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Research paper

Investigating freeze-proof durability of air-entrained C30 recycled coarse aggregate concrete

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Abstract: Incorporation of air-entraining agent has improved recycled concrete freeze-proof durability. However, it is very lacking to study the role of the entraining agent. In this paper, the influence of an air-entraining agent on freeze-proof durability for the ordinary C30 recycled coarse aggregate (RCA) concrete and air-entrained C30 RCA concrete was investigated with the laboratory comparative tests. The mass loss, the dynamic modulus of elasticity, ultrasonic wave velocity and cubic compressive strength were measured during freeze-thaw cycles. The test result showed the concrete's performance was similar to the ordinary concrete and was better than that of other recycled concretes when the content of RCA was 50% and 0.03% of air-entraining agent was added for C30 RCA concrete. Meanwhile, the addition of air-entraining agent has an improved effect on the performance of recycled concrete, but the effect was limited.

Keywords: Air-entraining agent; C30 recycled coarse aggregate concrete; freeze-thaw cycle; freeze-proof durability

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1. Introduction

With the rapid development of the construction industry, an increasing amount of construction waste is generated, and the proportion of waste concrete is the largest [3]. Recycling of waste concrete is an inevitable choice for saving natural resources, protecting the environment, and reducing construction costs [15]. Meanwhile, recycling is also an important aspect of achieving sustainable development. The replacement of natural coarse aggregate with recycled coarse aggregate after crushing waste concrete in the production of new concrete is effectively conducted via recycling. At present, the mechanical properties of recycled concrete are mostly studied, but the research on durability is relatively scarce. The concrete structure damage caused by freeze–thaw cycles is one of the common issues encountered in the current concrete durability problems.

The global distribution of frozen soil accounts for approximately a quarter of the land area, while 53.5% of the area in China is seasonally frozen. Freezing damage extensively affects the durability of buildings in these areas. The concrete structure is easily damaged during the cyclical process of freeze–thaw, thus considerably increasing the cost of repair and reconstruction and also seriously threatening the safety of the buildings [4][7][10]. Therefore, studying the freeze-proof durability of recycled concrete considering environmental protection and resource-saving is crucial.

At present, many scholars have studied the influence of recycled aggregate content on the freeze-proof durability of recycled concrete. Roumiana [13] discussed the characteristics of recycled aggregate and its influence on the performance of recycled concrete and concluded that the recycled aggregate content is the basic factor affecting the freeze-proof durability of recycled concrete. Orie et al. [11] tested the compressive strength of recycled concrete with 0%, 30%, 50%, 80%, and 100% recycled coarse aggregate. Their results showed that the compressive strength of recycled concrete decreases with the increase in recycled coarse aggregate. Bogas [6] then investigated the surface scaling, mass loss, length change, residual ultrasound pulse velocity, and residual compressive strength for different fine recycled aggregate replacement ratios (0%, 20%, 50%, and 100%) subjected to 300 freeze–thaw cycles. The compressive strength generally decreases with the incorporation of fine recycled aggregate, especially in high-strength concrete. Subsequently, Zhang [16] prepared recycled thermal insulation concrete with different recycled aggregate contents and studied its basic mechanical properties at room temperature and after freeze–thaw cycles. The best freeze-proof durability and strength could be obtained when the replacement rate of recycled aggregate was 30%–50%. Various properties began to decline when the replacement rate was more than 50%.

Some scholars have adopted the method of adding air-entraining agents and studied the change in the internal structure of recycled concrete specimens to improve the freeze-proof durability of recycled concrete [2][14]. Gokce et al. [1] conducted freeze–thaw damage tests and explored the microstructure of freeze–thaw damage. Their results showed that the addition of the air-entraining agent alleviated the generation of cracks and reduced the number of voids in the recycled concrete. Li et al. [5] measured the compressive and flexural strengths of recycled fine aggregate mortar by adding different contents of air-entraining agent. Compressive and flexural strength could correspondingly be enhanced when the content of air-entraining agents was 0.25%, which was the optimal dosage. The influence of the air content on the concrete elastic modulus was studied using the Mori–Tanaka estimation method by Jiang et al. [12]. Results showed that the effective elastic moduli of the recycled concrete decreased with the air content.

Overall, studies on the influence of air-entraining agents on the freeze-proof durability of recycled concrete with different replacement rates of recycled coarse aggregate are few. The variations of mass loss, dynamic elastic modulus, ultrasonic velocity, cube compressive strength, and peak stress and strain of C30 recycled concrete and C30 air-entrained recycled concrete with 0, 25%, 50%, 75%, and 100% recycled coarse aggregate during 200 freeze–thaw cycles were studied, and the test results were compared and analyzed. The influence of air-entraining agents on the freeze-proof durability of recycled concrete with different recycled aggregate contents was obtained.

2. Materials and methods

2.1 Materials and mix proportion

Composite Portland cement with strength grade of 32.5 was selected in this test, and all physical and mechanical indexes met the Common Portland Cement (GB175-2007). The coarse aggregate includes natural coarse aggregate (NA) and recycled coarse aggregate (RA). The RA comprised C30 waste concrete by crushing. The size range of natural coarse aggregate was 5–40 mm with continuous grading. The fine aggregate was natural river sand with fineness modulus of 2.75 and an apparent density of 2594 kg/m^3, which belongs to medium sand. The air-entraining agent was powder, and the maximum air content limit of concrete mixed with an air-entraining agent was 4.5% according to the Code for Concrete Admixture Application (GB 50119-2013).

The strength grade of recycled concrete designed in this experiment was C30. In this work, the water–binder (W/B) and sand ratios were 0.46 and 45%, respectively. The RA replaced the NA with 0, 25%, 50%, 75%, and 100%. On this basis, the dosage of the additional air-entraining agent was 0.05%, and the water reduction rate was calculated as 6%. The specimens were named RAC0, RAC25, RAC50, RAC75, and RAC100 according to the five replacement rates. The mix proportions of the recycled concretes are listed in Table 1.

Table 1. Mix proportions of the recycled concretes

Specimen	W/B	Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	NA (kg/m^3)	RA (kg/m^3)
RAC0					1341.62	0
RAC25					985.68	335.41
RAC50	0.46	361.48	565.93	165.93	657.12	670.81
RAC75					301.18	1006.23
RAC100					0	1341.62

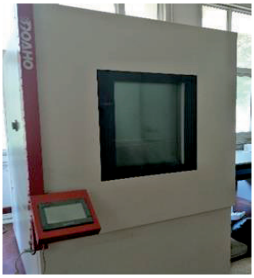
The air-entraining agent was added following the different replacement rates of RA, which are 0%, 25%, 50%, 75%, and 100%, and the specimens were respectively named YRAC0, YRAC25, YRAC50, YRAC75, and YRAC100. The mix proportions of the air-entrained recycled concretes are shown in Table 2.

Table 2. Mix proportions of the air-entrained recycled concretes

Specimen	W/B	Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	NA (kg/m^3)	RA (kg/m^3)	Air entraining agent (kg/m^3)
YRAC0					1197.04	0	
YRAC25					897.78	299.26	
YRAC50	0.46	361.48	539.25	165.93	598.52	598.52	0.18
YRAC75					299.26	897.78	
YRAC100					0	1197.04	

2.2 Test contents

A total of 200 freeze–thaw cycles of C30 recycled concrete (RAC) and C30 air-entraining recycled concrete (YRAC) were conducted in this experiment. The freeze-thaw cycle consists of freezing and thawing. Before freezing, the specimens should be saturated with water, and then put into the freeze-thaw tester for freeze-thaw cycle test. The freezing temperature is - 20℃ and the freezing time is 4h. After freezing, the specimens were thawed in 20℃ constant temperature water for 4h, and a freeze-thaw cycle was completed. The mass, dynamic modulus of elasticity, and ultrasonic wave velocity of concretes were tested every 25 cycles. Simultaneously, the compressive strength and peak stress and strain of concretes were tested. The main apparatuses are shown in Fig. 1.



(a) Freeze-thaw tester

(b) Dynamic modulus of elasticity of tester

(c) Tester Ultrasonic wave

(d) Uniaxial compression tester

Fig. 1 Experiment apparatuses

2.3 Grouping test and specimen numbering

Two types of concrete specimen sizes according to different tests are available. The first type of concrete specimens was cuboid (100 × 100 × 400 mm). Specimens were numbered as CRAC/CYRAC + replacement percentage + serial number + number of freeze–thaw cycles, where CRAC and CYRAC respectively represented recycled aggregate concrete cuboid specimens and air-entraining recycled aggregate concrete cuboid specimens; replacement percentage was the percentage of recycled coarse aggregate instead of natural aggregate, serial number denoted the same batch specimen number, and the number of freeze–thaw cycles indicated the number of freeze–thaw cycles experienced by concrete. The second type of concrete specimens was cube (150 × 150 × 150 mm). Specimens were numbered as LRAC/LYRAC + replacement percentage + serial number + number of freeze–thaw cycles, where LRAC and LYRAC respectively represented recycled aggregate concrete cube specimens and air-entraining recycled aggregate concrete cube specimens. The mass loss, dynamic modulus of elasticity, and ultrasonic wave velocity for the cuboid recycled concrete specimens after each 25 freeze–thaw cycles were tested from 0 to 200 freeze–thaw cycles. The cubic recycled concrete specimens were subjected to uniaxial compressive tests after the same freeze–thaw cycle.

3. Test result and analysis

3.1 Mass loss percentage

The mass loss of the specimen during the freeze–thaw cycle directly reflects the damage degree of the concrete. Fig. 2 shows the mass loss percentage of the RAC and the YRAC with different numbers of freeze–thaw cycles.

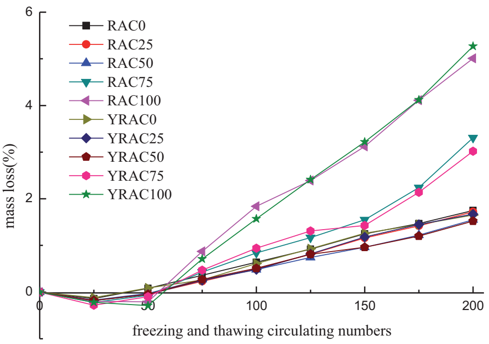


Fig. 2 Mass loss percentage of recycled concretes during freeze–thaw cycles

Fig. 2 indicates that the mass loss percentage of RAC and YRCA specimens revealed the same change trend during the entire freeze–thaw process. The mass of recycled concrete specimens slightly increased from 0 to 25 freeze–thaw cycles and gradually decreased after 25 times. The mass growth is attributed to the unnoticeable damage of recycled concrete specimens at the initial stage of freeze–thaw cycles. At this time, the moisture absorbed inside is larger than the mass loss. Therefore, the mass of recycled concrete specimens increased. After 25 freeze–thaw cycles, the curves of the mass loss percentage of recycled concrete with replacement rates of 0%, 25%, and 50% were considerably close, and the value of mass loss rate is substantially small at approximately −0.4%–1.5%. However, the mass loss percentage of recycled concrete with a replacement rate of 75% rapidly changed, reaching 3% at 200 freeze–thaw cycles. Particularly, the recycled concrete with 100% RA content had the fastest change in mass loss rate, reaching 5% at 200 times of freeze–thaw cycles, which exceeded the requirement of Standard for Long-term Performance and Durability Testing Method of Ordinary Concrete [8]. Therefore, the mass loss index reveals that the freeze-proof durability of the recycled concrete with a replacement rate of 100% did not meet the specification requirements. In addition, the RAC and the YRAC for recycled concrete with the same RA content almost coincided with the change law in mass loss. At the same time, the addition of air entraining agent has a slight effect on the mass loss rate of recycled concrete. This is because the frost resistance of concrete is not only related to the air content in the concrete mixture, but also related to the arrangement of air bubbles.

After 200 freeze–thaw cycles, the mass loss rates of recycled concretes with different RA contents were ranked as follows: YRAC100 > RAC100 > RAC75 > YRAC75 > RAC0 > RAC25 > YRAC25 > YRAC0 > RAC50 > YRAC50. The above results indicate that the value of mass loss was the minimum when the proportion of RA was 50% for the recycled concrete.

3.2 Dynamic modulus of elasticity

The dynamic modulus of elasticity of recycled concrete is an important performance parameter and closely related to its structure. From a macro perspective, the dynamic modulus of elasticity is a measure of the capability of recycled concrete to resist elastic deformation. Therefore, the dynamic modulus of elasticity can be used to evaluate the freeze-proof durability of the recycled concrete. The RAC and YRCA concrete specimens with different RA contents were divided into 10 groups, with 3 specimens in each group. The dynamic elastic modulus under different freeze-thaw cycles is tested, as shown in Fig. 3.

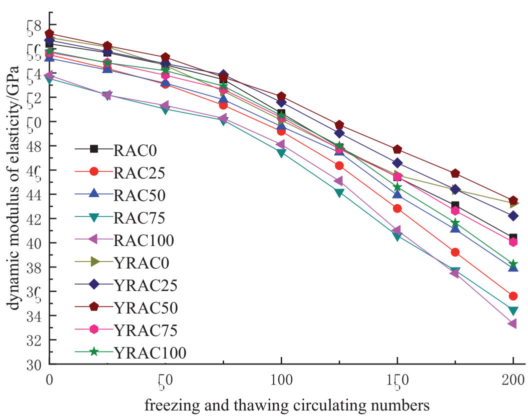


Fig. 3 Dynamic modulus of recycled concretse during freeze–thaw cycles

The dynamic modulus of elasticity of each specimen was measured before the freeze–thaw cycles. Fig. 3 shows that the RAC and the YRAC have similar trends in the change law of the dynamic modulus of elasticity during the entire process of freeze–thaw cycles. The trend gradually decreased with the increase in freeze–thaw cycle times. The relative dynamic modulus of elasticity was gradually reduced at this time. The dynamic elastic modulus of YRAC was larger than that of RAC when the RA content and freeze–thaw cycles were the same. This result indicates that the addition of air-entraining agents can improve the dynamic elastic modulus of recycled concrete. When the content of recycled aggregate is 50%, the dynamic elastic modulus of air entrained recycled concrete is the largest, which is 57.25 GPa. Meanwhile, with the addition of air-entraining agents, the initial dynamic elastic modulus of YRAC50 increases by approximately 3.0 GPA compared with RAC50. After 200 freeze–thaw cycles, the order of the dynamic modulus of elasticity was shown as follows: YRAC50 > YRAC0 > YRAC25 > RAC0 > YRAC75 > YRAC100 > RAC50 > RAC25 > RAC75 > RAC100. This order revealed that the dynamic elastic modulus of YRAC50 is always the largest, and its frost-resisting durability is superior to that of other recycled concrete. After 200 freeze-thaw cycles, the dynamic elastic modulus of RAC is less than that of YRAC, which indicates that air entraining agent can reduce the loss of dynamic elastic modulus of recycled concrete during freeze-thaw cycles. The statistical results of the relative dynamic modulus for the RAC and YRAC are presented in Table 3. After 200 freeze–thaw cycles, the relative dynamic modulus of elasticity of concrete specimens was ordered as follows: YRAC0 > YRAC50 > YRAC25 > RAC0 > YRAC75 > RAC50 > YRAC100 > RAC75 > RAC25 > RAC100. The results show that the relative dynamic elastic modulus of YRAC0 and YRAC50 concrete is larger, that is, the relative dynamic elastic modulus loss rate of YRAC0 and YRAC50 concrete is smaller, and their frost resistance is better than other concrete.

Table 3. Relative dynamic elastic modulus of recycled concretes

Specimen	No.	Freezing and thawing circulating numbers（times）								
		0	25	50	75	100	125	150	175	200
RAC0	1	100	98.0	96.7	94.5	89.3	84.1	80.7	78.5	75.2
	2	100	99.2	97.4	95.6	90.2	85.5	79.2	73.9	68.6
	3	100	98.9	96.6	94.2	90.0	85.0	81.6	76.8	71.2
RAC25	1	100	98.9	96.7	93.4	89.9	84.3	77.6	70.9	63.6
	2	100	97.9	95.8	91.5	87.9	82.4	76.7	69.5	63.7
	3	100	97.0	94.3	92.7	88.1	83.8	77.2	71.6	65.0
RAC50	1	100	98.4	96.9	93.8	90.0	85.9	79.7	74.8	68.3
	2	100	98.9	96.9	93.7	89.5	85.7	79.0	73.0	67.9
	3	100	97.5	95.0	94.0	90.0	86.3	80.1	75.5	69.6
RAC75	1	100	97.6	96.1	94.0	88.3	81.7	75.1	68.9	61.4
	2	100	96.9	94.9	92.8	87.9	81.1	75.7	71.3	63.2

Specimen	No.	Freezing and thawing circulating numbers（times）								
		0	25	50	75	100	125	150	175	200
	3	100	98.0	95.0	94.0	89.7	84.7	76.6	71.1	68.3
RAC100	1	100	96.0	94.4	92.7	89.9	83.0	76.0	69.9	60.3
	2	100	97.3	95.6	94.0	88.8	82.5	75.9	69.4	60.2
	3	100	97.6	96.1	93.6	89.5	85.9	76.9	69.6	65.1
YRAC0	1	100	98.9	97.9	93.5	88.3	84.9	81.7	79.2	76.2
	2	100	98.2	94.4	91.0	87.9	84.0	79.9	77.9	76.6
	3	100	98.9	95.4	92.2	87.9	83.0	78.6	76.8	75.2
YRAC25	1	100	98.9	98.0	95.9	91.9	87.3	84.6	79.9	75.6
	2	100	98.1	96.0	94.5	88.9	83.4	78.7	75.5	73.7
	3	100	97.9	95.9	94.7	92.1	88.9	83.1	79.6	74.0
YRAC50	1	100	98.9	96.8	94.1	91.5	87.7	83.9	80.9	76.3
	2	100	97.9	96.1	93.8	89.8	85.9	83.0	79.0	75.9
	3	100	97.9	96.8	93.2	91.5	86.9	83.1	79.5	75.6
YRAC75	1	100	98.1	96.5	94.9	89.8	84.9	81.1	77.0	71.9
	2	100	97.6	95.9	92.8	88.9	84.1	80.7	75.3	72.3
	3	100	98.2	95.8	94.3	90.9	86.7	81.6	76.1	70.3
YRAC100	1	100	98.8	98.0	95.9	92.0	87.8	82.0	76.9	71.4
	2	100	98.0	96.6	93.2	88.1	83.5	77.9	72.4	66.2
	3	100	98.0	96.8	95.6	91.5	86.9	79.9	74.6	68.1

After 200 freeze–thaw cycles, the relative dynamic modulus of elasticity of RAC and YRAC specimens was larger than 60%, which did not exceed the specification requirements[17] in this case. Therefore, the dynamic elastic modulus of RAC and YRAC could meet the requirements of freeze-proof durability.

3.3 Ultrasonic wave velocity

The ultrasonic wave can directly reflect the density of the concrete internal structure. A high ultrasonic wave velocity of the recycled concrete usually leads to an improved density of the internal structure. This finding indicates that the damage of the recycled concrete after undergoing the freeze–thaw cycles was small. Therefore, the ultrasonic wave velocity can be used to analyze the freeze-proof durability of recycled concretes. The ultrasonic wave velocities of RCA and YRCA in this study were tested during the freeze–thaw cycles. The test results are shown in Fig. 4.

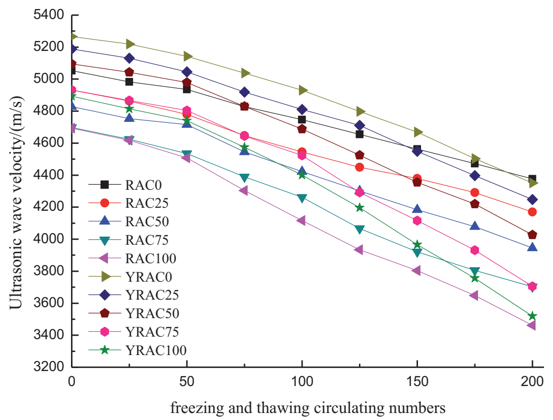


Fig. 4 Ultrasonic wave velocities of recycled concretes during freeze–thaw cycles

The change trend of the two kinds of recycled concrete was the same during the freeze–thaw cycle. The ultrasonic and the relative ultrasonic wave velocities gradually decreased with the increase in the freeze–thaw cycle times. The minimum relative ultrasonic wave velocity was not less than 70%, as shown in Fig. 4. Before the start of the freeze–thaw cycle, the initial ultrasonic wave velocity of specimens was ordered as follows: YRAC0 > YRAC25 > YRAC50 > RAC0 > RAC25 > YRAC75 > YRAC100 > RAC50 > RAC75 > RAC100. The addition of air-entraining agents could increase the initial ultrasonic wave velocity of recycled concrete. However, the initial ultrasonic wave velocity value decreases with the increase in RA content. This finding shows that the addition of air-entraining agents could improve this value but could not exceed the influence of the RA proportion. The ultrasonic wave velocity of YRAC decreased faster than that of the RAC with the same RA content after 100 freeze–thaw cycles. Therefore, air-entraining agents could accelerate the decreasing rate of the ultrasonic wave velocity. After 200 freeze–thaw cycles, the ultrasonic wave velocity of different concrete specimens was ordered as follows: RAC0 > YRAC0 > YRAC25 > RAC25 > YRAC50 > RAC50 > YRAC75 > RAC75 > YRAC100 > RAC100. Under the same freeze–thaw cycles, the ultrasonic wave velocity gradually decreased with the increase in RA content. Under the same RA content and freeze–thaw cycle times, the ultrasonic wave velocity value of YRAC is larger than that of RAC. This result indicates that the addition of air-entraining agents can improve the value of ultrasonic wave velocity.

3.4 Cubic compressive strength

Compressive strength, which is one of the evaluation indexes and acceptance standards of concrete mechanical properties, is crucial to the engineering structure. This index is also the intuitive expression of mechanical properties of recycled concrete. The test results of mass loss and dynamic elastic modulus of RAC and YRAC with different freeze–thaw cycles were verified by testing the cubic compressive strength.

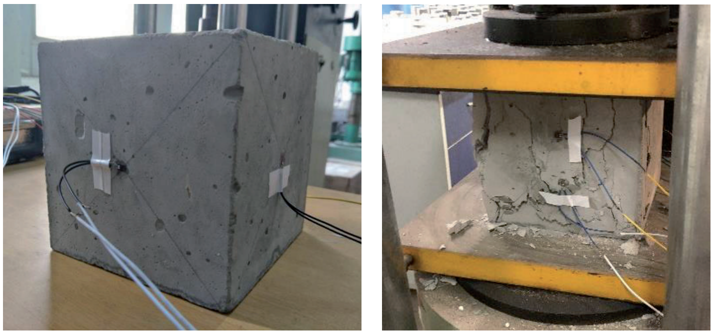
Table 4. Test results of compressive strength of recycled concretes

Specimen	No.	Freezing and thawing circulating numbers（times）								
		0	25	50	75	100	125	150	175	200
RAC0	1	38.96	38.59	37.69	35.99	34.59	33.64	32.21	30.08	29.28
	2	39.71	39.49	38.08	36.12	35.24	34.09	32.76	31.21	29.35
	3	38.99	38.72	37.86	35.94	34.96	33.78	32.49	30.44	28.64
RAC25	1	38.26	37.56	37.04	35.69	34.21	33.36	31.12	29.21	26.59
	2	38.11	37.39	36.99	35.37	34.71	33.47	31.06	28.59	26.38
	3	38.02	37.32	37.02	35.79	34.41	33.56	31.24	29.33	26.44
RAC50	1	38.26	37.56	36.89	35.49	33.19	32.12	32.12	29.78	27.08
	2	37.71	37.59	36.78	35.24	33.36	32.21	31.64	29.31	26.75
	3	37.99	37.12	36.56	35.31	33.28	32.07	31.84	29.24	27.17
RAC75	1	38.35	37.86	36.34	35.02	33.89	31.89	29.97	28.09	25.77
	2	38.24	37.9	36.25	34.94	33.96	31.99	29.96	28.01	25.64
	3	38.51	37.83	36.41	35.11	34.07	32.01	30.08	27.98	26.07
RAC100	1	37.96	36.56	35.19	33.99	32.33	31.12	28.86	26.94	23.95
	2	38.35	36.59	35.28	33.13	31.96	30.89	28.96	26.97	24.56
	3	38.28	37.12	35.76	34.81	32.68	30.97	28.89	27.08	24.68
YRAC0	1	39.96	39.70	39.06	37.31	35.88	34.90	33.84	31.65	29.23
	2	39.81	39.63	38.57	37.01	36.12	34.57	33.24	31.29	29.03
	3	39.79	39.59	38.76	37.08	36.08	34.87	33.55	31.06	28.83
YRAC25	1	38.16	37.08	36.03	34.63	33.10	32.04	30.55	28.56	26.25
	2	37.88	36.43	35.05	33.88	32.75	31.22	30.27	27.93	25.73
	3	37.94	36.69	35.37	34.13	32.48	30.89	29.90	28.06	25.62
YRAC50	1	38.70	38.22	37.58	36.22	34.49	33.36	31.86	29.93	28.06
	2	38.61	38.15	37.48	35.76	34.78	33.91	32.24	30.12	27.88
	3	38.52	37.93	37.58	35.91	34.48	33.23	31.73	29.87	27.56

Specimen	No.	Freezing and thawing circulating numbers（times）								
		0	25	50	75	100	125	150	175	200
YRAC75	1	38.15	37.40	36.23	35.07	33.33	31.34	29.05	26.42	23.35
	2	38.11	37.01	36.24	34.82	33.46	31.50	29.10	26.77	23.65
	3	38.14	37.47	36.44	34.54	32.98	30.94	28.65	26.57	23.53
YRAC100	1	37.98	36.81	35.59	34.01	31.97	30.76	27.74	25.43	22.44
	2	38.05	36.68	35.38	33.63	32.09	30.65	27.97	25.24	22.47
	3	38.08	37.00	35.57	34.63	32.13	30.43	27.60	25.03	22.27

The compressive strength of RAC and YRAC under the freeze–thaw cycle demonstrated the same change trend, that is, the compressive strength revealed a decreasing trend, as shown in Table 4. When the freeze–thaw cycle was 0, the initial values of the cube compressive strength of RAC and YRAC with different RA contents had minimal difference. This result indicates that the RA content has slight influence on the cube compressive strength of recycled concrete in a natural state. When the freeze–thaw cycle reached 200 times, the difference in compressive strength of concrete with different replacement rates of RA increased. This increase indicates that the freeze–thaw cycle has considerable influence on the compressive strength of recycled concrete. With the increase in the replacement rate of RA, the compressive strength of RAC and YRAC gradually decreased. However, the compressive strength of RAC25 was slightly lower than that of RAC50. This trend was related to the cement-based surface of recycled coarse aggregate and cracks generated in the crushing process. Under the same RA content, the compressive strength loss rate of YRAC was larger than that of RAC. The results show that air entraining agent has little effect on the compressive strength of recycled concrete, which may be due to the small number and small diameter of bubbles introduced into recycled concrete by air entraining agent. However, with the increase of freeze-thaw cycles, the amount of air entraining agent reduces the compressive strength of concrete.

3.5 Peak stress–strain analysis



(a) Specimen attached with strain gauges (b) Specimen compression process

Fig. 5 The process of uniaxial compression test

Compared with the strength characteristics of concrete, the deformation characteristics of concrete are the main mechanical properties of concrete materials. The stress–strain curve reflects the characteristics of the stress–strain process of the specimens. The stress–strain curves of recycled concrete specimens with different RA contents are obtained at every 25 freeze–thaw cycles in 0–200 cycles through the uniaxial compression test. The experimental process is shown in Fig. 5. The stress–strain curve of specimens indicates that the peak stress and strain of specimens were obtained. The peak stress and strain test results of RAC and YRAC under different freeze–thaw cycles are shown in Table 5.

Table 5. Peak stress and strain of recycled concretes under freeze-thaw cycle

Specimen	Items	Freezing and thawing circulating numbers（times）								
		0	25	50	75	100	125	150	175	200
RAC0	Peak stress δ (MPa)	39.7	39.2	37.1	37.22	35.7	34.83	33.6	32.08	31.28
	Peak strain ε (με)	1206	1231	1315	1365	1359	1384	1401	1412	1430
RAC25	Peak stress δ (MPa)	37.71	37.56	36.56	35.49	34.89	34.12	33.12	32.08	31.17
	Peak strain ε	1433	1443	1460	1477	1486	1500	1512	1562	1576

	(με)									
RAC50	Peak stress δ (MPa)	38.42	38.32	37.78	36.74	35.79	34.91	33.93	32.91	31.75
	Peak strain ε (με)	1491	1381	1381	1401	1432	1764	1898	1899	2080
RAC75	Peak stress δ (MPa)	38.35	37.86	36.34	35.02	33.96	33	31.39	30.18	29.07
	Peak strain ε (με)	1974	1988	1991	2198	2278	2294	2299	2299	2279
RAC100	Peak stress δ (MPa)	38.35	37.56	36.28	34.81	33.96	32.21	31.96	25.57	27.68
	Peak strain ε (με)	1908	2138	2199	2285	2329	2332	2392	2452	2531
YRAC0	Peak stress δ (MPa)	39.96	39.31	38.64	37.82	35.98	34.55	33.84	32.88	31.68
	Peak strain ε (με)	1206	1231	1315	1335	1359	1371	1391	1400	1421
YRAC25	Peak stress δ (MPa)	38.45	38.04	36.96	36.58	36.46	36.12	34.12	34.08	32.17
	Peak strain ε (με)	1539	1596	1593	1662	1737	1796	1809	1812	1820
YRAC50	Peak stress δ (MPa)	38.42	38.12	37.98	36.74	35.96	34.78	33.99	32.36	31.93
	Peak strain ε (με)	1682	1696	1824	1879	1932	1999	2029	2085	2263
YRAC75	Peak stress δ (MPa)	38.24	37.79	36.64	35.32	33.96	33	31.39	30.18	29.07
	Peak strain ε (με)	1986	2015	2114	2198	2278	2309	2361	2355	2421
YRAC100	Peak stress δ (MPa)	38.65	37.56	36.35	34.81	33.96	32.61	30.98	29.63	28.38
	Peak strain ε (με)	1979	2115	2148	2241	2279	2319	2360	2448	2531

The change trend in peak stress and strain of RAC and YRAC were the same during freeze–thaw cycles. That is to say, with the freeze–thaw cycle, the peak stress and strain of RAC and YRAC with different replacement rates of RA contents gradually decreased and increased, respectively. Under the same RA content and the freeze–thaw cycles, the difference in peak stress between YRAC and RAC was small, and this difference was between 1 and 2 MPa.

The peak strain gradually increased with the RA content. When the content of RA is 0%, 75%, and 100%, the peak strain of YRAC was the same as that of RAC. When the content of RA is 25% and 50%, the peak strain of YRAC was significantly different from that of RAC, that is, the former was large. This finding indicates that the addition of air-entraining agents has a significant impact on the peak strain of recycled concrete with 25% and 50% RA contents.

4. Conclusions

C30 recycled coarse aggregate concrete was chosen as the research material in this test. Under the freeze–thaw cycles, the test was conducted for RAC and YRAC concretes with RA contents of 0, 25%, 50%, 75%, and 100%. The mass loss, dynamic modulus of elasticity, ultrasonic wave velocity, cubic compressive strength, and peak stress and strain of the RAC and YRAC specimens were compared and analyzed in this paper. The main conclusions were obtained as follows.

(1) With the increase of freeze-thaw cycles, the dynamic elastic modulus, ultrasonic wave velocity, cube compressive strength, and peak stress of RAC and YRAC decreased. However, during the freeze-thaw cycle, the mass of RAC and YRAC recycled concrete specimens slightly increased from 0 to 25 freeze–thaw cycles and gradually decreased after 25 times.

(2) According to the test results, the mass loss rate of YRAC50 is the smallest and the dynamic elastic modulus is the largest after 200 freeze–thaw cycles. Therefore, the freeze-proof durability of YRAC50 is better than that of other recycled concretes.

(3) The change trend in peak stress and strain of RAC and YRAC concretes with different RA contents is the same. The addition of air-entraining agents has minimal and significant effects on the peak stress and strain of recycled concrete with 25% and 50% RA, respectively. However, such agents have a slight effect on the peak strain of recycled concrete with 0%, 75%, and 100%.

(4) Under the same RA content and freeze–thaw cycle, the dynamic elastic modulus, ultrasonic wave velocity, and cube compressive strength of YRAC are higher than those of RAC. This finding indicates that air-entraining agents can improve the freeze-proof durability of recycled concretes.

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