- Technical Paper -

THE FROST EVALUATION OF DRIED CONCRETE USING RECYCLED COARSE AGGREGATE BY THE ACCELERATED FREEZE-THAW TEST AND THE CRITICAL DEGREE OF SATURATION TEST

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ABSTRACT

The accelerated freeze-thaw test and the critical degree of saturation test are widely used as frost resistance methods. However, different evaluation results by the two methods are reported. In this study, a test was conducted to figure out the connection between the two methods. Along with this, the effects of coarse aggregate, that is the ordinary aggregate (SZ) and the recycled aggregate (RM), air content and drying degree on the frost resistance were investigated. According to the results, concrete including more air showed a better frost resistance. The frost resistance from the accelerated freeze-thaw test was agreed with that from the critical degree of saturation test in nonAE concrete, whereas the frost resistances showed different trends in AE concrete. By comparing the dyed portions of RM with SZ, the interface of RM is weak and cracks are more easily to emerge on the RM.

Keywords: recycled aggregate, drying degree, frost resistance, accelerated freeze-thaw test, the critical degree of saturation test

1. INTRODUCTION

The accelerated freeze-thaw test according to JIS A 1148 Method A and the critical degree of saturation test by RILEM CDC 3 are widely used for evaluating concrete frost resistance. However, for concrete with different water-cement ratios and air contents, different frost resistance results were obtained by the two evaluation methods [1]. Besides, according to the results by Tomita [2], drying influences the frost resistance evaluation in the accelerated freeze-thaw test. Concrete frost resistance improves when concrete is subjected to minor drying, whereas the frost resistance descends if excessive drying is applied to the concrete. Also, over 3% moisture weight loss of concrete causes significant frost resistance reduction.

In this experiment, the accelerated freeze-thaw test and the critical degree of saturation test were carried out for the ordinary and recycled coarse aggregate concrete experienced different drying degrees. The effect of coarse aggregate on the concrete frost resistance was evaluated by the two methods. A flaw detection test using dye agent was also conducted to examine the influence of coarse aggregate on the frost resistance. In addition, the influences of different drying degrees and air contents on the frost resistance estimation by the two methods have been examined.

2. EXPERIMENTAL PLAN

Fig.1 shows the experimental flow and the experimental plan is exhibited in Table 1. In this experiment, specimens with different coarse aggregates and air contents were manufactured and different drying degrees were applied to the specimens. Their effects on the frost resistance by the two methods were investigated. The water-cement ratio of the specimen was 50% and the target air contents were 2.0% and 4.5%, respectively. After curing in water for 2 weeks, all the specimens experienced drying in an oven at 50 ℃. Drying process was ceased as the moisture weight loss of the specimens reached to 0%, 2%, 3% and 4%, respectively. When the target drying degrees were reached, the specimens were taken out and cured in water condition again until 4 weeks.

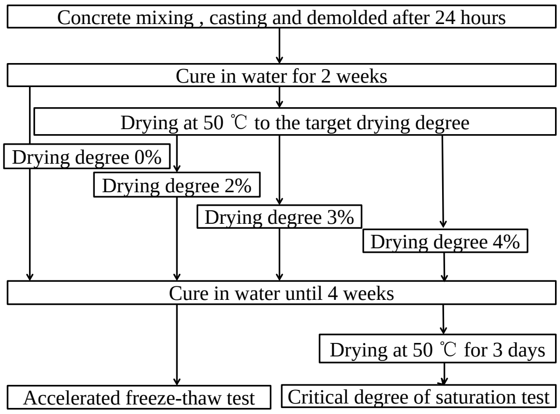

Fig.1 Experimental flow

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Table 2 shows the procedures of the two tests to estimate the frost resistance for AE and nonAE concrete.

In the accelerated freeze-thaw test, the test was conducted according to JIS A 1148 method A. The dimension of the specimen was set as 75 × 75 × 400 mm. Durability factor (DF) was used as the frost resistance in this test.

The critical degree of saturation test is based on the fact that concrete has critical water saturation (Scr) [3]. Besides, it causes deterioration during freeze-thaw cycles when the water saturation of the specimen exceeds Scr. However, damage does not take place when the water saturation is lower than Scr even after numerous freeze-thaw cycles. In this paper, cylindrical specimens with a size of 100 φ × 200 mm were used. Scr was the water content when the relative dynamic elastic modulus of the specimen decreased rapidly after the freeze-thaw cycles. In addition, it was assumed that Scr of concrete did not change in spite of different drying degrees.

Another test in the critical degree of saturation test is bottom surface water absorption test for determining the capillary degree of saturation (Scap). The size of the samples was 100 φ × 30 mm. The samples were cut out from 100 φ × 200 mm cylinders which had been dried at 50℃to the target drying degree 0%, 2%, 3% and 4%, respectively. The samples were set in a tray filled with water and the tray was covered with an impermeable cover in order to prevent evaporating from its top surface. The samples were able to absorb water by its bottom surface. The weights of the samples were measured at suitable intervals and the water absorption curves were made according to the weight changes.

Tpl [1] is used as an evaluation of the frost resistance in the critical degree of saturation test. Tpl is the time ($h^{1/2}$) at which the water content (Scap) reaches Scr. When the value Tpl is large, it indicates that the concrete has good frost resistance.

To ascertain the basic properties of the coarse aggregate, the tests in Table 3 were carried out. The basic properties of the coarse aggregate are shown in Table 4. Table 5 exhibits the mix proportions and basic properties of concrete.

In order to investigate the influence of different coarse aggregates on the frost deterioration, a flaw detection test using dye agent was conducted. Since concrete is a porous material, the dye agent is able to permeate through the whole surface to some extent, especially in the area where cracks initiate. The undamaged cylinder specimens used for the Scr test were subjected to freeze-thaw cycles for another time. After the freeze-thaw cycles, the specimens were cut to the size of 100 φ × 30 mm and then polished. The dye agent was applied to the surface of the sample for 30 minutes and then the extra dye agent was removed. Before taking photos of the samples, developer was painted to the surface of the samples. As the dye agent in the micro cracks was able to emerge in the developer owing to the capillary function, the position where cracks appeared was able to be determined.

Fig.2 shows the photo of the sample in the flaw detection test. In this paper, the photo of the sample was taken by a digital camera. The photo was acquired by irradiating the surface of the sample with constant light. Commercial used image analysis software was used to extract the dyed area. Besides, in order to extract the dyed area, the areas where the color corresponded to the conditions (Hue: H> 230, Saturation: S> 130, Brightness: B> 170) in the HSB color space were picked out as the dyed area. These conditions were set based on the properties between the developer and the dye agent.

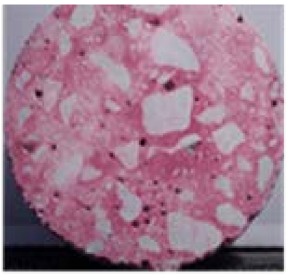


Fig.2 Sample in the flaw detection test

Table 1 Experimental plan

W/C (%)	Air Content (%)	Aggregate (Symbol)	Experimental Method	Size (mm)	Drying Degree
50	nonAE 2% AE 4.5%	Ordinary aggregate (SZ) Recycled aggregate (RM)	The accelerated freeze-thaw test (JIS A 1148 Method A)	75×75×400	0% 2% 3% 4%
			The critical degree of saturation test (RILEM CDC3)	Scr: 100φ×200 Scap: 100φ×30	
			The flaw detection test	100φ×30	

Table 2 Experimental methods

Experimental Type	Experimental Methods
The Accelerated Freeze-thaw Test (JISA 1148 Method A)	1. Dry the specimens to the target drying degree(0%, 2%,3%,4%) at 50℃. 2. Measure the primary resonance frequency, the mass and the length of the specimens every 10-30 cycles. 3. Repeat the freeze-thaw cycles in water until 300 cycles or the relative dynamic elastic modulus becomes 60% or less.
The Critical Degree of Saturation Test (RILEM CDC3)	Scr: 1. Dry the specimens for 3 days at 50℃. 2. Conduct vacuum water absorption test. 3. Adjust the saturation degrees to 8 levels at 50℃. 4. Seal the specimens. 5. Conduct 6 cycles of freeze-thaw in the air. (Freeze: -20℃/18 hours Thaw: 20℃/6 hours) 6. Measure the relative elastic modulus before and after the freeze-thaw cycles. Scap: 1. Dry the specimens to the target drying degree(0%, 2%,3%,4%) at 50℃. 2. Conduct the bottom surface water absorption test. 3. Measure the weight at suitable intervals.

Table 3 Experimental method of coarse aggregate

Experimental Type	Experimental Method	Initiation State	Object
Water Absorption Test	1000 g aggregate is immersed in water and the weight is continuously measured. Exam duration: 7 days.	Air dried Absolutely dried	Ordinary aggregate Recycled aggregate
Simple Freeze-thaw Test	1000 g aggregate suffers from 10 freeze-thaw cycles. In one cycle, the lowest temperature is -18 ° C or below for 1 day and the highest temperature is 20 ° C for 1 day. The mass loss is measured.	Absolutely dried	
Stability Test	Conduct stability test of aggregate with sodium sulfate.		
Attached Mortar Test	1000 g aggregate is immersed in about 10% hydrochloric acid and the mass loss is measured.		Recycled aggregate

Table 4 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 5 Mix proportions and basic properties of concrete

Specimen Type	Target Air Content (%)	W/C (%)	Fine Aggregate (%)	Unit Amount (kg/m^3)				Admixture (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

3. RESULTS AND DISSUSITION

3.1 Results of the accelerated freeze-thaw test

Fig. 3 shows the change of the relative dynamic elastic modulus in the accelerated freeze-thaw test. In the specimens of nonAE concrete SZ and RM, frost deterioration was proceeding immediately after the freeze-thaw cycle begun. However, for the specimens SZ-a and RM-a in AE concrete, the frost resistance was higher than that in non-AE concrete. The durability factor (DF) is shown in Fig.4. An adequate amount of air was effective in improving frost resistance even when the concrete was made up of recycled coarse aggregate or was under the influence of drying. Besides, the frost resistance deteriorated as the drying degree increased. However, there was no sign that the frost resistance was improved by drying according to the results by Tomita [2]. It is considered that the drying degree 2% was an excessive drying condition for the concrete. Besides, drying effect was canceled for the specimens were cured in water again after drying.

Even though severe deterioration occurred in nonAE concrete in the accelerated freeze-thaw test, the weight change rate of nonAE concrete was not obvious. The weight change rate of AE concrete in the accelerated freeze-thaw test is shown in Figure 5. A little weight change was observed in RM-a and SZ-a at drying condition 0%. As the weight change rate of SZ-a at drying condition 0% was larger than that of SZ-a at drying condition 2%, 3% and 4%. Besides, in the RM-a, the weight loss was intensified as the degree of drying was larger. Drying influenced the deterioration of recycled aggregate concrete. Compared to the SZ-a, RM-a had a weaker interface area due to the use of recycled aggregate. In the RM, cracks and spalling were more easily to emerge at drying conditions

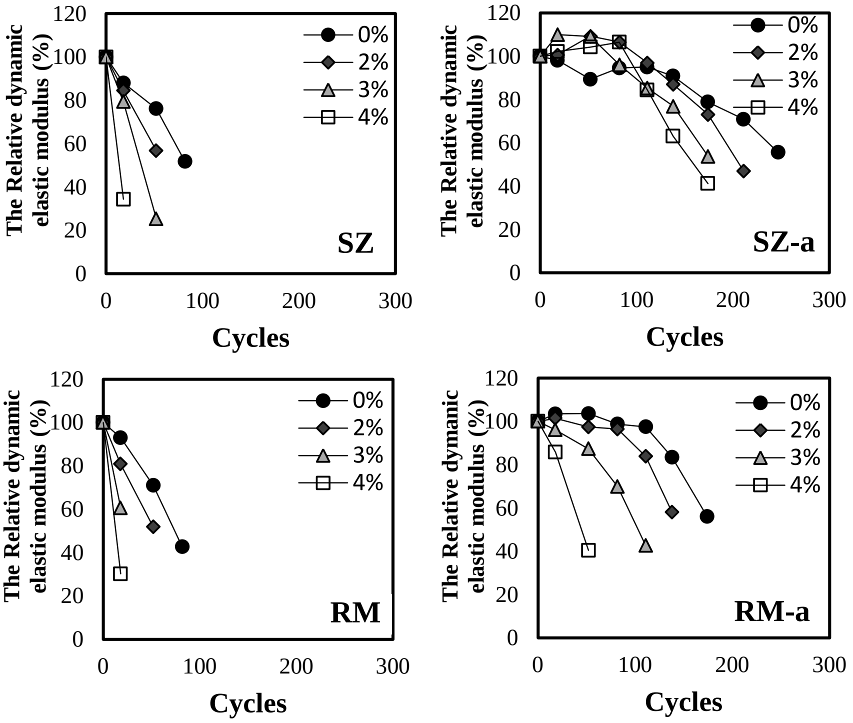


Fig.3 Change of the relative dynamic elastic modulus

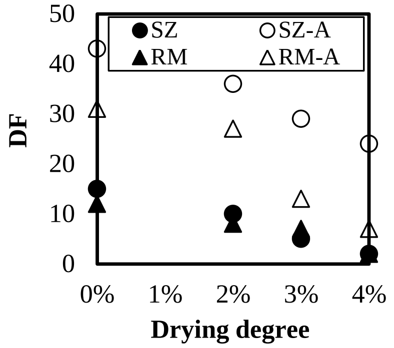


Fig.4 Relationship between DF and drying degree

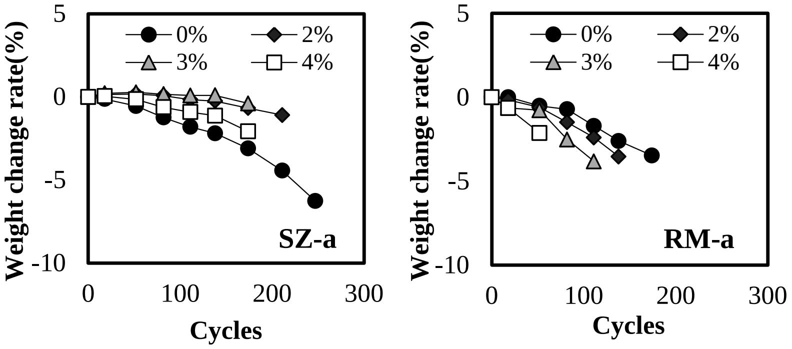


Fig. 5 Weight change rate of AE concrete

3.2 Results of the critical degree of saturation test

Fig.6 indicates the relationship between Tpl and drying degree. The difference of Tpl between SZ and RM was insignificant when the drying degree was 0%. However, the Tpl of SZ was considerably different from that of SZ-a. The large amount of air content in AE concrete prevented the samples from absorbing water in the bottom surface water absorption test. Owing to this effect, the Tpl in AE concrete was smaller than that in nonAE concrete.

The difference of Tpl between SZ and SZ-a or RM and RM-a decreased dramatically when the samples were dried to the drying degree 2%. It is believed that micro cracks appeared in the samples because of drying and due to these micro cracks it became easier for the samples to absorb water in the bottom surface water absorption test.

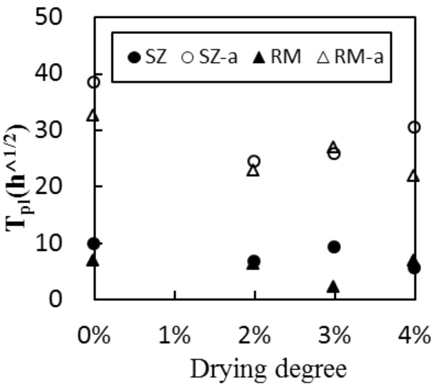


Fig.6 Relationship between Tpl and drying degree

Fig.7 shows the relationship between the relative dynamic elastic modulus and the dyed area measured from the photo in the flaw detection test. In the SZ specimens, the relative dynamic modulus decreased with the increase of the dyed area. The two parameters showed a linear relationship. Besides, since the entrained air bubbles in the SZ-a specimens were colored by the dye agent, the dyed area was larger than that in the SZ. However, the variations of RM and RM-a in Fig.7 were noticeable. Because the dyed portion mainly consisted of the interface of the attached mortar, the variations in the RM and RM-a were obvious. Thus, the difference between SZ and RM was apparent and not able to be confirmed. However, regardless of the variations, as the relative dynamic elastic modulus decreased in each type of concrete, the size of dyed area tended to increase. Therefore, it is thought to be that the frost resistance degradation caused by the freeze-thaw cycles agreed with the dyed portion of the samples.

The dyed portions of ordinary and recycled coarse aggregate concrete with the similar relative dynamic elastic modulus are shown in Fig.8. As shown in Fig.8, the dyed area of the RM specimen was much larger than that in the SZ specimen. Therefore, more micro cracks were thought to have appeared in RM. It is thought that due to the use of recycled aggregate, the interface area was weak and micro cracks were more easily to emerge.

The properties of the recycled aggregate greatly affected by the attached mortar content were the water absorption and density [5], respectively. With the increase of the attached mortar, density decreased while the water absorption went up. Moreover, according to the research of Takahashi [6], concrete compressive strength declined with the increasing amount of the attached mortar. However, attached mortar amount of RM was 20.4% and its compressive strength was almost same as that of SZ. In the case of the W/C of the attached mortar was lower than the W/C of the recycled aggregate concrete, the compressive strength became similar to the ordinary aggregate concrete. It is considered to be that the attached mortar was the defects of the concrete and frost deterioration started from these defects.

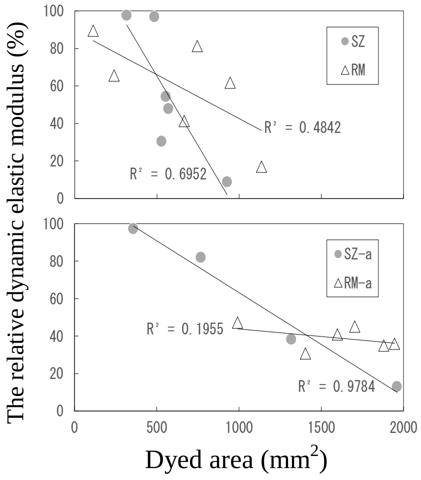
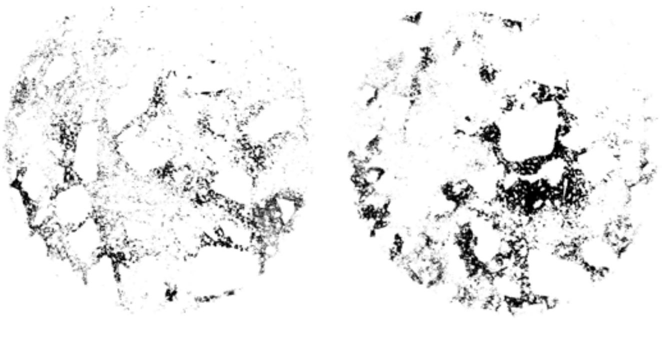


Fig.7 Relationship between dyed area and the relative dynamic elastic modulus



SZ: the relative dynamic elastic modulus 54%

RM: the relative dynamic elastic modulus 61%

Fig.8 Dyed location extracted from the image

3.3 The comparison of frost resistance between DF and Tpl

The comparison of frost resistance between DF and Tpl is shown in Fig.9. DF was in accordance with Tpl for nonAE concrete SZ and RM. However, for AE concrete, especially for the RM-A samples with the drying degree 3% and 4%, the frost resistance (DF) by the accelerated freeze-thaw test decreased obviously, whereas the frost resistances (Tpl) by the critical degree of saturation method almost remained the same. It is considered that for AE concrete, concrete was more easily to be destroyed by cracks by drying in the accelerated freeze-thaw test.

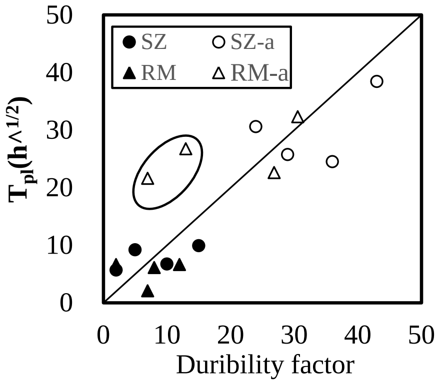


Figure 9 Relationship between Tpl and DF

4. CONCLUSION

This study experimentally investigated the effect of coarse aggregate, air content and drying degree on the frost resistance by the critical degree of saturation test and the accelerated freeze-thaw test. The conclusions are as follows:

1. The frost resistance of AE concrete was better than that of nonAE concrete in the accelerated freeze-thaw test. Therefore, properly use of admixture improved concrete frost resistance. Besides, with the increase of drying degree, the frost resistance went down.
2. The increase of air content enhanced the concrete frost resistance in the critical degree of saturation test. The increasing drying degree caused the decrease of the concrete frost resistance, especially in AE concrete. However, the frost resistance stayed constant when the drying degree exceeded 2%.
3. The frost resistance by the accelerated freeze-thaw test agreed with that by the critical degree of saturation test in nonAE concrete. However, in AE concrete, as the drying degree increased, the DF decreased significantly, while Tpl remained steady.
4. According to the results of the dyed area in the flaw detection test, it is considered that deterioration partially begun in the recycled aggregate concrete.

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