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**Technical Paper**

# A new concrete frost resistance evaluating method considering moisture content increase under outdoor exposure

**Dequn Ma*, Osamu Senbu, and Ryoma Kitagaki**

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**Abstract**: Three kinds of concrete specimens were made and cured in water for two weeks. Then, half of the specimens were conducted with the accelerated freeze-thaw test and the critical degree of saturation test, directly. Besides, the other half were set in the actual outdoor environment for one year before conducting the same tests. In the accelerated freeze-thaw test, there exists a critical mass moisture content which almost equals to the mass moisture content of the critical saturation $S_{cr}$ in the critical degree of saturation test. In addition, the cycle where the critical mass moisture content is reached is defined as the critical freeze-thaw cycle $N_f$. The effect of different outdoor exposure on concrete frost resistance can be evaluated by $N_f$. The outdoor exposure has a negative effect on concrete frost resistance.

**Keywords**: Critical mass moisture content, freeze-thaw, outdoor environment, concrete frost resistance.

## 1 Introduction

Concrete structures are exposed to different mechanical and physical forms of attacks during their service life. Even though many concrete structures provide excellent long-term performance, a portion of these concrete have recently shown deterioration, especially during freeze-thaw [1]. Nowadays, two concrete frost evaluation tests, the accelerated freeze-thaw test and the critical degree of saturation test are widely used throughout the world. However, there are occasions that the evaluation results by the accelerated freeze-thaw test does not match with that by the critical degree of saturation test [2].

Nokken et. al figured out that different from the specific 2-5 hours in the ASTM standard accelerated freeze-thaw test, the length of the freeze-thaw cycles in the actual outdoor exposure was considerably longer and ranged from 11-206 hours. [3] Besides, the longer freezing period has been found to be more severe to concrete by Stark. [4] Ma clarified that the effect of the different lowest temperatures on concrete frost resistance. The lower the lowest temperature is, the faster the concrete specimen is damaged by frost. [5] Therefore, it is of great importance to evaluate the effect of actual outdoor exposure on concrete frost resistance.

In this paper, three kinds of concrete specimens with different water to cement ratios and air contents were made. The accelerated freeze-thaw test and the critical degree of saturation test were conducted, respectively. The mechanism of concrete suffered from freeze-thaw has been unveiled through comparing the mass moisture content change between the two test methods and a new concrete frost resistance evaluation method has been proposed. Furthermore, the effect of the outdoor exposure on concrete frost resistance has also been clarified by the newly proposed method. Results will hopefully cast more light into the major mechanism of concrete frost damage.

## 2 Experimental Outline

Table 1 shows the experimental plan. Three kinds of concrete specimens were made and then cured with different curing conditions. Then, the specimens were conducted with the accelerated freeze-thaw test and the critical degree of saturation test, respectively.

In this paper, Type I Portland cement was used as the cementitious materials. Fine aggregate was the sand with a fineness modulus of 2.68 and the coarse aggregate was the crushed stones with the nominal maximum dimension of 20 mm. Table 2 shows the mix proportion of the concrete specimens.

All the specimens were made in the laboratory. The prism specimens with a dimension of 75 × 75 ×

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***Corresponding author Dequn Ma*** *is a Ph.D. Candidate in the Graduate School of Engineering, Hokkaido University, Japan.*
***Osamu Senbu*** *is a Professor in the Graduate School of Engineering, Hokkaido University, Japan.*
***Ryoma Kitagaki*** *is a Professor in the Graduate School of Engineering, Hokkaido University, Japan.*

400 mm and the cylindrical specimens with a size of $\Phi$100 × 200 mm were cast. All the specimens were removed from the mold on the second day and then submerged in tap water at 20℃ for two weeks. The specimens then experienced three kinds of curing conditions; curing condition I: conduct the freeze-thaw test directly, curing condition II: place the specimens directly on the roof of a 2-floor building for 1 year, curing condition 3: place the specimen on a platform on the same roof for 1 year. Compared with condition DJ, moisture is hard to accumulate in condition DD, and dry effect in the actual environment is more prominent. The condition DJ and D represents the concrete specimens exposed to the different moisture environments.

Fig. 1 shows the actual curing condition II and III. For the specimen denotation (e.g 35%-1%-N, 35%-1%-DJ, 35%-1%-DD), the first two parameters indicate the W/C ratio and the air content while the last parameter N, DJ and DD represent the specimens under various curing condition I, II and III.

Concrete resistance to the freeze-thaw was evaluated by the accelerated freeze-thaw method according to JIS A 1148 A and the critical degree of saturation method based on the RILEM. In the accelerated freeze-thaw test, the 75 × 75 × 400 mm prism specimens experienced cyclic freeze-thaw cycles. The test was paused at suitable time intervals and the specimens were taken out to measure the weight in the air and water, the expansion by length change and the damage by the relative dynamic modulus of elasticity (RDM). The accelerated freeze-thaw test was ceased when RDM fell to 60% or 300 cycles, whichever came first. Then dried the specimen in an oven at 105℃ to constant weight and the weight was measured.

The $\Phi$100 × 200 mm cylindrical specimens were used for the critical degree of saturation test. The test was divided into two parts. One part is to determine the critical moisture saturation $S_{cr}$ and the other one is for deciding the potential degree of saturation at moist condition $S_{cap}$. In the $S_{cr}$ test, specimens were firstly vacuum saturated. Then the specimens were dried at 50℃ to the desired moisture degree and wrapped with preservative film to experience freeze-thaw cycles. The weight and RDM were measured before and after the cycles. $S_{cr}$ is achieved at the point when RDM decreases dramatically.

The degree of saturation $S_{cap}$ was calculated by the single surface water absorption test in an isothermal room with constant temperature 20℃ and relative humidity RH 60%. Samples with a dimension of $\Phi$100 × 30 mm were cut from the cylindrical specimens and dried at 50℃ for three days. Then all the samples were set in a stainless tray filled with water. The samples were taken out at suitable time intervals to measure its weight. The time $T_{pl}$ when $S_{cap}$ reaches to the $S_{cr}$ is defined as a concrete frost resistance evaluation criterion.

Fig. 1 – Curing condition II and III

Table 1 – Experimental plan

| Concrete type | Curing condition | Test method |
|---|---|---|
| 35-1<br>55-1<br>55-4.5 | Condition I: conduct the test directly (N)<br>Condition II: set on the roof for 1 year (DJ)<br>Condition III: set on a platform on the roof for 1 year (DD) | The accelerated freeze-thaw test<br>The critical degree of saturation test |

Table 2 – Concrete mix proportion

| *w/c* | Target air content (%) | Unit amount ($kg/m^3$) | | | | Admixture (C×%) | | | Actual air content (%) | Slump (cm) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | W | C | S | G | 303A | 404 | SP8SV | | |
| 35 | 1 | 165 | 471 | 827 | 975 | | 0.011 | 0.47 | 1.3 | 22.5 |
| 55 | 1 | 180 | 329 | 936 | 943 | | 0.05 | | 1.1 | 17.5 |
| | 4.5 | 180 | 329 | 843 | 943 | 0.014 | | | 4.9 | 21.5 |

## 3 Experimental Results

### 3.1 The mechanism of concrete under F-T cycles

Enlightened by the moisture degree increase in the critical degree of saturation test, the moisture degree of concrete in the accelerated freeze-thaw test should also increase with the conduction of the freeze-thaw cycles. Therefore, RDM in the accelerated freeze-thaw test should also show an obvious decrease once the critical moisture saturation Scr is reached. In this paper, the mass moisture content of the specimen in the two freeze-thaw tests are calculated and compared with each other to verify the mechanism of concrete under freeze-thaw.

The mass moisture content after N cycles ($W_n$) in the accelerated freeze-thaw test is listed below.

$$W_n = \frac{m_{n,air} - V_n \times \rho_{105℃}}{V_n \times \rho_{105℃}} \times 100\% \qquad (1)$$

where $W_n$ is the mass moisture content after *N* cycles. $V_n$ is the volume of the specimen after *N* cycles and $\rho_{105℃}$ is the density of the oven dry specimen.

The critical mass moisture content $M_{cr}$ in the critical degree of saturation $S_{cr}$ is calculated as follows:

$$M_{cr} = \frac{m_{cr} - V \times \rho_{105℃}}{V \times \rho_{105℃}} \times 100\% \quad (2)$$

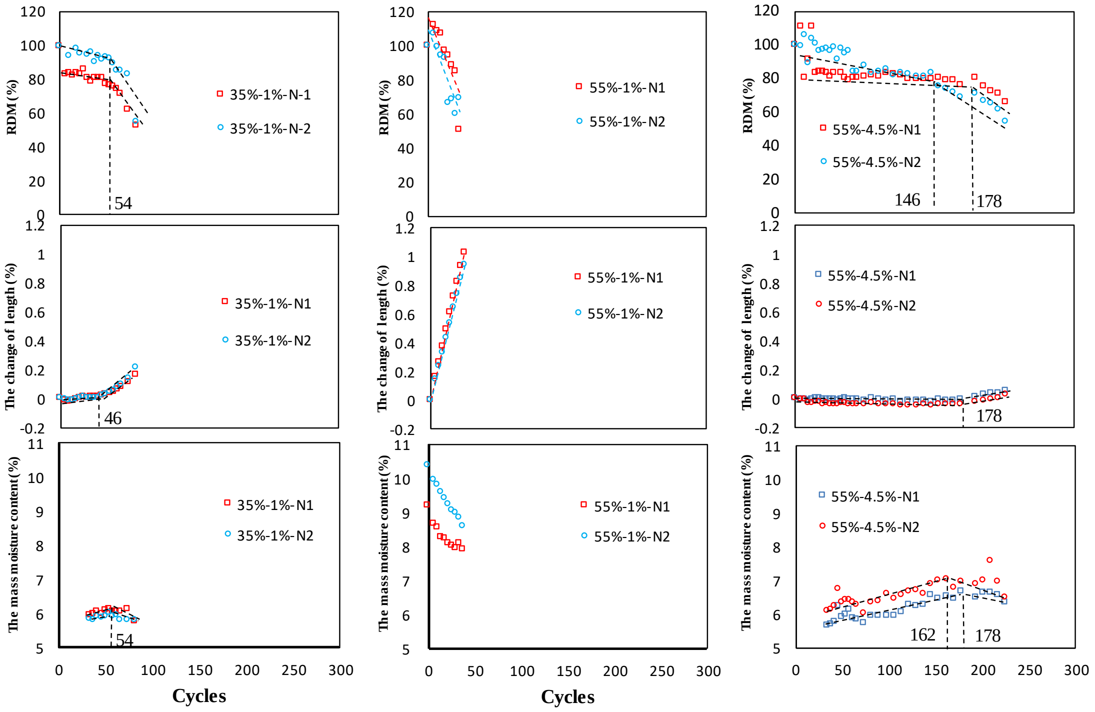
where $M_{cr}$ is the mass moisture content at $S_{cr}$ and the $m_{cr}$ is the weight of the specimen at $S_{cr}$.

Fig.2 shows the results of the length, RDM and mass moisture content change of three types of concrete specimens in the accelerated freeze-thaw test. As shown in the figure, for the W/C35%-1% specimens, the RDM almost kept the same before 54 cycles before it dropped significantly afterward. The length curve also showed similar tendency that the nickpoint of the length change occurred at 46 cycles. The mass moisture content change is also exhibited in Fig.2. The mass moisture content increased continuously until 54 cycles and then it started to decrease. It is reckoned that the expanded volume when the water in the capillary frozen into ice causes the microcracks of the matrix. Therefore, more external water intrudes into the specimens through these microcracks and furtherly exacerbates frost damage. When the saturation degree reaches the critical degree of saturation $S_{cr}$, specimen will show apparent damage and begin to peel off, which has been figured out by the decrease of the mass moisture content.

The mass moisture contents at the nick point of the specimens in the two tests are illustrated in Table 3. Despite some differences in the W/C35%-1% specimens, the mass moisture contents $W_n$ at the nick points of the length change correspond with that of the RDM change and the mass moisture content change. Furthermore, the $W_n$ calculated in the accelerated freeze-thaw test almost equals the $M_{cr}$ in the critical degree of saturation test. Hence, it is suggested that concrete exists a critical mass moisture content under freeze-thaw action and it is not affected by the different freeze-thaw methods. Concrete exhibits obvious frost damage when the critical mass moisture content is achieved.

Besides, since the results of the length change are easy to achieve, and the length change curve has fewer variations than the RDM and mass moisture content. In this paper, the nickpoint in the length change is defined as the critical freeze-thaw cycle $N_f$ and its mass moisture content represents the critical mass moisture content $W_{cr}$.

The nickpoints of the length, RDM, and mass moisture content change in the W/C55%-4.5% specimens also appear at similar freeze-thaw cycles, and they almost share identical mass moisture content, which is close to the $M_{cr}$. However, the W/C55%-1% specimens show completely different tendency during the freeze-thaw cycles. The curves of the length, RDM and mass moisture content change exhibit dramatic change even from the beginning of the freeze-thaw cycles, and no obvious nick points can be figured out. As shown in Table 3, even the mass moisture content at 0 cycle $W_0$ has already exceeded the $M_{cr}$. Therefore, concrete is damaged by freeze-thaw right after the start of the freeze-thaw cycles. The results of three types of specimens have verified the existence of the critical mass moisture content $W_{cr}$ during the freeze-thaw cycles.



W/C35%-1% W/C55%-1% W/C55%-4.5%

Fig. 2 – The results of length, RDM and mass moisture content change of three types specimens

Table 3 – The mass moisture content of three types specimens in curing condition I

| Type<br>(No exposure) | The critical degree of saturation test | The accelerated freeze-thaw test | | | |
|---|---|---|---|---|---|
| | $M_{cr}$<br>(mass moisture content of $S_{cr}$) | $W_0$ (%) | $W_n$ (%) (mass moisture content at the nick point) | | |
| | | | Length | RDM | Mass moisture content |
| 35-1-N | 6.10 | 5.87<br>(34 cycles)* | 5.91<br>(46 cycles) | 6.05<br>(54 cycles) | 6.05<br>(54 cycles) |
| 55-1-N | 7.10 | 9.80<br>(0 cycle) | — | — | — |
| 55-4.5-N | 7.08 | 5.86<br>(34 cycles)* | 6.80<br>(178 cycles) | 6.76<br>(178 cycles-N1)<br>(146 cycles-N2) | 6.83<br>(178 cycles-N1)<br>(162 cycles-N2) |

*The mass moisture content is calculated from the 34 cycles for the 35%-1%-N and 55%-4.5%-N specimens

### 3.2 The effect of outdoor exposure on concrete frost resistance

According to the results above, the critical freeze-thaw cycle $N_f$ can be regarded as the demarcation point of the concrete damage by freeze-thaw. Thus, the effect of different outdoor exposures DJ and DD on concrete frost deterioration has been evaluated by $N_f$ in this paper. The specimens after outdoor exposure DJ and DD were firstly cleaned and submerged in water for 2 weeks before conducting the accelerated freeze-thaw test, and the length, the weight in the air and water were also measured at suitable time intervals during the freeze-thaw cycles. The results of the effect of one-year outdoor exposure are listed below.

Fig. 3 exhibits the length change of the W/C 35%-1%-DJ and DD specimens after one-year outdoor exposure. Compared with the nickpoint appearing at 42 cycles in the W/C35%-1%-N specimens, the length of 35%-1%-DJ and DD increased dramatically right after the start of the freeze-thaw cycles and there emerges no apparent nickpoints during the freeze-thaw cycles. Therefore, it can be concluded that one-year outdoor exposure has a negative effect on concrete frost resistance and the critical freeze-thaw cycles $N_f$ for DJ and DD specimens are regarded as 0 cycle. Moreover, there shows almost no obvious different between DJ and DD. Therefore, it is suggested that the different outdoor exposures DJ and DD have few influences on $N_f$. The mass moisture content of the specimens changing with time is exhibited in Fig. 4. As shown in the figure, compared with the peak point appearing at 54 cycles in the W/C 35%-1%-N specimen, the mass moisture content of DD and DJ specimens increased slightly until 8 cycles before it began to decrease continuously afterward. Table 4 exhibits the mass moisture content of W/C 35%-1% specimens with different curing conditions. As shown in the figure, the mass moisture content of W/C35%-1%-DJ at the critical freeze-thaw cycle $N_f$ is almost equivalent to the $M_{cr}$. However, for the W/C35%-1%-DD specimen, the mass moisture content at 0 cycles has exceeded the $M_{cr}$. W/C35%-1% concrete should appear significant damage right after the start of the freeze and thaw cycles, which also corresponds with the results by the length, RDM, and mass moisture content change. The DD condition is regarded as a more severe outdoor condition for W/C35%-1% specimens based on the fact that the length and mass moisture content change of 35%-1%-DD showing a higher value than that of the 35%-1%-DJ specimens. It is believed that the dry shrinkage during the summer in condition DD is stronger than in condition DJ. The dry shrinkage may help to result in more microcracks, which enhances the moisture absorption gradient during the freeze-thaw cycles.

The length change of 55%-1%-DJ and DD specimens are exhibited in Fig. 5. The length of 55%-1%-DJ and DD also increased much more rapidly than that of 55%-1%-N specimens. The one-year outdoor exposure also degraded W/C55%-1% concrete frost resistance. The mass moisture content change of 55%-1%-DJ and DD are exhibited in Fig. 6. Similar to W/C 55%-1%-N specimen, the mass moisture contents of DJ and DD decreased dramatically from the start of the cycles as well. Besides, the mass moisture contents at 0 cycle of 55%-1%- DJ and DD were inferior to that of 55%-1%-N specimen. It is reckoned that the W/C55%-1% specimens were damaged by freeze-thaw during the outdoor exposure before conducting the accelerated freeze-thaw test. Compared with the 55%-1%-N specimens, the frost damage was exacerbated during the outdoor exposure, and thus the mass moisture contents of 55%-1%-DJ and DD at the start of the cycles were below the W0 of 55%-1%-N. Furthermore, the mass moisture content of 55%-1%-DD at 0 cycle was less than that of 55%-1%-DJ specimen. The degradation by the curing condition DD is also severer in the W/C55%-1% specimens.

The length change of 55%-4.5%-DJ and DD specimens are illuminated in Fig.7. The length change of the specimens in both DJ and DD conditions increased significantly until 88 cycles, while the nickpoint cycle for the 55%-4.5%-N specimens was 178 cycles. The one-year outdoor exposure also has an adverse impact on $N_f$ of W/C55%-4.5%. Fig. 8 illustrates the mass moisture content changes with freeze-thaw cycles. As shown in the figure, the nickpoint cycle in the mass moisture content curve of 55%-4.5%-DJ and DD specimens appeared at 88 and 64 cycles, respectively. Moreover, as shown in Table 4, the mass moisture content $W_{cr}$ at the nick point almost equals to the $M_{cr}$. Therefore, the outdoor exposure also shows a negative effect on W/C55%-4.5% concrete frost resistance.

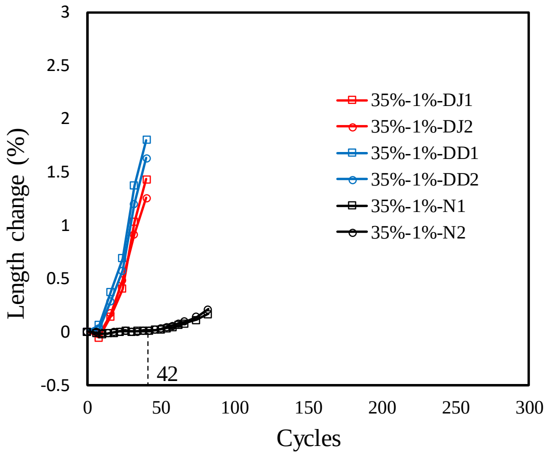


Fig. 3 – The length change of W/C35%-1%

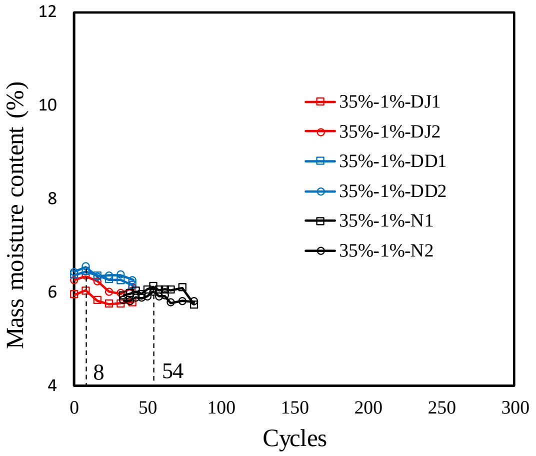


Fig. 4 – The mass moisture content of W/C35%-1%

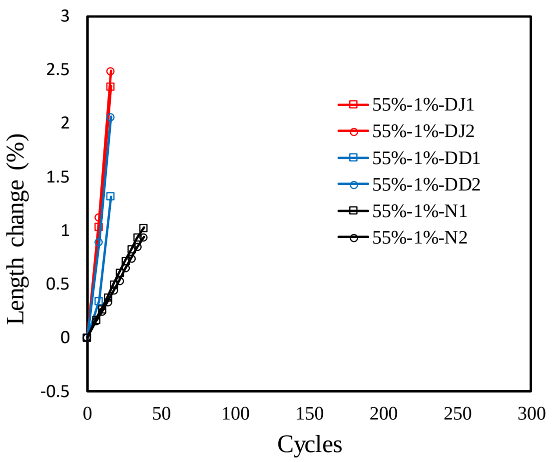


Fig. 5 – The length change of W/C55%-1%

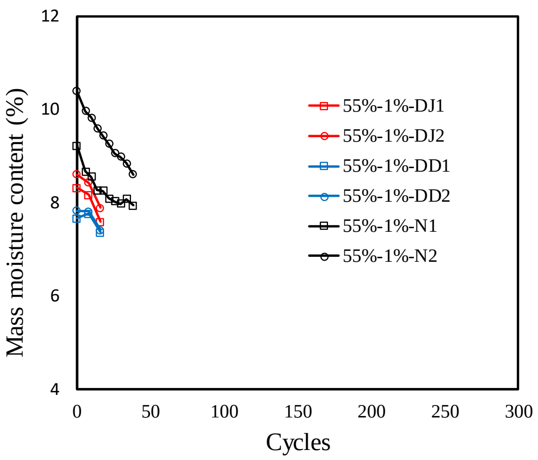


Fig. 6 – The mass moisture content of W/C55%-1%

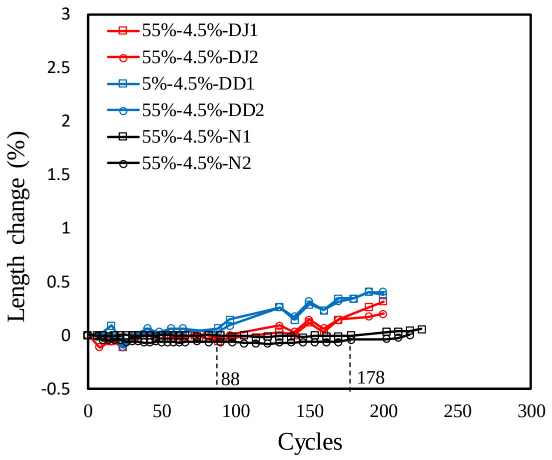


Fig. 7 – The length change of W/C55%-4.5%

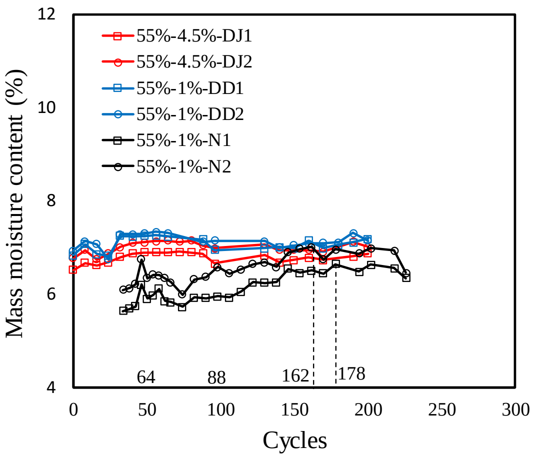


Fig. 8 – The mass moisture content of W/C55%-4.5%

Table 4 – The mass moisture content of specimens with outdoor exposure II and III

| Type | | The critical degree of saturation test | The accelerated freeze-thaw test | | |
|---|---|---|---|---|---|
| | | $M_{cr}$ (%) (mass moisture content of Scr) | W0 (%) | $W_n$ (%) (mass moisture content at the nick point) | |
| | | | | Length | Mass moisture content |
| 35-1 | DJ | 6.10 | 6.10 | 6.10 (0 cycle) | 6.18 (8 cycles) |
| | DD | | 6.40 | 6.40 (0 cycle) | 6.49 (8 cycles) |
| 55-1 | DJ | 7.10 | 8.46 | — | — |
| | DD | | 7.74 | — | — |
| 55-4.5 | DJ | 7.08 | 6.64 | 6.95 (88 cycles) | 6.95 (88 cycles) |
| | DD | | 6.88 | 7.14 (88 cycles) | 7.27 (64 cycles) |

## 4 Conclusion

This study investigates the relationship between the critical degree of saturation test and the accelerated freeze-thaw test by. A new concrete frost resistance criterion $N_f$ has been proposed. Furthermore, the effect of different outdoor exposures on concrete frost deterioration has been elucidated with by the $N_f$. The primary conclusions are listed as follows.

1. Concrete own a critical mass moisture content Wcr and it is not affected by the test methods. Once the critical moisture content is reached, concrete appears obvious deterioration under freeze-thaw exposure. The freeze-thaw cycle where $W_{cr}$ is

achieved is regarded as the critical freeze-thaw cycle $N_f$ and the $N_f$ is a new concrete frost resistance criterion.

2. The effect of different curing conditions on concrete frost resistance can be evaluated by $N_f$. Outdoor exposure has an adverse effect on concrete frost resistance. Besides, the condition that specimens set on the platform is a more severe condition for concrete frost deterioration.

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