperature kept constant at about 0℃ in condition B. It is suggested that the melted snow on the rooftop surface caused by the heat from the building may result in the constant temperature. As can be seen from the RH of the three kinds of concrete specimens, the RH of the specimens in condition B was larger than the RH in condition C, especially for the W/C35%-1% specimens. It is suggested that the specimens in condition C were on the platform during the outdoor exposure and therefore these specimens were difficult to absorb water.




(a) The temperature and RH of W/C35%-1% specimens






(b) The temperature and RH of W/C55%-1% specimens


(c) The temperature and RH of W/C55%-4.5% specimens

Fig.4.4 The temperature and RH of three kinds of specimens

#### 4.3.4 Calculation of the critical freeze and thaw cycles of the outdoor exposed specimens

Fig.4.5 shows the temperature of 35-1-B specimen changing from 2017.11.01 to 2017.12.01. As shown in the figure, four freeze and thaw cycles with different lowest temperatures were figured out throughout the month. The freeze and thaw cycle with the lowest temperature higher than -1℃ and the highest positive temperature lower than 1℃ have not been counted because the freeze and thaw effect was not obvious and thus the frost deterioration could be neglected [8]. Table 4.2 shows the freeze and thaw cycles with various lowest temperatures and its freeze and thaw effect was converted to the critical freeze and thaw cycle *Nf* calculated by the standard accelerated freeze and thaw test. The converted effect of four freeze and thaw cycles have been summed up and the one-month freeze and thaw effect in the actual environment accounted for 1.60 standard accelerated freeze and thaw cycles.

Table 4.3 shows the converted freeze and thaw cycle *Nf** of the three types of concrete specimens during the one-year outdoor exposure. The detailed data is exhibited in Appendix A.5. As shown in the table, the *Nf** of the three kinds of specimens in condition B was smaller than that in condition C. It is supposed that due to the heat from the building, the temperature of the specimens were kept at around 0℃. Therefore, the converted freeze and thaw cycle *Nf** in condition B was inferior to the *Nf** in condition C.

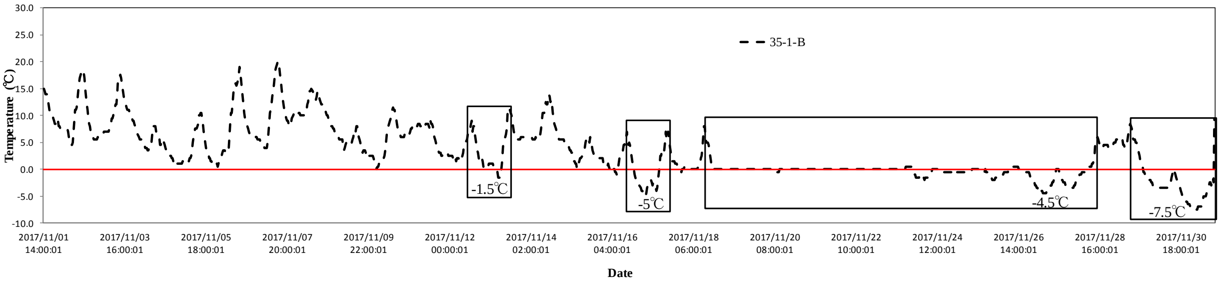



Fig.4.5 The temperature change of 35-1-B from 2017.11.01 to 2017.12.01

Table 4.2 The freeze and thaw cycle with different lowest temperatures

| Freeze and thaw cycles | Lowest temperature | $(1/Nf_T)/(1/Nf_{-18℃})$ |
|---|---|---|
| 1 | -1.5℃ | 0.26 cycles |
| 2 | -5.0℃ | 0.42 cycles |
| 3 | -4.5℃ | 0.39 cycles |
| 4 | -7.5℃ | 0.53 cycles |
| Sum | | 1.60 cycles |

Table 4.3 The converted *Nf** during the one-year exposure

| Specimen type | Time period | *Nf** |
|---|---|---|
| 35-1-B | 2017.11.01-2018.12.01 | 1.60 cycles |
| | 2018.12.01-2018.02.25 | 1.66 cycles |
| | 2018.02.25-2018.03.14 | 1.21 cycles |
| | 2018.03.14-2018.04.17 | 1.75 cycles |
| Sum | | 6.22 cycles |
| 35-1-C | 2017.11.01-2018.12.01 | 1.82 cycles |
| | 2018.12.01-2018.02.25 | 6.46 cycles |
| | 2018.02.25-2018.03.14 | 1.26 cycles |
| | 2018.03.14-2018.04.17 | 1.82 cycles |

| | | |
|---|---|---|
| Sum | | 11.36 cycles |
| 55-1-B | 2017.11.01-2018.12.01 | 1.53 cycles |
| | 2018.12.01-2018.02.25 | 2.36 cycles |
| | 2018.02.25-2018.03.14 | 0.89 cycles |
| | 2018.03.14-2018.04.17 | 1.32 cycles |
| Sum | | 6.10 cycles |
| 55-1-C | 2017.11.01-2018.12.01 | 1.96 cycles |
| | 2018.12.01-2018.02.25 | 5.63 cycles |
| | 2018.02.25-2018.03.14 | 1.08 cycles |
| | 2018.03.14-2018.04.17 | 1.43 cycles |
| Sum | | 10.10 cycles |
| 55-4.5-B | 2017.11.01-2018.12.01 | 1.78 cycles |
| | 2018.12.01-2018.02.25 | 2.42 cycles |
| | 2018.02.25-2018.03.14 | 2.10 cycles |
| | 2018.03.14-2018.04.17 | 1.73 cycles |
| Sum | | 8.03 cycles |
| 55-4.5-C | 2017.11.01-2018.12.01 | 1.27 cycles |
| | 2018.12.01-2018.02.25 | 7.31 cycles |
| | 2018.02.25-2018.03.14 | 1.17 cycles |
| | 2018.03.14-2018.04.17 | 2.21 cycles |
| Sum | | 11.96 cycles |

## 4.4 THE COMPARISON OF THE *NF* RESULTS BY THE ACCELERATED FREEZE AND THAW TEST BEFORE AND AFTER OUTDOOR EXPOSURE

### 4.4.1 The outline of the experiment

Table 4.4 shows the outline of the experiment. The concrete specimens exposed for one year under different outdoor exposure conditions B and C were then conducted with the accelerated freeze and thaw test and the critical degree of saturation test. Besides, the specimens cured in water for two weeks as exhibited in Chapter 2.3 were regarded as the control group A and the results achieved by the accelerated freeze and thaw test have been used to compare with the results in condition B and C.

Table 4.4. The outline of the experiment

| Specimen type | Exposure condition | Experimental method |
|---|---|---|
| W/C35%-1% | Condition A: No exposure (control group) | 1. The accelerated freeze and thaw test<br>2. The critical degree of saturation test |
| W/C55%-1% | Condition B: Set on the roof for 1 year | |
| W/C55%-4.5% | Condition C: Set on a platform for 1 year | |

**4.4.2 Experimental methods**

Concrete mix proportion and the curing condition were same with the specimens shown in Chapter 2.3. The specimens after different outdoor exposure conditions were then conducted with the accelerated freeze and thaw test, and the critical degree of saturation test. The critical freeze and thaw cycle *Nf'* and the critical mass moisture content $W_{cr}$ in the accelerated freeze and thaw test were compared with the critical mass moisture content $M_{cr}$ in the critical degree of saturation test.

**4.4.3 Results and discussion**

(a) The critical degree of saturation test

Table 4.5 shows the results of the critical degree of saturation test. The detailed data is exhibited in Appendix A.6. The critical mass moisture contents $M_{cr}$ of the three kinds of concrete specimens decreased after the one-year outdoor exposure. Besides, the $T_{pl}$ in condition B was slightly smaller than that in condition C among all the three types of concrete specimens. The changes of concrete frost resistance showed similar tendency as in previous studies [9], and the critical degree of saturation test could be used to evaluate concrete frost deterioration due to the outdoor exposure.

Table 4.5 The results of the critical degree of saturation test

| Specimen type | | $S_{cr}$ ($M_{cr}$) (wt.%) | $T_{pl}$ ($h^{1/2}$) |
|---|---|---|---|
| W/C35%-1% | A | 0.98 (6.10) | 25.72 |
| | B | 0.90 (5.80) | 6.93 |
| | C | | 9.80 |
| W/C55%-1% | A | 0.86 (7.10) | 2.73 |
| | B | 0.68 (5.96) | 4.81 |
| | C | | 4.83 |
| W/C55%-4.5% | A | 0.68 (7.08) | 1.91 |
| | B | 0.74 (6.96) | 4.87 |
| | C | | 5.17 |

(b) The accelerated freeze and thaw test

1) The results of W/C35%-1% specimens

Fig.4.6 shows the length change of W/C35%-1% concrete without outdoor exposure (condition A) and exposed to the outdoor environment for one year (condition B and C). As shown in the figure, compared with the nickpoint appearing at 42 cycles of the 35-1-A specimens, the length of the 35-1-B and C specimens increased dramatically right after the start of the freeze and thaw cycles and no nickpoint was figured out. Therefore, the critical freeze and thaw cycles *Nf'* for the 35-1-B and 35-1-C specimens were regarded as 0 cycle. The one-year outdoor exposure degraded the W/C35%-1% concrete frost resistance. Besides, as shown in the figure, no obvious difference could be found out between 35-1-B and 35-1-C specimens. As shown in Table 4.3, the freeze and thaw effect of the outdoor exposure conditions B and C were 6.22 and 11.36 standard accelerated freeze and thaw cycles, which were much smaller than the *Nf* without outdoor exposure (42cycles). However, the critical freeze and thaw cycle *Nf'* after the one-year outdoor exposure became 0 cycle. Therefore, it is supposed that other environmental factors, like the drying effect, coupled with the freeze and thaw function, worked together to degrade concrete frost resistance.

The RDM change of W/C35%-1% specimen is exhibited in Fig.4.7. Like the length change of 35-1-B and C, the RDM of 35-1-B and C specimens also decreased rapidly from the beginning of the freeze and thaw cycles and the 35-1-B and C specimens were regarded as not frost-resistant concrete.

Fig.4.8 shows the mass moisture content change of W/C35%-1% specimens. As shown in the figure, except for a slight increase of the mass moisture content at the beginning of the cycles, the mass moisture content of 35-1-B and C exhibited a decreasing trend during the whole freeze and thaw cycles. Besides, Table 4.6 presents the mass moisture content change of the W/C35%-1% specimens. As shown in Table 4.6, the mass moisture content of 35-1-B and C at 0 cycle have already exceeded its critical mass moisture content $M_{cr\text{-}B,C}$ (5.80).

Hence, based on the results of the length, RDM, and mass moisture content change, the one-year outdoor exposure decreased the W/C35%-1% concrete frost resistance and accelerated concrete freeze and thaw deterioration.

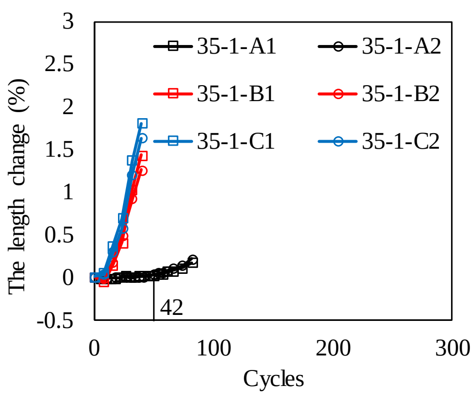


Fig.4.6 The length change of 35-1

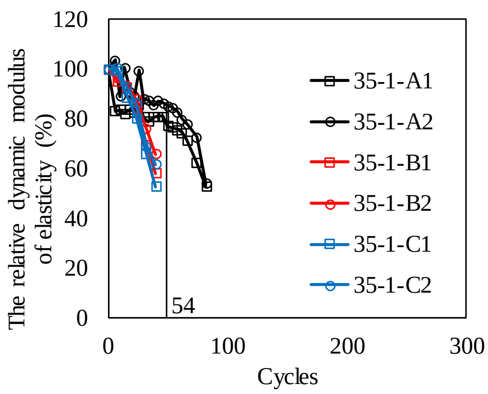


Fig.4.7 The RDM change of 35-1

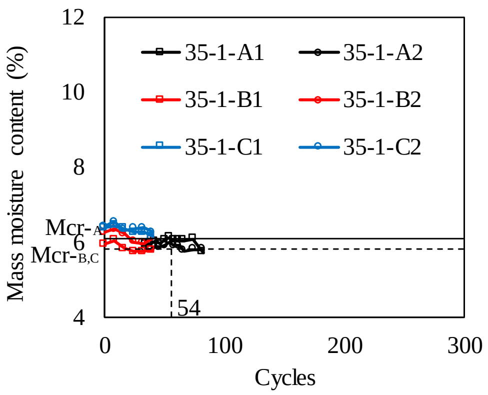



Fig.4.8 The mass moisture content of 35-1

Table 4.6 The mass moisture content of W/C35%-1%

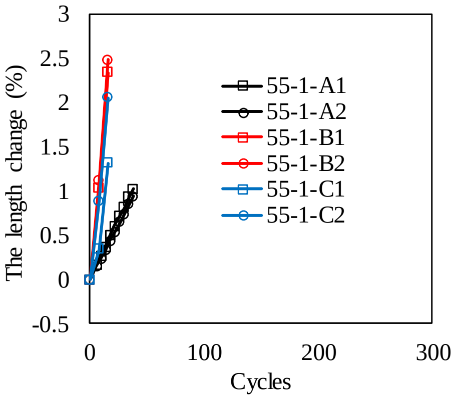
| Specimen type | | Mass moisture content (wt.%) | | |
|---|---|---|---|---|
| | | The accelerate freeze-thaw test | | |
| | | 0 cycle | *Nf'* | Final cycle |
| 35-1 | B | 6.33 | - (0 cycle) | 6.09 (40 cycles) |
| | C | 6.42 | - (0 cycle) | 6.24 (40 cycles) |

2) The results of W/C55%-1% specimens

Fig.4.9 shows the length change of W/C55%-1% specimens. As shown in the figure, the length of 35-1-B and C also increased dramatically right after the beginning of the freeze and thaw cycle. The critical freeze and thaw cycle *Nf'* for the 55-1-B and C after the outdoor exposure were also regarded as 0 cycle. As shown in the figure, compared with the 55-1-A specimens whose *Nf* was 0 cycle, the length change increasing gradient of 55-1-B or C was much larger than that of 55-1-A specimens. Besides, the converted freeze and thaw cycle *Nf** of one-year outdoor exposure accounted for 6.10 and 10.10 cycles under condition B and C, respectively. The *Nf** has already exceeded the *Nf*, and it is supposed that concrete frost deterioration has accelerated during the outdoor exposure.

The RDM change of W/C55%-1% specimen is shown in Fig.4.10. The RDM of 55-1-B and C showed similar tendency with the RDM of 55-1-A specimens. The RDM decreased dramatically right after the start of the cycles and no obvious nickpoint was found out during the whole freeze and thaw cycles.

The mass moisture content change is exhibited in Fig.4.11. Similar to the mass moisture content change of 55-1-A specimens, the mass moisture content of 55-1-B and C also decreased rapidly from the start of the cycles. Besides, as shown in Table 4.7, the mass moisture contents at 0 cycle of 55-1-B and C have already surpassed the critical mass moisture content $M_{cr\text{-}B,\,C}$ (5.96). The specimens were regarded as not frost resistant even before the outdoor exposure and the specimens were already deteriorated by freeze and thaw during the outdoor exposure.



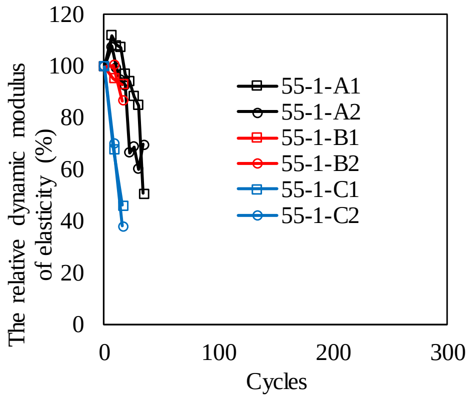




Fig.4.9 The length change of 55-1  Fig.4.10 The RDM change of 55-1

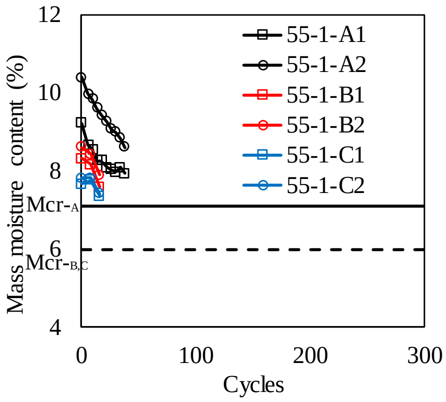



Fig.4.11 The mass moisture content of 55-1

Table 4.7 The mass moisture content of W/C55%-1%

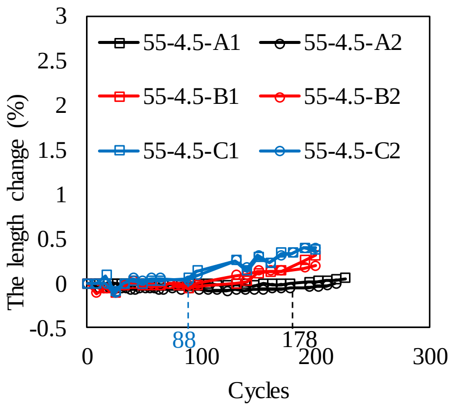
| Specimen type | | Mass moisture content (wt.%) | | |
|---|---|---|---|---|
| | | The accelerate freeze-thaw test | | |
| | | 0 cycle | *Nf'* | Final cycle |
| 55-1 | B | 8.46 | - (0 cycle) | 7.74 (16 cycles) |
| | C | 7.74 | - (0 cycle) | 7.38 (16 cycles) |

3) The results of W/C55%-4.5% specimens

Fig.4.12 shows the length change of W/C55%-4.5% specimens. Similar to the trend of the 55-4.5-A specimens, the length change of 55-4.5-B and C also appeared obvious nickpoints which showed up at 88 cycles. The length change remained almost the same until 88 cycles before it increased dramatically. Therefore, the 88 cycles were regarded as the critical freeze and thaw cycle *Nf'* for the 55-4.5-B and C specimens. The critical freeze and thaw cycle *Nf* of the 55-4.5-A specimen was 178 cycles, and the converted freeze and thaw cycle of the effect of the outdoor exposure only accounted for 8.03 and 11.96 cycles in condition B and C. Even the difference between *Nf* and environmental effect $Nf^*_C$ which was a relatively severe condition, (178-11.96=166.04), was much larger than the critical freeze and thaw cycle *Nf'* after one-year outdoor exposure (88 cycles). Therefore, other environmental factors coupled with the freeze and thaw function to degrade W/C55%-4.5% concrete frost resistance.

The RDM change is exhibited in Fig.4.13. As shown in the figure, the nickpoint cycle of 55-4.5-B and C specimens appeared at 96 cycles. The nickpoint cycles of the RDM were also similar to the critical freeze and thaw cycle *Nf'* calculated by the length change (88 cycles).

Fig.4.14 shows the mass moisture content change of the W/C55%-4.5% specimens. The mass moisture increased slightly until the 88 and 64 cycles for the 55-4.5-B and C before they began to decrease. As shown in Table 4.8, the mass moisture contents of 55-4.5-B and C at the peak were similar with each other and were almost equal to the mass moisture content at the critical mass moisture content $M_{cr\text{-}B,\,C}$ (6.96). Based on the results above, the one-year outdoor exposure had an adverse effect on the concrete frost resistance of W/C55%-4.5%, which was clarified by the critical freeze and thaw cycle decreasing from 178 to 88 cycles by outdoor exposure.



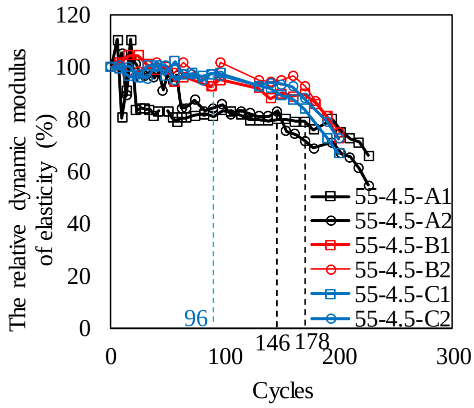




Fig.4.12 The length change of 55-4.5    Fig.4.13 The RDM change of 55-4.5

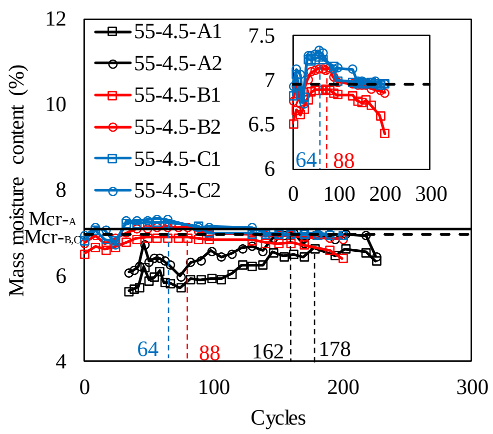



Fig.4.14 The mass moisture content of 55-4.5

Table 4.8 The mass moisture content of W/C55%-4.5%

| Specimen type | | Mass moisture content (wt%) | | |
|---|---|---|---|---|
| | | The accelerate freeze-thaw test | | |
| | | 0 cycle | *Nf'* | Final cycle |
| 55-4.5 | B | 6.64 | 6.95 (88 cycles) | 6.63 (200 cycles) |
| | C | 6.88 | 7.14 (88 cycles) | 6.96 (200 cycles) |

## 4.5 THE EVALUATION OF THE NEWLY PROPOSED CONCRETE FROST DETERIORATION PREDICTING METHOD

A new concrete frost deterioration predicting method has been proposed that concrete specimens are regarded as damaged by frost when the freeze and thaw effect of the outdoor exposure *Nf** exceeds the critical freeze and thaw cycle *Nf* of the concrete specimens. Table 4.9 exhibits the evaluation of the newly proposed predicting method. As shown from Table 4.9, for the 35-1-D and 55-1-N/D concrete specimens, the predicted residual concrete frost resistance *Nf-Nf** is equal to the *Nf'*. However, for the 35-1-N and 55-4.5-N/D concrete specimens, concrete emerges obvious frost damage at *Nf'* even the predicted residual concrete frost resistance *Nf-Nf** has not been achieved. Therefore, it is supposed that other environmental factors in the actual environment may also degrade concrete frost resistance.

Table 4.9 The evaluation of the newly proposed concrete frost deterioration predicting method

| specimen | Drying condition | *Nf* | *Nf** | | The residual concrete frost resistance (*Nf-Nf**) | | The residual concrete frost resistance by *Nf'* |
|---|---|---|---|---|---|---|---|
| | | | B | C | B | C | |
| 35-1 | N | 42 | 6.22 | 11.36 | 35.78 | 30.64 | 0 |
| | D | 0 | | | 0 | 0 | 0 |
| 55-1 | N | 0 | 6.10 | 10.10 | 0 | 0 | 0 |
| | D | 0/16 | | | 0/9.9 | 0/5.9 | 0 |
| 55-4.5 | N | 178 | 8.03 | 11.96 | 169.97 | 166.04 | 88 |
| | D | 512 | | | 332.97 | 329.04 | 88 |

## 4.6 CONCLUSION

In this chapter, the effect of one-year outdoor environment on concrete frost deterioration is expounded by the critical freeze and thaw cycle *Nf* through measuring the temperature of concrete specimens exposed to the outdoor environment. The results are shown below.

(1) The one-year outdoor exposure has a negative effect on the three types of concrete frost resistance in the accelerated freeze and thaw test.

(2) There are occasions that the effect of the freeze and thaw function of the outdoor exposure on concrete deterioration by *Nf* is not in good accordance with the results obtained from the specimens after the outdoor exposure. Therefore, it is suggested that other than the freeze and thaw, other environmental factors like drying also affect concrete frost deterioration.

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**CHAPTER 5**
**CONCLUSION AND FUTURE WORKS**

## 5.1 CONCLUSION

In this study, concrete frost resistance considering the additional water absorption effect by freeze and thaw in the critical degree of saturation test has been evaluated. Based on this, the accelerated freeze and thaw test and the critical degree of saturation test were conducted and the relationship between the two methods has been clarified. In the accelerated freeze and thaw test, the mass moisture content of the specimen increases with the freeze and thaw cycles. Severe frost damage emerges when the mass moisture content W reaches the mass moisture content $M_{cr}$ of the $S_{cr}$ in the critical degree of saturation test. The freeze and thaw cycle *Nf* where the mass moisture content W reaches the $M_{cr}$ is regarded as a new criterion for concrete frost damage prediction. Therefore, a new concrete frost resistance criterion *Nf* has been proposed. Besides, the effect of different lowest temperatures on concrete frost resistance criterion *Nf* has been clarified, and the equation between the lowest temperature and the *Nf* has been proposed. Hence, the effect of the freeze and thaw function of the one-year outdoor exposure can be clarified by *Nf*, and a new concrete frost deterioration predicting method has been proposed. Besides, the specimens after the outdoor exposure were then conducted with the accelerated freeze and thaw test to figure out its critical freeze and thaw cycle *Nf'* after the outdoor exposure and the newly proposed concrete frost deterioration predicting method has been verified through comparison of the results. The results of this dissertation are listed as follows.

1) Because of the pumping effect in the single surface water absorption test upon freeze and thaw, moisture will ingress into the specimens. However, there are occasions that the saturation degree of the specimen under freeze and thaw cannot reach to the critical degree of saturation. Hence, a stronger freeze and thaw function should be added to achieve the specimens damaged by freeze and thaw.

2) In the accelerated freeze and thaw test, the length, RDM and mass moisture content change showed obvious nickpoints of similar freeze and thaw cycles. Hence, the nickpoint cycle was defined as a new concrete frost resistance criterion *Nf*, and its mass moisture content was regarded as the critical mass moisture content $W_{cr}$. The $W_{cr}$ in the accelerated freeze and thaw test was in good accordance with the mass moisture content $M_{cr}$ of the $S_{cr}$ in the critical degree of saturation test. Therefore, the critical mass moisture content $W_{cr}$ could be regarded as not affected by the different test methods. Furthermore, there was no clear relationship between the *Nf* and $T_{pl}$, however, a linear relationship between DF and *Nf* can be achieved.

3) Concrete specimens were conducted the accelerated freeze and thaw test with different lowest temperatures -5℃ and -10℃, and the corresponding critical freeze and thaw cycle has been calculated. The results showed that the critical freeze and thaw cycle *Nf* increased with the increase of the lowest temperature. However, the critical mass moisture content $W_{cr}$ was not affected by the different lowest temperatures. The $W_{cr}$ could be regarded as a concrete frost characteristic value. The proportion E of the effect of one freeze and thaw cycle with the lowest temperature -5℃ or -10℃ to the effect of one standard accelerated freeze and thaw cycle on concrete frost damage has been clarified by the *Nf*. It has been found that the proportion E of the effect increases almost linearly with the decrease of the lowest temperature.

4) The specimens after the one-year outdoor exposure were conducted with the accelerated freeze and thaw test and its critical freeze and thaw cycle *Nf'* has been calculated. It is clarified that the one-year outdoor exposure showed an adverse effect on concrete frost resistance. Besides, the effect of the freeze and thaw function during the outdoor exposure has also been converted to the critical freeze and thaw cycle *Nf**. Therefore, a new concrete frost deterioration predicting method has been proposed that concrete is damaged by frost when the environmental freeze and thaw effect *Nf** reaches to the critical freeze and thaw cycle *Nf*. However, as shown from the results, concrete emerges apparent frost damage even though the residual concrete frost resistance *Nf-Nf** after the outdoor exposure is still much larger than the *Nf'*. There are occasions that the predicted concrete frost resistance *Nf-Nf** is not in good accordance with the results achieved by *Nf*. Therefore, other environmental factors like the drying effect may also affect concrete frost resistance.

## 5.2 FUTURE WORKS

This research has proposed a new concrete frost resistance criterion *Nf* based on the accelerated freeze and thaw test and the critical degree of saturation test. The relationship between the lowest temperatures and *Nf* has been figured out and the freeze and thaw function during the outdoor exposure has been qualified based on the relationship. Moreover, the effect of the freeze and thaw function during the outdoor exposure on concrete frost resistance has also been clarified by *Nf**. However, the effect of the freeze and thaw function only accounts for part of the concrete deterioration. Therefore, there are other environmental factors like the dry condition in the hot summer that affects concrete frost resistance *Nf*. These environmental factors together with the freeze and thaw function are coupled together to degrade concrete frost resistance. Therefore, the effect of other environmental factors on concrete frost resistance should also be clarified and the importance order of these factors should be addressed.

# Appendix

## A.1

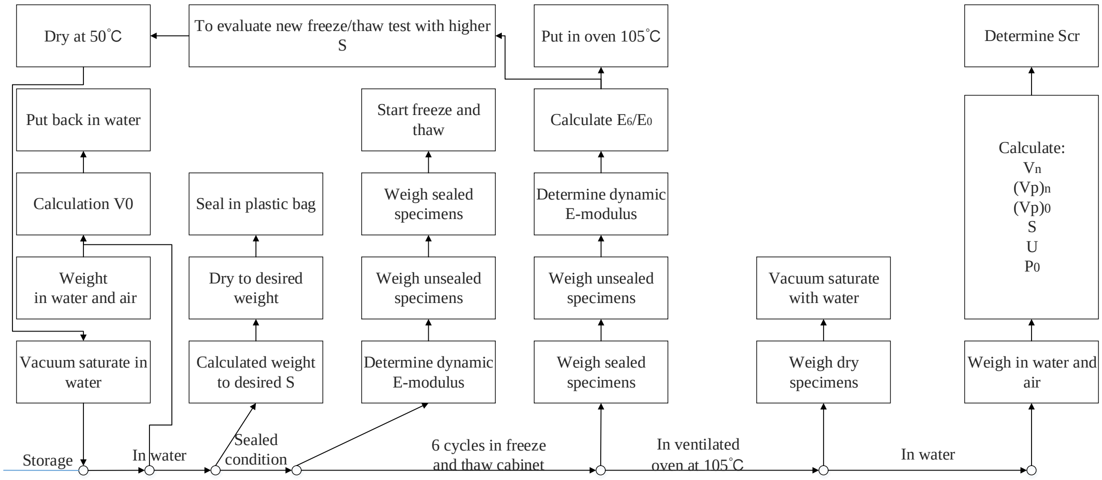



Fig. A.1 The flow of calculating $S_{cr}$

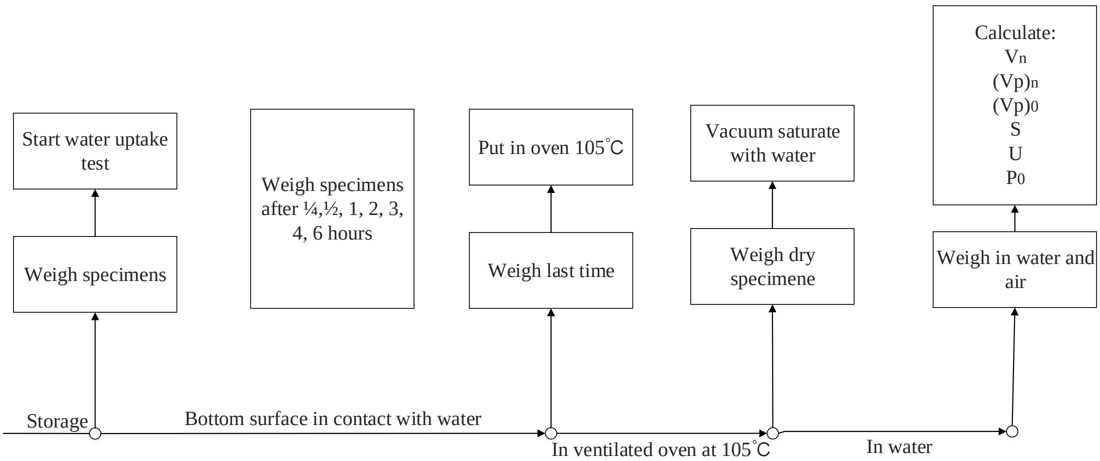
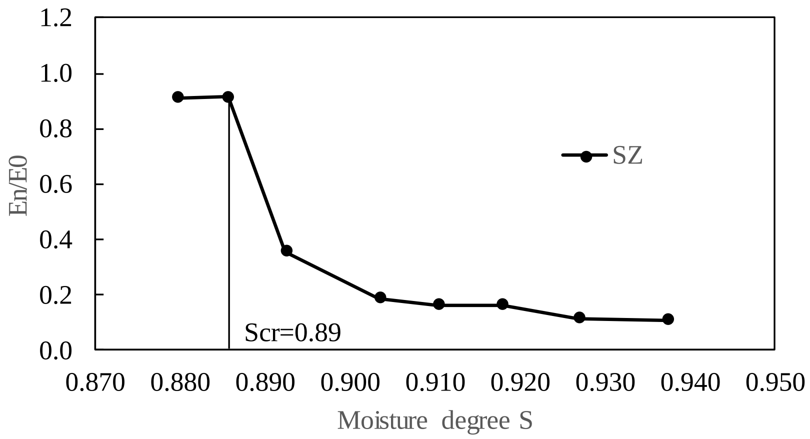
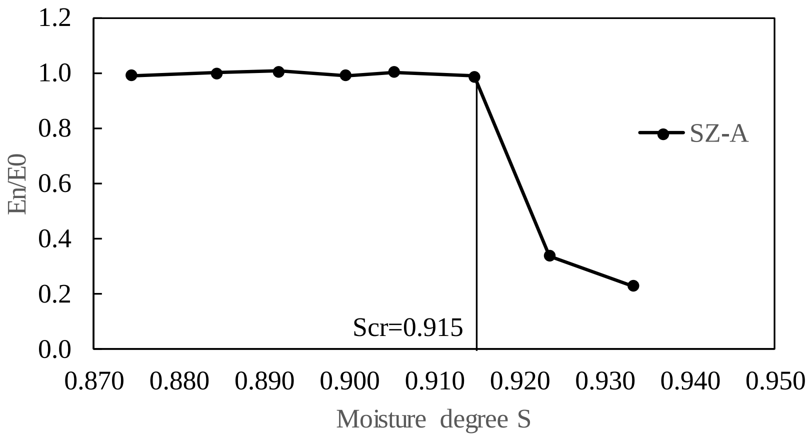


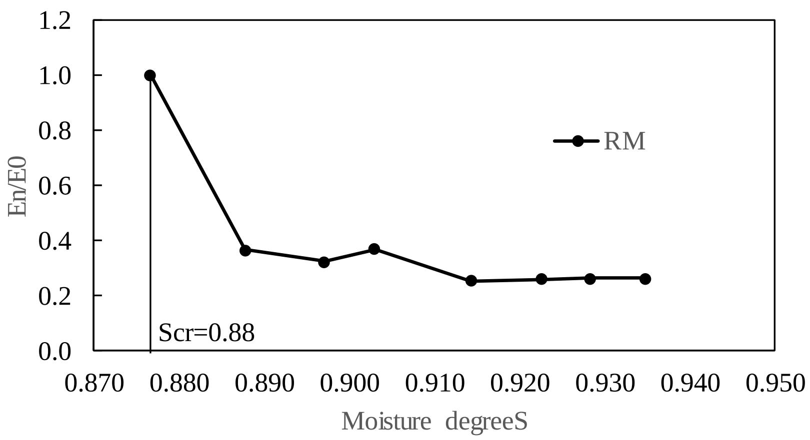

Fig. A.2 The flow of calculating $S_{cap}$

**A.2**

The critical degree of saturation $S_{cr}$ of SZ, SZ-A, RM and RM-A are calculated as shown below.



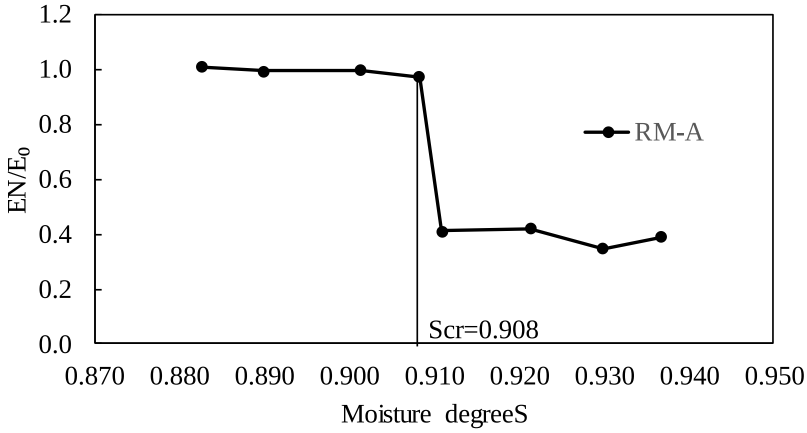



Fig. A.3 The critical moisture degree $S_{cr}$

The concrete frost resistance $T_{pl}$ calculated by the time that the $S_{cap}$ reaches the $S_{cr}$ is exhibited as below.

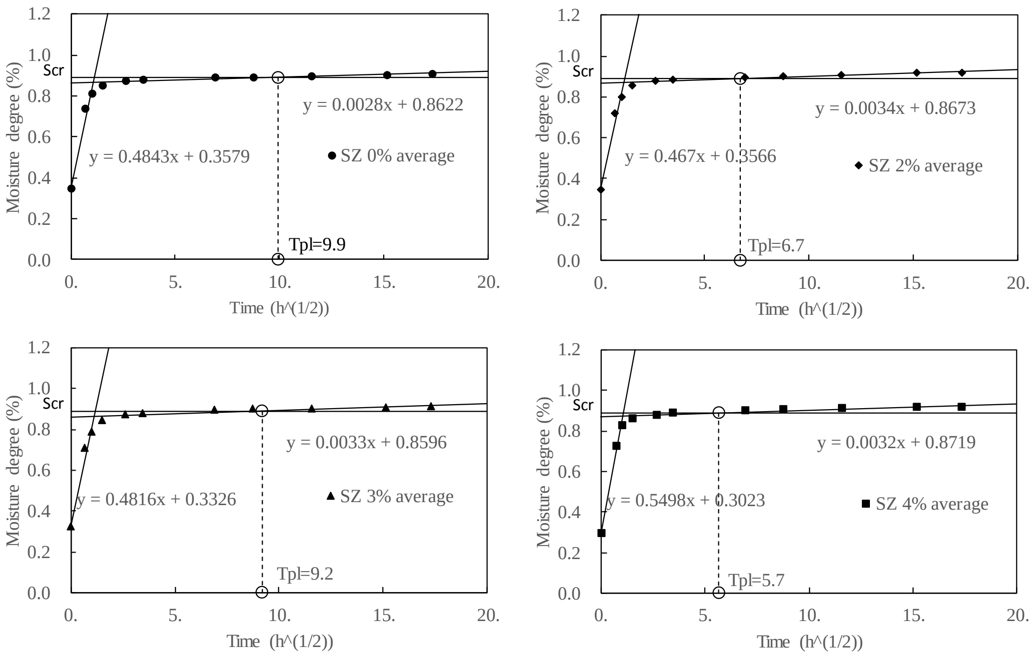
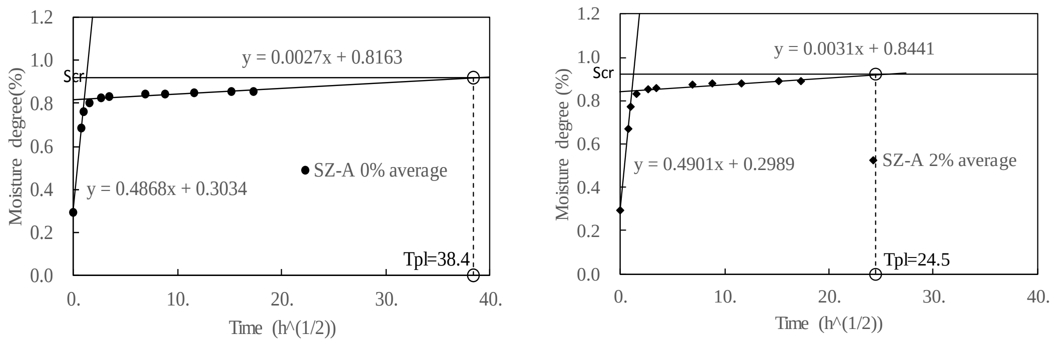



Fig.A.4 The $T_{pl}$ of SZ



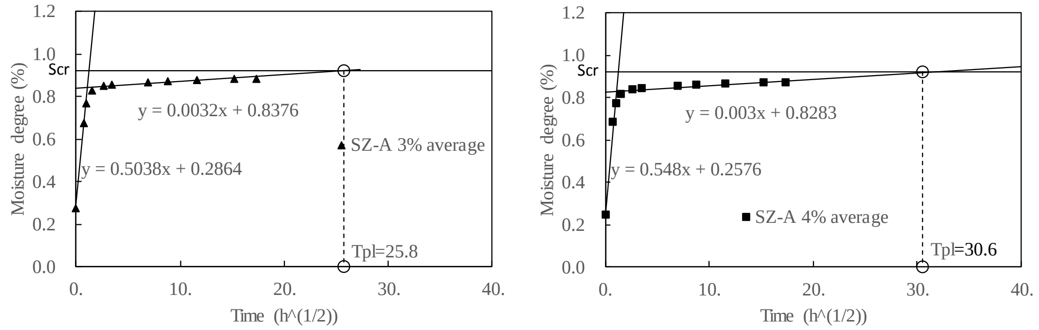



Fig.A.5 The $T_{pl}$ of SZ-A

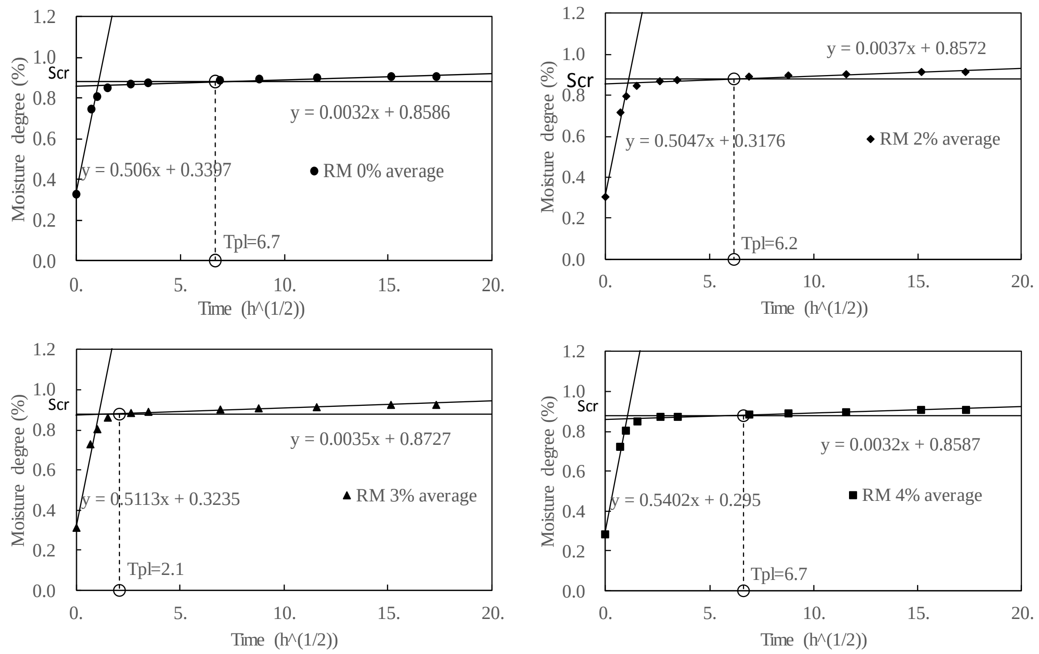



Fig.A.6 The $T_{pl}$ of RM

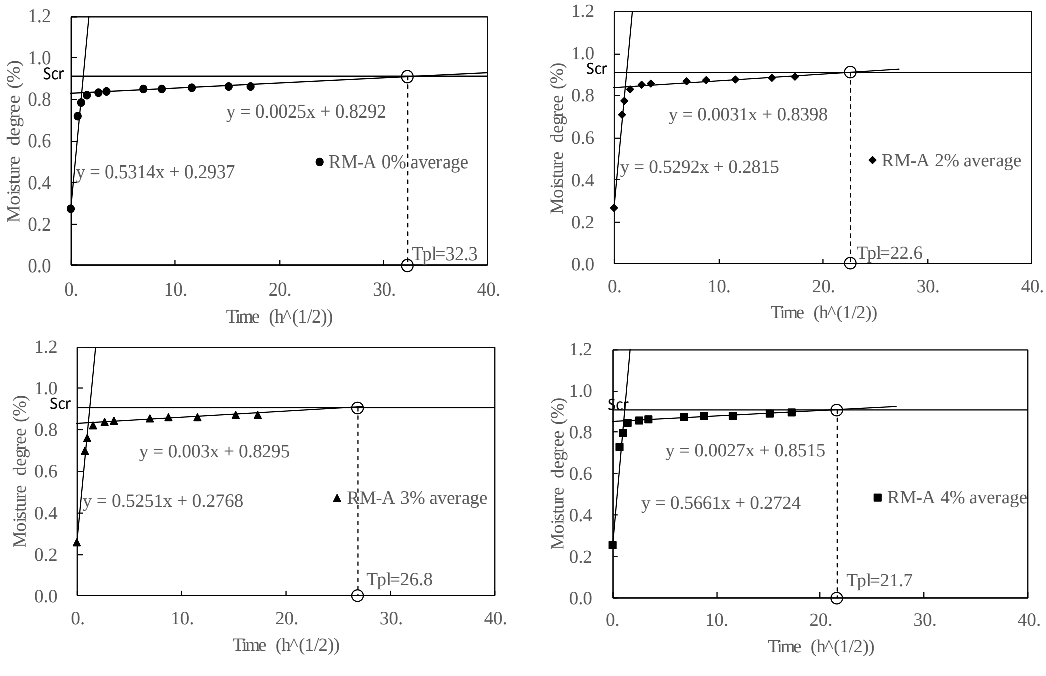



Fig.A.7 The $T_{pl}$ of RM-A

**A3**

The critical degree of saturation $S_{cr}$ of W/C35%-1%, W/C55%-1% and W/C55%-4.5% are listed below.

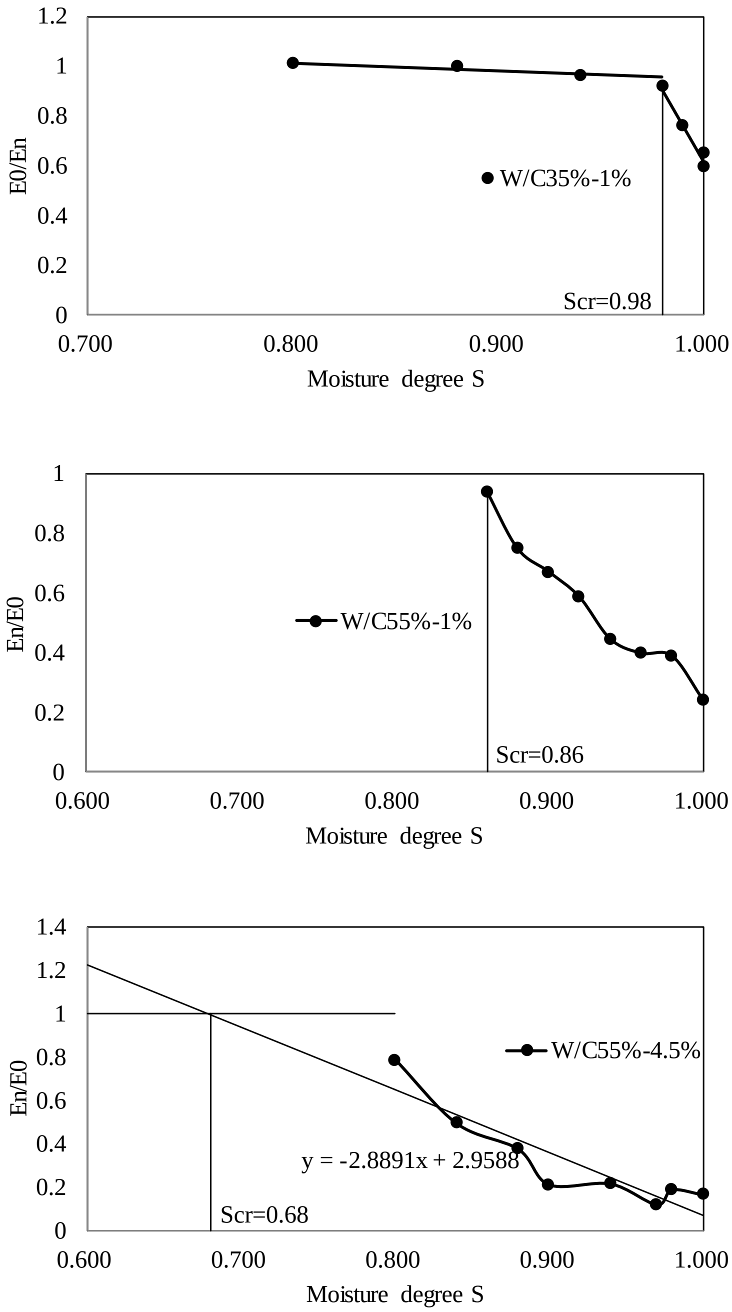



Fig.A.8 The critical moisture degree

The concrete frost resistance $T_{pl}$ calculated by the time that the $S_{cap}$ reaches the $S_{cr}$ is exhibited as below.

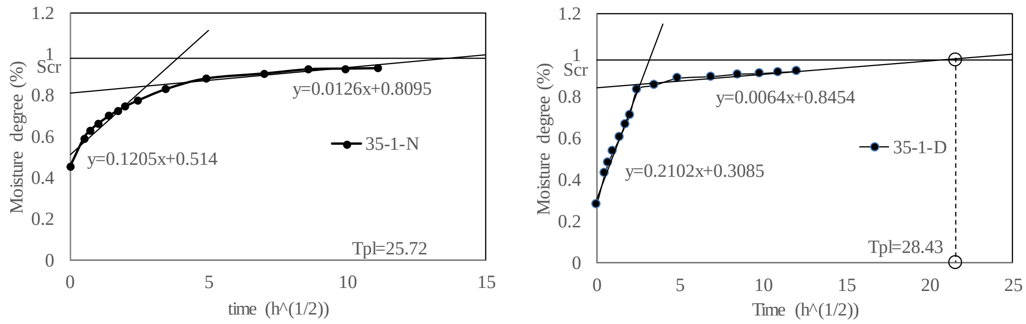



Fig.A.9 The $T_{pl}$ of W/C35%-1%

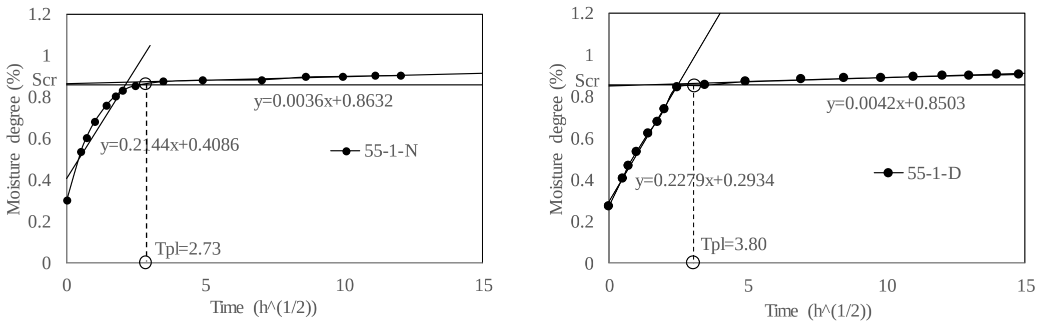



Fig.A.10 The $T_{pl}$ of W/C55%-1%

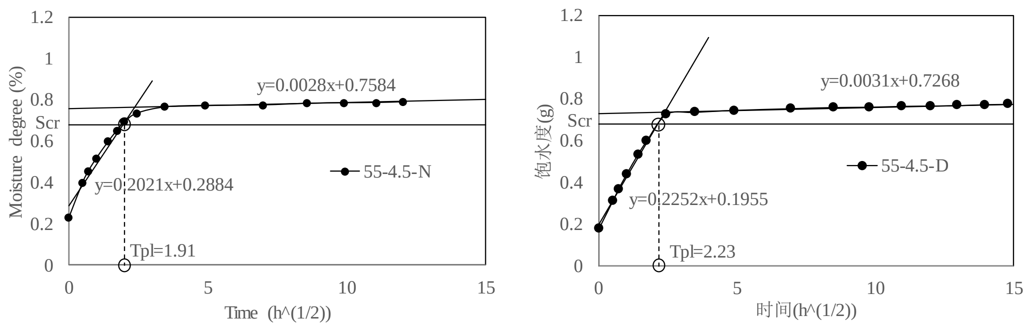



Fig.A.11 The $T_{pl}$ of W/C55%-4.5%

**A.4**

The critical degree of saturation $S_{cr}$ of W/C35%-1%, W/C55%-1% and W/C55%-4.5% are listed below.

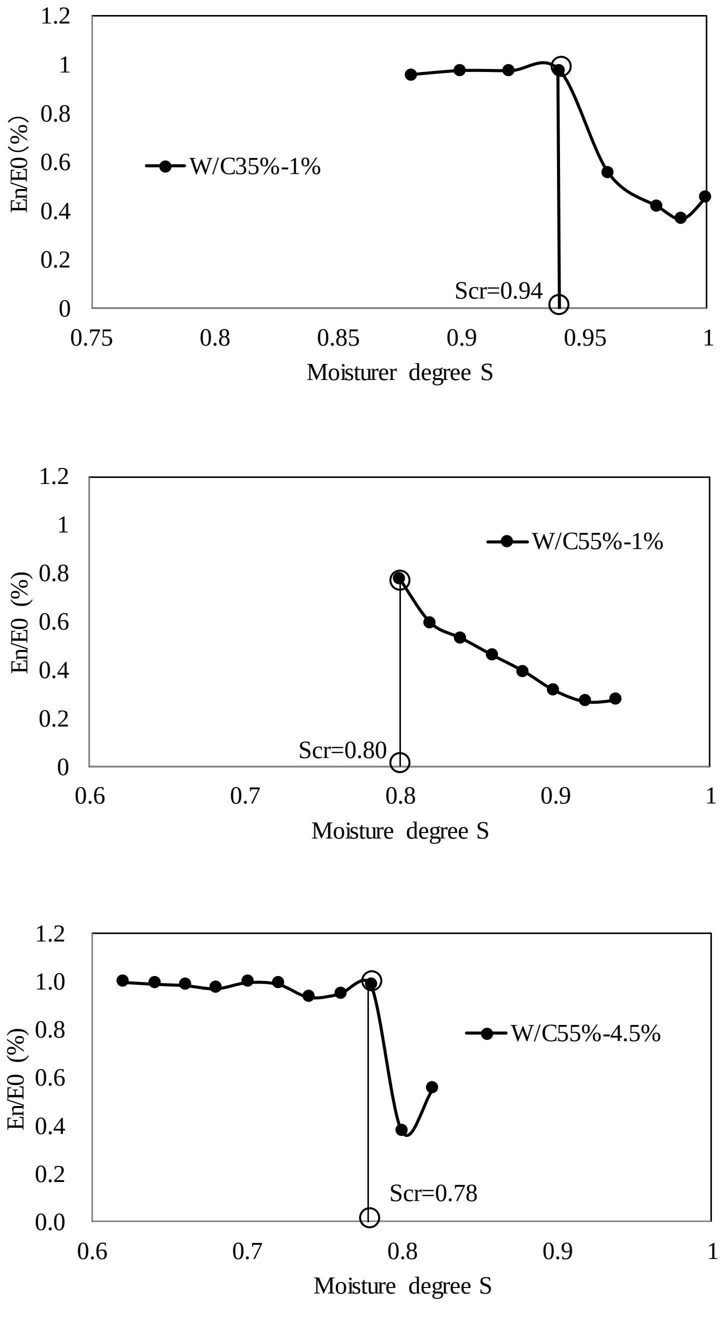



Fig. A.12 The critical moisture degree

The concrete frost resistance $T_{pl}$ calculated by the time that the $S_{cap}$ reaches the $S_{cr}$ is exhibited as below.

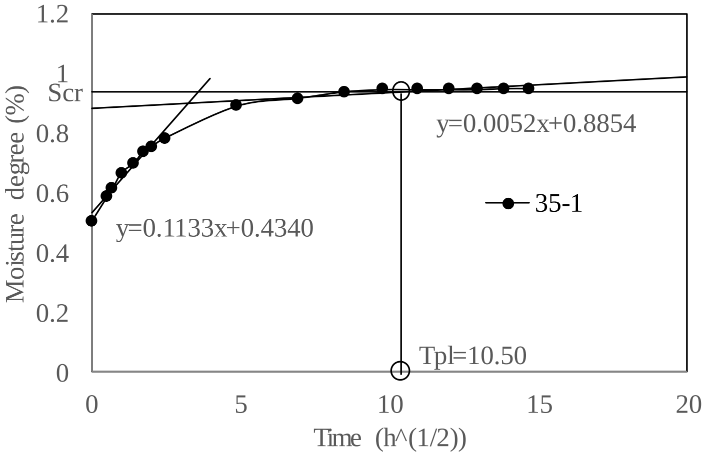



Fig.A.13 The $T_{pl}$ of W/C35%-1%

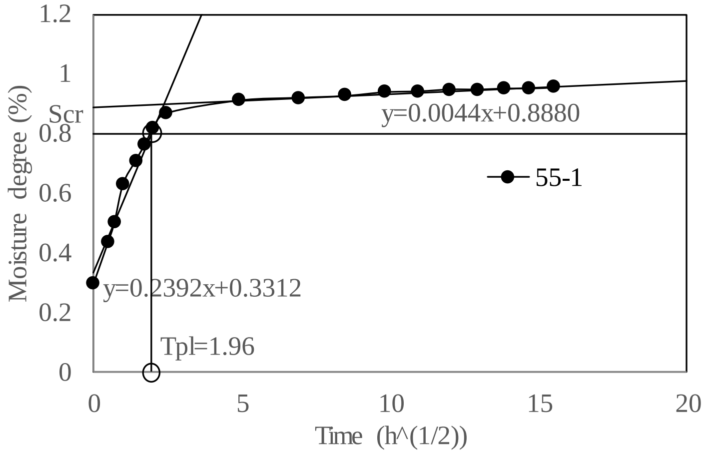



Fig.A.14 The $T_{pl}$ of W/C55%-1%

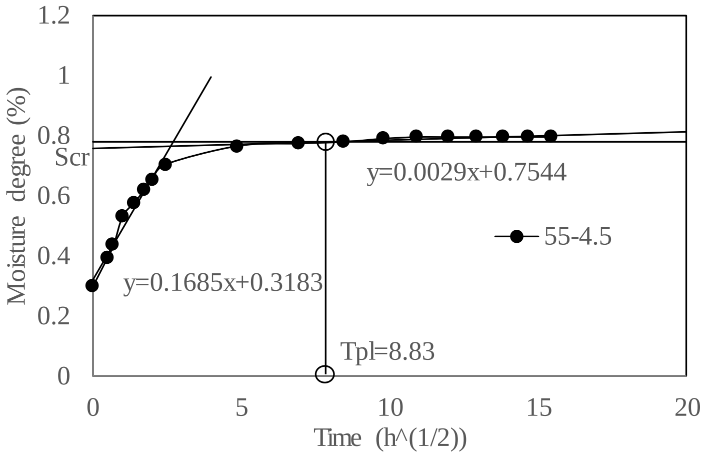



Fig.A.15 The $T_{pl}$ of W/C55%-4.5%

**A.5**

1)W/C35%-1%

The temperature of the W/C35%-1% specimens of the one-year outdoor exposure is exhibited below and the freeze and thaw cycles with the lowest temperature are enclosed.

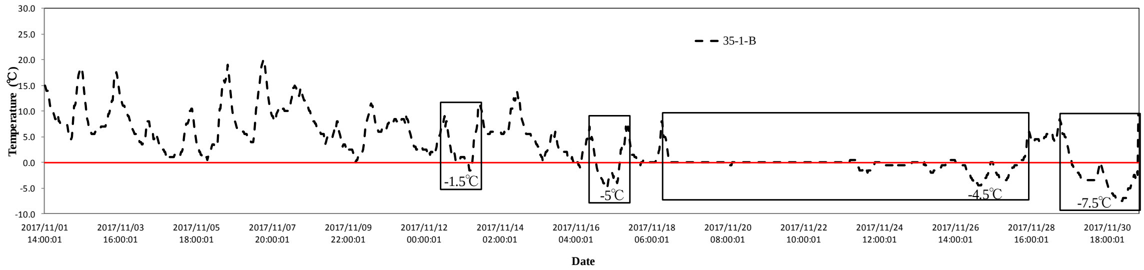



Fig.A.16 The temperature change of 35-1-B from 2017.11.01 to 2017.12.01

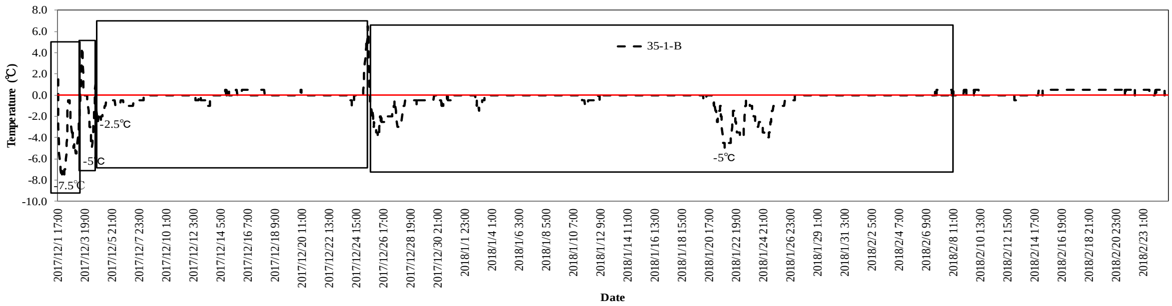



Fig.A.17 The temperature change of 35-1-B from 2017.12.01 to 2018.02.25

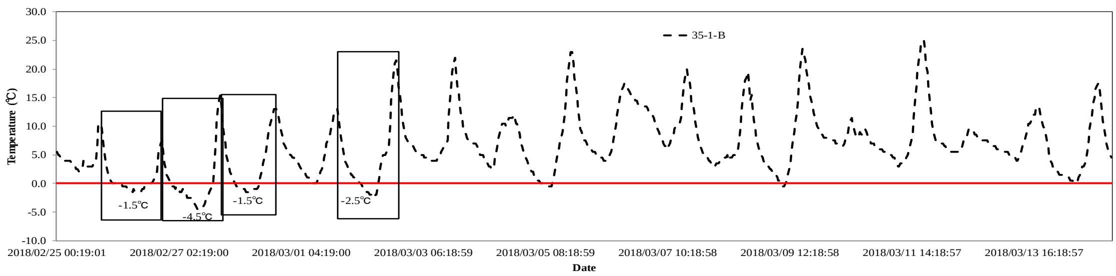



Fig.A.18 The temperature change of 35-1-B from 2018.2.25 to 2018.03.14

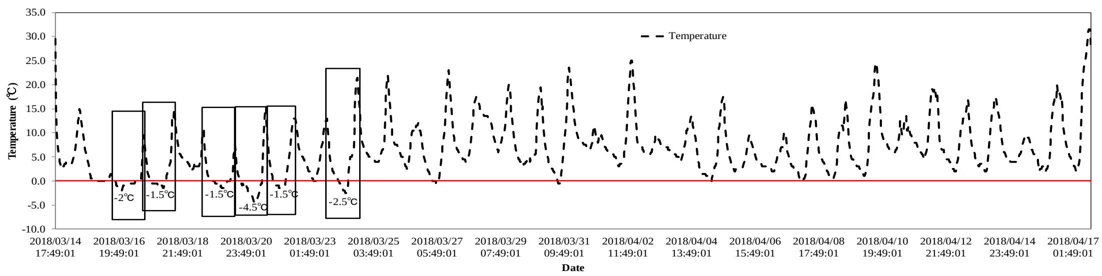



Fig.A.19 The temperature change of 35-1-B from 2018.3.14 to 2018.04.17

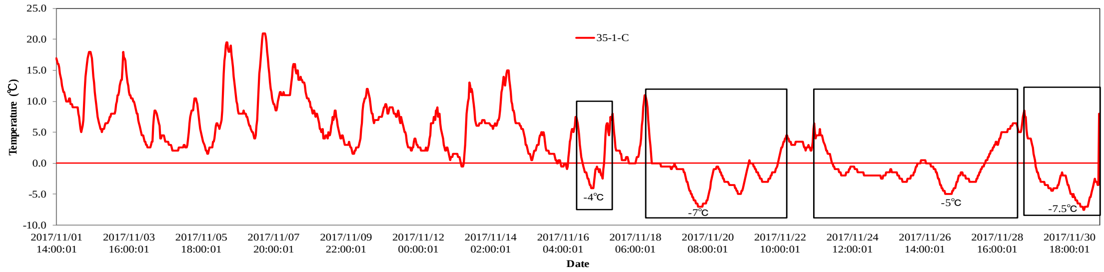



Fig.A.20 The temperature change of 35-1-C from 2017.11.01 to 2017.12.01

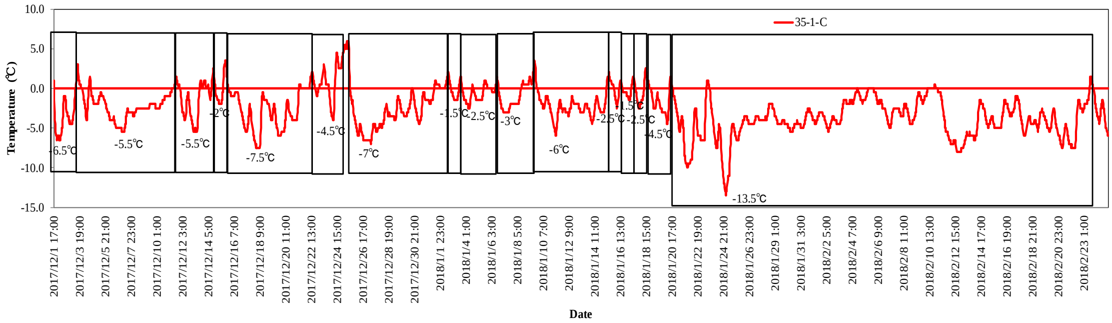



Fig.A.21 The temperature change of 35-1-C from 2018.12.01 to 2018.02.25

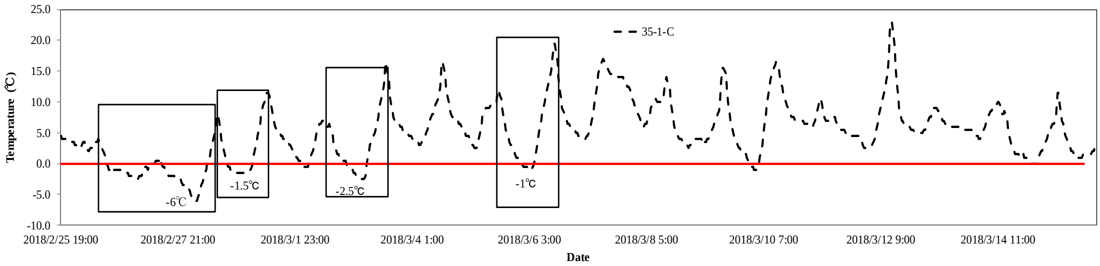



Fig.A.22 The temperature change of 35-1-C from 2018.2.25 to 2018.03.14

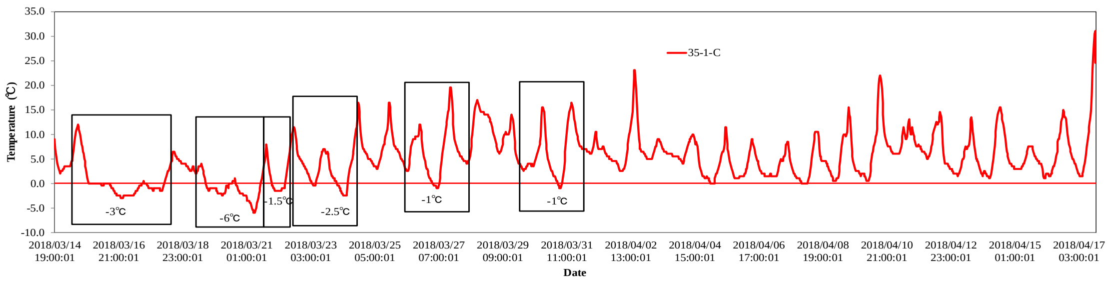



Fig.A.23 The temperature change of 35-1-C from 2018.3.14 to 2018.04.17

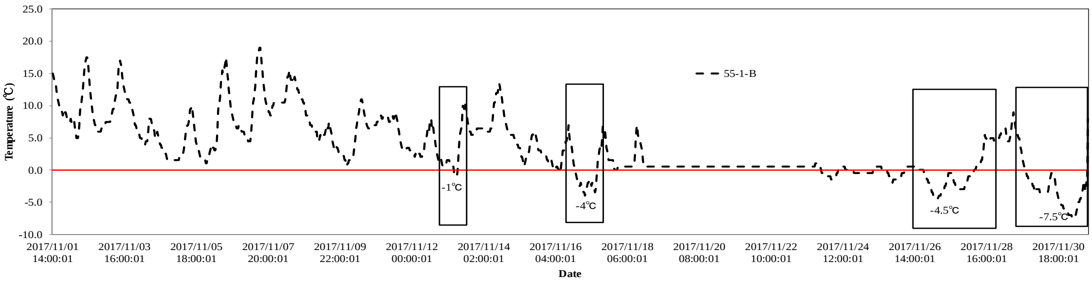



Fig.A.24 The temperature change of 55-1-B from 2017.11.01 to 2017.12.01

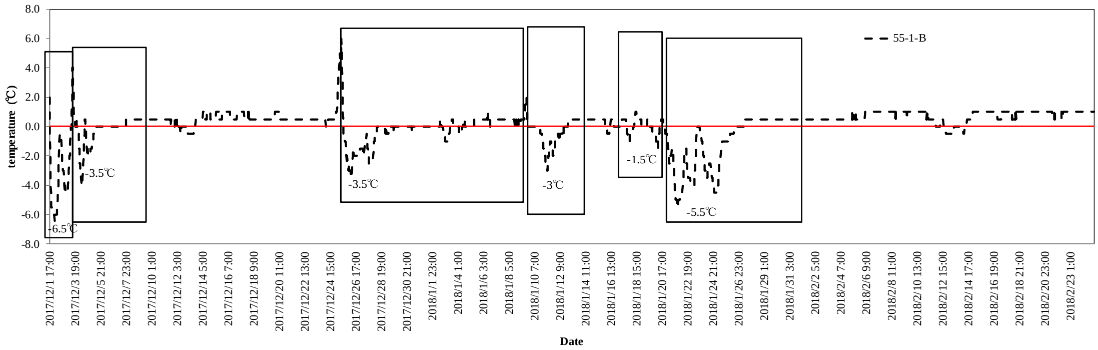



Fig.A.25 The temperature change of 55-1-B from 2017.12.01 to 2018.02.25

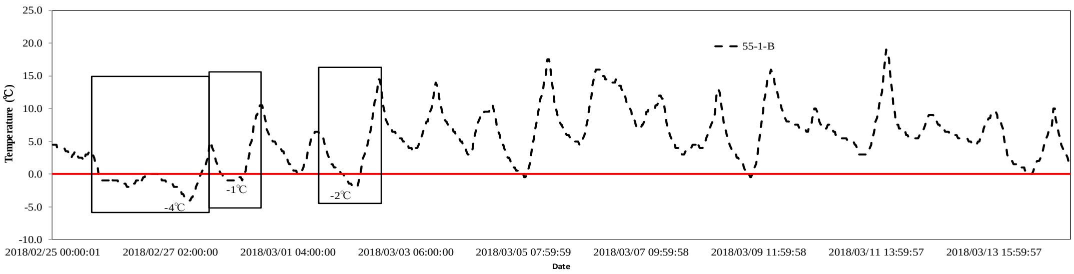



Fig.A.26 The temperature change of 55-1-B from 2018.2.25 to 2018.03.14

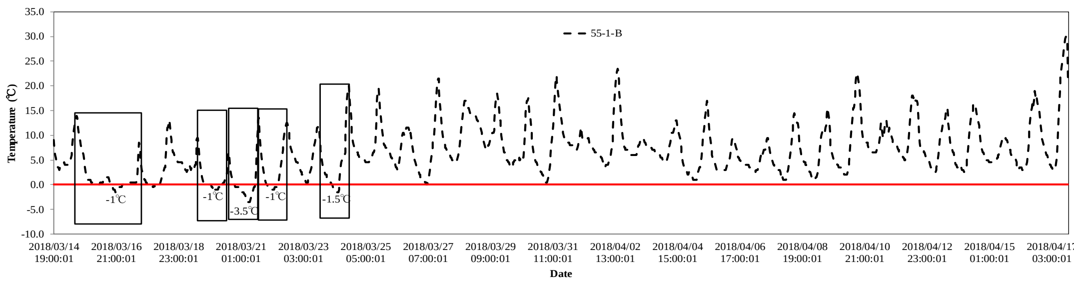



Fig.A.27 The temperature change of 55-1-B from 2018.3.14 to 2018.04.17

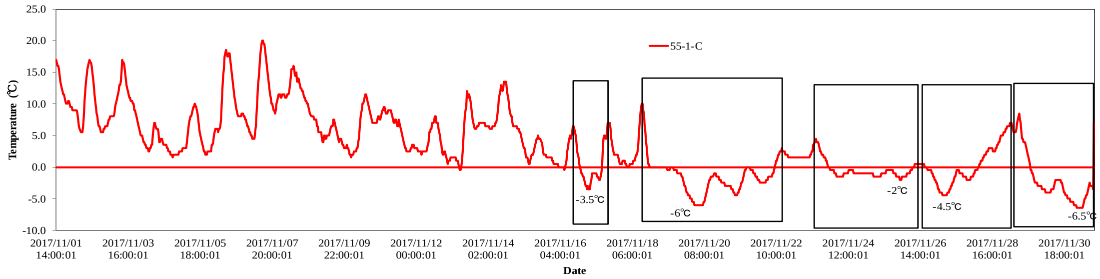



Fig.A.28 The temperature change of 55-1-C from 2017.11.01 to 2017.12.01

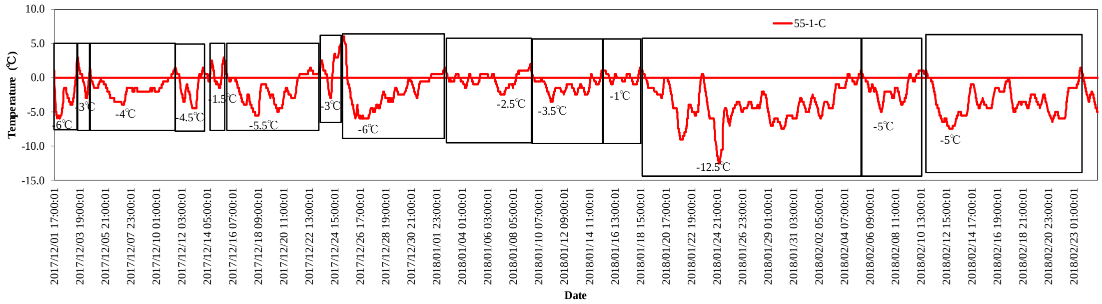



Fig.A.29 The temperature change of 55-1-C from 2017.12.01 to 2018.02.25

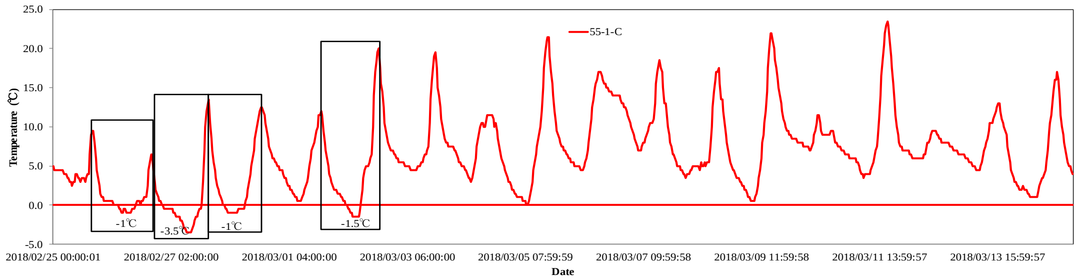



Fig.A.30 The temperature change of 55-1-C from 2018.2.25 to 2018.03.14

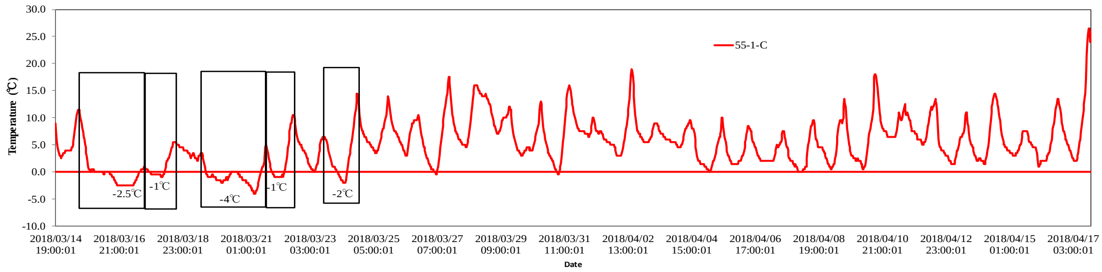



Fig.A.31 The temperature change of 55-1-C from 2018.3.14 to 2018.04.17

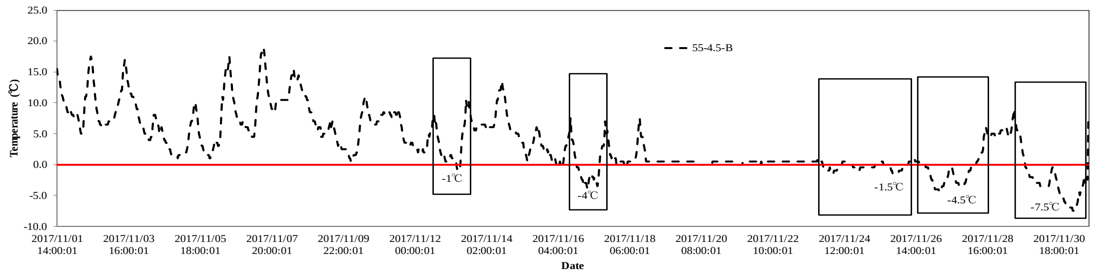



Fig.A.32 The temperature change of 55-4.5-B from 2017.11.01 to 2017.12.01

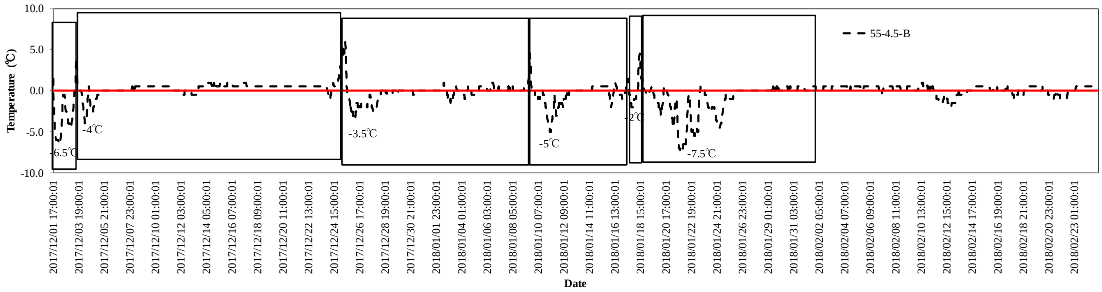



Fig.A.33 The temperature change of 55-4.5-B from 2017.12.01 to 2018.02.25

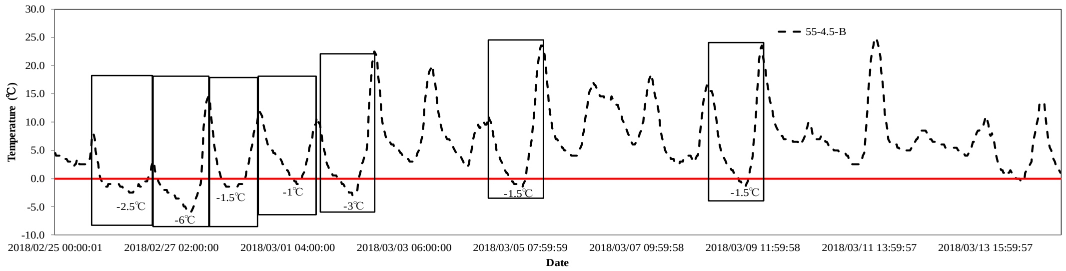



Fig.A.34 The temperature change of 55-4.5-B from 2018.2.25 to 2018.03.14

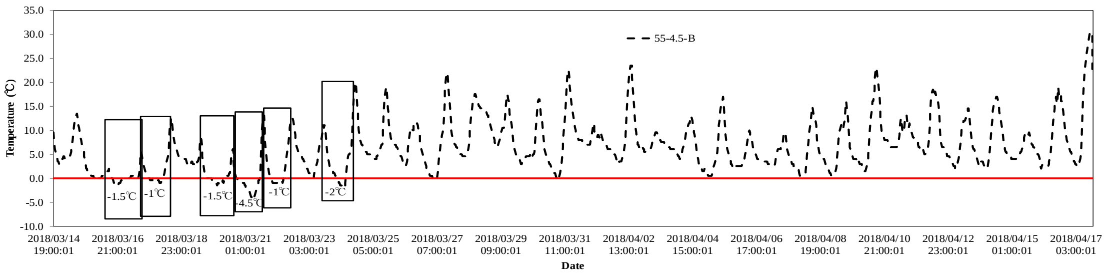



Fig.A.35 The temperature change of 55-4.5-B from 2018.3.14 to 2018.04.17

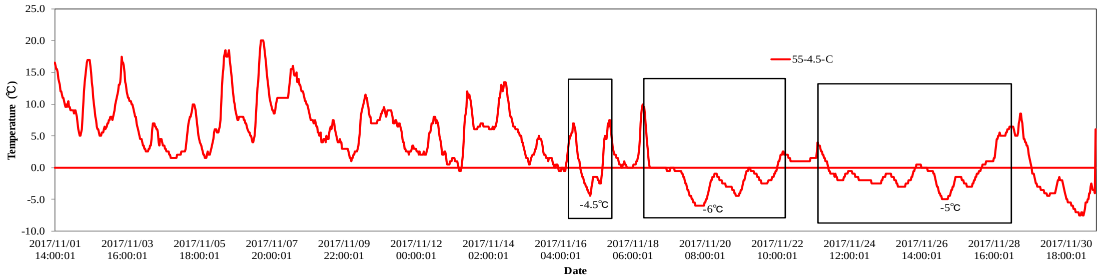


Fig.A.36 The temperature change of 55-4.5-C from 2017.11.01 to 2017.12.01

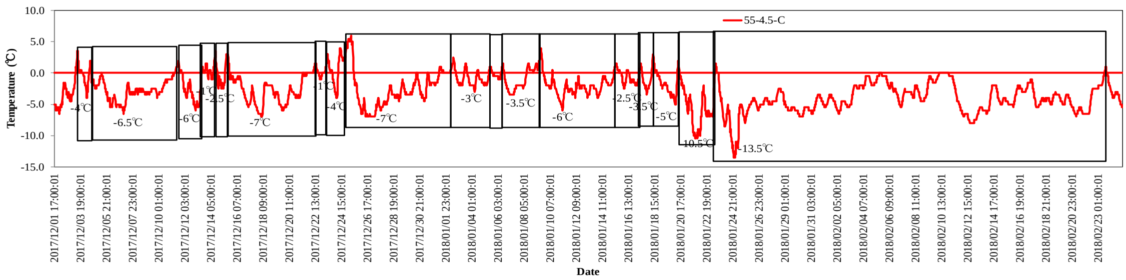


Fig.A.37 The temperature change of 55-4.5-C from 2017.12.01 to 2018.02.25

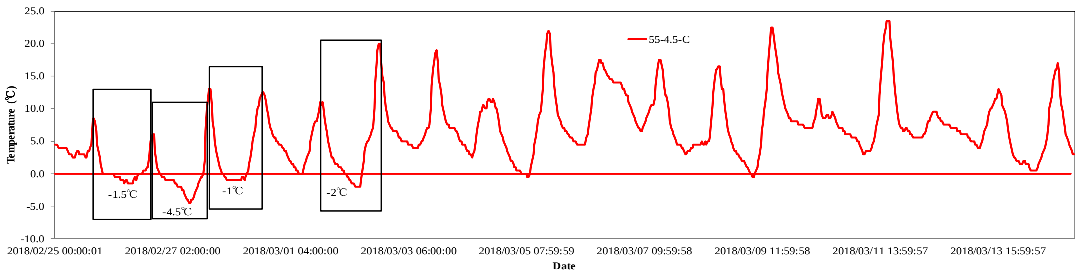


Fig.A.38 The temperature change of 55-4.5-C from 2018.2.25 to 2018.03.14

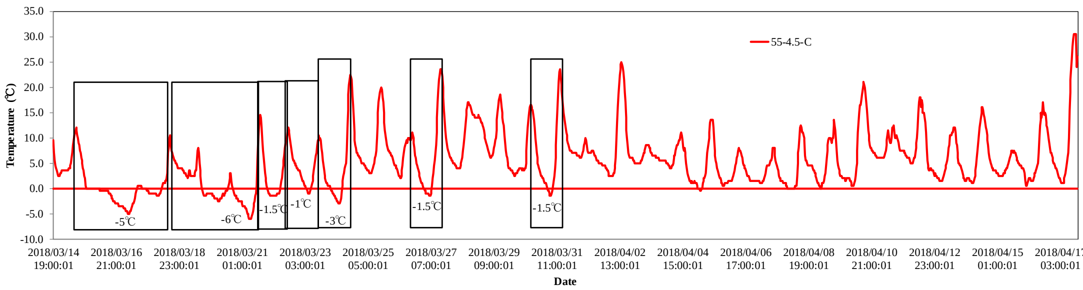
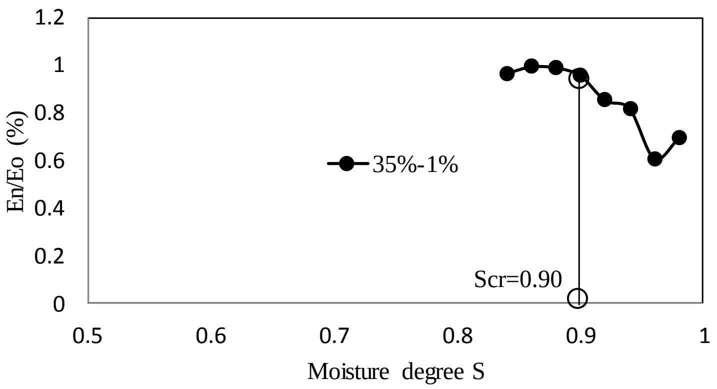
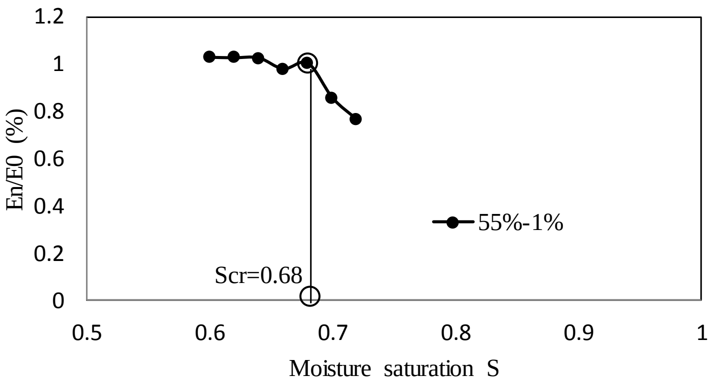


Fig.A.39 The temperature change of 55-4.5-C from 2018.3.14 to 2018.04.17

**A6**

The critical degree of saturation $S_{cr}$ of W/C35%-1%, W/C55%-1% and W/C55%-4.5% are listed below.



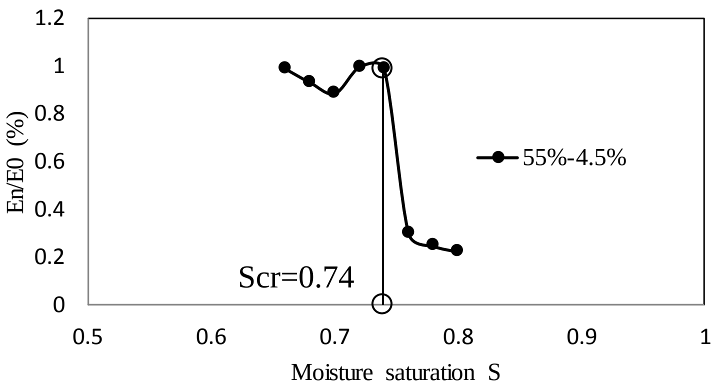
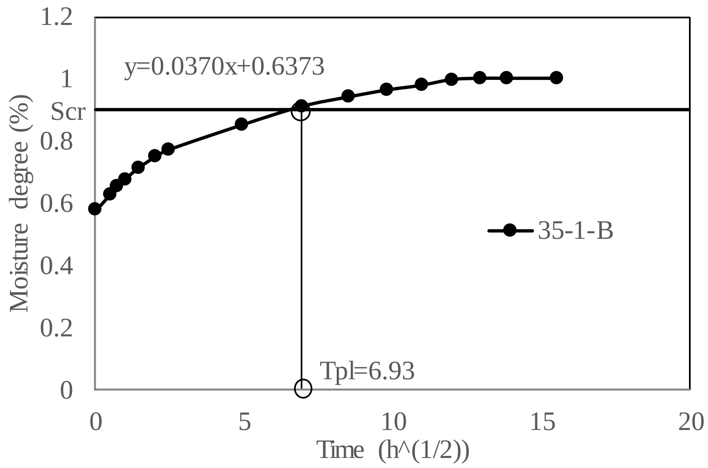




Fig. A.40 The critical moisture degree

The concrete frost resistance $T_{pl}$ calculated by the time that the $S_{cap}$ reaches the $S_{cr}$ is exhibited as below.



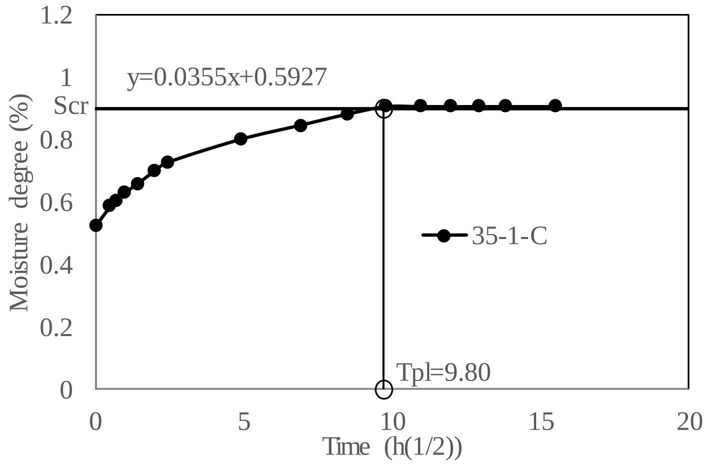
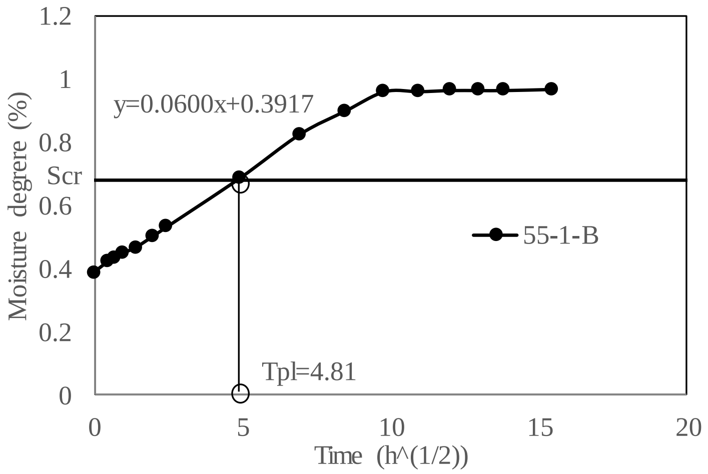




Fig.A.41 The $T_{pl}$ of W/C35%-1%



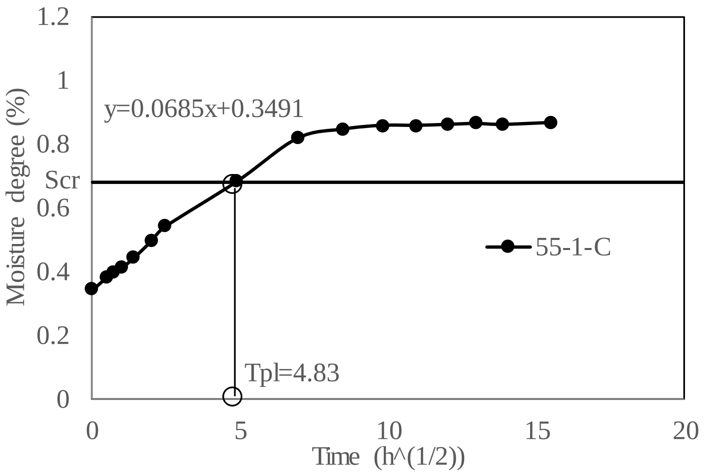
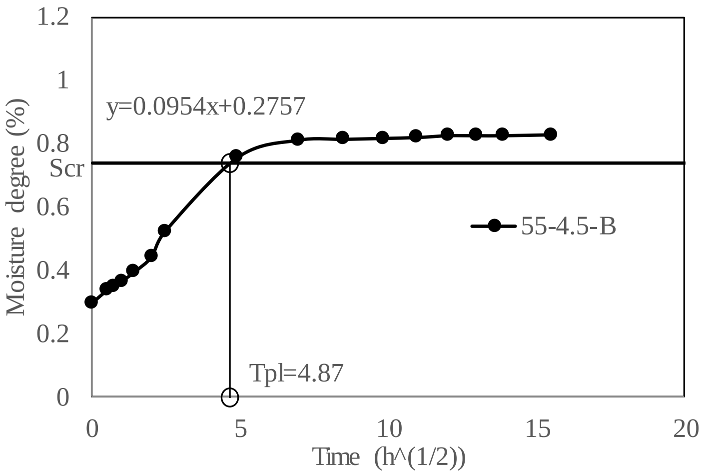



Fig.A.42 The $T_{pl}$ of W/C55%-1%



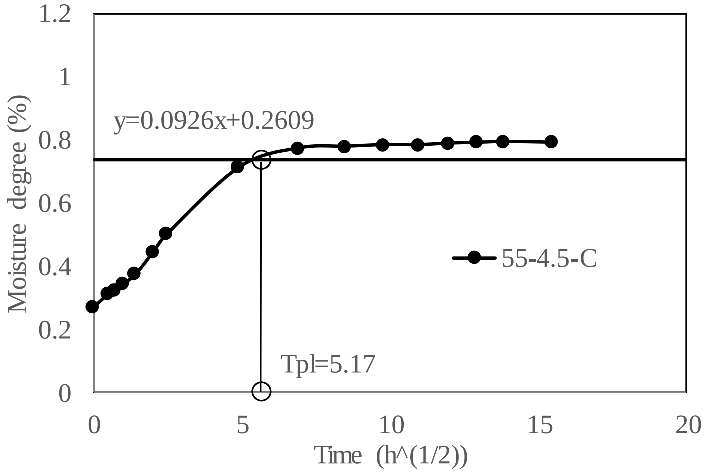




Fig.A.43 The $T_{pl}$ of W/C55%-4.5%