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- Technical Paper -

THE EFFECT OF LOWEST TEMPERATURE IN THE ACCELERATED FREEZE-THAW TEST ON CONCRETE FROST DETERIORATION

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ABSTRACT

In the accelerated freeze-thaw test, the length and the relative dynamic modulus of elasticity sometimes changes dramatically at almost same cycle. Based on this, we proposed a new frost resistance index named the critical freeze-thaw cycle. The moisture content of concrete increases and reaches to the critical value at the critical cycle and severe damage will occur. In this paper, we examined the effect of different lowest temperature on the critical freeze-thaw cycle. Besides, the ratio of the effect with different lowest temperatures to that with -18℃in one freeze-thaw is figured out.

Keywords: lowest temperature, mass moisture content, critical cycle, concrete frost deterioration

1. INTRODUCTION

Concrete frost durability is a major technological problem with unanswered questions [1]. Nowadays, two freeze-thaw test methods, the accelerated freeze-thaw test and the critical degree of saturation test, are widely used. However, the results calculated by the two test methods do not match well with each other [2]. Some researchers have found that concrete has a critical mass moisture content (W_{cr}) during freeze-thaw cycles [3]. The concrete is damaged by freeze-thaw as long as its mass moisture content is larger than W_{cr} regardless of the test methods. Ma reported the critical freeze-thaw cycle (N_f) in the accelerated freeze-thaw test corresponded with the mass moisture content W_{cr} and N_f could be defined as a new concrete frost resistance evaluation [4]. Therefore, the service life of the structure in actual environment can be evaluated by N_f.

Besides, different lowest temperatures can affect the ice formation process in concrete and thus influences concrete frost resistance [5]. The lowest temperature of the standard accelerated freeze-thaw test according to JIS A 1148A is -18℃. However, the actual environment sometimes is warmer than the accelerated freeze-thaw test. For example, the lowest temperature of the central prismatic specimens with a size of 75×75×400mm in Sapporo can only reach to about -10℃ [6]. Therefore, it is necessary to clarify the influence of the lowest temperature on concrete frost damage.

In this paper, 3 kinds of concrete specimens with different water cement ratios and air contents were made and cured in water for two weeks. Then the accelerated freeze-thaw test and the critical degree of saturation test were conducted, respectively. The lowest temperatures of the accelerated freeze-thaw test are -5℃ and -10℃, respectively. The critical freeze-thaw cycle N_f in each test can be determined by the sharp change in the length or the relative dynamic modulus of elasticity (RDM) change. The ratio of the effect of the lowest temperature -5℃ and -10℃ on concrete frost damage to the effect of the accelerated freeze-thaw test with the lowest temperature -18℃ can be achieved by the conversion equation adopting the critical freeze-thaw cycle N_f.

2. EXPERIMENT

2.1 Synopsis of Experimental Plan

Table 1 shows the experimental plan. Three kinds of concrete specimens were used. The accelerated freeze-thaw test with the lowest temperature -5℃ and -10℃ were conducted. Besides, the critical degree of saturation test has also been conducted.

2.2 Mix Proportion

In this experiment, the ordinary cement (made in Taiheiyo company) with a density of 3.16 g/cm^3 was used as the cementitious materials. The fine aggregate was the sand with a fineness modulus of 2.68 and the coarse aggregate was crushed stone with the maximum dimension 20mm. Two kinds of water cement ratio (W/C) 55% and 35% were used in this paper. For the W/C55% specimens, the defoamer and the air-entraining agent were used to achieve the specimens with the air content 1% and 4.5%. In the W/C 35% specimens, only the defoamer was adopted to acquire an air content of 1%. Besides, superplasticizer with a dosage of 0.33g/kg cement was used to maintain suitable workability. Table 2 shows the mix proportion of the concrete. The prism specimens with a size of 75×75×400mm and the cylindrical specimens with a size of Φ100×200mm were cast and then demolded on the second day. All the specimens were cured in water for 2 weeks before conducting the test.

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Table 1 Experimental plan

Specimen type	Experimental methods	Dimension (mm)
W/C35%-air1% W/C55%-air1% W/C55%--air4.5%	1. The accelerated freeze-thaw test with the lowest temperatures -5℃ and -10℃ (JIS A 1148 Method A)	75×75×400
	2. The critical degree of saturation test (RILEM CDC3)	Φ100×200

Table 2 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		0.0055	0.33	0.7	22.5
55	1	180	329	936	943		0.005		0.9	14
	4.5	180	329	843	943	0.029			4.6	21.5

*Note:1)303A:Air entraining agent. 404: Defoamer agent. SP8SV X2: Superplasticizer.

2.3 Methodology

The critical degree of saturation test followed the standard of RILEM CDC3. The accelerated freeze-thaw test was carried out according to the standard of the JIS A 1148A method. Nevertheless, the lowest temperature of the central specimen in the freeze-thaw apparatus during the freeze-thaw cycle was set to -5℃ and -10℃, respectively. For the freeze-thaw cycle with the lowest temperature -5℃, the freezing period lasted for 30 minutes. The thawing period also took 30 minutes to arrive at 5℃. For the freeze-thaw cycle with the lowest temperature -10℃, both the freezing and thawing period were set to 45 minutes to accommodate the freezing and thawing speed of the lowest temperature -5℃ freeze-thaw test. The prismatic specimens were taken out of the apparatus after suitable freeze-thaw cycles. The vertical length, the weight in the air and the water and the fundamental transverse frequency were measured respectively. The relative dynamic modulus of elasticity (RDM), which is widely used to evaluate concrete frost resistance, was calculated [7]. When RDM falls to 60% or 300 cycles, whichever came first was reached, the accelerated freeze-thaw test was ceased, and then all the specimens were set in an oven with the temperature 105℃ to dry to constant weight. According to JISA 1148, durability factor (DF), which is calculated by RDM, has been regarded as a frost evaluation criterion for various concrete specimens.

All the cylindrical specimens were used for the critical degree of saturation test. The critical moisture degree (S_{cr}) was recognized as the largest saturation degree of concrete which cannot be severely deteriorated by freeze-thaw in existing literatures [8] [9]. However, once the saturation degree exceeds S_{cr}, concrete will inevitably be damaged by frost fiercely even with only a few freeze-thaw cycles. The test to determine the value of S_{cr} is called the S_{cr} test and the procedure of the test is showed as follows. 8 cylindrical specimens in each kind of mix proportion are firstly vacuum saturated for 2 days. The specimens were then dried in an oven at 50℃ to the desired weight and then wrapped with the preservative film to prevent moisture from evaporating. All the specimens experience at least 8 cycles of freeze-thaw cycles. The weight and the RDM are measured before and after the freeze-thaw cycles. The saturation degree where the RDM decreased dramatically is regarded as the S_{cr}. The mass moisture content at the S_{cr} is named as M_{cr}.

Besides, the water absorption test by the single surface in room temperature (20℃, relative humidity 60%) is also carried out to determine the water absorption ability of concrete. This test gives a sort of potential degree of saturation which can be reached depending on the moist conditions. It is called the capillary degree of saturation, S_{cap}. Samples with a size of Φ100×thickness 30mm are sliced from the cylinders and then dried at 50℃ for 3 days to evaporate the moisture in the air void while causing no harm to the microstructure of the samples. Then the samples are set in a stainless container filled with water and the preservative film is covered to avoid water evaporation. The samples are taken out to measure the weight at suitable time intervals. The moisture absorption curve and the S_{cap} can be determined by the weight change.

The time (T_{pl}) when the moisture absorption curve reaches to the S_{cr} has been defined as index of concrete frost resistance [10]. Thus, the T_{pl} can be used to compare the concrete frost resistance.

3. RESULTS

3.1 Results of the Accelerated Freeze-thaw Test

The standard accelerated freeze-thaw test with the lowest temperature -18℃ was carried out on the specimens with the same mix proportion [4]. With the increase of freeze-thaw cycles, the mass moisture content of the specimens increased. When the mass moisture content reaches to W_{cr}, concrete will be deteriorated by freeze-thaw. Besides, W_{cr} can also be acquired by the sharp change of gradient in the curves of either the length or the RDM change. Therefore, the length and the RDM change of the specimens suffered from 3 kinds of freeze-thaw cycles with different lowest temperatures have been compared as follows.

3.1.1 Results of W/C 35%-air1% Specimens

For the denotation (e.g. -5℃-1), the first part means the lowest temperature in the freeze-thaw test, while the last part represents number 1of the specimen.

Figure 1 exhibits the change of length of W/C35%-air1% specimens. As can be seen from the figure, similar to the length change of the lowest temperature -18℃, the curve of the length change also increased significantly at some cycle in the curves of both -5℃ and -10℃ freeze-thaw test. The cycle is the 84th cycle in the -10℃ test and the 117th cycle in the -5℃ test, respectively. On the other hand, the changes of RDM under the freeze-thaw cycle of the lowest temperatures -5℃ and -10℃ are exhibited in Figure 2. As can be seen from the figure, the RDM of -5℃ and -10℃ specimens dropped significantly at 127th and 90th cycles respectively. The nickpoint cycle of the length change is different from that of the RDM change. It is supposed that the sensitivity of the two parameters may be diffident from each other and thus result in the different nickpoint cycles between the two parameters. However, the two nickpoint cycles can be regarded as corresponding to each other in spite of the variations.

Besides, as can be seen in Figure 1 and 2, compared to the RDM change, the length change is much stable and has few deviations. We decided to use the nickpoint cycle of length change as the critical freeze-thaw cycle N_f in this paper. Therefore, the N_f of the W/C35%-air1% specimens with the lowest temperatures -5℃ and -10℃ are 117th and 84th.

3.1.2 Results of W/C 55%-air1% Specimens

The length change of W/C55%-air1% is shown in Figure 3. As can be seen from the figure, the obvious nick point cannot be figured out in the length change. The length change increased significantly right after the freeze-thaw cycles. Besides, the different lowest temperatures had almost no effect on the length change. It is supposed that the moisture content at the 0th cycle has already exceeded W_{cr} and the specimens are damaged by frost once freeze-thaw cycle begins. Thus, the N_f is regarded as 0th cycle and the W/C55%-air1% specimens are regarded as not frost resistant.

3.1.3 Results of W/C 55%-air4.5% Specimens

Figure 4 exhibits the length change of W/C55%-air4.5% specimens. From the figure, damage by freeze-thaw can be figured out at 178th cycles in the specimens with the lowest temperature -18℃. While the specimens experienced the freeze-thaw with the lowest temperatures -5℃ and -10℃, it still showed no obvious change during the whole freeze-thaw cycles. Hence, it is believed that no fierce frost damage can be figured out during the whole freeze-thaw cycles with the lowest temperature -5℃ and -10℃. Therefore, the W/C55%-air4.5% specimens can be regarded as frost resistant with the lowest temperature -5℃ and -10℃ during the whole freeze-thaw cycle. The critical freeze-thaw cycle N_f cannot be achieved only according to the Figure 4.

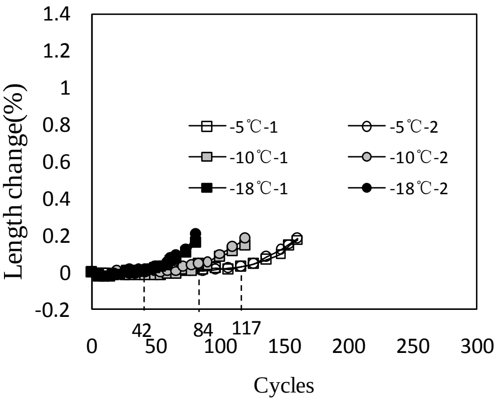


Figure 1 The length change of W/C35%-air1%

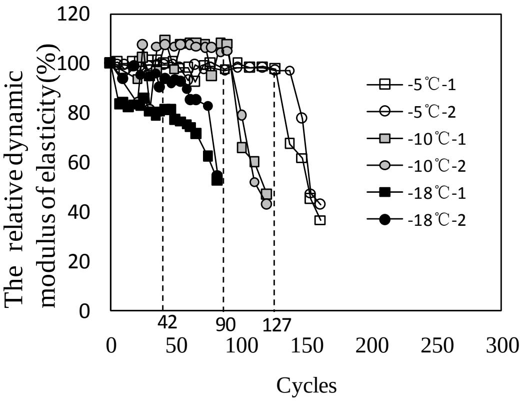


Figure 2 The RDM change of W/C35%-air1%

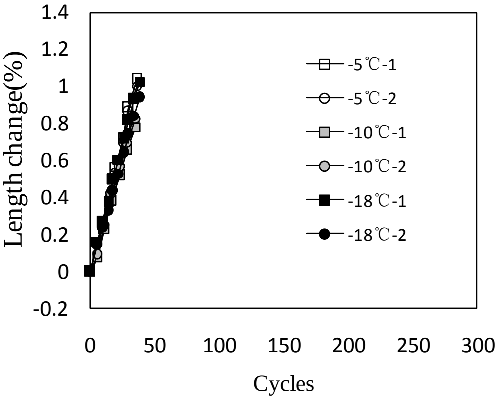


Figure 3 The length change of W/C55%-air1%

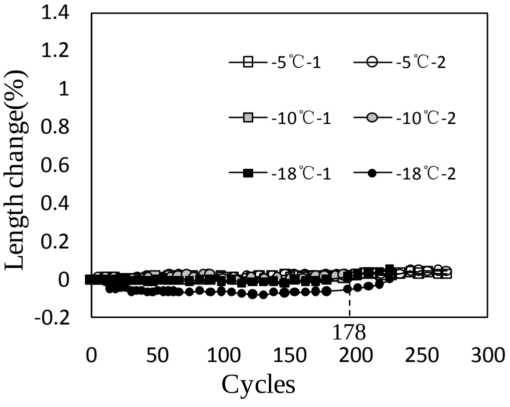


Figure 4 The length change of W/C55%-air4.5%

3.2 Result of Critical Degree of Saturation Test

In the critical degree of saturation test, concrete frost resistance is evaluated by the T_{pl}. Table 3 exhibits the S_{cr}, T_{pl} and DF. Figure 5 displays the relationship between DF and T_{pl}. As shown in the figure, DF was not in good accordance with T_{pl} except for the W/C55%-air1% specimens. No clear relationship can be figured out between DF and T_{pl}.

Table 3 The S_{cr}, T_{pl} and DF of 3 kinds of concrete

Specimen type		S_{cr}	T_{pl} ($h^{1/2}$)	DF
35%-1%	-5℃	0.94	10.95	28.99
	-10℃			23.39
55%-1%	-5℃	0.80	2.94	3.18
	-10℃			5.27
55%-4.5%	-5℃	0.78	8.65	38.47
	-10℃			47.49

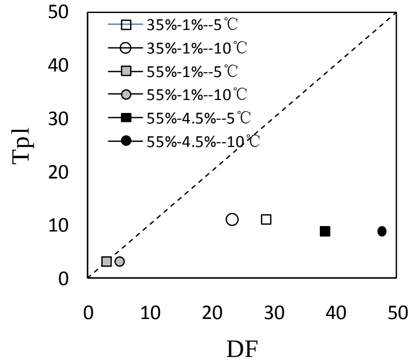


Figure 5 The relationship DF and T_{pl}

3.3 The Mass Moisture Content Change by Different Lowest Temperatures

3.3.1 Moisture Content Change by Lowest Temperature in W/C35%-air1% Specimens

The mass moisture contents (W_n) of the specimens at the freeze-thaw cycle n in the accelerated freeze-thaw test can be calculated according to the Eq.1 below [4].

$$W_n = \frac{M_{air,n} - \rho_{105} * (M_{air,n} - M_{water,n})}{\rho_{105} * (M_{air,n} - M_{water,n})} \quad (1)$$

M_{air}: Specimen weight in the air at n cycle
M_{water}: Specimen weight in the water at n cycle
ρ_{105}: the oven-dried density

The mass moisture content at the N_f cycles is regarded as the critical mass moisture content (W_{cr}). The mass moisture content of W/C35%-air1% changes is shown in Figure 6 (a). The mass moisture content in the -10℃ freeze-thaw test increased gradually to 84th cycles and then it began to decrease rapidly. A nick point also showed up at 117th cycles in the -5℃ test. The critical freeze-thaw cycle of the mass moisture content in either -5℃ or -10℃ freeze-thaw test is the same as the critical freeze-thaw cycle of the length. It is supposed that external moisture has been pushed into the specimens and thus the moisture content increases gradually. When the W_{cr} is reached, concrete is damaged by freeze-thaw fiercely. Afterwards, the aggregate scaled off which resulted in the decrease of the mass moisture content.

Table 4 shows the mass moisture content. From the table, the average critical mass moisture content W_{cr} in the -10℃ test is 6.92, while the value in the -5℃ test is 6.95. The two values are almost equal to each other. Concrete will be damaged by freeze-thaw once its mass moisture content reaches to the W_{cr} regardless of the lowest temperatures.

The mass moisture content M_{cr} in the critical degree of saturation test is calculated as follows.

$$M_{cr} = \frac{M_{air,cr} - M_{105℃}}{M_{105℃}} * 100\% \quad (2)$$

$M_{air.cr}$: specimen weight at the S_{cr}
$M_{105℃}$: oven-dry specimen weight

The M_{cr} of W/C35%-air1% is 6.20, which is a little different from W_{cr}. The different size of the specimens used in the two methods may result in the difference. Besides, the proportion of the effect with the lowest temperature -5℃ or -10℃ to the effect with the lowest temperature -18℃ in one freeze-thaw cycle can be determined by the N_f. The Eq.3 is given as follows.

$$\begin{aligned} E^{35-1}_{-5℃} / E^{35-1}_{-18℃} &= Nf^{35-1}_{-5℃} / Nf^{35-1}_{-18℃} = 0.359 \\ E^{35-1}_{-10℃} / E^{35-1}_{-18℃} &= Nf^{35-1}_{-10℃} / Nf^{35-1}_{-18℃} = 0.500 \end{aligned} \quad (3)$$

$E^{35\text{-}1}_{x℃}$: the effect of 1cycle freeze thaw with the lowest temperature x℃ on frost damage

3.3.2 Moisture Content Change by Lowest Temperatures in W/C55%-air1% Specimens

Figure 6 (b) exhibits the mass moisture content of the specimens with the lowest temperature -5℃ and -10℃, respectively. The mass moisture content decreased significantly from the beginning of the cycles. It is suggested that the aggregate scaled off fiercely, which resulted in the sharp decrease in the mass moisture content. As shown in Table 4, even the mass moisture content of the 0th cycle is much larger than the M_{cr}, which verifies that concrete will be damaged by frost once the freeze-thaw cycle begins. The W/C55%-air1% concrete can be regarded as not freeze-thaw resistant with the lowest temperature -5℃ and -10℃. Therefore, the equation of the effect of the lowest temperature on concrete frost deterioration is neither available nor meaningful.

3.3.3 Moisture Content Change by Lowest Temperature in W/C55%-air4.5% Specimens

Figure 6 (c) exhibits the curve of the mass moisture content of W/C55%-air4.5% specimens. As can be seen from the figure, the mass moisture content of the specimens in the -5℃ and -10℃ lowest temperatures freeze-thaw test increased gradually and no nick point was found in the curves. As shown in Table 4, the critical mass moisture content M_{cr} is not achieved even at the end of the cycles.

The critical mass moisture content M_{cr} can also be used to determine concrete damage by frost. For both -5℃ and -10℃ specimens, the mass moisture contents have been linear fitted. The fitting function and the fitting degree (R^2) are exhibited in Figure 6 (c). As can be seen from figure, the fitting degrees R^2 of all the specimens are about 90%. Thus, in this paper, we regard the mass moisture content increases linearly with the freeze-thaw cycles. By extending the fitting function of the mass moisture content to the M_{cr}, the predicted critical freeze-thaw cycle can be acquired. The average value of the evaluated cycles has been regarded as the N_f for the accelerated freeze-thaw test with the lowest temperature -5℃ and -10℃. The ratio of the effect with the lowest temperatures -5℃ and -10℃ to the effect with the lowest temperature -18℃ in one freeze-thaw cycle can be calculated by the Eq.4 below.

$$E^{55-4.5}_{-5℃} / E^{55-4.5}_{-18℃} = Nf^{55-4.5}_{-5℃} / Nf^{55-4.5}_{-18℃} = 0.532$$

$$E^{55-4.5}_{-10℃} / E^{55-4.5}_{-18℃} = Nf^{55-4.5}_{-10℃} / Nf^{55-4.5}_{-18℃} = 0.589 \qquad (4)$$

$E^{55\text{-}4.5}_{x℃}$: the effect of 1cycle freeze thaw with the lowest temperature x℃ on frost damage

3.4 The Relationship between the Correction Coefficient and the Lowest Temperatures

In the actual environment, the lowest temperature of a structure changes with time. Thus, it is significant to predict the effect of various lowest temperatures on concrete frost damage for evaluating the effect of the lowest temperature on concrete frost damage more accurately. The correlation coefficients of Eq.3 and 4 represent the ratio of the effect with different lowest temperatures to the effect with the lowest temperature -18℃ in one freeze-thaw cycle. The relationship between the correction coefficient and the lowest temperature is exhibits in Figure 7. As can be seen from the figure, the correction coefficients decreased with the increase of the lowest temperatures. For the W/C35%-air1% specimens, the correction coefficient almost decreased linearly with the lowest temperatures, while for the W/C55%-4.5% specimens, the correction coefficient almost remained the same as the lowest temperature raising from -10℃ to -5℃. Therefore, the accelerated freeze-thaw test with other lowest temperatures should be conducted to figure out the relationship between the correction coefficient and the lowest temperatures.

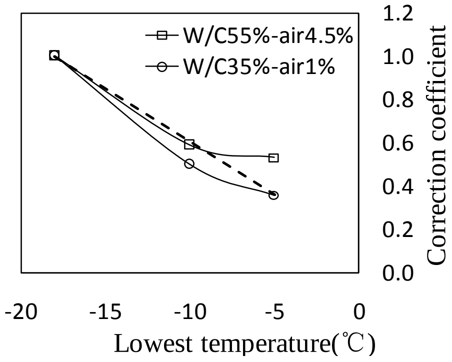
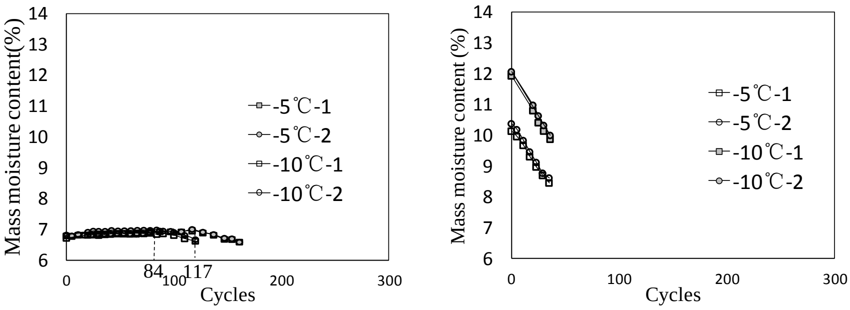
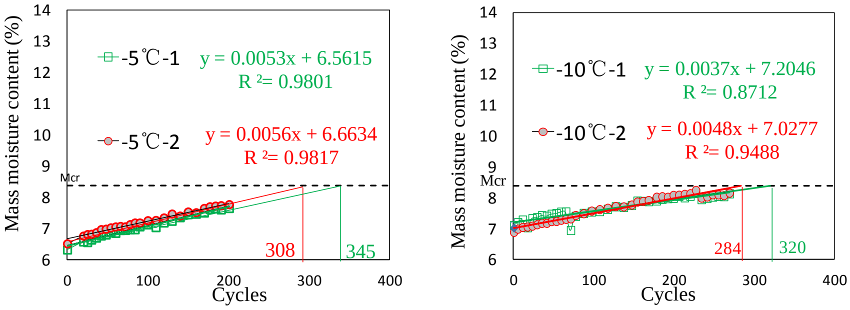


Figure 7 The relationship between the correction coefficient and lowest temperature



(a)W/C35%-air1%

(b)W/C55%-air1%



(c)W/C55%-air4.5%

Figure 6 The mass moisture content in the accelerated freeze-thaw test

Table 4 The mass moisture content of the specimens

Specimen type		Mass moisture content			
		The accelerate freeze-thaw test			The critical degree of saturation test
		W_{0cycle} (0 cycle)	W_{cr} (N_f cycle)	$W_{final\ cycle}$ Final cycle	M_{cr}
35%-1%	-5℃	6.86	6.95	6.68	6.20
	-10℃	6.76	6.92	6.64	
55%-1%	-5℃	10.25	-	8.53	7.24
	-10℃	12.00	-	9.93	
55%-4.5%	-5℃	6.52	-	7.79	8.39
	-10℃	6.41	-	7.71	

4. CONCLUSION

The experiment investigates the effect of different lowest temperatures on concrete frost deterioration by the accelerated freeze-thaw test. The effect of different lowest temperatures can be evaluated by the critical freeze-thaw cycle N_f. The conclusions are listed as follows.

(1) Concrete will be damaged by freeze-thaw once the critical mass moisture content is achieved regardless of the different lowest temperatures.

(2) We proposed a conversion equation of calculating the ratio of the effect of 1 freeze-thaw cycle with the lowest temperature -5℃ and -10℃ to the effect of -18℃ freeze-thaw test by the N_f of different lowest temperatures.

(3)The relationship between the correction coefficient of the conversion equation and the different lowest temperatures has been figured out.

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