

# Study on the Frost Resistance Durability of Recycled Aggregate Concrete under an Extreme Cold Environment

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**ABSTRACT:** Recycled aggregate concrete (RAC), as a way to reuse waste concrete, is good for solving environmental and resource problems. In this paper, the frost resistance durability of RAC under an extreme cold environment was studied, RAC specimens with different replacement rates were designed, and then the indexes of the specimens, such as mass loss rate, were calculated and compared. It was found that when the replacement rate of recycled concrete aggregate (RCA) was 30%, the strength of the specimen was the best; under an extreme cold environment, the higher the replacement rate of RCA was, the more significant the improvement of the compressive strength was, but with the progress of the freeze-thaw cycle, the higher the replacement rate of RCA was, the worse the frost resistance durability was. The mass loss rate of RAC-3 (100% RCA replacement rate) was 5.56%, the strength loss rate was 40.86%, and the relative dynamic elastic modulus was 61.89%, all of which were significantly lower than that of RAC-0. The experimental results verify that the excessively large replacement rate of RCA is not conducive to the frost resistance durability of concrete. The replacement rate of RCA needs to be paid attention to when used in an extremely cold environment.

**Keywords:** recycled aggregate concrete, frost resistance durability, extremely cold environment, replacement rate

## 1 INTRODUCTION

Recycled aggregate concrete (RAC) (Rui et al. 2016) refers to the concrete prepared by partially or completely replacing natural aggregates with recycled concrete aggregate (RCA) (Wijayasundara et al. 2017). RAC can not only alleviate the shortage of construction materials (Golafshani & Behnood 2018) but also achieves the harmless treatment and effective use of construction waste (Tam et al. 2015), which is more environmentally friendly and economical (Chaiyasarn et al. 2021) and conducive to the sustainable development of the construction industry (Xie et al. 2015). RAC has also been commonly used in practice (Behnood et al. 2015). At present, the preparation and performance of RAC have been extensively studied (Silva et al. 2015). Fu et al. (2015) studied the torsional capacity of concrete beams with 100% RCA in ABAQUS and found that the RAC beams had a good seismic performance. Haddad et al. (2017) studied the porosity, connectivity, etc. of RAC. They found by an ultrasonic technique that the pore connectivity of RAC increased with the increase of RCA replacement rate, which improved the open porosity. Silva et al. (2015) analyzed the carbonation behavior of RAC and found through the accelerated carbonation test that the carbonation depth of concrete increased significantly with the increase of substitution level.

Chen et al. (2014) designed steel fiber reinforced RAC (SFRAC) by adding steel fibers and analyzed its fracture behavior at high temperatures. They found that the addition of steel fibers slowed down the crack generation and improve the fracture performance of RAC at high temperature. Under an extreme cold environment, the performance of concrete will change significantly, and the frost resistance durability of buildings has an impact on the service life of buildings. However, there are fewer studies about the performance of RAC under an extreme cold environment, and most of the studies focus on ordinary concrete. Therefore, this paper studied the frost resistance durability of RAC under an extreme cold environment. Specimens with different replacement rates of RCA were designed, and the indexes of the specimens, such as mass loss rate, were calculated and compared to understand the effect of RCA replacement rate on the frost resistance durability. This work provides some reference and guidance for the better application of RAC in an extreme cold environment.

## 2 MATERIALS AND METHODS

### 2.1 Experimental materials

Cement: ordinary silicate cement with a cement mark of P.O42.5, and its specific properties are shown in Table 1.

Table 1. Basic properties of cement.

Compressive strength/Mpa	3 d	16.0
	28 d	42.5
Coagulation time (h:m)	Initial setting time	≥ 0:45
	Final setting time	≥ 10:00
Chemical composition/%	CaO	63.49
	SiO <sub>2</sub>	21.38
	Al <sub>2</sub> O <sub>3</sub>	4.66
	Fe <sub>2</sub> O <sub>3</sub>	3.19
	SO <sub>3</sub>	2.37
	MgO	1.68
	Ignition loss	3.23

Fly ash: Grade I fly ash, and its chemical composition is shown in Table 2.

Table 2. Chemical composition of fly ash/%.

SiO <sub>3</sub>	50.30
Al <sub>2</sub> O <sub>3</sub>	32.95
Fe <sub>2</sub> O <sub>3</sub>	6.76
CaO	4.63
Na <sub>2</sub> O, K <sub>2</sub> O	1.69
SO <sub>3</sub>	1.10
MgO	0.35

Fine aggregate: natural river sand with an apparent density of 2682 kg/m<sup>3</sup> and a mud content of 2.7%, and its sieving curve is shown in Figure 1.

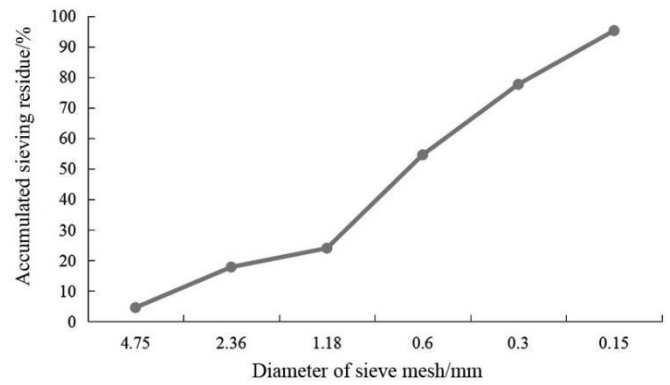


Figure 1. The sieving curve of fine aggregate.

Coarse aggregates: ① natural aggregates: gravel; ② RCA: waste C30 concrete. The basic properties of the two aggregates are shown in Table 3.

Table 3. Basic properties of coarse aggregates.

	Gravel	RCA
Grain size/mm	4.75-25	4.75-25
Apparent density (kg/m <sup>3</sup> )	2775	2655
Bulk density (kg/m <sup>3</sup> )	2283	2147
Water absorption rate/%	0.28	0.54

Water-reducing agent: polycarboxylate superplasticizer with a water reduction rate of 25%-40%

Water: tap water

### 2.2 Specimen preparation

The concrete strength grade was C30. According to Specification for Mix Proportion Design of Ordinary Concrete JGJ55-2011, the water-cement ratio was finally determined to be 0.45, and the RCA replacement rates were 0%, 30%, 50% and 100%, respectively. The specific mix proportions are shown in Table 4.

Table 4. Design of the mix proportion in RAC.

Specimen number	RAC-0	RAC-1	RAC-2	RAC-3
Cement (kg/m <sup>3</sup> )	341	341	341	341
Fly ash (kg/m <sup>3</sup> )	114	114	114	114
Fine sand (kg/m <sup>3</sup> )	700	700	700	700
Gravel (kg/m <sup>3</sup> )	1016	711	508	0
RCA (kg/m <sup>3</sup> )	0	305	508	1016
Water reducing agent/%	1	1	1	1
Water (kg/m <sup>3</sup> )	250	250	250	250

The specimen was prepared by mechanical mixing. The order of adding materials was coarse aggregate → fine aggregate → fly ash → cement → water. The water reducing agent was dissolved in water in advance. The mixing lasted for 90 s every time. After the materials were mixed evenly, the mixture was poured into a mold for vibration. The mold was removed 36 h after moulding. Then, the specimen was cured for 28 d under 25 °C.

The specification of the specimen was 100 mm × 100 mm × 100 mm. The specific conditions of the specimens are shown in Table 5. The average values were taken as the test results.

Table 5. Specific conditions of test specimens.

Experimental content	The number of specimens
Mechanical performance test	6 specimens each group, 3 for testing the compressive strength and another 3 for testing the tensile strength
Compressive strength test under an extreme cold environment	6 specimens each group, 3 cured under -10 °C and another 3 under -20 °C
Frost resistance durability test	6 specimens each group, 3 as a control group and another 3 as a test group

### 2.3 Mechanical performance test

The compressive strength test followed Standard for Test Method of Mechanical Properties on Ordinary Concrete. The equipment was a YA-2000 pressure testing machine. After reaching the specified age, the specimen was taken out, dried and placed in the center of the testing machine. The position of the specimen was adjusted to ensure that the pressure-bearing surface was evenly stressed. The load was continuously applied at a speed of 0.5-0.8 MPa/s. When the peak load rapidly declined or the specimen rapidly deformed, the valve was closed, and the data were recorded. The compressive strength of the specimen was calculated as follows:

$$f_c = \frac{F}{A}, \quad (1)$$

where  $F$  is the failure load of the specimen and  $A$  is the bearing area.

The tensile strength test is as follows. The specimens which have been cured for a specified age were taken out, dried, and placed on the center of the pressing plate of the testing machine. After the backing strips were put between the pressing plates, the testing machine was turned on. The load was gradually increased at a speed of 0.02 ~ 0.05 MPa/s until the test specimen failed. The failure load was recorded. The calculation formula of the tensile strength of the specimen is:

$$f_s = \frac{2F}{\pi A}, \quad (2)$$

where  $F$  is the failure load of the specimen and  $A$  is the bearing area.

### 2.4 Compressive strength test under an extreme cold environment

The test method of the compressive strength is the same as the last section. The specimens were put into an incubator. The temperature decrease rate was 1 °C/min. After decreasing to -10 °C and -20 °C, the constant-temperature curing was conducted. After reaching the specified age, the specimens were taken out and dried for the compressive strength test.

### 2.5 Frost resistance durability test

The frost resistance test adopted the fast-freezing method. The cured specimen was immersed in (20 ± 2) °C water, and the liquid level was 20 mm higher than the test specimen. After four days of immersion, the fast-freezing test was carried out using a NELD-DTV freeze-thaw circulation box. Before freeze-thaw, it was dried, and the quality and transverse fundamental frequency of the specimen was

detected. The water level in the box was 5 mm higher than the test specimen. The specimen was taken out every 25 cycles for measurement. Finally, the test specimen experienced 100 cycles.

### 2.6 Frost resistance durability evaluation index

(1) Mass loss rate  $\Delta w_n$ : Under the action of freeze-thaw, the slurry on the surface of the specimen fell off. At that moment, the mass of the specimen decreased. The larger the  $\Delta w_n$  was, the more the specimen lost the slurry, and the worse the frost resistance durability was. Its calculation formula is:

$$\Delta w_n = \frac{G_0 - G_n}{G_0}, \quad (3)$$

where  $G_0$  refers to the mass of the non-cycled specimen and  $G_n$  refers to the mass of the specimen after N cycles.

(2) Compressive strength loss rate  $\Delta f_c$ : After freeze-thaw damage, the strength of the specimen will also drop. The larger the  $\Delta f_c$  was, the more the strength of the specimen decreased, and the worse the frost resistance durability was. The formula is:

$$\Delta f_c = \frac{f_{c0} - f_{cn}}{f_{c0}}, \quad (4)$$

where  $f_{c0}$  refers to the compressive strength of the comparison group and  $f_{cn}$  refers to the compressive strength after N cycles.

(3) Relative dynamic elastic modulus  $P$ : It was used to characterize the damage to the internal structure of the specimen under the action of freeze-thaw. The larger the value was, the higher the degree of freeze-thaw damage to the specimen was, and the worse the frost resistance durability was. Its calculation formula is:

$$\Delta f_c = \frac{f_n^2}{f_0^2}, \quad (5)$$

where  $f_0$  refers to the horizontal fundamental frequency of the non-cycled specimen and  $f_n$  refers to the transverse fundamental frequency after N cycles.

## 3 EXPERIMENTAL RESULTS

The compressive and tensile strength of the test specimens under different replacement rates are shown in Table 6.

Table 6. The compressive and tensile strength of RAC specimens.

		Compressive strength/M Pa	Average compressive strength/M Pa	Tensile strength/M Pa	Average tensile strength/M Pa
RA C-0	1	32.74	34.36	3.41	3.36
	2	34.68		3.28	
	3	35.67		3.39	
RA C-1	1	36.12	35.67	4.27	4.20
	2	35.78		4.09	
	3	35.12		4.16	
RA C-2	1	31.27	29.27	3.88	3.77
	2	27.68		3.79	
	3	28.86		3.65	
RA C-3	1	26.36	26.82	3.81	3.72
	2	25.78		3.62	
	3	28.32		3.73	

It was seen from Table 6 that the average compressive strength of RAC-1 was 3.81% higher than that of RAC-0 (35.67 MPa vs. 34.36 MPa). Then, with the increase of the replacement rate, the compressive strength of the specimens decreased, and the average compressive strength of RAC-3 became 36.82 MPa, which was 24.81% lower than RAC-1. The average tensile strength of RAC-1 was 25% higher than that of RAC-0 (4.20 MPa vs. 3.36 MPa), and the tensile strength of RAC-2 and RAC-3 was not as good as RAC-1. It was found that the strength of the specimen was good when the replacement rate was 30%.

The compressive strength of the test specimens under an extreme cold environment is shown in Table 7.

Table 7. The average compressive strength of RAC specimens under an extreme cold environment (unit: MPa).

	25 °C	-10 °C	-20 °C
RAC-0	34.36	38.67	49.87
RAC-1	35.67	39.58	49.92
RAC-2	29.27	37.87	47.63
RAC-3	26.82	36.64	46.74

It was seen from Table 7 that the compressive strength of the test specimens significantly increased with the decrease of the temperature. Under -20 °C, the compressive strength of RAC-0, RAC-1, RAC-2 and RAC-3 increased by 45.14%, 39.95%, 62.51% and 74.27%, respectively. It was found that the higher the replacement rate of RCA was, the larger the improvement amplitude of the compressive strength was, which might be because water in the internal gap of the specimens froze under the extreme cold environment.

The masses and loss rates ( $\Delta w_n$ ) of RAC specimens with different replacement rates of RCA are shown in Table 8 and Figure 2.

Table 8. Variations of the mass and  $\Delta w_n$  of RAC specimens.

Number of freeze-thaw cycles/time	0					
	25	50	75	100		
RAC-0	Mass/g	9876	9746	9732	9626	9601
	$\Delta w_n$ /%	-	1.3	1.4	2.5	2.78
RAC-1	Mass/g	9801	9702	9819	9604	9422
	$\Delta w_n$ /%	-	1.0	-	2.0	3.87
RAC-2	Mass/g	9794	9788	9691	9550	9369
	$\Delta w_n$ /%	-	0.0	1.0	2.4	4.34
RAC-3	Mass/g	9812	9780	9848	9687	9266
	$\Delta w_n$ /%	-	-	-	1.2	5.56

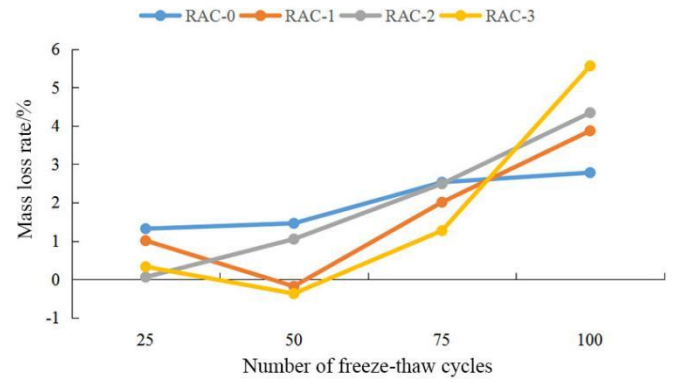


Figure 2. Variations of the mass and  $\Delta w_n$  of RAC specimens.

It was seen from Table 8 and Figure 2 that as the experiment proceeded, the  $\Delta w_n$  showed an increasing trend, and when the number of freeze-thaw cycles was less than or equal to 50 times, the  $\Delta w_n$  of the specimens were less than 2%, among which, RAC-1 showed negative values after 50 cycles, and RAC-3 was also negative after 25 and 50 cycles, which might be because RCA with greater water absorption rate than natural aggregates produced more cracks under freeze-thaw and fully absorbed water before freeze-thaw damage, and the slurry on the surface of the specimens has not yet fallen off. After the number of cycles reached 75, the  $\Delta w_n$  of the specimen added with RCA was smaller than that of RAC-0, but after the cycle reached 100 times, the  $\Delta w_n$  of RAC-1 and RAC-2 showed a significant increase, among which, the  $\Delta w_n$  of RAC-3 was the largest (5.56%) and was 50% larger than RAC-0. When the number of cycles increased from 75 to 100, the  $\Delta w_n$  of RAC-0 only increased by 0.25%, while RAC-1, RAC-2, and RAC-3 all showed a substantial increase. It was probably because the freeze-thaw damage of RCA was more severe after the occurrence of freeze-thaw damage due to a greater water absorption rate. Overall, the higher the replacement rate of RCA was, the larger the  $\Delta w_n$  of the specimen was.

The variation of the compressive strength of the specimens is shown in Table 9.

Table 9. Variation of the compressive strength of RAC specimens.

		Comparison group		Test group	
		Compressive strength/M Pa	Average value of compressive strength/MPa	Compressive strength/M Pa	Average value of compressive strength/MPa
RA C-0	1	31.28	33.50	27.86	28.24
	2	35.64		26.87	
	3	33.57		29.98	
RA C-1	1	36.78	34.56	27.21	27.97
	2	32.16		29.67	
	3	34.74		27.03	
RA C-2	1	30.12	29.12	24.66	23.32
	2	28.07		23.52	
	3	29.16		21.77	
RA C-3	1	32.12	31.67	20.16	18.73
	2	32.46		18.05	
	3	30.44		17.98	

It was seen from Table 9 that the compressive strengths of the comparison groups were all significantly higher than those of the test groups. The compressive strengths of the test groups showed that the compressive strengths of the specimens after freeze-thaw decreased continuously as the RCA replacement rate increased. The average value of the compressive strength of RAC-0 was 28.24 MPa, the corresponding value of RAC-1 was 27.97 MPa, which was 0.96% smaller than that of RAC-0, and the corresponding value of RAC-2 was 23.32 MPa, which was 17.42% smaller than RAC-0, and the corresponding value of RAC-3 was 18.73 MPa, which was 33.68% smaller than RAC-0. The strength loss rate  $\Delta f_c$  of different specimens was calculated, and the results are shown in Figure 3.

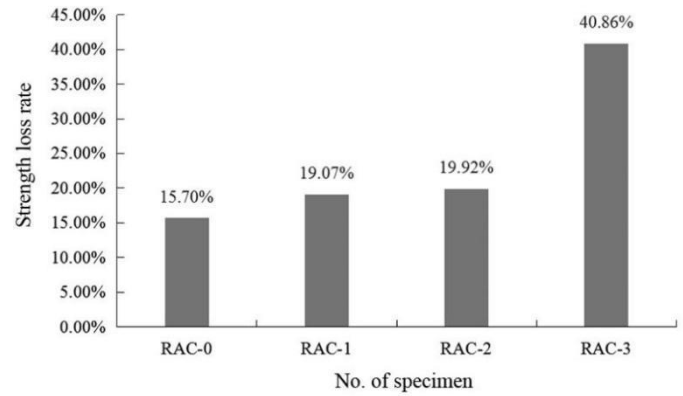


Figure 3. Variation of  $\Delta f_c$  of RAC specimens.

It was seen from Figure 3 that as the RCA replacement rate increased, the  $\Delta f_c$  of the specimen increased continuously; the  $\Delta f_c$  of RAC-0) was 15.7%, the  $\Delta f_c$  of RAC-1 was 19.07%, which was 3.37 % larger than that of RAC-0, and the  $\Delta f_c$  of RAC-2 was 19.92%, which was 4.22% larger than that of RAC-0, indicating that the influence on the strength of the specimen was small when the replacement rate of RCA was below 50%. The  $\Delta f_c$  of RAC-3 was 40.86%, which was 25.16% larger than that of RAC-0 and about 20% larger than that of RAC-1 and RAC-2, indicating that the strength of the specimen significantly decreased when the replacement rate of RCA reached 100%.

The relative dynamic elastic modulus P of different specimens was compared, and the results are shown in Figure 4.

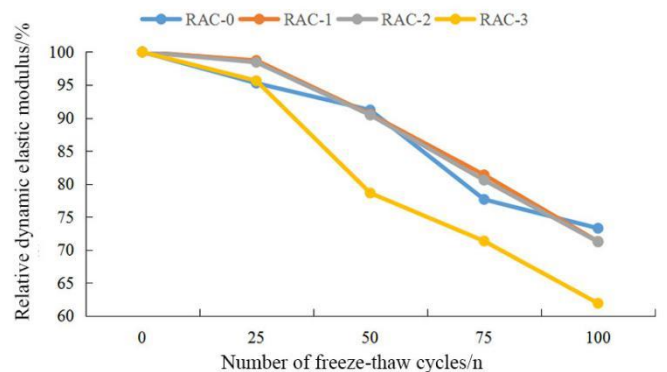


Figure 4. Variation of P of RAC specimens.

It was seen from Figure 4 that with the increase of the number of freeze-thaw cycles, the P value of the specimens decreased gradually, among which, the P value of RAC-3 decreased the most. Before the test, the P value of RAC-3 was 100%, while after 100 freeze-thaw cycles, the P value of RAC-3 dropped to 61.89%, which was 38.11% lower compared to before, the P value of RAC-0 was 72.27%,

which decreased by 27.73% only, and the P values of RAC-1 and RAC-2 were also around 70%. After 25 freeze-thaw cycles, the P values of the specimens decreased slightly, all within 5%, and when the number of cycles reached 50, the decrease of the P value of the specimens became significantly larger, for example, the P value of RAC-1 decreased from 95% to 80% and even 70%.

#### 4 DISCUSSION

With the progress of society, the construction industry is also developing, and the renovation of old houses and infrastructure construction brings more and more construction waste (Xie et al. 2021), of which concrete accounts for more than half of the total (Tam et al. 2015). At present, construction waste is usually disposed of by landfill or stacking (Ding et al. 2016), which not only occupies a large number of land resources but also brings negative impact to the environment (Huang 2020). In addition, the construction of cities cannot be separated from the consumption of construction materials. Aggregate, as a natural resource, is not renewable in the short term, and excessive mining and use of aggregate will also cause a shortage of resources. Therefore, the treatment and utilization of construction waste are particularly important (Lotfi et al. 2015), which can not only reduce the pollution of the environment but also help to alleviate the problem of resource shortage (Baena et al. 2016). Thus, research on RAC is increasingly becoming a focus (Li et al. 2021), such as fatigue performance (Liu et al. 2015), bonding performance (Prince and Singh, 2015), strength prediction (Khademi et al. 2016), and service life prediction (Stambaugh et al. 2018).

In this paper, the frost resistance durability of RAC was studied to analyze the effect of different RCA replacement rates. The experimental results showed that the higher the RCA replacement rate was, the worse the mechanical performance was. When the replacement rate was 30%, the compressive and tensile strength of the specimens were good. Moreover, the higher the replacement rate of RCA was, the better the compressive strength of the specimens was, but the worse the frost resistance durability of the specimens was. When RCA was not added, the mass of the specimens decreased from 9876 g to 9601 g after 100 times of freeze-thaw, and the mass loss rate  $\Delta w_n$  was 2.78%; when the RCA replacement rate was 100%, the mass of RAC-3 decreased from 9812 g to 9266 g, and the  $\Delta w_n$  was 5.56%, which was 2.78% higher than that of RAC-0. In terms of strength loss rate ( $\Delta f_c$ ), there was a big difference between the comparison groups and the

test groups. After freeze-thaw cycles, the strength of the specimens all showed a significant decrease; the higher the RCA replacement rate was, the greater the degree of decrease was. Combined with Figure 3, it was found that the increase in the  $\Delta f_c$  of RAC-1 and RAC-2 was not significant compared to RAC-0, but the  $\Delta f_c$  of RAC-3 and RAC-4 significantly increased. After freeze-thaw cycles, the  $\Delta f_c$  of RAC-3 reached 40.86%. Finally, in terms of the relative dynamic elastic modulus (P value), after 50 freeze-thaw cycles, the P values of the specimens began to decrease significantly, and the decrease of RAC-3 was the most obvious, from 100% before freeze-thaw to 61.89%.

Although some results have been achieved in this paper on the frost resistance durability of RAC under an extreme cold environment, this paper has some shortcomings, for example, whether there are other factors affecting the frost resistance durability of specimens, such as the strength of RCA, specimen matching ratio, etc., besides the RCA replacement rate, which need to be addressed in future work.

#### 5 CONCLUSION

In this paper, the frost resistance durability of RAC under an extreme cold environment was investigated, and specimens with different RCA replacement rates were designed. After the mechanical performance test, it was found that the strength of the specimen was good when the replacement rate was 30%; the higher the replacement rate of RCA was, the higher the compressive strength of the specimen was. However, it was found from the test of frost resistance durability that:

- (1) the higher the RCA replacement rate was, the greater the mass loss rate of the specimen was;
- (2) the higher the RCA replacement rate was, the greater the strength loss rate of the specimen was;
- (3) the higher the RCA replacement rate was, the lower the relative dynamic elastic modulus of the specimen was.

The experimental results show that an excessively large RCA replacement rate is not conducive to the frost resistance durability of the specimen; therefore, the RCA replacement rate needs to be controlled for applications of RAC in extremely cold environments to meet the service requirements.

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