sciendo
DOI: 10.2478/ace-2019-0047
ARCHIVES OF CIVIL ENGINEERING
Vol. LXV ISSUE 4 2019

FREEZE-PROOF DURABILITY OF CONCRETE INCORPORATING RECYCLED COARSE AGGREGATE

Xianghui Deng[1] **Liyuan Xue**[2] **Rui Wang**[3] **Xiaoyue Gao**[4]

The recycle of the building and demolition waste could reduce project expenses and save natural resources as well as solve problem about environmental risks incurred during the disposal of building waste. In this study, waste C30 concrete is taken an experimental material. The mass loss, ultrasonic velocity, dynamic modulus of elasticity and cubic compressive strength of recycled coarse aggregate concrete whose coarse aggregate replacement percentage is 25%, 50%, 75%, and 100% are tested and compared with NAC when the cycles of freezing and thawing are 0, 25, 50, 75, 100, 125, 150, 175, and 200 times. The results show: (1) Generally, the loss of mass, ultrasonic velocity, dynamic modulus of elasticity and cubic compressive strength constantly increase with the growth of freezing and thawing cycles. (2) Compared with the recycled concrete of other replacement percentages, the RAC50 shows relatively close performance to NAC in mass loss, the change of dynamic modulus of elasticity and cubic compressive strength. (3) Performances of RAC25 specimens are better than the other RAC specimens for the ultrasonic wave velocity.

Keywords: Recycled coarse aggregate concrete, freeze-thaw cycles, freeze-proof durability, investigation

---

[1] School of Civil and Architecture Engineering, Xi'an Technological University, No. 2 of Xuefu Road in Xi'an, shaanxi, China, E-mail: xianghuideng@xatu.edu.cn

[2] School of Civil and Architecture Engineering, Xi'an Technological University, No. 2 of Xuefu Road in Xi'an, shaanxi, China, E-mail: xueliyuanq1@qq.com

[3] School of Civil and Architecture Engineering, Xi'an Technological University, No. 2 of Xuefu Road in Xi'an, shaanxi, China, E-mail: wangrui@xatu.edu.cn

[4] School of Civil and Architecture Engineering, Xi'an Technological University, No. 2 of Xuefu Road in Xi'an, shaanxi, China, E-mail: 731558805@qq.com

1. INTRODUCTION

According to research statistics from the Chinese Academy of Sciences, China's construction waste generated in 2017 reached 2 billion tons, and an average of more than 2 billion tons of construction waste will be produced each year in the next 10 years. However, due to the lack of recycling technology, the annual recycling rate of construction waste is less than 10% [1]. Construction waste leads to numerous environmental problems, such as occupying a lot of land, polluting the environment, and so on. Therefore, it is very necessary and important to study the recycling of construction waste [2, 3]. The application of recycled aggregates (RA) as substitutes for natural aggregates (NA) in the engineering is deemed to be an important way, thereby achieving sustainability in the resource utilization [4]. In the past few decades, there are extensive scientific research conducted and many research results have been achieved on the aspect [5].

In the research of recycled concrete, since a large amount of recycled concrete may be used in cold regions, it is very important to study the frost resistance durability of recycled concrete [6]. From current research, the research mainly focuses on three aspects, namely the recycling of concrete fine aggregate, the recycling of coarse aggregate and the impact of admixture on the frost resistance durability of recycled concrete. On the effect of fine aggregate, Bogas et al. characterized the freeze-thaw durability of normal-strength and high-strength concrete with different replacement of fine recycled concrete aggregates [7]. As per the conclusion, incorporation of fine recycled aggregates did no harm to the freeze-thaw durability of recycled concrete. In some subsequent studies, some scholars suggested that the usage of fine concrete aggregates undergone recycling was not necessarily inauspicious [8, 9]. On mechanical properties of recycled coarse aggregate concrete, some studies showed that the increase in recycled coarse aggregate replacement rate would affect the strength of recycled concrete. Meanwhile, the compressive strength could be 10–25% lower than conventional concrete for 100% replacement [10]. Etxeberria et al. reported losses of 20–25% for 100% replacement, retaining the same effective w/c percentage (0.50) and the same cement content [11]. However, the other research suggested that the use of 20%-30% recycled coarse aggregate produces no significant changes with respect to the control mixture with 0% recycled coarse aggregate [12]. In the recycled aggregate concrete, the use of fly ash may drastically boost the resisting capacity to chloride ingress and resistance to sulphate erosion. Therefore, the service life of concrete may be lengthened when the concrete exposed to such environment [13, 14]. Salem and Burdette suggested that the air-entrained had negative effects on the recycled aggregate concrete in frost resistance [15]. In addition, the recycled aggregate concrete could be as durable as natural aggregate concrete by adding air-entraining agent and fly ash. Gokce et al. [16] investigated the role of air content in demolished concrete. The results showed that recycled coarse aggregate produced from non-air-entrained concrete incurred poor freeze-thaw resisting ability. From the current three items of recycled concrete above, coarse aggregates account for a large proportion of concrete, such research of recycled coarse aggregate is of great significance for saving resources, protecting the environment, and achieving sustainable development. However, due to the complex source of recycled coarse aggregate concrete materials, it is easy to lead to unstable anti-freezing performance of recycled coarse aggregate concrete. Therefore, it is necessary to study the anti-freeze durability of recycled coarse aggregate concrete from different material sources.

Though recycled coarse aggregate concrete shows discrepancy with the ordinary concrete, the test methods investigating freeze-proof durability of ordinary concrete can be adopted. C30 concrete was selected as the research object since it was extensively used in civil engineering. The mass loss, dynamic modulus of elasticity, ultrasonic velocity and cubic compressive strength of the recycled coarse aggregate concrete specimens were tested after undergoing a number of freeze-thaw cycles. Freeze-proof permanence of C30 recycled coarse aggregate concrete was then assessed based on the results.

2. MATERIAL AND METHOD

2.1. EXPERIMENTAL MATERIALS AND SPECIMENS

The concretes specimen C30 was a compound of cement, water, sand and aggregates. Ordinary cement (strength grade: P.032.5) of Portland. Clean river sand (fineness modulus: 2.75). Natural aggregate (max particle size: 40 mm). As well as high-quality crushed aggregate (max particle size: 10 mm) were involved. The virgin aggregate used in the concretes was crushed pebble coarse aggregate and the fine aggregate was natural river sand. The recycled coarse aggregate used in this work is made of waste road concrete. The waste road concrete breaking and screening results are shown in Fig.1. The design strength of the waste road concrete investigated is C30, the core specimen examination implies that the compressive strength of the waste concrete is from 32.4MPa to 35.1MPa. Seen from Table 1, natural coarse aggregate (NCA), basic properties of recycled coarse aggregate (RCA) and the aggregate used in recycled road concrete (RRCA) were noted. Since wet mixed concrete has been widely used in China as a safe, economical and efficient construction method, the wet mixing method was adopted in this test. The wet mixing process is as follows: Firstly, add about 30% of the total water consumption to the mixture of sand and aggregate, and stir fully. Secondly, put the cement into the compound and stir. Ultimately, add around 70% of the gross water consumption, mix and stir all of them.


(a) Waste concrete (b) Breaking waste concrete (c) Screening coarse aggregate

Fig. 1 The waste road concrete collection site and screening results

Table 1 Basic properties of coarse aggregate

Coarse aggregate type	Grading (mm)	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Water absorption (%)	Density (kg/m^3)	Crushing index (%)
NCA	5.0-40.0	1432	2854	0.4	2650	17.7-18.9
RCA	5.0-40.0	1394	2498	4.6	2730	20.1-23.9
RRCA	5.0-40.0	1458	2584	0.8	2620	19.6-21.3
Sand	4.75	1508	2594	1.3	-	-

In Table 1, by contrast with natural coarse aggregate, the recycled coarse aggregate has lower density, higher absorbing rate, and higher crush index, which indicates that the recycled coarse aggregate has higher porosity and lower strength. The main reason is that the surface of the recycled coarse aggregate is covered by some cement mortar.

2.2. EXPERIMENTAL CONTENTS

(1) The mass loss of concrete specimen was tested during freezing thawing cycles. (2) The dynamic modulus of elasticity of concrete specimen was measured during the time period as above. (3) The velocity of ultrasonic of concrete specimen was assessed in the freeze-thaw cycle process. (4) The cubic compressive strength of concrete specimen was measured for different numbers during above mentioned period. All items and specifications of specimens of current study are in Table 2. The key devices are illustrated in Fig.2.

Table 2 Test items and specimen specification

Test items	Specifications of specimens (mm×mm×mm)
Mass loss, dynamic modulus of elasticity, Ultrasonic wave	100×100×400
Cubic compressive strength	150×150×150

(a) Quick concrete freeze-thaw tester (b) DT-20W dynamic modulus of elasticity of tester

(c) YA-2000 digital display pressure tester (d) Ultrasonic wave tester

Fig. 2 Experiment apparatuses

2.3. EXPERIMENT METHODS AND PROCEDURES

In this work, 200 freezing thawing cycles were conducted. The quick freezing method was used in this test because every freezing thawing cycle costs 2-4h [17]. Five replacement percentages of recycled coarse aggregate which are 0%, 25%, 50%, 75%, and 100% respectively were used in this test. Specimens were made according to the five replacement rates and named NAC, RAC25, RAC50, RAC75, and RAC100. When it comes to the admixture methodology, given the high water absorption percentage of recycled aggregates, a pre-wetting was a must. Hence, 10 minutes of water compensation was conducted, the quality was 50% of the recovered aggregate absorption. This value was used, since it presented the best result about the mechanical properties of the concretes among the pre-wetting contents evaluated as per studies of Troian. The mix proportions of the concretes are listed in Table 3.

Table 3 Mix proportions of concretes

Specimen	Cement (kg/m^3)	Sand (kg/m^3)	NA (kg/m^3)	RA (kg/m^3)	Water (kg/m^3)	W/C	Density (kg/m^3)
NAC	406	536	1252	0	166	0.41	2422
RAC25	406	536	938	314	166	0.41	2436
RAC50	406	536	628	628	166	0.41	2418
RAC75	406	536	314	938	166	0.41	2422
RAC100	406	536	0	1252	166	0.41	2428

The freeze–thaw cycle tests were carried out using the automatic quick concrete freeze–thaw tester in the laboratory. At present, the Chinese standard specification stipulated that when one of the following conditions occurred in the freeze-thaw cycle, the test could be stopped: 1) the specified number of freeze-thaw cycles was reached; 2) the relative dynamic modulus elasticity of specimens dropped to 60%; 3) the mass loss rate of specimens was up to 5% (GB/T50082-2009, China). Combined with the current research, the termination condition was reached 200 times. The freeze-thaw cycle was simulated 200 times and each freeze-thaw cycle should be completed in 2-4 h and the temperature ranged from 5°C to -20°C.

Under the conditions that the water-to-cement effective ratio was 0.41, 0.46, and 0.51, concrete specimens with RCA concrete replacement ratio being 0%, 25%, 50%, 75%, and 100%(by quality) of the NCA concrete were prepared. There were two types of specimens, namely a cube measuring 150×150×150 mm and a rectangular parallelepiped measuring 100×100×400 mm respectively (shown in Table 2). There were 3 rectangular parallelepiped specimens and 27 cube specimens prepared for each replacement percentage of recycled coarse aggregate concrete; 18 rectangular parallelepiped concrete specimens and 135 cube concrete specimens in total. In addition, average compressive strength of NAC, RAC25, RAC50, RAC75, and RAC100 were 39.2MPa, 38.0MPa, 38.1MPa, 38.4MPa, and 38.2MPa before the freeze-thaw cycles.

2.4. GROUPING TEST AND SPECIMENS NUMBERING

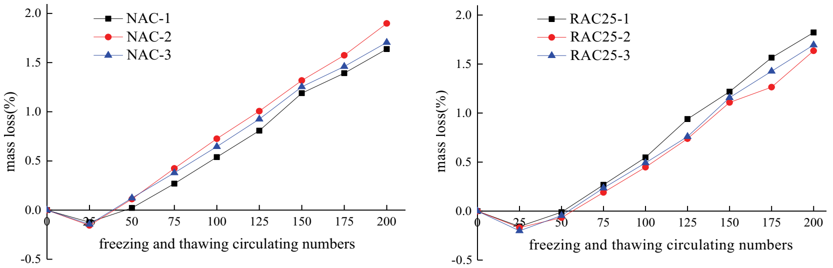
Specimens were numbered as RAC+ replacement percentage + serial number, where RAC represented recycled aggregate concrete; replacement percentage represented percentage of recycled coarse aggregate instead of natural aggregate, while, serial number indicated the same batch specimen number.

3. PROCEDURES AND RESULT ANALYSIS

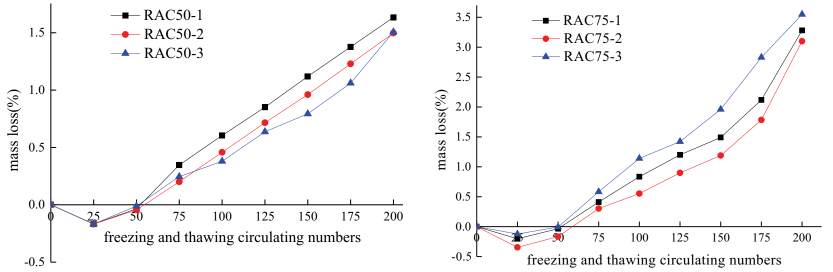
3.1. PERCENTAGE OF MASS LOSS

Table 4 Quality of concretes under freeze-thaw cycle

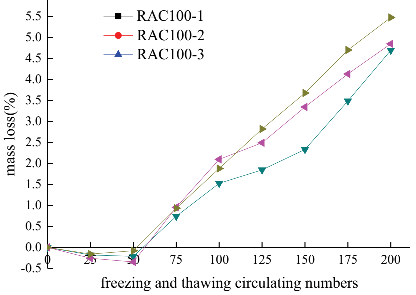
Specimen	Group	Freezing and thawing circulating numbers（times）								
		0	25	50	75	100	125	150	175	200
NAC	1	9.59	9.61	9.59	9.57	9.54	9.50	9.47	9.44	9.27
	2	9.54	9.55	9.54	9.52	9.49	9.47	9.43	9.42	9.26
	3	9.58	9.63	9.60	9.55	9.52	9.52	9.48	9.46	9.29
RAC25	1	9.58	9.60	9.57	9.56	9.54	9.50	9.47	9.44	9.27
	2	9.53	9.55	9.54	9.52	9.49	9.47	9.43	9.42	9.26
	3	9.57	9.61	9.63	9.57	9.54	9.51	9.45	9.46	9.29
RAC50	1	9.55	9.57	9.55	9.52	9.48	9.44	9.44	9.42	9.39
	2	9.50	9.52	9.51	9.48	9.46	9.44	9.41	9.39	9.36
	3	9.59	9.61	9.59	9.57	9.55	9.53	9.51	9.49	9.44
RAC75	1	9.61	9.63	9.61	9.57	9.53	9.50	9.47	9.41	9.30
	2	9.58	9.62	9.60	9.56	9.53	9.50	9.47	9.41	9.29
	3	9.57	9.58	9.57	9.51	9.46	9.43	9.38	9.30	9.23
RAC100	1	9.62	9.64	9.64	9.55	9.47	9.44	9.39	9.28	9.17
	2	9.58	9.60	9.61	9.49	9.38	9.34	9.26	9.18	9.11
	3	9.60	9.61	9.61	9.51	9.42	9.33	9.25	9.15	9.07



(a) NAC (b) RAC25



(c) RAC50 (d) RAC75



(e) RAC100

Fig. 3 Mass loss percentage of specimens during freeze–thaw cycles

The data in Table 4 demonstrates the quality of concretes at the RCA proportion of 0, 25, 50, 75 and 100% after 200 freeze-thaw cycles. The mass of concrete specimens decrease with the increase of freezing-thawing cycle. Fig.3 indicates that the mass loss of the NAC specimens and RAC specimens increases with the increase of freeze-thaw cycles. The mass loss of the NAC specimens and RAC specimens begins to increase after 50 freeze-thaw cycles. The reason is that the concrete has not peeled off in the early stage, but there are some micro-cracks generated on the surface and inside, which absorb water and lead to an increase in concrete mass. After 75 freeze-thaw cycles, the mass loss of RAC specimens begins to increase rapidly and the damage of concrete specimens begins to appear with the increment of cycle times. Surface of test piece has spall, and the mass loss ratio of each group of concrete begins to increase. Fig. 3 also shows that the mass of the concrete specimen drops mildly between 50 and 100 freeze-thaw cycles. The cause may be that the internal micro-pore of concrete is damaged and the water content of the concrete specimen grows. Mass loss is slightly greater than increment of water content, which constantly rises after 100 freeze-thaw cycles. When reaching 200 freeze-thaw cycles, mass loss percentages of NAC-1, NAC-2, and NAC-3 are 1.64%, 1.90% and 1.71% respectively. At this time, the mass loss percentages of recycled coarse aggregate concrete RAC25-1, RAC25-2, RAC25-3, RAC50-1, RAC50-2, RAC50-3, RAC75-1, RAC75-2, RAC75-3, RAC100-1, RAC100-2, and RAC100-3 are 1.82%, 1.64%, 1.70%, 1.63%, 1.50%, 1.51%, 3.28%, 3.10%, 3.55%, 4.70%, 4.85%, and 5.47% respectively. The result of cube compressive strength is better than the previous research result, because the recycled coarse aggregate used is selected. The water absorption rate of recycled coarse aggregate is 4.6 percent, which is slightly lower than the general recycled coarse aggregate. From the test results, the mass loss of RAC50 is smaller than that of the NAC and other recycled coarse aggregate concrete.

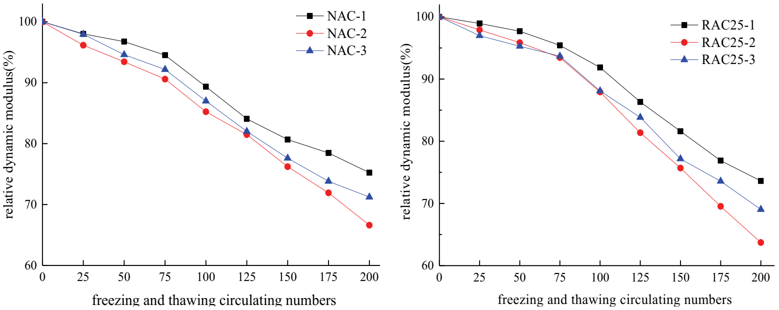
3.2. DYNAMIC MODULUS OF ELASTICITY TEST

The dynamic elasticity modulus of concrete is closely associated with the structures. The inner structure of concrete under-going the different freeze-thaw cycles would be damaged to some extent. As a consequence, the values changed after different freeze-thaw cycles could be used to evaluate concrete anti-freezing performance.

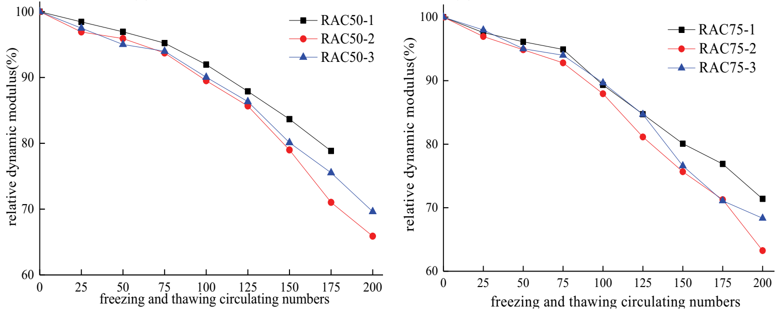
Table 5 Dynamic elasticity modulus of concretes under freeze-thaw cycle

Specimen	Group	Freezing and thawing circulating numbers（times）								
		0	25	50	75	100	125	150	175	200
NAC	1	55.49	54.38	53.68	52.45	49.57	46.65	44.76	43.54	41.74
	2	57.08	56.60	55.61	54.56	51.50	48.79	45.22	42.19	39.16
	3	56.67	56.07	54.74	53.37	50.99	48.17	46.25	43.53	40.36
RAC25	1	54.79	54.21	52.97	51.18	49.23	46.20	42.52	38.84	34.86
	2	56.08	54.91	53.75	51.29	49.30	46.19	43.01	38.99	35.73
	3	55.67	53.99	52.48	51.59	49.05	46.68	42.96	39.84	36.21
RAC50	1	54.28	53.44	52.62	50.93	48.83	46.62	43.24	40.62	37.09
	2	56.18	55.57	54.45	52.65	50.29	48.13	44.37	41.02	38.14
	3	55.17	53.78	52.42	51.85	49.67	47.63	44.19	41.66	38.41

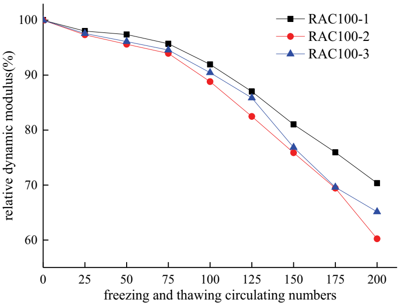
RAC75	1	51.28	50.03	49.29	48.21	45.29	41.91	38.50	35.32	31.48
	2	55.18	53.50	52.34	51.21	48.53	44.77	41.75	39.33	34.90
	3	54.17	53.08	51.47	50.92	48.56	45.88	41.49	38.51	37.02
RAC100	1	53.79	51.65	50.77	49.88	48.38	44.66	40.90	37.62	32.46
	2	52.46	51.06	50.16	49.29	46.59	43.27	39.80	36.42	31.59
	3	55.17	53.84	53.02	51.63	49.35	47.37	42.40	38.40	35.93



(a) NAC (b) RAC25



(c) RAC50 (d) RAC75



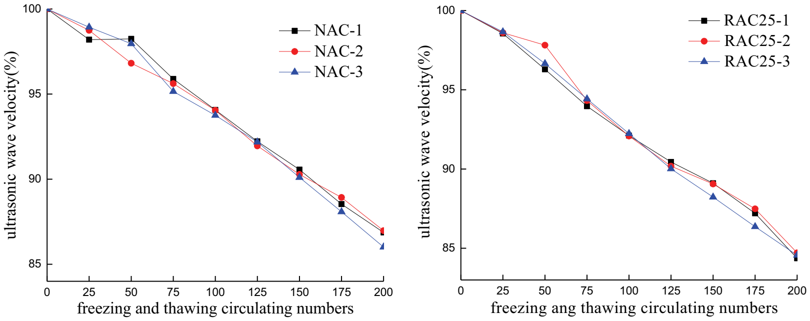
(e) RAC100

Fig. 4 Relative dynamic elasticity modulus of specimens during freeze-thaw cycles

Table 5 presents the dynamic elasticity modulus of concretes recycled concrete with five different coarse aggregate contents during freeze-thaw cycles. The dynamic elasticity modulus of concrete specimens decrease with the increase of freezing-thawing cycle. The relative dynamic elasticity modulus in Fig. 4 drops with the increase of freeze-thaw cycle times. The growth in freeze–thaw cycle times gives rise to mild enlargement of the specimen and inner fissure, whereby reducing the dynamic elasticity modulus of concrete. After 75 freeze-thaw cycles, the dynamic elasticity modulus of RAC specimens begins to increase rapidly with the increase of cycle times. The relative dynamic elasticity modulus of NAC specimens relative to the original value falls 24.8-33.4% after 200 freeze-thaw cycles. The values of RAC25, RAC50, RAC75 and RAC100 fall 26.4-36.3%, 25.6-34.8%, 28.7-36.8%, and 29.7-39.8% respectively. Compared with test results, the relative dynamic modulus of elasticity of RAC50 is the best at the different replacement percentage of RAC concrete specimens. Meanwhile, NAC and RAC concrete specimens reach the specification requirements.

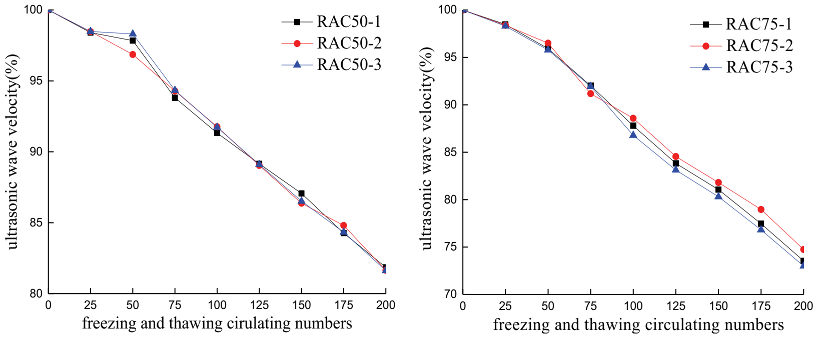
3.3. ULTRASONIC WAVE VELOCITY TEST

Measured ultrasonic wave velocity in this test corresponds to the propagation velocity of the ultrasonic wave in samples. Velocity of which in concrete is connected to its elastic property and internal structure (pore, material composition, etc.). Usually, when many defects occur to concrete after freeze-thaw cycles (fissures, holes, etc.), the speed in these sections is lower than in normal one. The changes in ultrasonic wave velocity of ordinary concrete and concrete specimens mixed with the different replacement percentage of recycled coarse aggregates were tested during the freeze-thaw cycles. The results are shown in Fig.5.

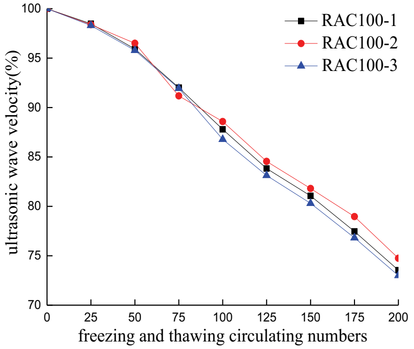


(a) NAC

(b) RAC25



(c) RAC50 (d) RAC75



(e) RAC100

Fig. 5 Ultrasonic wave velocity of specimens during freeze–thaw cycles

Fig. 5 shows that the ultrasonic wave velocity decrease with the increase of cycle times. After 75 freeze-thaw cycles, the ultrasonic wave velocity of RAC specimens begins to increase rapidly. Up to the 200th time, the relative ultrasonic wave velocities of NAC specimens NAC-1, NAC-2, and NAC-3 after 200 cycles fall to 86.87%, 86.97% and 86.01% of the original values, respectively; the relative ultrasonic wave speeds of RAC25 samples (RAC25-1, RAC25-2, and RAC25-3) decrease to 84.37%, 84.71%, and 84.55% of the original values, respectively. However, there is less reduction for the speeds of relative ultrasonic wave of RAC50 samples. The relative ultrasonic wave velocities of RAC50-1, RAC50-2, and RAC50-3 specimens decrease to 81.85%, 81.64%, and 81.62% of the original values, respectively. The test results also show a similar rule for RAC75 and RAC100 specimens. And the main difference is that ultrasonic wave velocities of RAC25 specimens are larger than that of other RAC specimens. From the test results, the drop of other replacement percentage

RAC specimens are smaller than that of NAC specimens and the relative ultrasonic wave velocities of RAC25 samples are closer to NAC specimens.

3.4. CUBIC COMPRESSIVE STRENGTH TEST

The compressive strength of concrete indicates its mechanical properties immediately. Therefore, this index is also critical to engineering structure. Cubic compressive strength test after curing the test piece under standard conditions for 28 days was conducted in accordance with Test Method of Mechanical Properties on Ordinary Concrete Standard (GB/ T 50081-2002) [17]. YA-2000 digital display pressure testing machine was used in this test. Loading speed of the testing machine is 8 KN/s. The test procedures are shown in Fig.6.

(a) Elastic stage (b) Micro crack generation stage

(c) Crack development stage (d) Fail stage

Fig. 6 Cubic compressive strength procedure of specimens

During the test, as the load increased, small cracks began to appear beside the outer surface of the test piece. Then, those cracks gradually joined together. Finally, as the force continued, the surface of concrete started to swell and flake off, ultimately forming a positive and negative connected quadrangular pyramid. The whole procedure could be roughly divided into elastic stage, micro crack generation stage, crack development stage and failure stage.

Cubic compressive strength test were conducted during the freeze-thaw cycles, results are in Fig 7-Fig 9. In the test, the strength loss of the RAC specimens was larger than that of NAC specimens with the increase of freeze-thaw cycle times. The rule in the strength loss of RAC specimens during such process is basically consistent with the changing rule about mass, the dynamic modulus of elasticity and ultrasonic wave speed. After 200 cycles of freezing and thawing, the average compressive strength of NAC, RAC25, RAC50, RAC75, and RAC100 declined to 28.1MPa, 25.0MPa, 26.5MPa, 23.9MPa, and 22.6MPa. From the test results, all RAC specimens meet the requirements of the specification in the concrete strength. The result of cube compressive strength is better than the previous research result, because the recycled coarse aggregate used is selected. The water absorption rate of recycled coarse aggregate is 4.6 percent, which is slightly lower than the general recycled coarse aggregate. However, from the value, the RAC50 reveals better performance than the other RAC specimens.

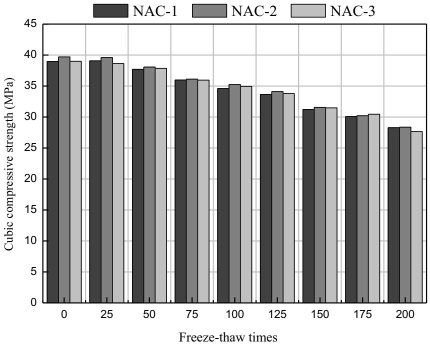
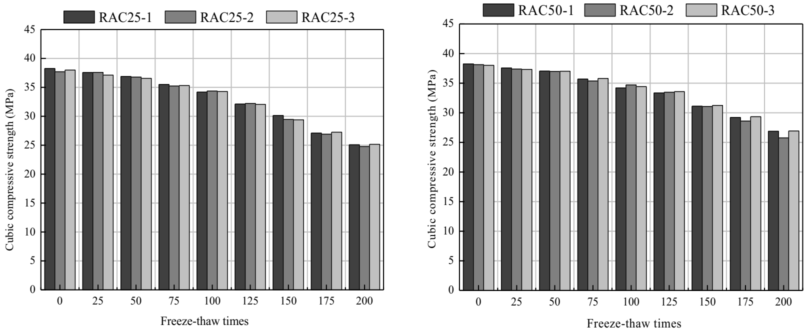
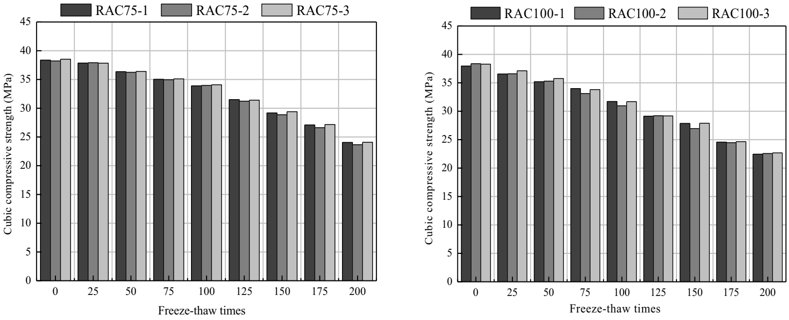


Fig. 7 Cubic compressive strength of NAC concrete specimens



(a) RAC25

(b) RAC50



(c). RAC75

(d). RAC100

Fig 8. Cubic compressive strength of RAC concrete specimens.

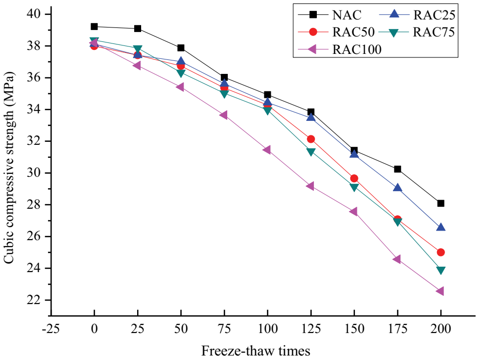


Fig. 9 Average cubic compressive strength curves

4. CONCLUSIONS

In this study, C30 concrete of waste road was selected as the materials, the fundamental properties of aggregates (bulk density, apparent density, density, water absorption, and crushing index) were conducted. Mechanical properties of RAC specimens (mass loss, dynamic modulus of elasticity and ultrasonic wave velocity, cubic compressive strength) had been investigated during the 200 freeze-thaw cycles. Meanwhile, test results were compared with the results of NAC specimens under the same circumstances. The main conclusions were presented as follows:

(1) Generally, the mass loss constantly increase with the growth of freezing and thawing cycles, the dynamic modulus of elasticity, ultrasonic velocity and cubic compressive strength decrease with the growth of freezing and thawing cycles.

(2) The mass loss of the NAC specimens and RAC specimens decreases with the increase of freeze-thaw cycles in the early stage. The mass loss of the NAC specimens and RAC specimens begins to increase after 50 freeze-thaw cycles. When reach the 200 freeze-thaw cycles, mass loss of NAC, RAC25, RAC50, RAC75, and RAC100 reach 1.9%, 1.8%, 1.6%, 3.6%, and 5.5%, which means RAC50 has a better freeze-thaw resistance compared with that of NAC and other RAC specimens.

(3) The dynamic modulus of elasticity decreases as the repetition of freeze-thaw cycles. The relative dynamic modulus of elasticity of NAC samples reduces by 24.8-33.4% relative to the original value. Nevertheless, relative dynamic modulus of elasticity of RAC specimens reduces by 26.4-36.3%, 25.6-34.8%, 28.7-36.8%, and 29.7-39.8% after 200 freeze-thaw cycles. Therefore, RAC50 is close to NAC and better than the other RAC specimens.

(4) For ultrasonic wave velocity test, the relative ultrasonic wave speeds of RAC specimens are smaller than the NAC specimens under the same freeze-thaw cycle times. In addition, the ultrasonic wave velocities of RAC25 specimens are larger than that of other RAC specimens, the density of RAC25 was better.

(5) The cubic compressive strength of concrete mixtures falls with the increase of freeze-thaw cycle times during freeze-thaw cycles. After 200 freeze-thaw cycles, all RAC samples meet the requirements of the specification in terms of the concrete strength. However, from the values, RAC50 has better performance than the other RAC specimens.

5. Acknowledgments

This research is financially supported by the Scientific Research Program (GXYD8.2) of the Science and Technology Department of Xi'an, the Key Research and Development Foundation (2018SF-391) of the Science and Technology Department of Shaanxi Province, the Housing and Urban-Rural Construction Foundation (2017-K55) of the Housing and Urban-Rural Department of Shaanxi Province.

REFERENCES

1. Amorim, N. S. Júnior, G. A. O. Silva, and D. V. Ribeiro. "Effects of the incorporation of recycled aggregate in the durability of the concrete submitted to freeze-thaw cycles", Construction and Building Materials., 161, 723-730, 2018.
2. S. Singh, S. Ramakrishna, M. K. Gupta. "Towards zero waste manufacturing: a multidisciplinary review, Journal of Cleaner Production", 168, 1230-1243, 2017.
3. L. Evangelista, J. Brito. "Durability performance of concrete made with fine recycled concrete aggregates, Cement and Concrete Composites", 32, 9-14, 2010.
4. K. K. Sagoe-Crentsil, T. Brown, A .H. Taylor. "Performance of concrete made with commercially produced coarse recycled concrete aggregate", Cement and Concrete Research, 31, 707-712, 2001.
5. X. H. Deng, Z. L. Lu, P. Li, T. Xu. "An investigation of mechanical properties of recycled coarse aggregate concrete", Archives of Civil Engineering, 62, 19-34, 2016.
6. J. H. Yan, K. H. Liu, C. Y. Zou, J. Wang. "Eccentric compressive behavior of recycled aggregate concrete columns after freeze-thaw cycles", Advances in Structural Engineering, 2018.
7. J. A. Bogas, J. de. Brito, D. Ramos. "Freeze-thaw resistance of concrete produced with fine recycled concrete aggregates", Journal of Cleaner Production, 115, 294-306, 2016.
8. L. Evangelista, J. de. Brito. "Mechanical behavior of concrete made with fine recycled concrete aggregates", Cement Concrete Composites, 29, 397-401, 2007.
9. J. M. Khatib. "Properties of concrete incorporating fine recycled aggregate. Cement Concrete Research", 35, 763-769, 2005.
10. J. X. Chen, X. H. Deng, Y. B. Luo, L. C. He, Q. Liu, X. Qiao. "Investigation of microstructural damage in shotcrete under a freeze-thaw environment," Construction and Building Materials, 83, 275-282, 2015.
11. M. Etxeberria, E. Vázquez, A .Marí, M. Barra. "Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete," Cement and Concrete Research, 37, 735-742, 2007.
12. C. Thomas, J. Setién, J. A. Polanco, P. M. Alaejos. "Sánchez De Juan. Durability of recycled aggregate concrete", Construction and Building Materials, 40, 1054-1065, 2013.
13. Kaur, G., Singh, S.P and Kaushik, S.K., Reviewing some properties of concrete containing mineral admixtures. Indian Concrete. 2012, pp. 35-51.
14. M. Limbachiya, M. S. Meddah, Y. Ouchagour. "Use of recycled concrete aggregate in fly-ash concrete",

Construction and Building Materials, 27, 439-449, 2012.
15. R. M. Salem, E. G. Burdette. "Role of chemical and mineral admixtures on the physical properties and frost resistance of recycled aggregate concrete", Materials Journal, 95, 558-563, 1998.
16. Gokce, S. Nagataki, T. Saeki. "Freeze-thaw cycles resistance of air-entrained concrete incorporating recycled coarse aggregate: the role of air content in demolished concrete", Cement and Concrete Research, 34, 799-806, 2004.
17. GB/T 50081-2002. Standard for Test Method of Mechanical Properties on Ordinary Concrete, Beijing: China Architecture and Building Press, 2002.

LIST OF FIGURES AND TABLES:

Received 22.06.2019
Revised 04.12.2019